ENGINE DESIGN AND TECHNOLOGY REQUIREMENTS
(Panel Discussion)

Warner L. Stewart, NASA Lewis Research Center, Cleveland, Ohio; William R. Collier, General Electric Company, Evandale, Ohio; Lindsay G. Dawson, Rolls-Royce, Derby, England; and Charles L. Joslin, Pratt & Whitney Aircraft, West Palm Beach, Florida

INTRODUCTION

Warner L. Stewart

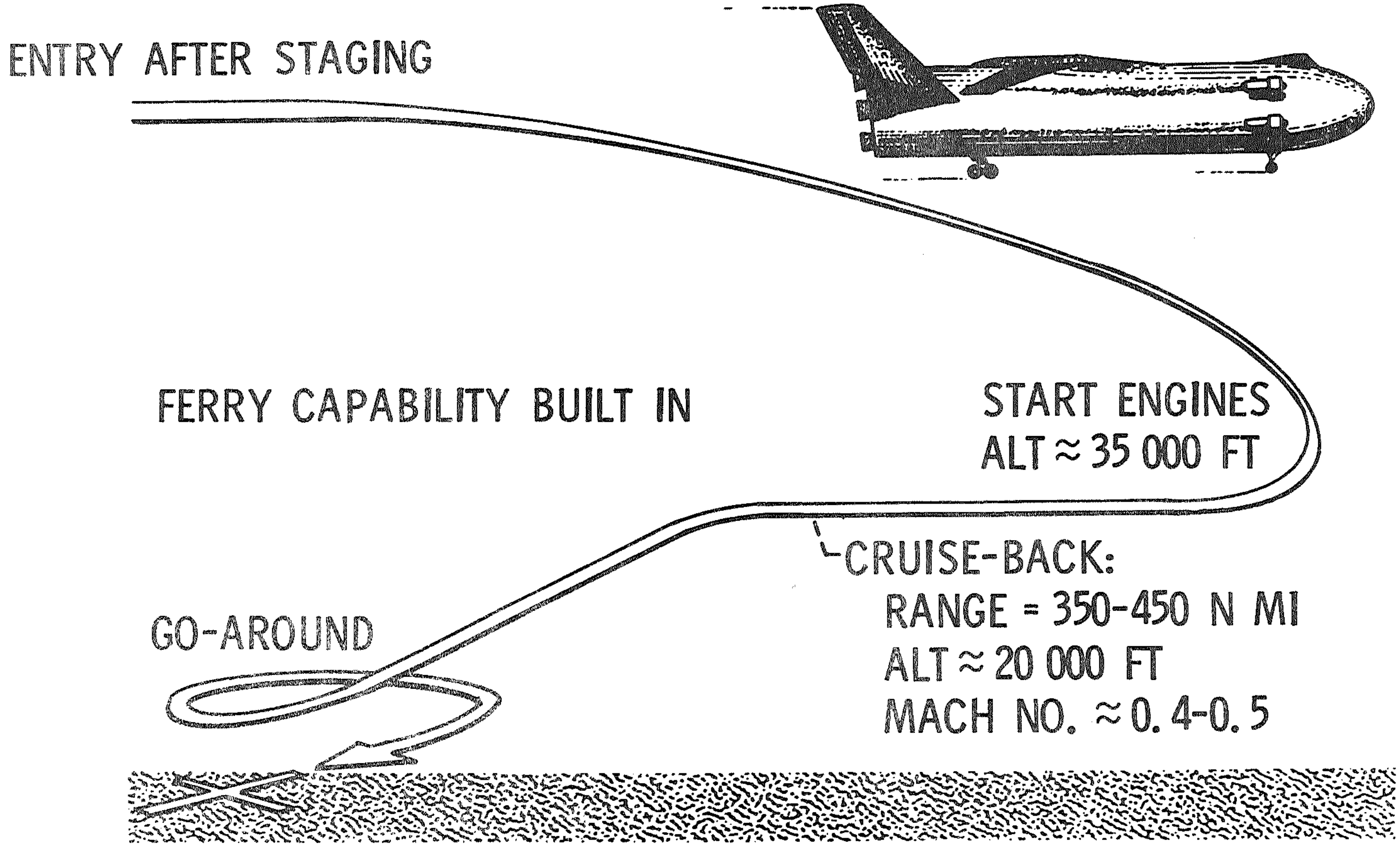
The shuttle concept as currently envisioned includes vehicle reuse for cost effectiveness and a semi-airline operating mode. Such characteristics result in the requirement for a third propulsion system (in addition to main and auxiliary) to provide for vehicle return and recovery. The airbreathing gas turbine engines thus employed would provide three principal functions (a) return cruise and landing glide-path control, (b) emergency go-around, and (c) vehicle ferrying.

Unique requirements for the shuttle mission result in non-conventional features for the airbreathing engines. The sensitivity of payload to inert weights has resulted in the consideration of hydrogen as the fuel and a desire for reduction in engine weight. Further, deviations from conventional engine internal design will be required to accommodate the new operating environments. This presentation will review some of the engine features and problem areas and then discuss those areas that are of greatest concern.

TYPICAL BOOSTER AIRBREATHING FLIGHT PROFILE

After staging, the booster reenters the atmosphere about 350 to 450 nautical miles away from its liftoff (and landing) site. The airbreathing engines are started at an altitude of about 35,000 feet, and the vehicle cruises back at an altitude of about 20,000 feet and a Mach number of .4 to .5. The engines are sized to meet the cruise requirement and this gives them enough thrust to provide go-around as well as self-ferry capability. The length of the flight time, which approaches two hours, makes the fuel consumption a major consideration for engine selection.

TYPICAL BOOSTER AIRBREATHING FLIGHT PROFILE



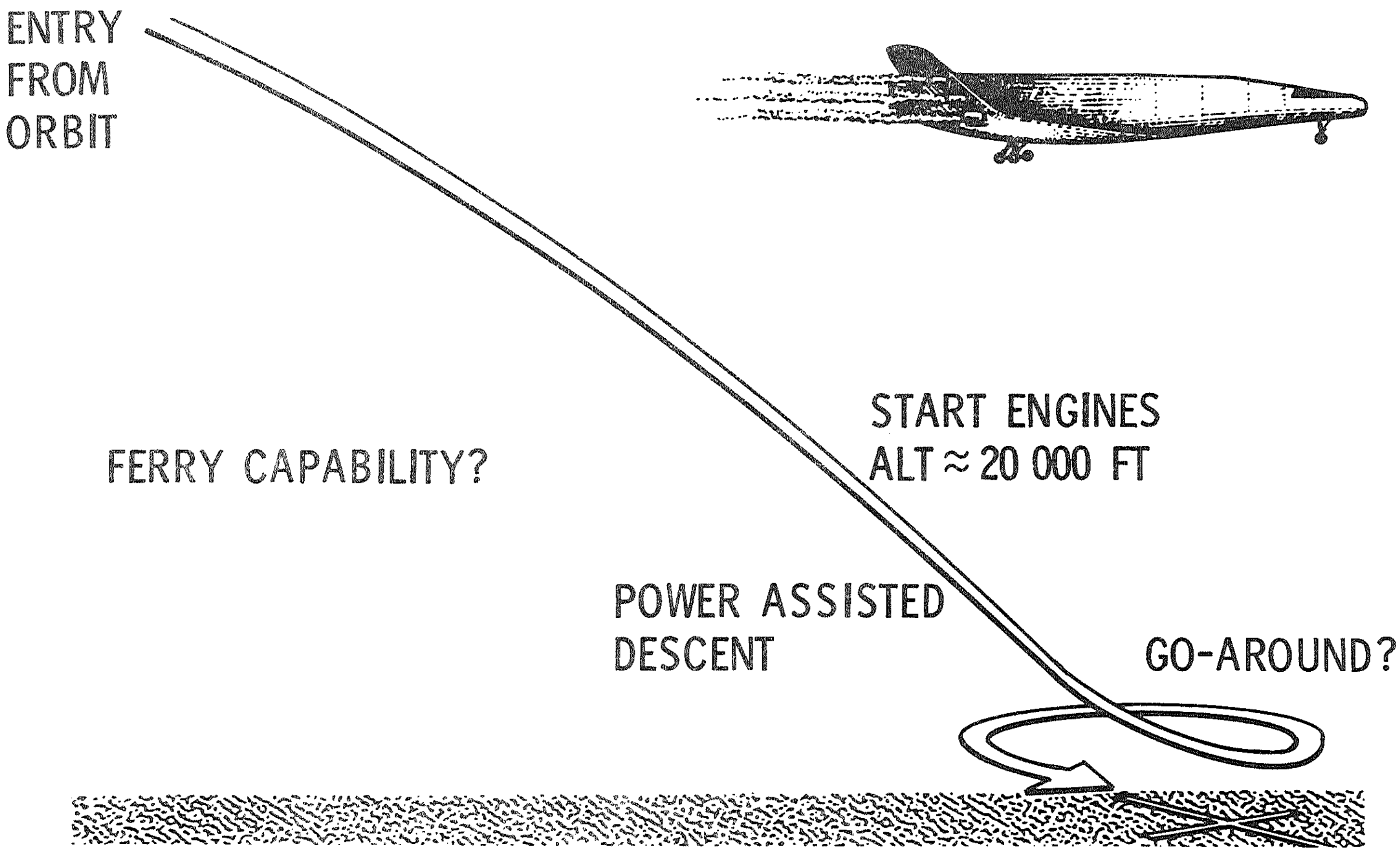
CS-54839

TYPICAL ORBITER AIRBREATHING FLIGHT PROFILE

After de-orbiting, the orbiter vehicle descends unpowered towards its landing site. The airbreathing engines are started at an altitude of about 20,000 feet, and the vehicle makes a power-assisted descent and landing. At present, go-around and self-ferry capability are required, and it is these requirements that size the engine. Since the engine operating time is very short, about 15 minutes, it is the engine weight that is a major consideration for engine selection.

If self-ferry and go-around requirements can be deleted, which is a current consideration, a significant weight reduction may result from the accompanying reduction in thrust requirement or possible elimination of the engines. However, any payload gain must be carefully weighed against mission safety considerations.

TYPICAL ORBITER AIRBREATHING FLIGHT PROFILE



CS-54838

ENGINE REQUIREMENTS

Except for the common use of hydrogen fuel, the engines for the booster and the orbiter vehicles have significantly different requirements. The booster engines must provide higher total thrust and longer life than the orbiter engines, but the weight of the booster engines does not affect payload as critically as does the weight of the orbiter engines. These differences in requirements together with the previously shown differences in mission imply that optimum engine cycles for the booster and the orbiter would be different. In addition, the orbiter engine requires protection against extended space vacuum and temperature exposure while the booster engine does not.

ENGINE REQUIREMENTS

	BOOSTER	ORBITER
FUEL	HYDROGEN	HYDROGEN
LOW WEIGHT - ENGINE/PAYLOAD WEIGHT SENSITIVITY	5/1	1/1
TOTAL INSTALLED THRUST (SLS), LB	140-200 000	60-80 000
LIFE, HR	500	50
SPACE EXPOSURE	MINUTES	$\leq$ 30 DAYS

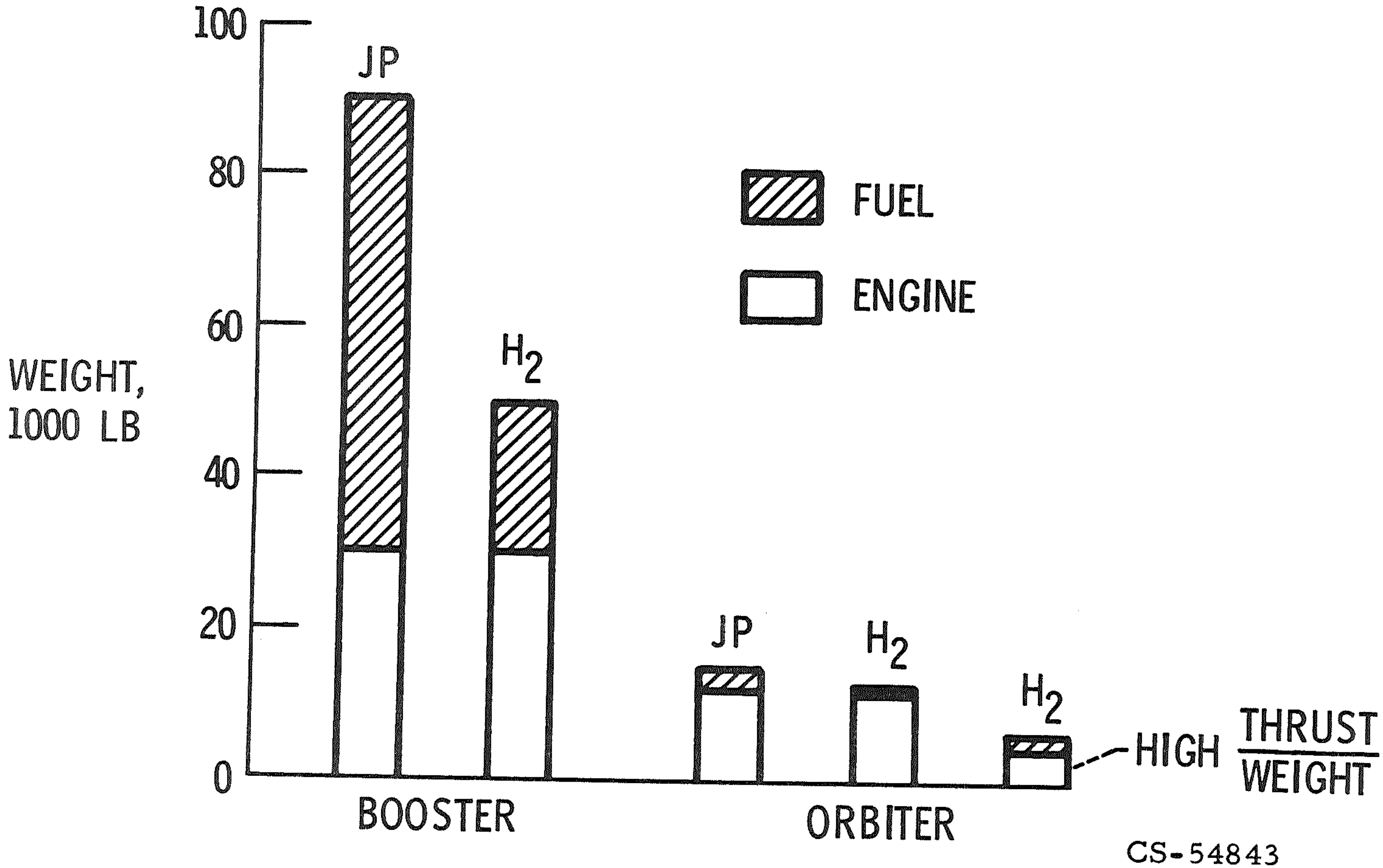
CS-54844

EXAMPLE EFFECTS OF FUEL TYPE AND ENGINE WEIGHT

For a typical booster mission, the amount of hydrogen required would be about 40,000 pounds less than the amount of JP fuel. This difference in fuel weight reflects a payload gain of about 8,000 pounds when using hydrogen. For the orbiter mission with its much shorter operating time, the approximately 2,000 pound savings in fuel directly corresponds to a 2,000 pound payload gain. Thus, the use of hydrogen as the fuel, while yielding payload gains for both vehicles, is especially attractive for the booster.

If the thrust-to-weight ratio of the orbiter engine could be doubled, then even with a doubling of the fuel consumption, there could result a payload gain of about 5000 pounds. For the booster, it can be seen that such a trade would yield a larger increase in fuel weight than would be the decrease in engine weight. Such a thrust-to-weight ratio improvement could possibly be achieved with advanced turbojet engines currently being studied for VTOL application. However, this type of engine in the size range required for the shuttle is not under development at present.

EXAMPLE EFFECTS OF FUEL TYPE AND ENGINE WEIGHT

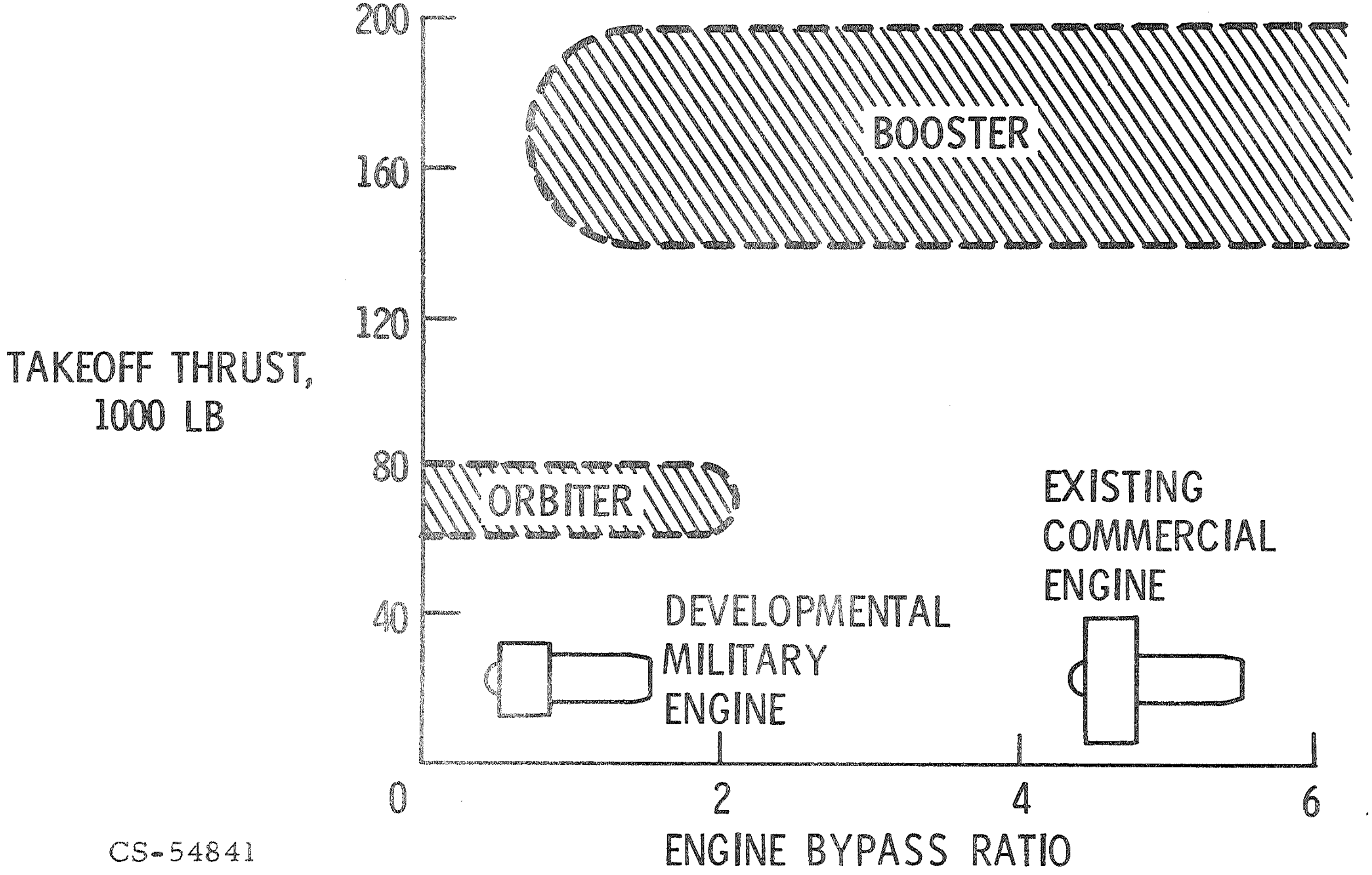


CONSIDERATION OF ENGINE COMMONALITY

It was stated previously that optimum engine cycles would probably differ for the booster and the orbiter. For the booster, turbofan engines of high bypass ratio would yield the desired low fuel consumption. However, other considerations, such as frontal area, extend downward the range of bypass ratios to be considered. For the orbiter, high thrust-to-weight ratio engines such as turbojets or low bypass ratio turbofans are considered.

As indicated in the figure, there is some overlap in the bypass ratio ranges being considered for each mission. Thus, the bypass ratio range of about .5 to 2 would be the area of interest for a common engine for both vehicles. While a common engine probably would not be optimum for either mission, the performance penalty might not be too severe and the monetary savings would be quite significant. As seen from the indicated thrust requirements, the use of a common engine would result in the booster requiring at least twice the number of engines as the orbiter.

CONSIDERATION OF ENGINE COMMONALITY



CS-54841

TECHNOLOGY AREAS

In considering the shuttle mission and engine requirements, we find that there are several new technology areas that must be explored before a firm design can be established. Experience with hydrogen fuel systems for jet engines has been very limited. With rocket engines, for which there is considerably more experience, the operating time is only a matter of minutes as compared to the several hundred hours required for the shuttle. The payload gain associated with engine weight reduction leads to the desire to explore lightweight-engine techniques and materials. The launch loads and vibration and the space vacuum and temperature environments require that examination be made of associated problems with materials, structures, bearings, and lubrication system.

TECHNOLOGY AREAS

HYDROGEN FUEL
- SYSTEM
- PUMP

LIGHTWEIGHT ENGINES

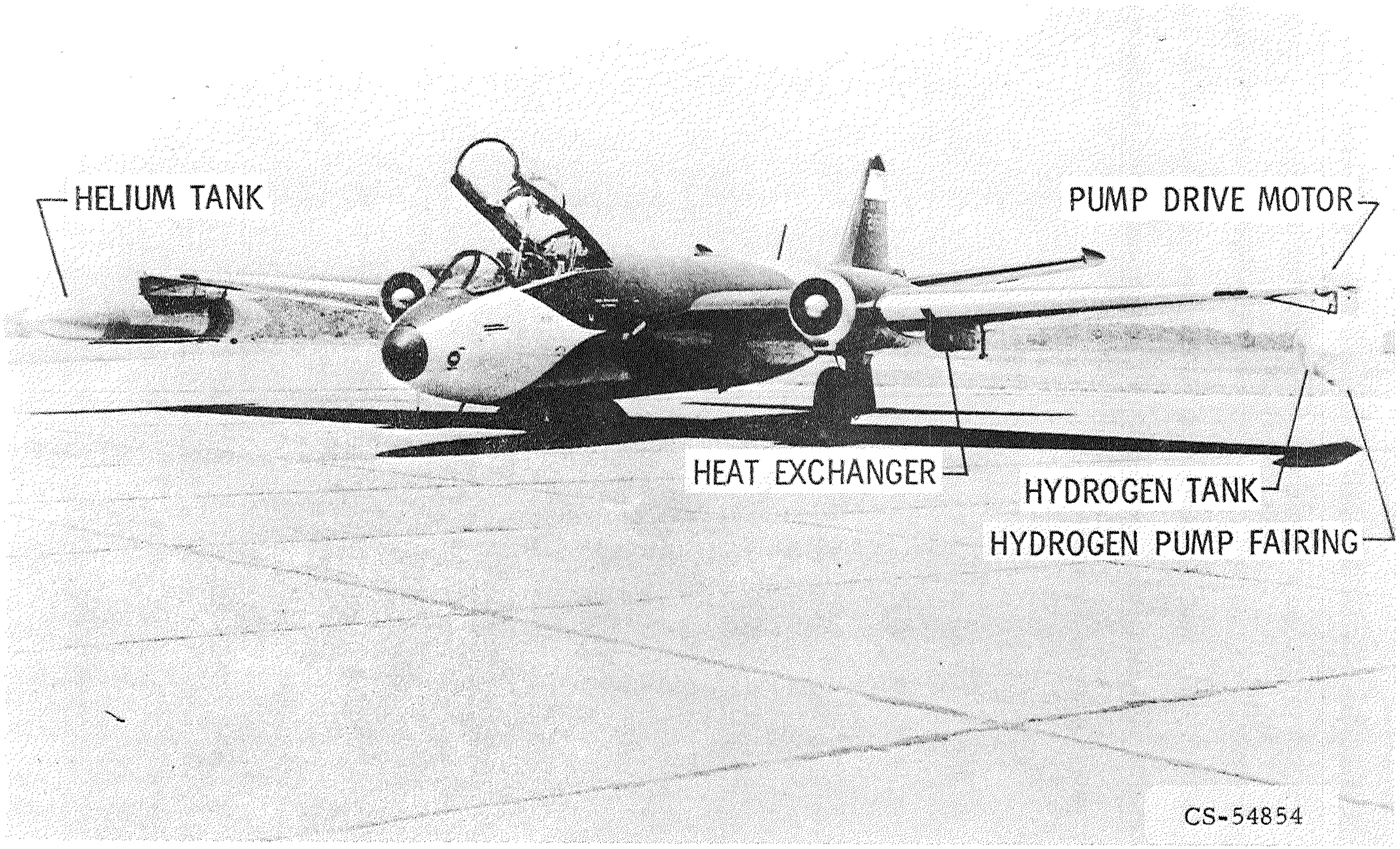
LAUNCH & SPACE ENVIRONMENT
- STRUCTURES & MATERIALS
- BEARINGS & LUBE SYSTEM

CS-54840

AIRCRAFT WITH PUMP-FED LIQUID HYDROGEN FUEL SYSTEM

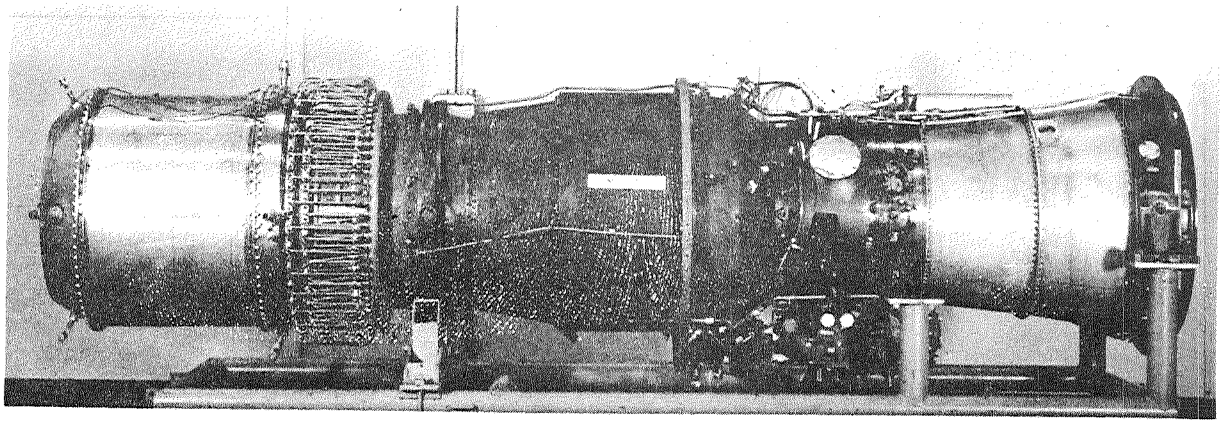
Jet engines have been run on a test basis using hydrogen fuel. This figure shows a B-57 airplane that was used for such a purpose at Lewis Research Center in the mid 1950s. Modifications were made such that the engine could be run on hydrogen fuel during altitude flight. Successful operation was achieved.

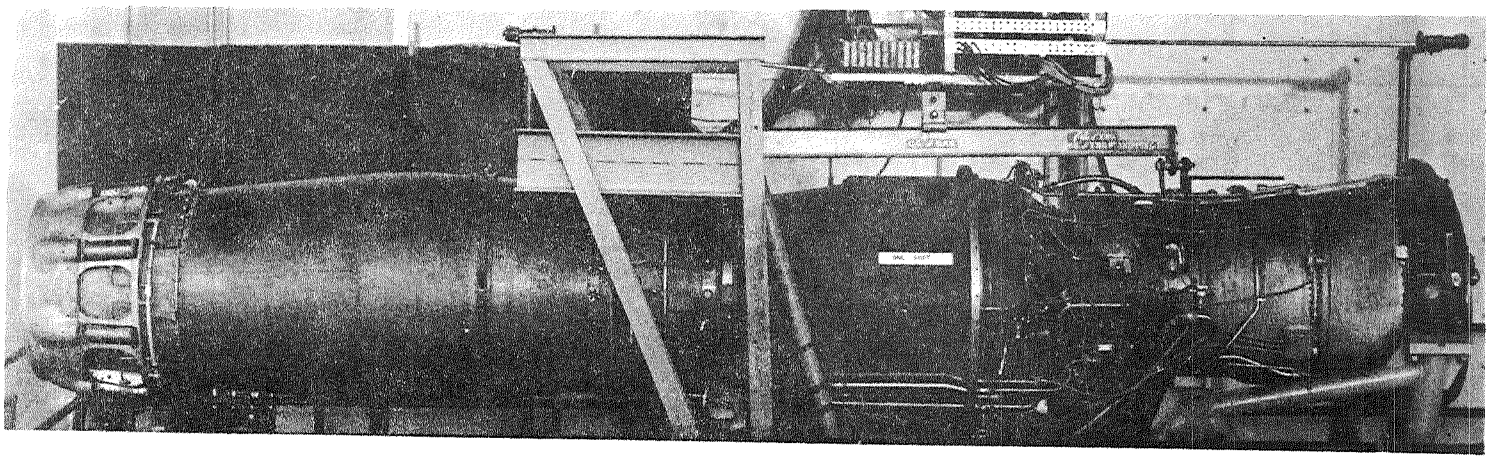
AIRCRAFT WITH PUMP-FED LIQUID-HYDROGEN FUEL SYSTEM



Charles L. Joslin

Experience with hydrogen at Pratt & Whitney Aircraft began in 1956. In 1957 the J-57 engine was converted to hydrogen fuel. The facing photograph shows the converted engine at the top compared with the standard JP fueled J-57. The shorter length of the modified version is due entirely to the afterburner being shortened to take advantage of the better burning characteristics of hydrogen.

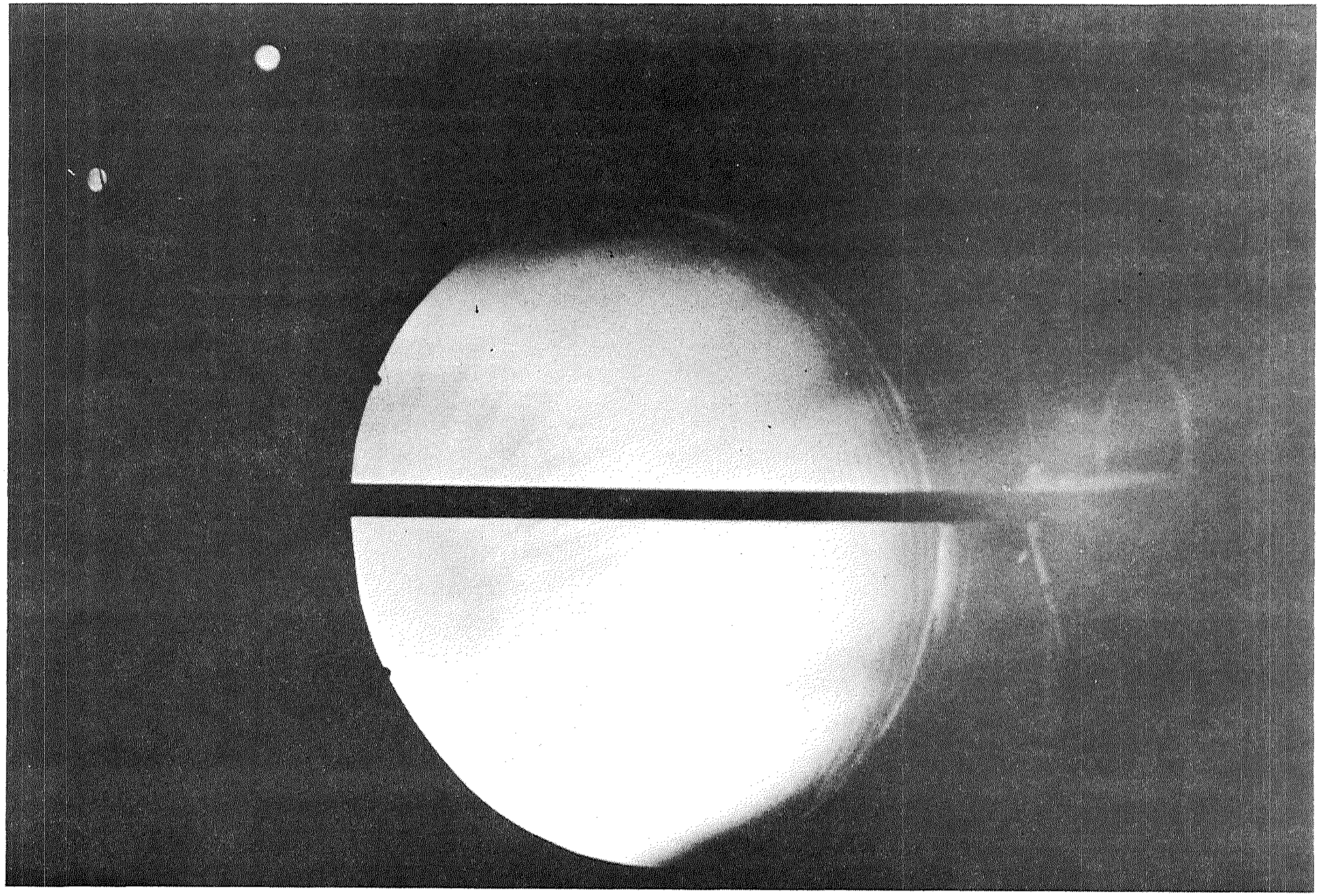




Comparison of J-57 Engine With H_2 Regeneratively Cooled Afterburner and With Standard Afterburner

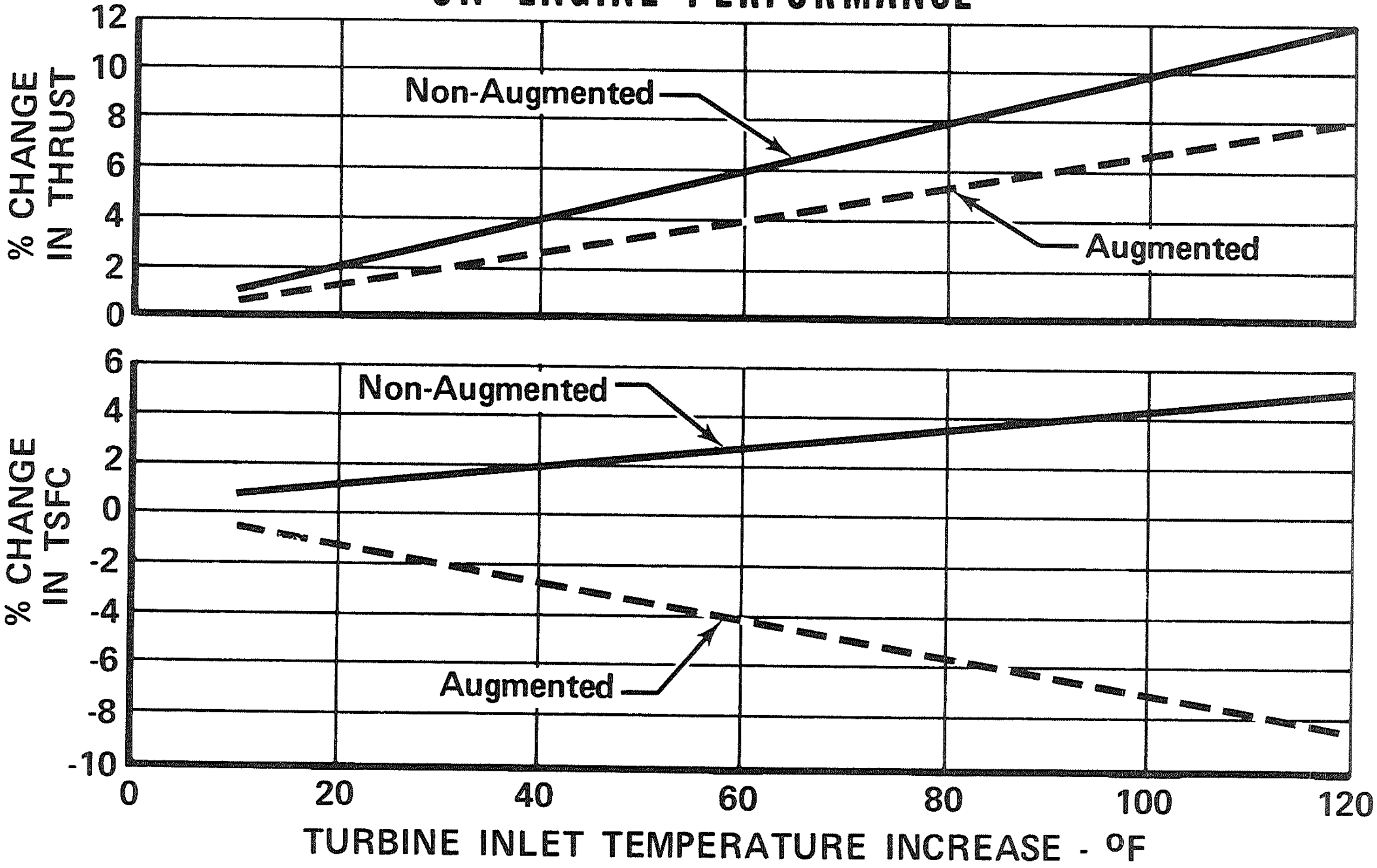
This photograph shows the tailpipe of the converted J-57 engine operating on hydrogen fuel at full afterburning thrust. Although the afterburner gas temperature is approximately 4150°R, the afterburner case is cold since it is regeneratively cooled with hydrogen.

HYDROGEN-FUELED AFTERBURNER IN OPERATION



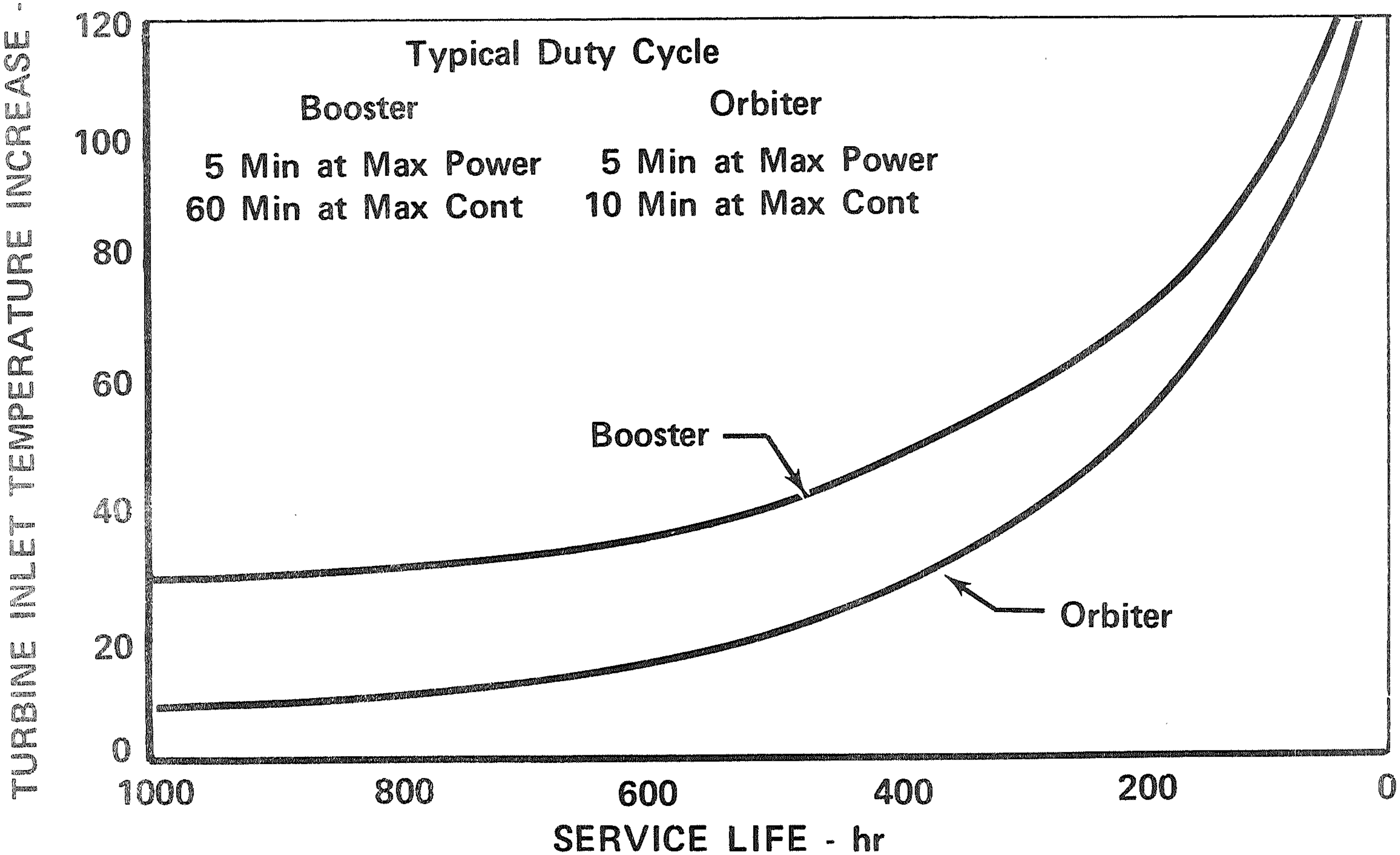
Relatively small increases in turbine inlet temperature can significantly improve engine performance. This figure illustrates the magnitude of this effect on a typical mixed flow turbofan engine. The higher temperature improves engine thrust-to-weight ratio. If the engine is augmented, increased turbine temperature also improves specific fuel consumption. If the engine is non-augmented, the specific fuel consumption increases slightly.

TYPICAL EFFECT OF TURBINE INLET TEMPERATURE ON ENGINE PERFORMANCE



The Space Shuttle requires considerably less engine service life than a conventional aircraft. Reduced life, in turn, permits increased turbine operating temperature. This chart shows the approximate magnitude of this effect for a typical mixed-flow turbofan engine, based on representative duty cycles for the Space Shuttle booster and orbiter.

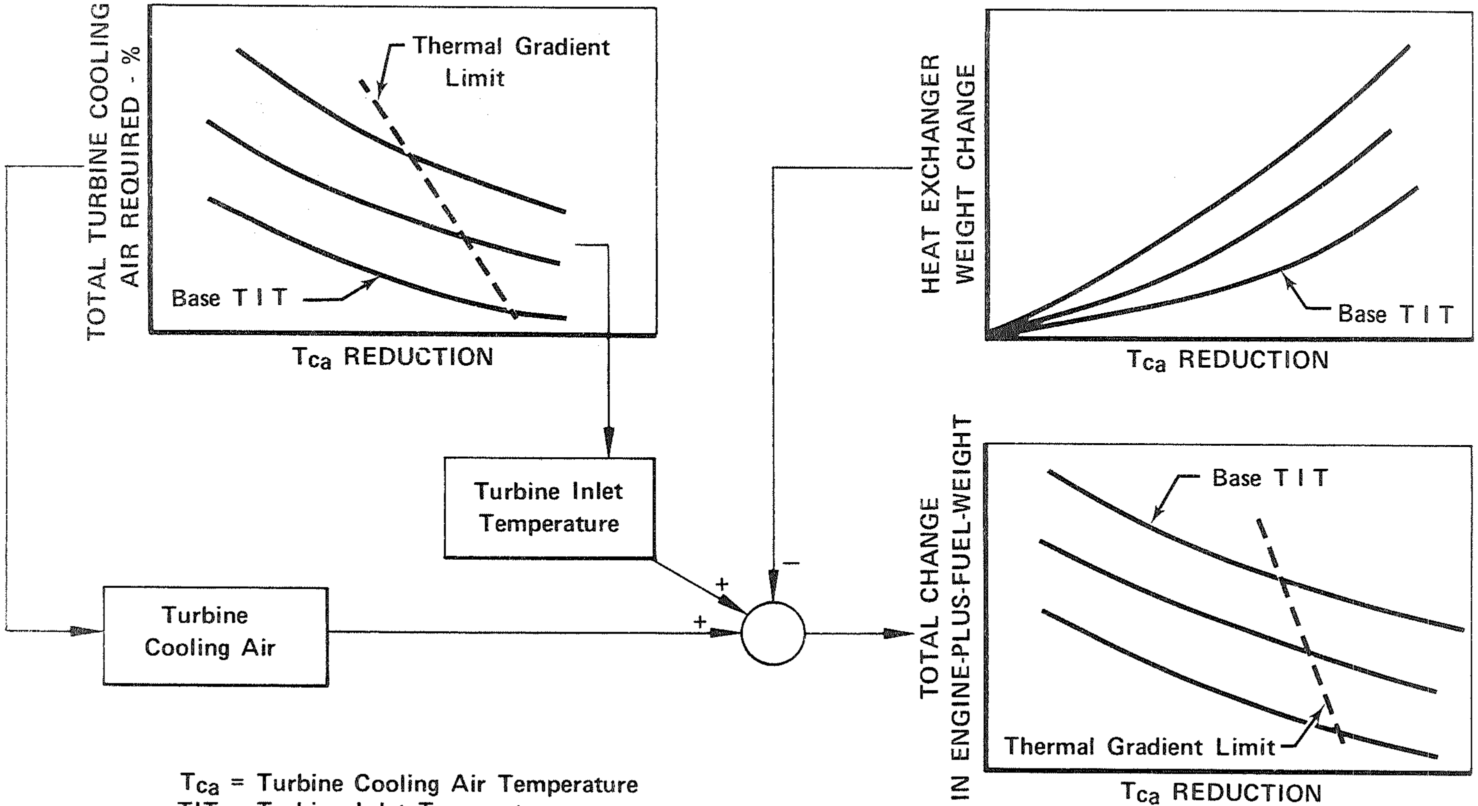
TURBINE TEMPERATURE CAN BE RAISED TO MATCH REDUCED LIFE REQUIREMENTS



The use of hydrogen fuel introduces the possibility of raising the turbine inlet temperature by cooling the turbine cooling air. The facing chart illustrates the trade-offs associated with this technique.

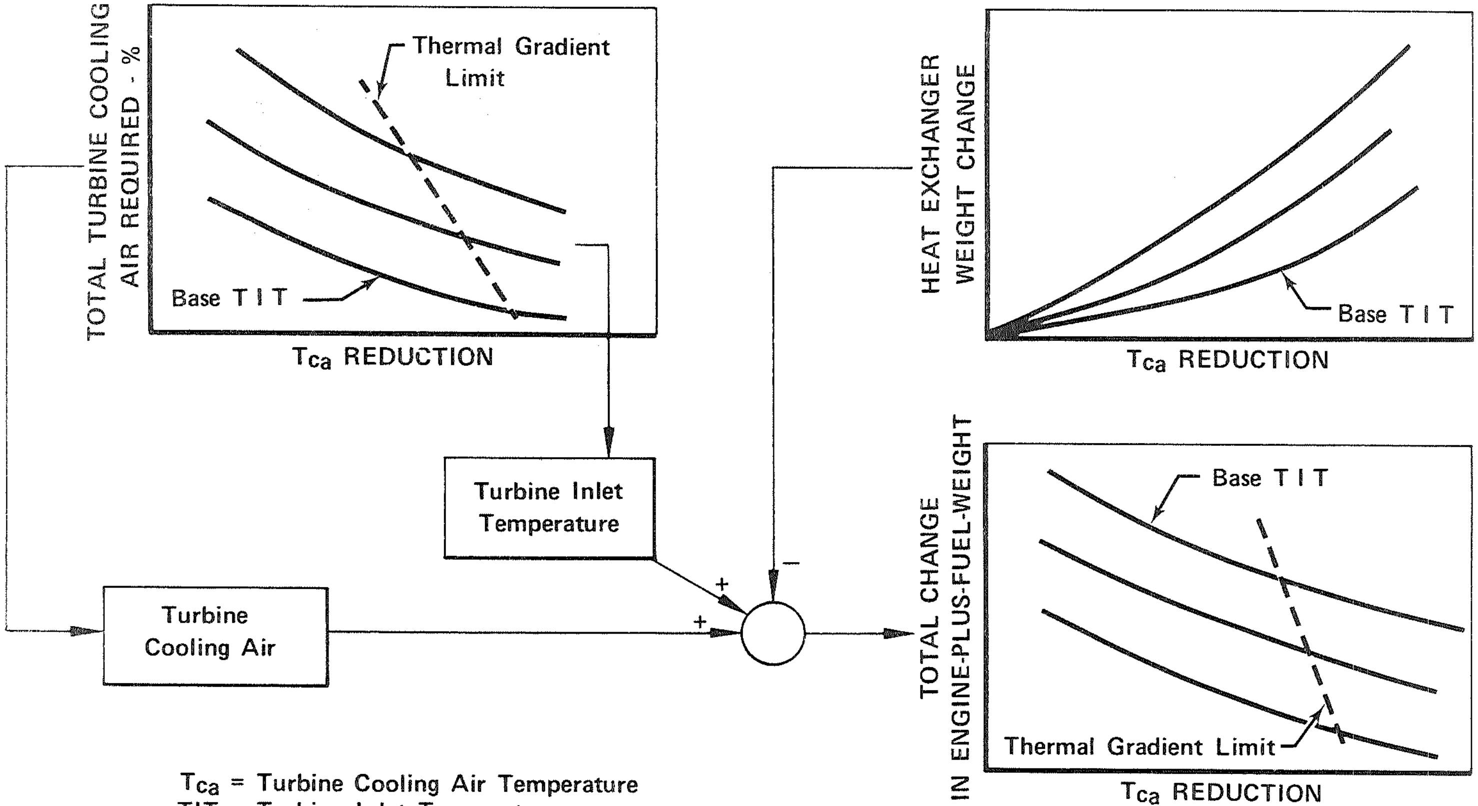
Reducing the amount of cooling air improves specific fuel consumption while increasing turbine temperature raises thrust-to-weight ratio. Both of these effects reduce engine-plus-fuel weight, but a heat exchanger is required and this increases weight. The proper trade-off should produce a net gain for the mission.

CHANGE OF ENGINE-PLUS-FUEL-WEIGHT WITH TURBINE INLET TEMPERATURE AND TURBINE COOLING AIR



T_{ca} = Turbine Cooling Air Temperature
TIT = Turbine Inlet Temperature

CHANGE OF ENGINE-PLUS-FUEL-WEIGHT WITH TURBINE INLET TEMPERATURE AND TURBINE COOLING AIR



T_{ca} = Turbine Cooling Air Temperature
TIT = Turbine Inlet Temperature

HYDROGEN FUEL SYSTEM

William R. Collier

The major modification necessary to adapt airbreathing engines to the Space Shuttle requirements is the conversion to cryogenic hydrogen fuel. NASA has a technology program to design and evaluate a hydrogen fuel system which will culminate in operation of a J85 engine on hydrogen fuel in 1971. The program will encompass the key development areas of pumping, regulation and metering of flow levels, and transient investigations.

While the actual combustion of hydrogen fuel is expected to be a routine development, a number of problems exist in supplying, metering and delivering the fuel in the proper state and quantity for combustion. The fuel is assumed to be supplied from the tank in the liquid phase, and at sufficient pressure at the main pump inlet to prevent cavitation.

The characteristic low starting fuel flow of a turbojet or turbofan engine necessitates a high pump turndown ratio, 40:1. This requirement coupled with a fast response places a stringent demand on the fuel supply system. A vane pump with variable speed drive is capable of delivering higher pressure in the low flow range than the more conventional centrifugal pumps. It is, however, recognized that little or no experience exists on vane pumps-pumping cryogenic fuels, and thus other types of pumps are also being studied.

HYDROGEN FUEL SYSTEM

- NASA/LEWIS TECHNOLOGY PROGRAM TO EVALUATE FUEL SYSTEM AND COMPONENTS BY ENGINE TESTING IN 1971

- DIRECTED TOWARD INVESTIGATION OF SUCH ITEMS AS
  - PUMPING
  - TEMPERATURE CONTROL
  - PRESSURE REGULATION
  - TRANSIENT CHARACTERISTICS
  - METERING
  - SAFETY

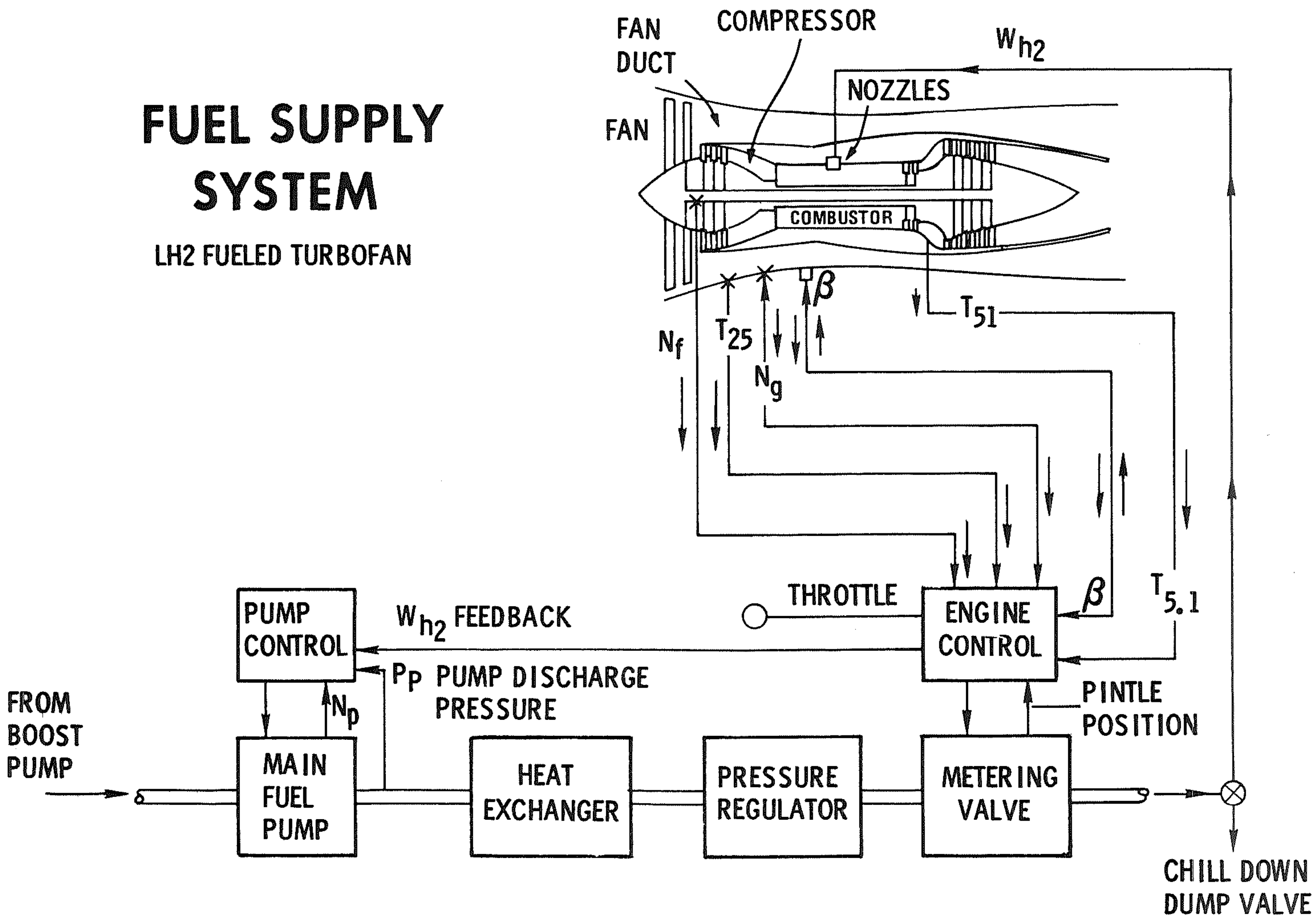
Control main fuel pump discharge is obtained by enclosing the pump in a closed servo-loop, with pump shaft speed regulated to maintain the discharge pressure at the constant reference level.

The heat exchanger is planned to provide sufficient heat addition to the fuel to assure that it will be gaseous as it enters the metering valve and will be designed for supercritical pressures to achieve a more predictable heat transfer coefficient.

The metering valve is designed for precise flow control and for accurate flow measurement. Area is varied as a function of the position of a fixed area plug which is positioned along the axis of the valve. The plug, or pintle, is controlled electro-hydraulically with the position measured and fed back by a linear variable differential transformer, (LVDT). The gas flow is then calculated from measured gas temperatures and pressures by the electronic computer and employed as a feedback signal in the fuel flow control loop. The metering valve area is thus controlled to maintain engine core speed during steady-state and transient operation.

FUEL SUPPLY SYSTEM

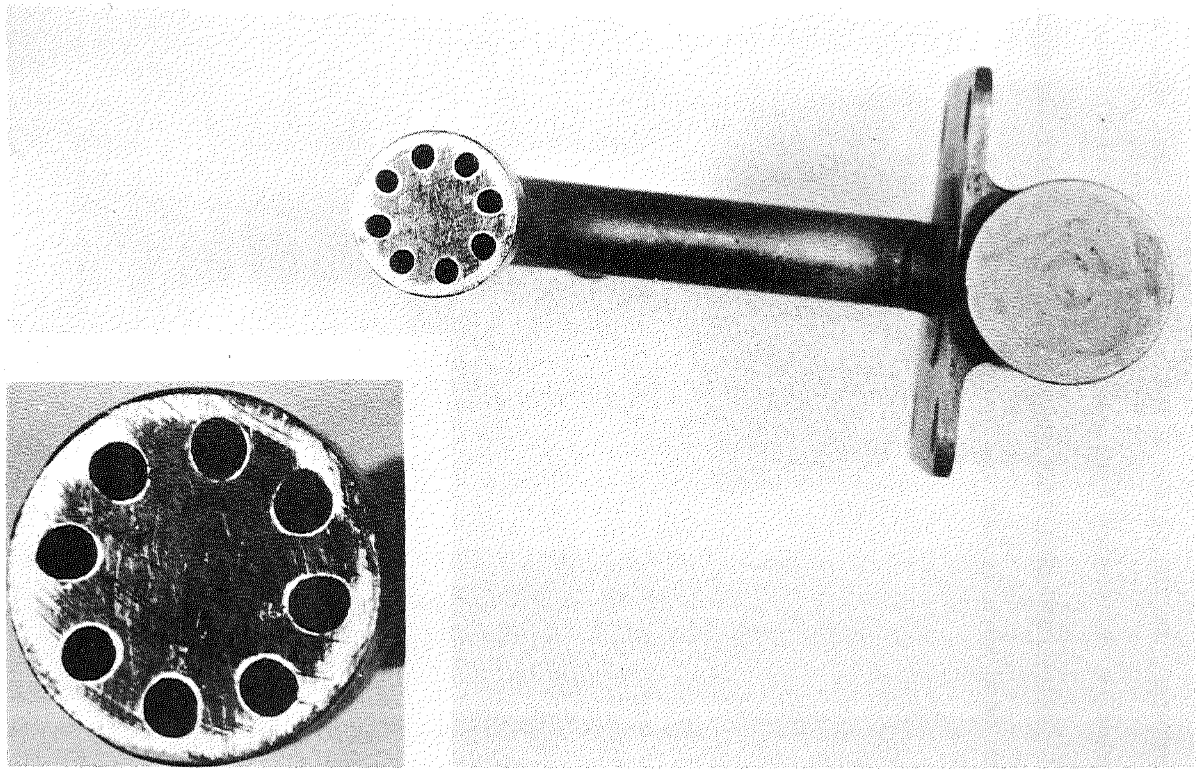
LH2 FUELED TURBOFAN



The need for the space shuttle to operate on cryogenic hydrogen fuel places a new set of requirements on the engine combustion system. No major problems are foreseen in burning hydrogen. Combustor sector testing and full scale testing of the J85 engine on gaseous hydrogen, as low as -244°F, have indicated smooth starts and stable operation. Slide 3 is a photograph of a hydrogen fuel injector used in the J85 engine test for 2 hours and 45 minutes.

The high reactivity of the fuel will in general improve light-off and stability limits, but it will also necessitate modification of the combustor liner to introduce more cooling air in the primary combustion zone. The reduced luminosity of the hydrogen flame will reduce radiation to the combustor liner so that some reduction in metal temperatures may be expected, improving part life.

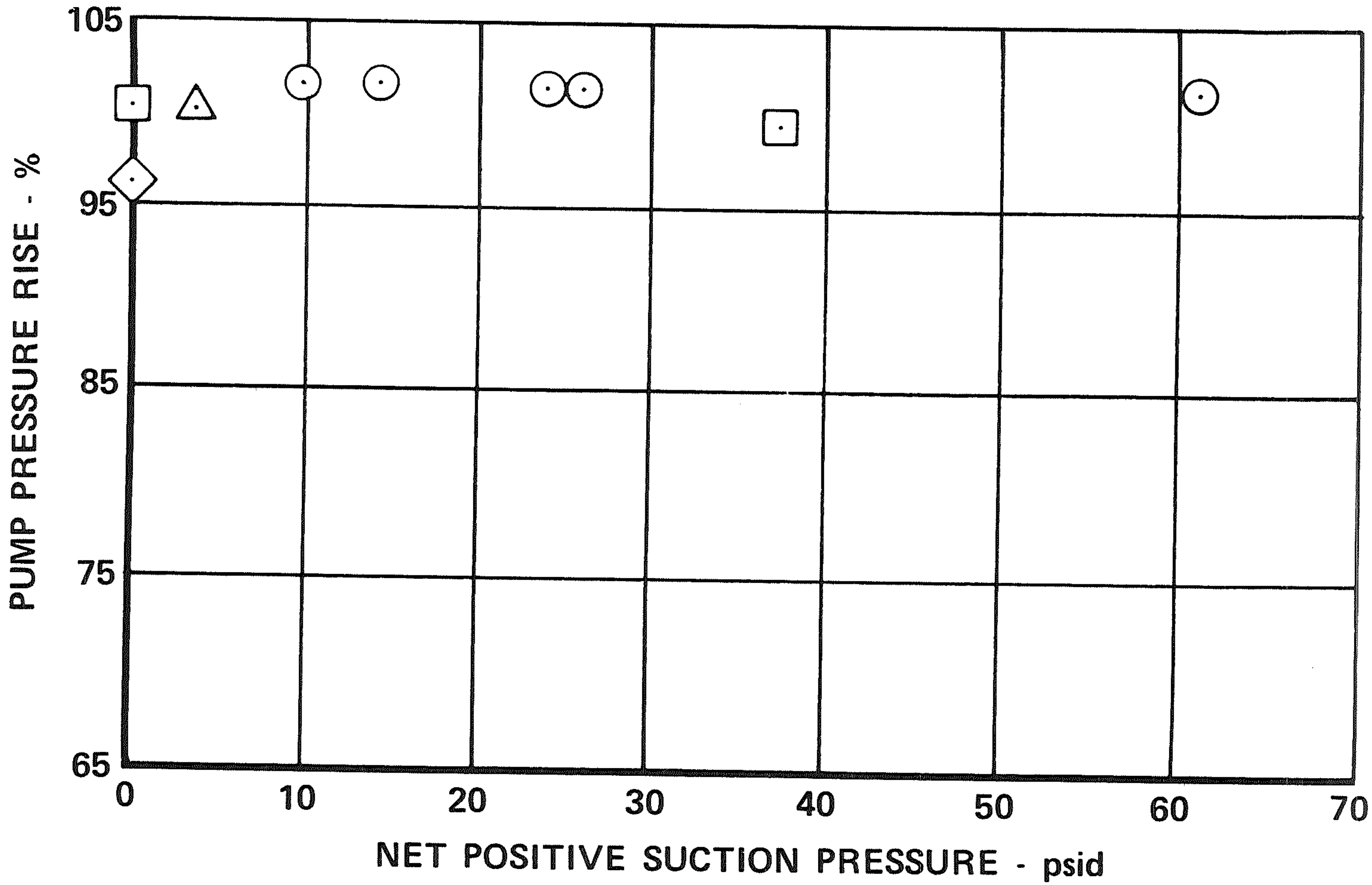
J85 HYDROGEN FUEL NOZZLE



Charles L. Joslin

The marriage of the engine to the Space Shuttle vehicle introduces a variety of interface considerations. Of major importance to the vehicle manufacturer, is the positive suction pressure that must be provided at the inlet to the engine fuel pump. As can be seen in this chart, the RL10 rocket engine hydrogen fuel pump has been successfully operated with zero suction head when liquid was provided at the pump inlet.

RL10A-3-7 FUEL PUMP PERFORMANCE



Another important interface requirement is the cooldown flow that must be provided to the engine. As can be seen in this figure, an increase in net positive suction pressure (possibly in conjunction with other techniques) can minimize cooldown time. There appears to be a trade-off between boost pump weight and cooldown propellant losses.

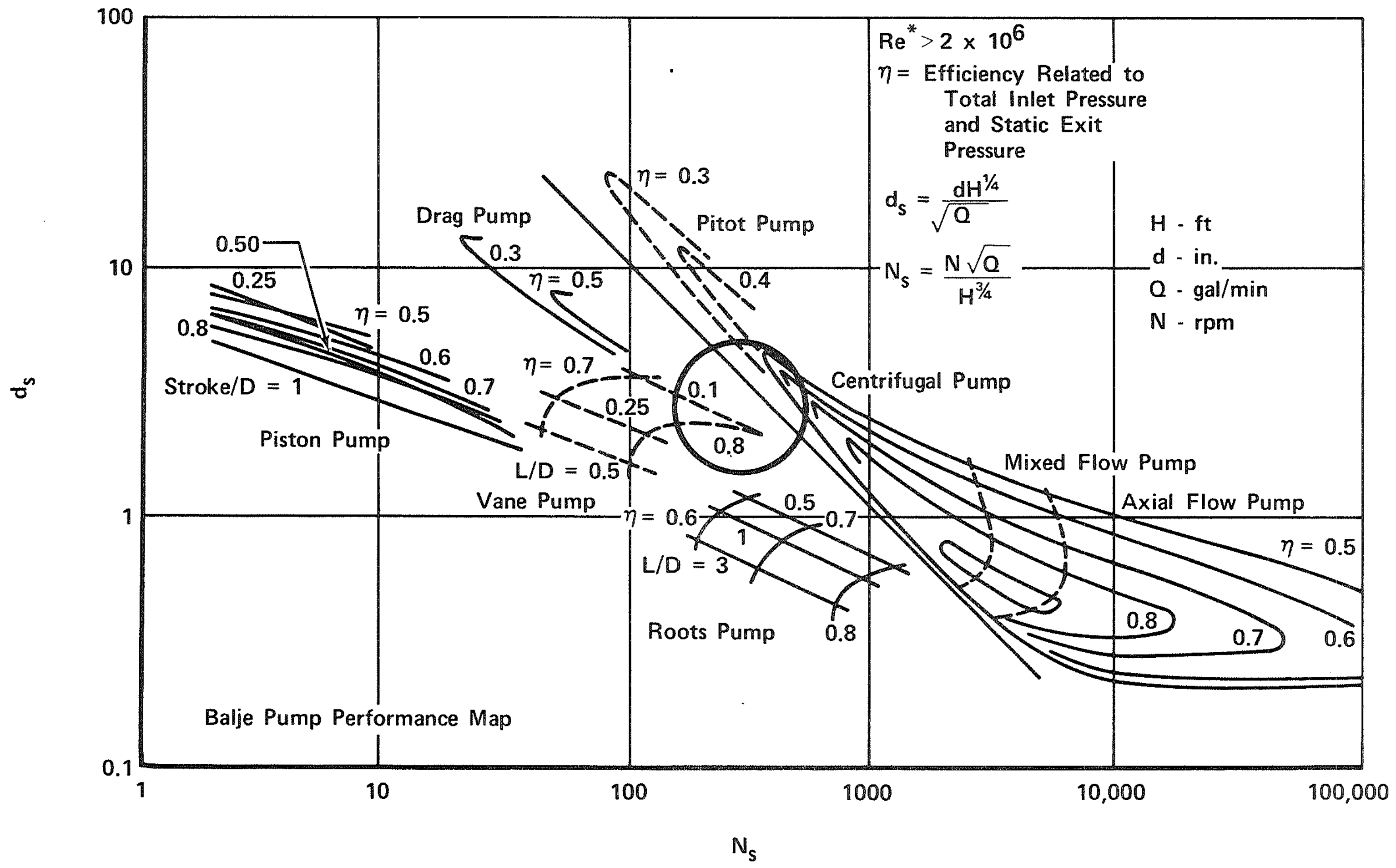
RL10 CRYOGENIC COOLDOWN EXPERIENCE

Time Period	Oxidizer Pump		Fuel Pump	
	Inlet Pressure, psia	Cooldown Required, sec	Inlet Pressure, psia	Cooldown Required, sec
1960 - 1964 Early Centaur Flights	110	20	45	20
1964 - 1965 Saturn Flights	45	10	35	40
1964 - 1965 Experimental RL10	45	0	55	0*

*KEL-F Internally Insulated Pump

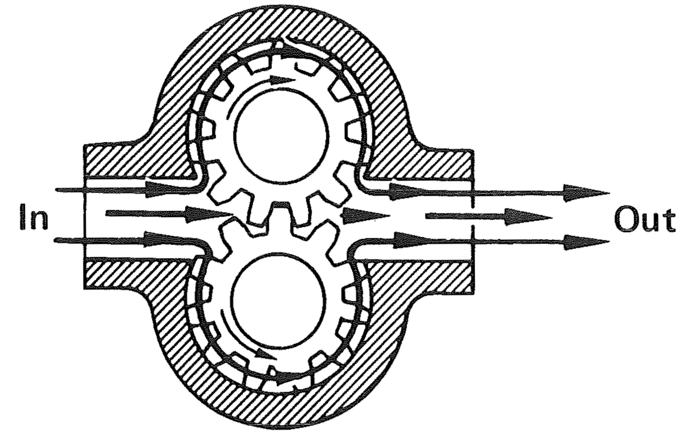
This figure shows the Baljé plot. In it, Baljé has correlated the best of the various types of pumps in terms of specific speed and specific diameter. The circle shows the region which appears to apply to the space shuttle airbreathing engine. As can be seen, both the vane type positive displacement pump and the centrifugal pump may be candidates.

SELECTION OF MOST SUITABLE PUMP REQUIRES EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS

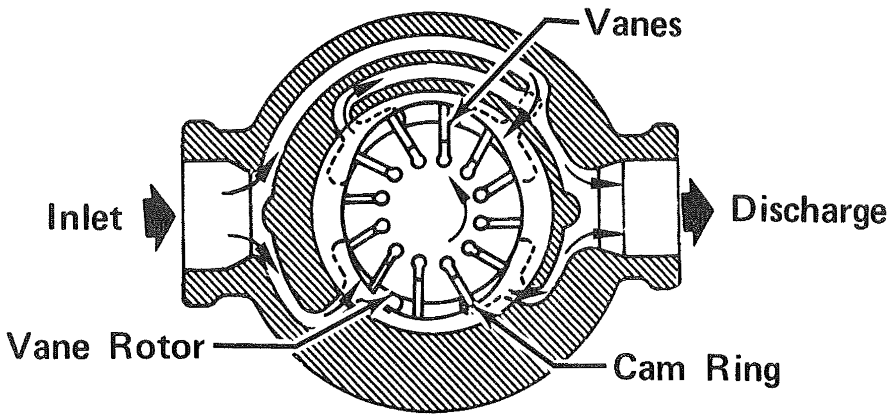


This figure shows schematics of representative positive displacement pumps. The positive displacement pump has some characteristics that are attractive for Space Shuttle application. However, no flight type cryogenic positive displacement pump has ever been developed.

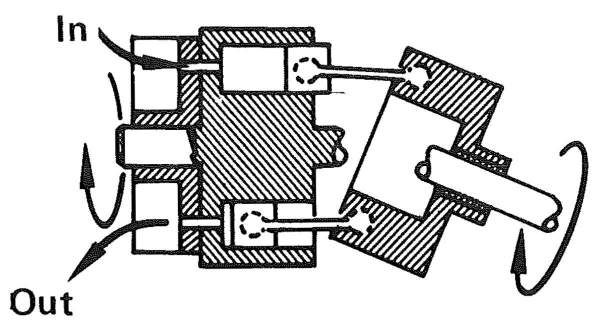
POSITIVE DISPLACEMENT PUMP TYPES



a. Gear Pump-External



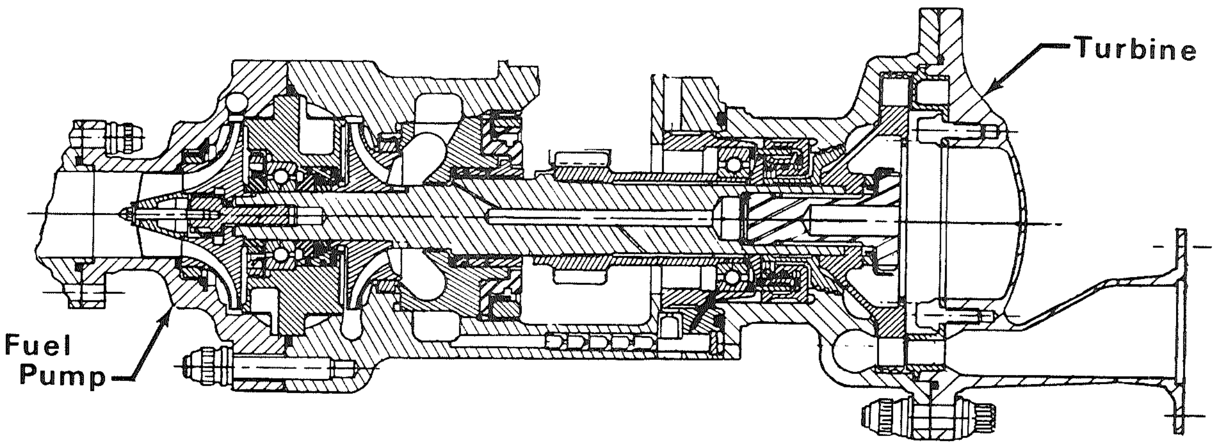
b. Balanced Rotor Vane Pump



c. Bent Axis Piston

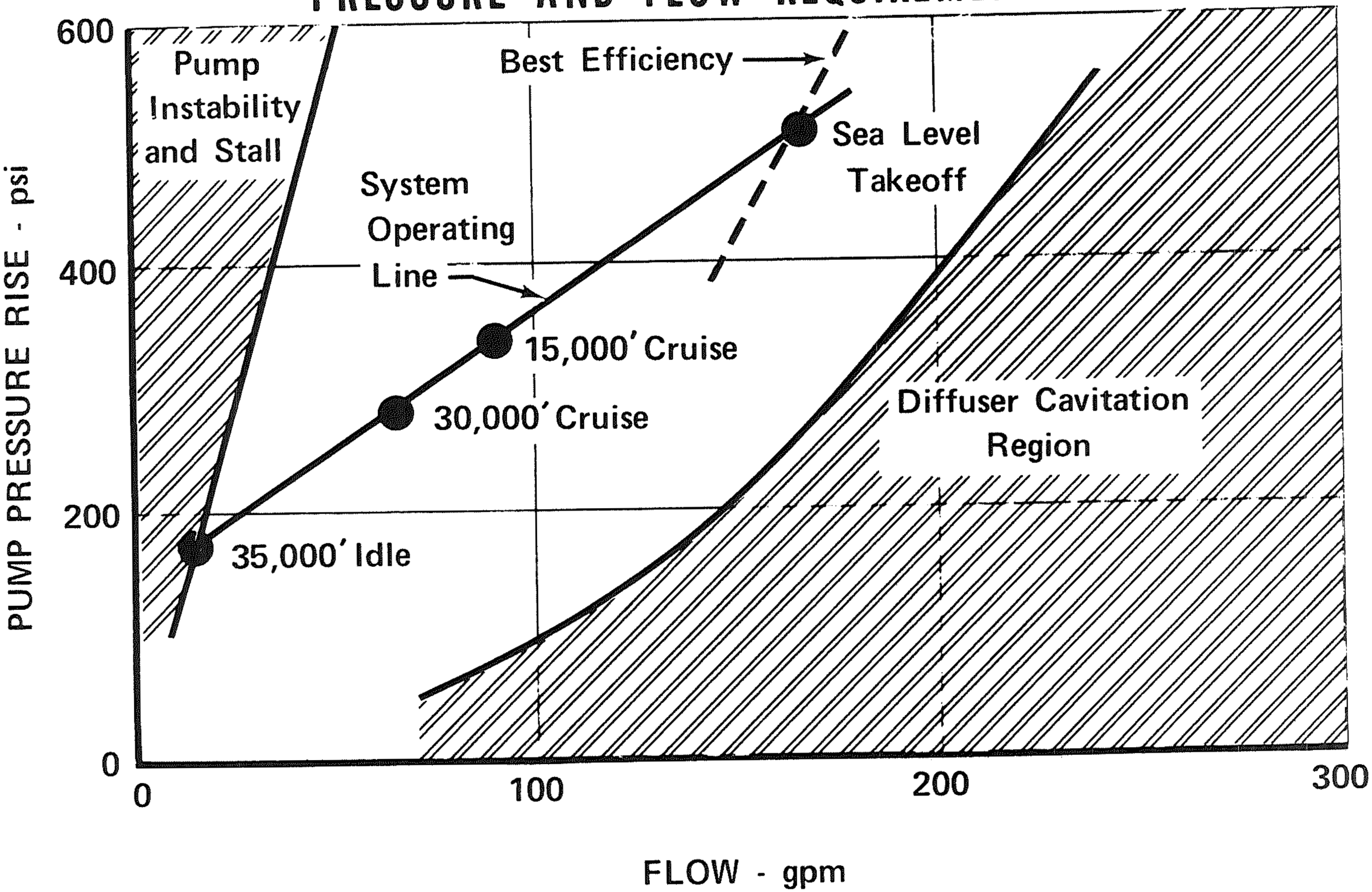
This figure is a schematic of a typical modern cryogenic centrifugal pump. The experience that has been gained with centrifugal hydrogen pumps provides a sound base for the Space Shuttle engine fuel system.

CENTRIFUGAL TURBOPUMP



In this chart the fuel flow requirements of the JT9D turbofan engine are plotted against typical centrifugal pump characteristics. Because of the wide flow range required, the pump may be operating in or near stall at the high altitude-low fuel flow conditions.

TYPICAL HYDROGEN PUMP WITH JT9D FUEL PRESSURE AND FLOW REQUIREMENTS



Previous hydrogen pumps have been developed for rocket engines with very low life requirements compared to an airbreathing engine. Although the service life of the Space Shuttle airbreathing engines has not been specified yet, a 250 to 500 hour life requirement for the engine may mean that the fuel pump should have a life of 500 to 1000 hours. This introduces a new area of hydrogen bearing technology, as can be seen in the facing table.

HYDROGEN COOLED BEARING TECHNOLOGY

Demonstrated Life

	Time, hr
80 mm (Ball) 4 Million DN	0.2
200 mm (Ball) 3 Million DN	1.2
35-40 mm (Ball) 1.2 Million DN	50
35-40 mm Roller 0.8 Million DN	50

Required Life

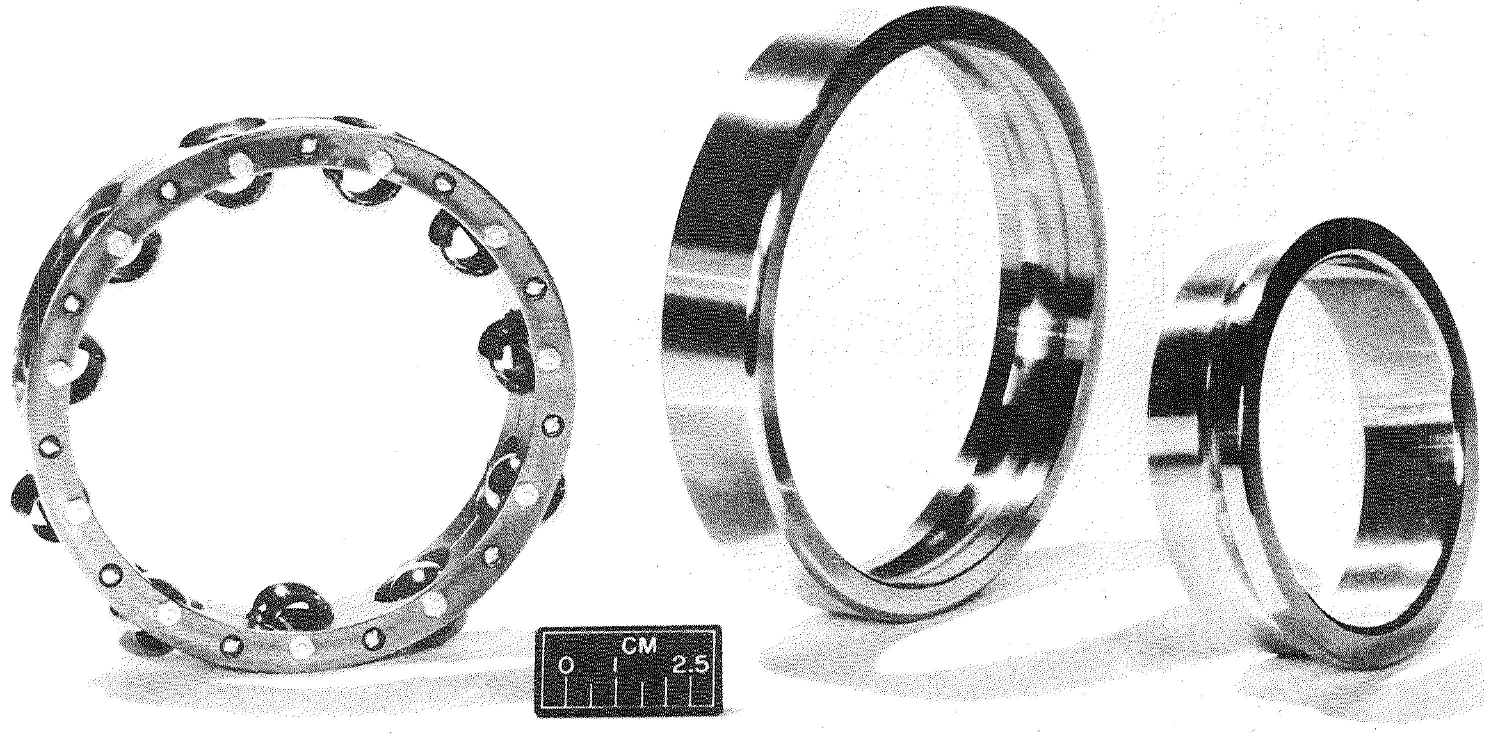
25-40 mm (Ball) 1.4 Million DN	500-1000
20 mm (Roller) 0.2 Million DN	500-1000

HOLLOWED BALL BEARINGS

Warner L. Stewart

Several advanced bearing concepts for operation in a cryogenic environment are being studied at Lewis Research Center. These bearing concepts have potential application for both the main rocket engine pumps and the airbreathing engine fuel pump. Being studied are a self-lubricating concept using lead-coated retainers and a concept using hollow (drilled) balls as shown in this figure. This type of bearing with oil lubrication has been run at 3 million DN for a period of 4 hours. Testing is being continued.

HOLLOWED BALL BEARING



C-69-1256
CS-54845

Airbreathing Engines for Shuttle Vehicles (VML 42793)

Lindsay G. Dawson

The facing diagram indicates the value of applying lift engine technology to the Orbiter vehicle gas turbine engines.

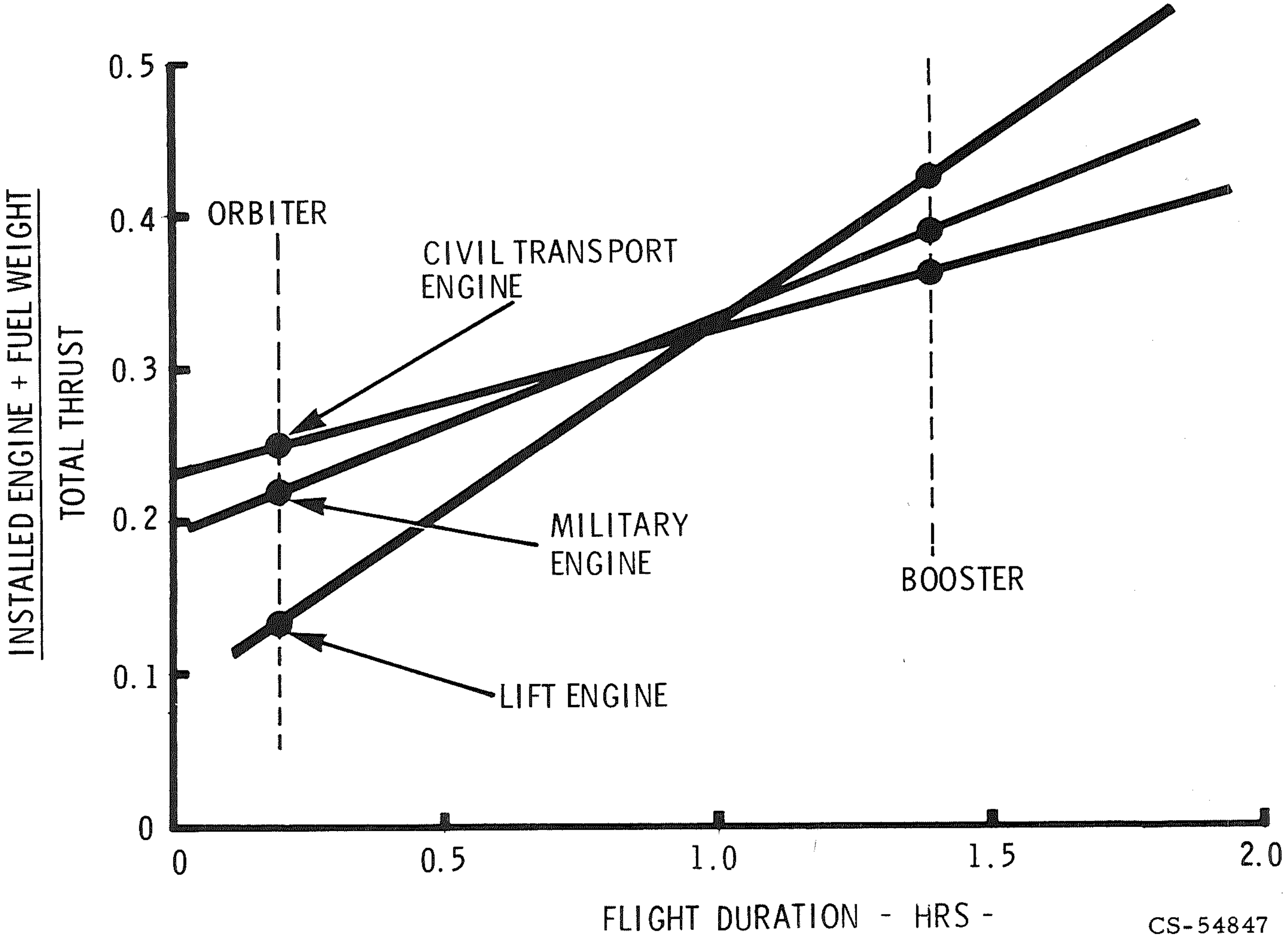
A saving of up to 50% in installed engine and fuel weight would appear possible as compared with advanced military and civil engine technology.

In the case of the Orbiter this saving is directly recoverable as payload.

In the case of the Booster low specific consumption civil engine technology results in a lower total engine and fuel weight due to the longer duration of the Booster cruise mission.

Further improvements to the installed weight can be expected by the application of short life engine technology to these engines.

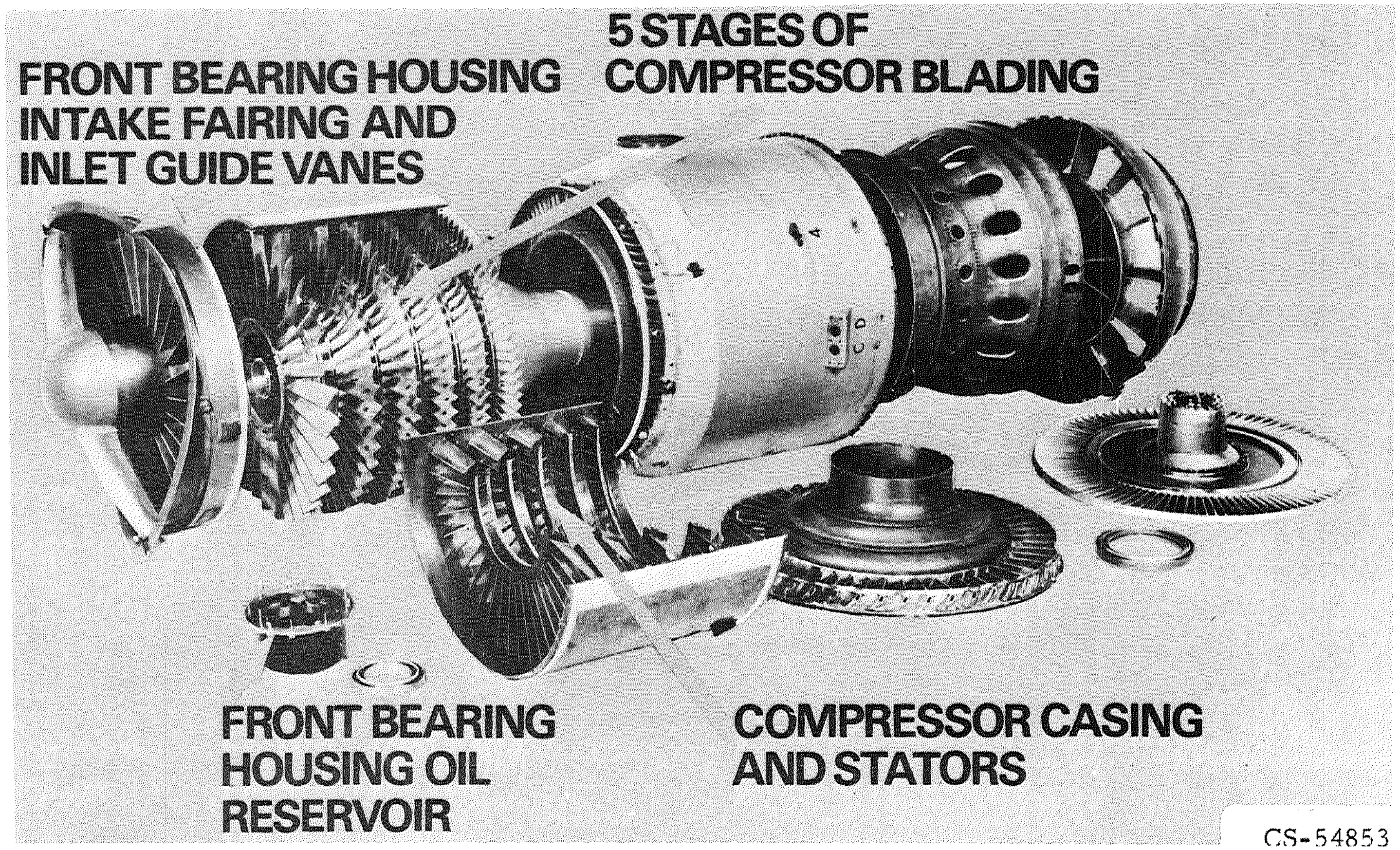
AIRBREATHING ENGINES FOR SHUTTLE VEHICLES



RB.162 - Components in Composite Material (Dec 1969 4513)

This picture shows the extensive use of fibre glass composite material in the RB.162 lift engine. Compressor blading, stator casings, front bearing housing, intake fairing, inlet guide vanes and front bearing housing oil resevoir, are all constructed of composite material. The stator case is in two halves joined by a renewable glass fibre bandage.

RB.162 – Components in composite material



CS-54853

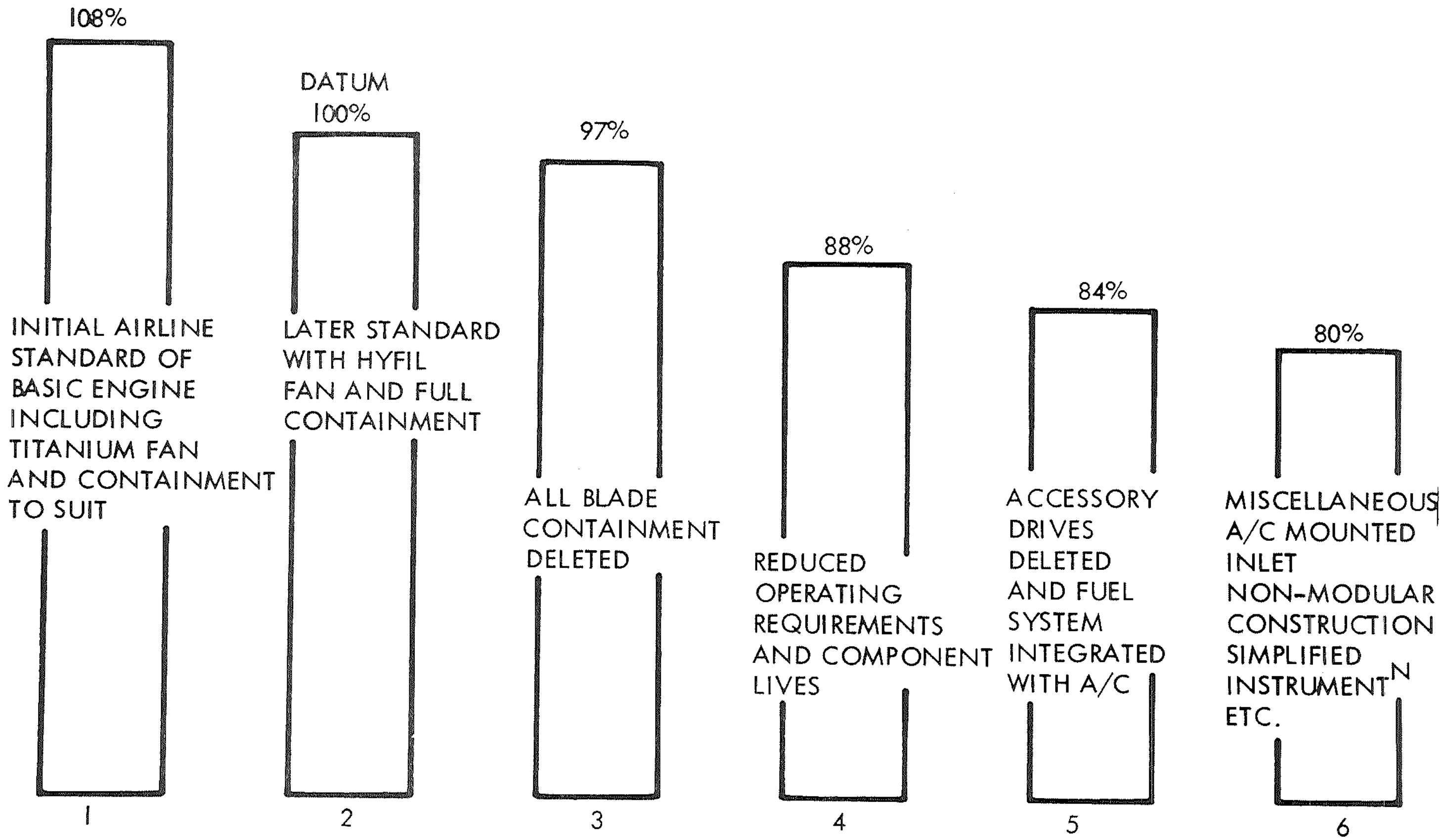
Potential Weight Saving for Space Shuttle Application (V[illegible]L 42814)

The chart illustrates the potential weight reduction obtained by deleting those features of a commercial fanjet which may not be required for Space Shuttle operation.

The first bar indicates the basic engine weight (less installation features) for initial airline supply and includes titanium fan blades.

The second bar is our datum for Space Shuttle application and is the eventual airline basic engine standard with Hyfil fan blades. From this datum we illustrate a progressive weight reduction by eliminating such features as, full blade containment, design for long life commercial operation, aircraft accessory drives, fuel systems, modular construction, cabin off-takes etc.

POTENTIAL WEIGHT SAVING FOR SPACE SHUTTLE APPLICATION
BASED ON RB 211 ENGINE



CS-54848

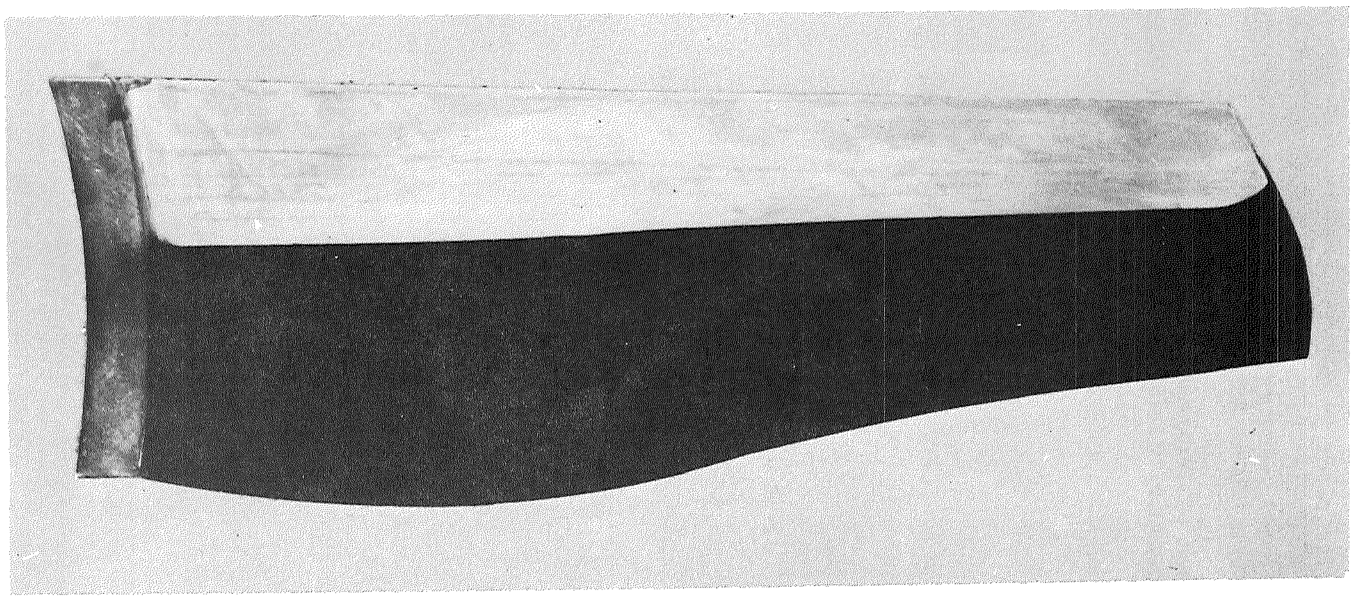
Hyfil Fan Blade (2024)

The Hyfil RB.211 fan blade has an aerofoil span of approximately 30 in. and weighs 10.6 lb.

The aerofoil has a metal foil reinforced leading edge because of hard object and bird ingestion, and the blade flanks are erosion coated.

The aerofoil is carried on a single curved dovetail root.

RB. 211 Hyfil fan blade



CS-54850

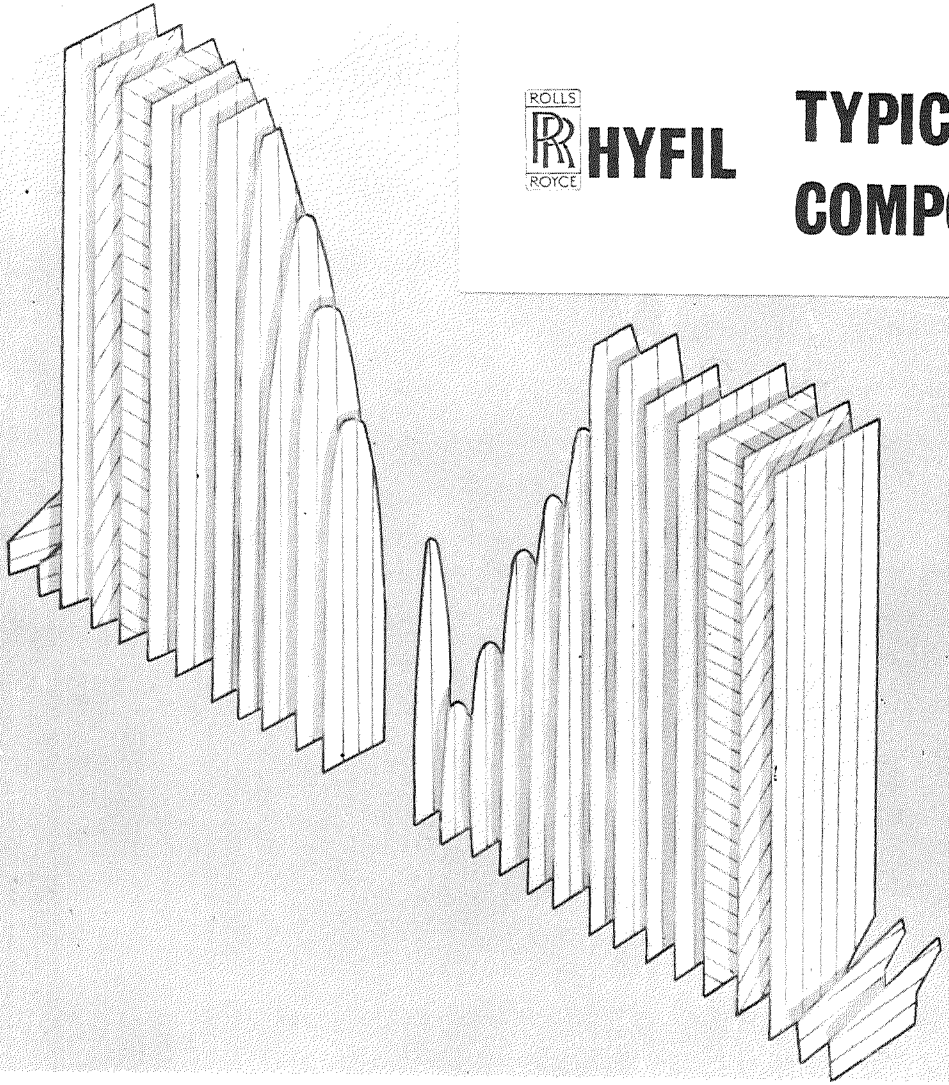
Typical Layup (14070/1)

The Hyfil blade is built up from shaped laminates stamped out of Hyfil sheet material. Most of the laminates have the carbon fibres running in the spanwise direction, though some have the carbon fibres angled.

The pack of laminates (including the metal foil) is die moulded to produce the finished aerofoil blade shape.

ROLLS ROYCE HYFIL

TYPICAL LAY-UP OF COMPOSITE ROTOR BLADE



CS-54852

Root Sections - Diagrammatic (VML 42435)

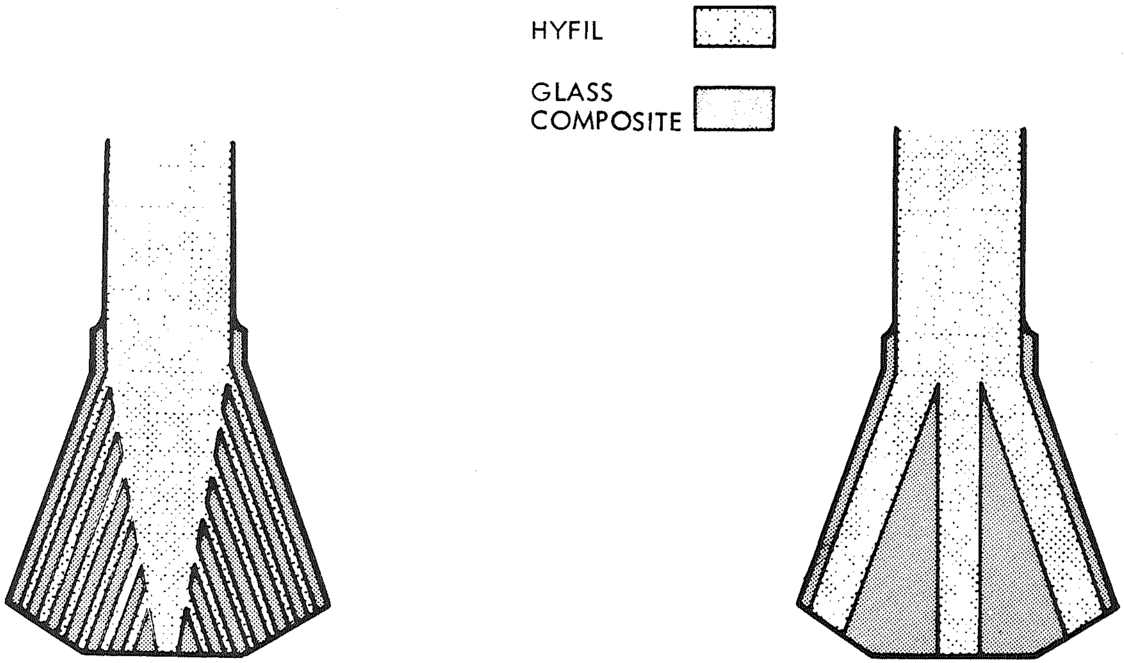
The Hyfil laminates comprising the blade aerofoil fit into the blade root, where they are interspersed with glass reinforced composite to make up the dovetail root fixing.

Currently, blades for the engine development programme are being made with the "interleaved" root, which rig and engine testing has shown to have adequate overspeed capability.

The "split wedge" root is an alternative construction which is being looked at, as it has a number of manufacturing advantages.

RB 211 HYFIL FAN BLADE

ROOT SECTIONS - DIAGRAMMATIC



INTERLEAVED ROOT

SPLIT-WEDGE ROOT

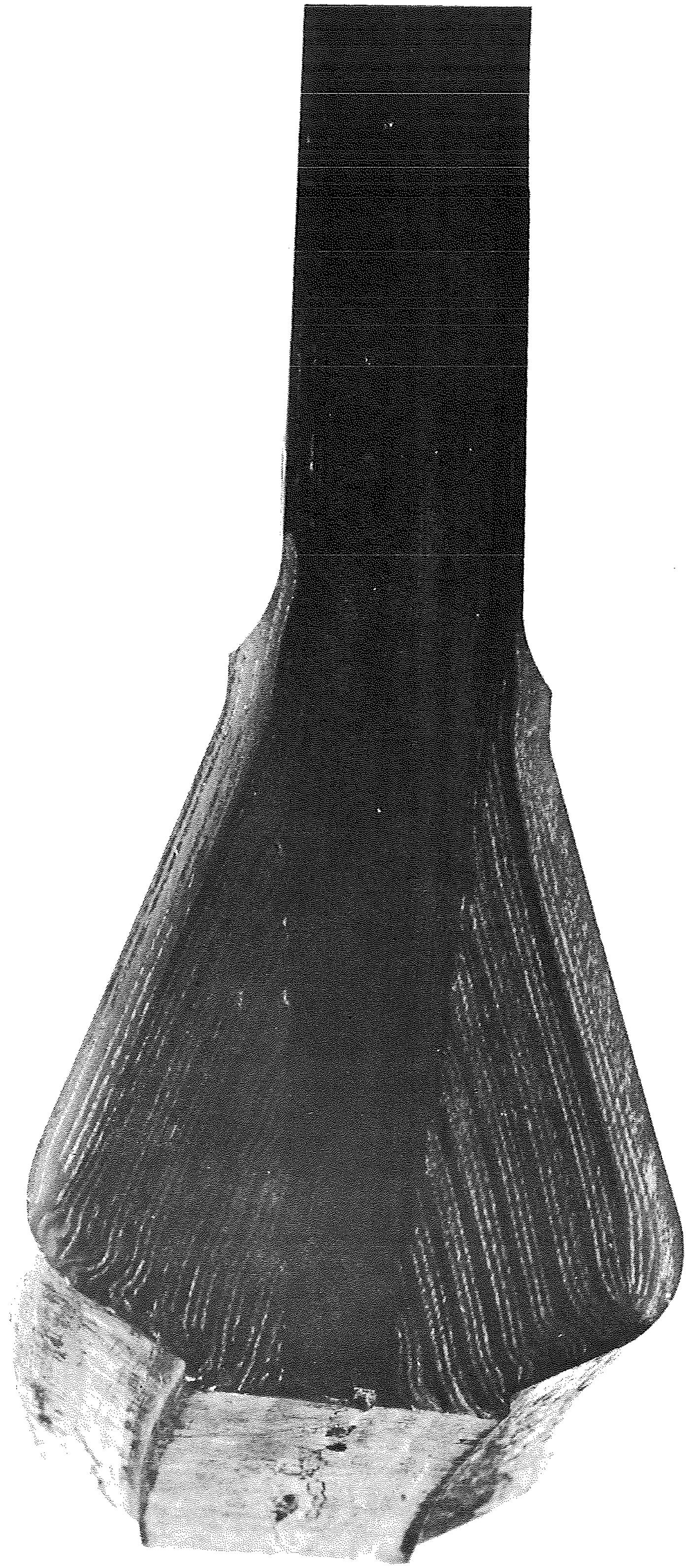
CS-54849

Blade Root Section (SMP 89237)

The picture opposite shows the actual cross section of an "interleaved" Hyfil fan blade root.

All blade roots are subject to N.D.T. (Non Destructive Testing) including X-ray and ultrasonic checks.

Blade root development includes static tensile testing of test pieces and of full size fan blades as well as blade spinning.



CS-54851

NEW ENVIRONMENTS FOR ENGINES

Warner L. Stewart

The airbreathing engines for the shuttle will be subjected to environments never before faced by jet engines in commercial or military service. The engine structures and materials must survive the launch loads and vibration, the reentry heating temperatures, and the space soak temperatures. Lubrication fluids have to be protected against evaporation during vacuum exposure. Outgassing of non-metallics must be considered. Space radiation may affect certain materials and fluids. The engine must start reliably in flight after exposure to the new environments. Some of these items are covered in the discussion to follow.

NEW ENVIRONMENTS FOR ENGINES

LAUNCH LOADS & VIBRATION

REENTRY HEATING TEMPERATURES

SPACE SOAK TEMPERATURES

HARD VACUUM

SPACE RADIATION

CS-54842

LUBE SYSTEM

William R. Collier

The space shuttle environment introduces two major problems in the area of the lubrication system. These are associated with the space environment and use of cryogenic fuel.

A potential problem is cold-welding of metal parts which are in intimate contact at very low pressures. Although this phenomenon may not be a serious concern based on available spacecraft experience, it warrants further investigation in certain key areas such as ball or roller bearings. Special coatings or dry film lubricants may be required to inhibit cold-welding of these parts. In the case of the orbiter, the main shaft bearings should be fully unloaded and vibration levels are expected to be low, thus it is unlikely that sufficient unit loading will occur to cause trouble.

Another point of concern is the danger of brinnelling the bearings during the launch phase. Experience has indicated that brinnelling problems can occur during engine shipment, when subjected to 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 problem may be insignificant. If it does occur, the engines could be motored slowly during the launch to continuously reseat the bearings.

ENGINE LUBRICATION SYSTEM

CURRENT ACTIVITY DIRECTED TOWARD MODIFICATION OF THE ENGINE LUBE SYSTEM IN CONSIDERATION OF:

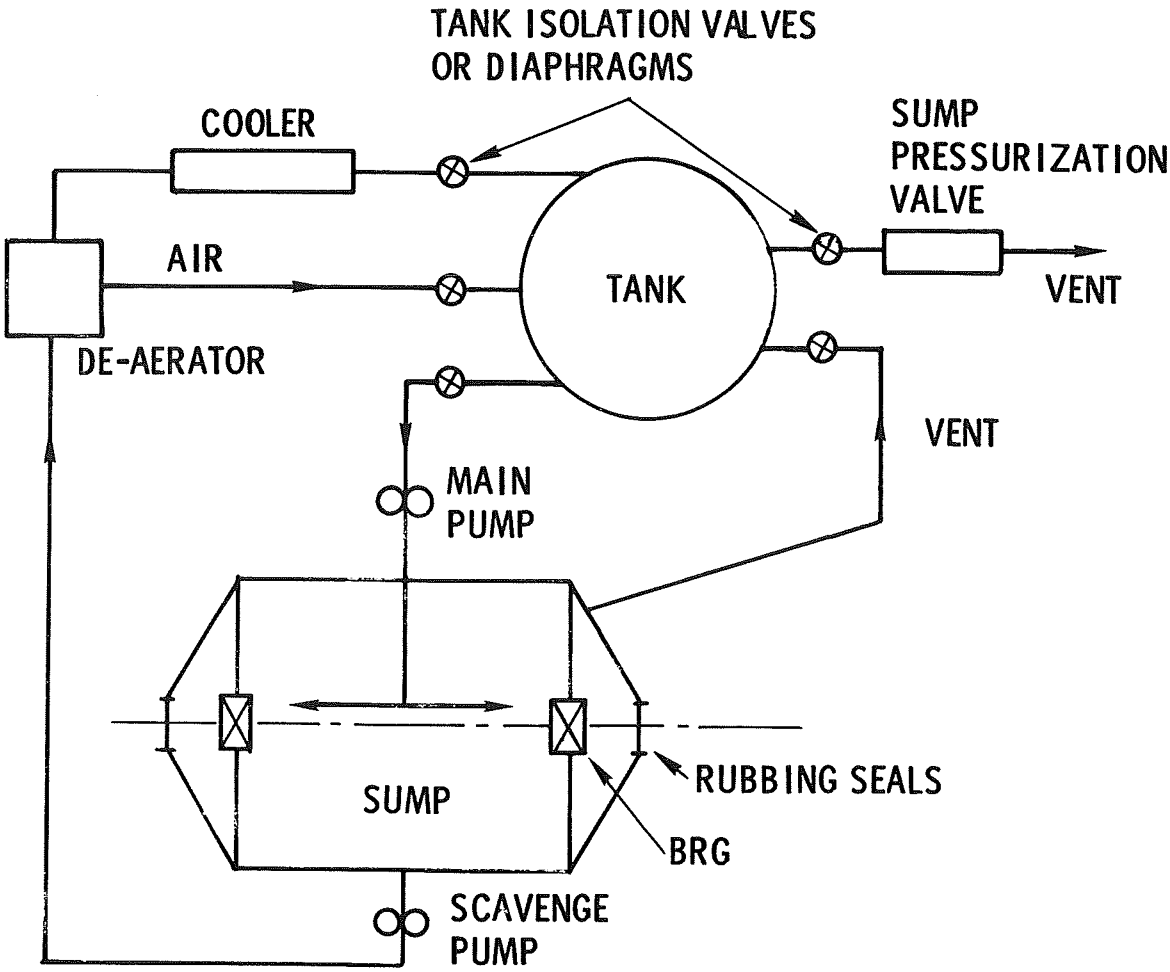
- ENVIRONMENT
  - POTENTIAL HIGH VACUUM
  - TEMPERATURE
  - ISOLATION
- COOLING DURING ENGINE OPERATION
  - OIL TO AIR HEAT EXCHANGER
- BEARING LIFE & RELIABILITY
  - BRINNELLING
  - "COLD WELDING"

Current engine technology employs a dry-sump lubrication system with the bulk of the oil stored in an external tank. Oil is supplied to all bearings and gears by an engine driven gear-type main oil pump, and scavenged from the sumps and gearboxes by multiple element scavenge pumps. It is then deaerated, cooled, and returned to the tank.

The vacuum environment, particularly for the orbiter, will expose the engine to pressures as low as 10^{-7} in. Hg. This could cause evaporation or outgassing of residual fluids through the shaft seals and engine vent, with possible deposition on critical surfaces of the vehicle. This problem can be controlled by isolating the oil in the tank by shutoff valves or diaphragms until the engine is readied for use. The temperature environment of the oil tank must also be such as to prevent freezing of the oil, or a heating element may be required. Alternate oils such as silicone types will also be considered from the standpoint of improved thermal characteristics.

The fact that the booster vehicle will be subsonic in its flight application permits the use of ram air for cooling the oil. Air/oil coolers could be mounted in the inlet ducts of the engines. This type of cooler would be highly desirable from a system reliability and safety standpoint, but would be generally heavier than its fuel/oil counterpart. The technology for such a heat exchanger is in-hand, and it has the advantage of keeping the lube system for each engine entirely self-contained, minimizing the number of interfaces with the vehicle.

LUBE SYSTEM SCHEMATIC



ENGINE MATERIALS & STRUCTURES

The use of current airbreathing aircraft engine technology in the space shuttle vehicles requires that the materials used in the engines be carefully reviewed in light of the pressures and temperatures to be encountered in the space environment. These conditions will be considerably more severe in the orbiter which must withstand up to 30 days in orbit than in the booster. This slide presents a typical list of the materials currently used in engines.

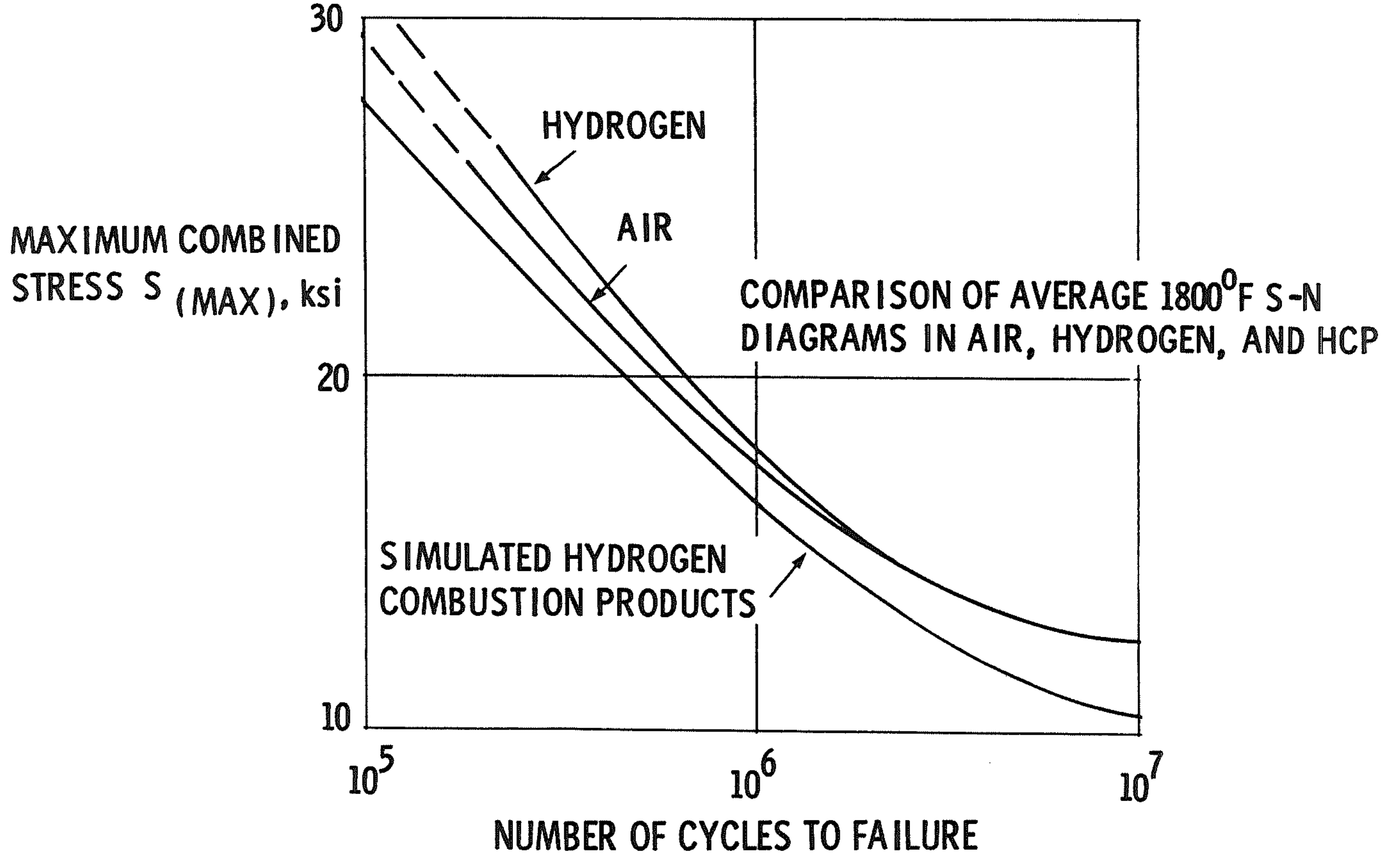
It is expected that the metallic materials will be unaffected by the orbiter environment, however, the non-metallic organic materials can suffer varying degrees of damage due to the low pressure (10^{-5} to 10^{-7} Torr) and temperature variations (-200 to + 300 F is possible, depending on the installation). Fortunately, the Viton A elastomer commonly used for the O-ring seals and the Teflon used for fuel and lubricant hoses, are among the better elastomers tested for spacecraft use. Most spacecraft evaluations, however, have not covered the entire possible temperature range for the orbital soak condition. The structural stability of various plastics and potting compounds used in electrical components must also be investigated. All lubricants and hydraulic system fluids will require careful study to determine if material as well as system changes must be made.

ENGINE MATERIALS & STRUCTURES

METALLICS	NON-METALLICS
FAN & COMPRESSOR SECTION • TITANIUM ALLOYS • NICKEL BASE ALLOYS	SEALS • ELASTOMERICS • VITON A
COMBUSTOR & TURBINE SECTION • NICKEL BASE ALLOYS	OIL HOSES • TEFLON
SHAFTING, GEARS & BEARINGS • HIGH STRENGTH STEELS - MARAGED - 9310 AND M-50	DUCT CASINGS • POLYIMIDE
GEARBOX • ALUMINUM OR MAGNESIUM ALLOYS	

A potential problem common to both booster and orbiter engines arises from the use of hydrogen as fuel. Considerable effort was expended by General Electric in 1957-1965 period investigating the effects of hydrogen combustion products on the high temperature alloys used for turbine hot parts. Reductions in fatigue and stress-rupture strengths were noted for several alloys when tested in hydrogen combustion products instead of air. While these tests were generally conducted with fuel-rich combustion, there is evidence that the high water vapor content of the hot gas was at least partly responsible for about 10% loss in fatigue and rupture strength. Degradation of the 1800°F fatigue strength of Rene'41 is shown in Slide 8.

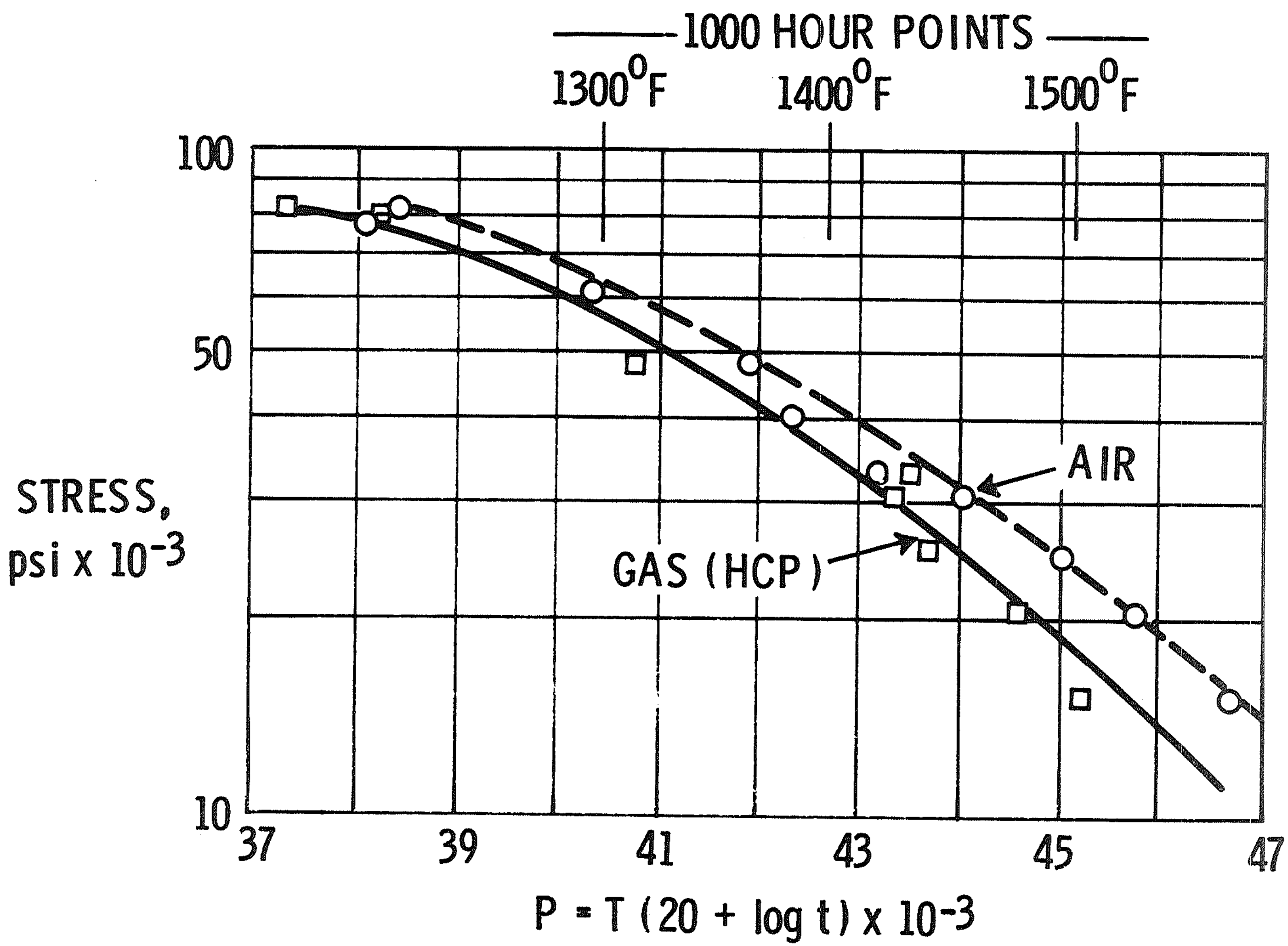
FATIGUE BEHAVIOR OF RENÉ 41



Slide 9 shows the effect on stress-rupture strength of this alloy. An assessment will be made of whether these effects will influence life or reliability of materials used in the selected engine.

In addition to the effects of hydrogen combustion products on hot parts, materials used in the fuel delivery system to the combustor must be carefully selected to assure that their mechanical properties are not harmfully degraded by liquid or gaseous hydrogen.

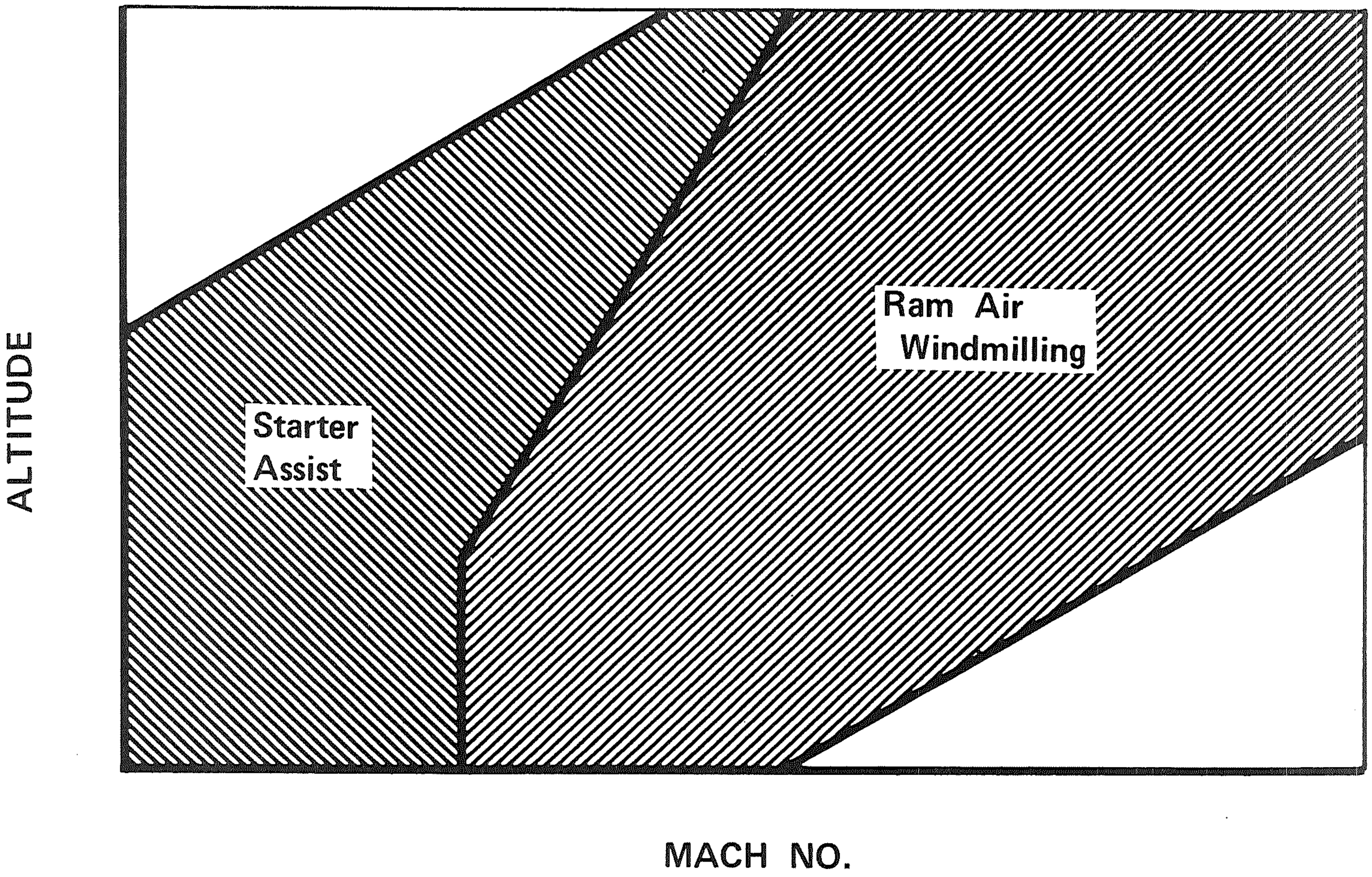
RENÉ 41 MASTER RUPTURE CURVES



Charles L. Joslin

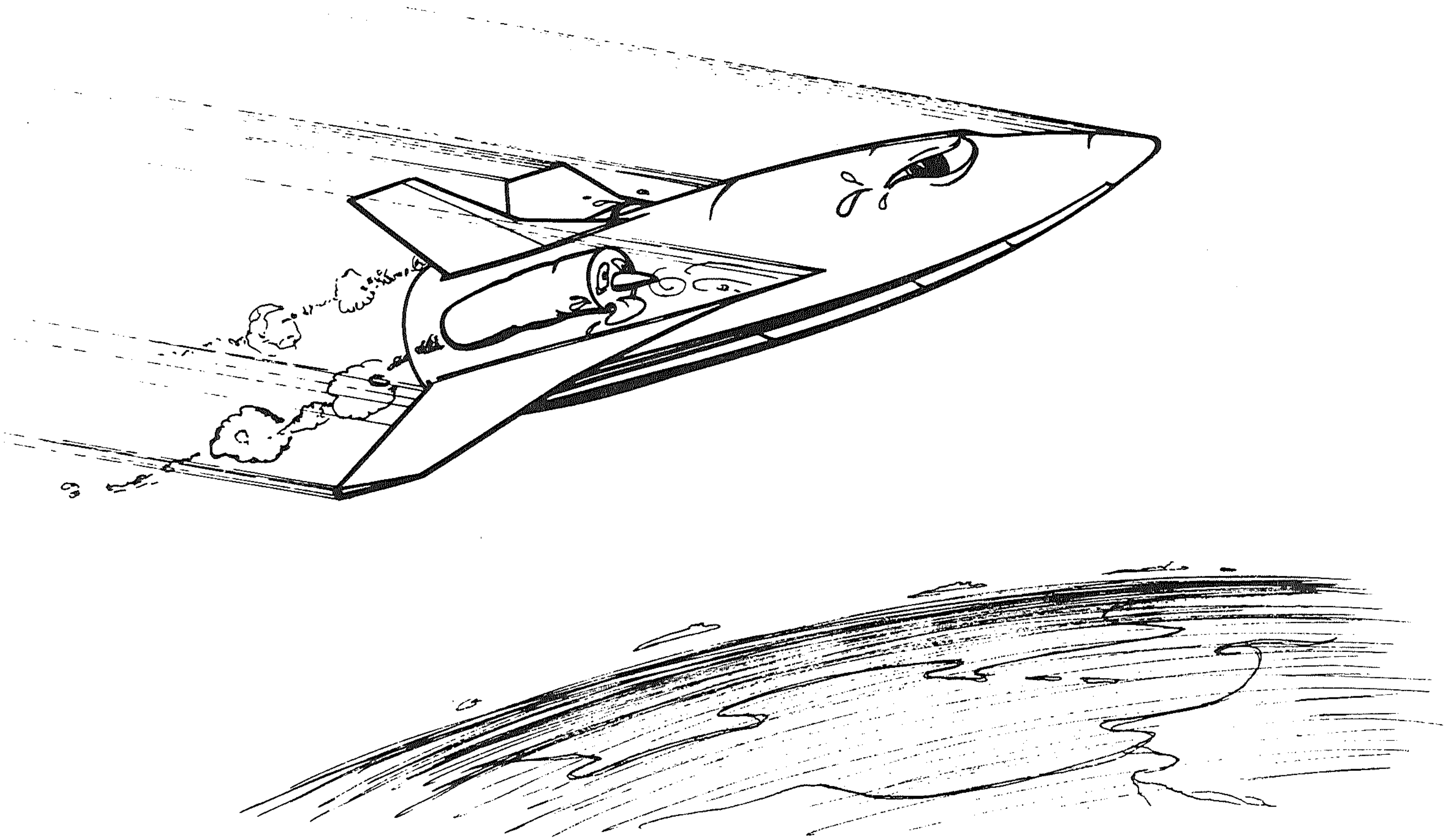
The airbreathing engines in the Space Shuttle must provide an absolutely reliable inflight starting capability, and the time available for the start sequence will be limited. This figure illustrates that in regions of low Mach number and high altitude, some on-board starting system may be required to assist in getting the engine up to self sustaining speed. At higher speeds and/or lower altitudes, ram air will windmill the engine for the start.

ENGINE RAM-AIR AND STARTER-ASSIST ENVELOPE



This sketch is intended to show what is perhaps the most important consideration in locating the airbreathing engines on the Space Shuttle. Although engine operation will be at subsonic flight speeds, the high angles of attack and rapid rate of descent of the Shuttle may produce areas of very irregular airflow. The engines must be located with some care to provide sufficiently undistorted inlet airflow for reliable starting.

INFLIGHT STARTING REQUIRES AIR TO THE ENGINE

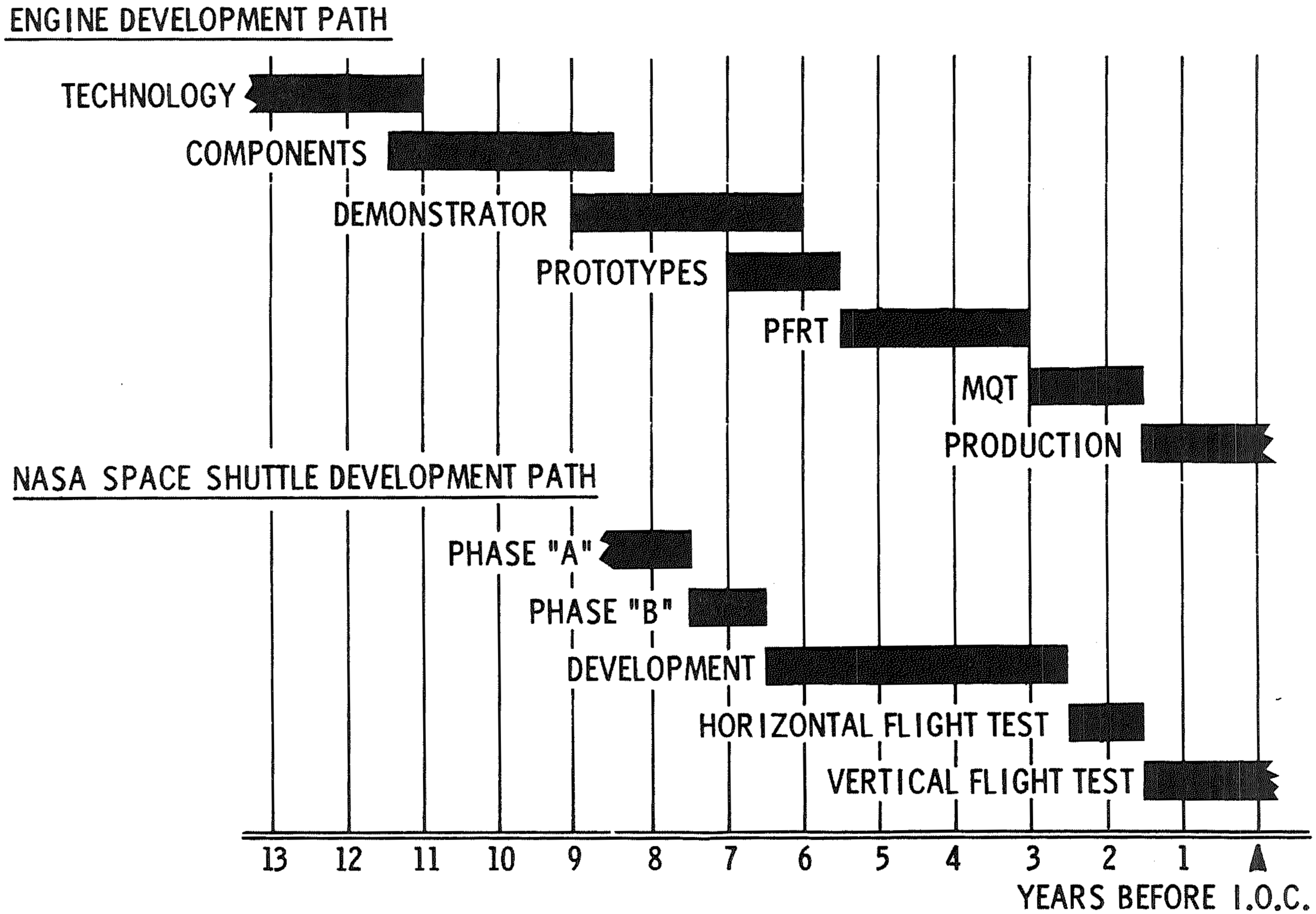


AIRBREATHING ENGINE QUALIFICATION/CERTIFICATION

The major elements of the development cycle of an airbreathing engine include the development testing, qualification requirements, and schedule. Current experience is based on engine development programs conducted for USAF weapons systems and for commercial aircraft applications requiring FAA certification. Specific and unique space shuttle requirements have not yet been fully identified. Engine development and qualification or certification is a time and dollar consuming task which grows more difficult and expensive as specialized proof testing requirements are added.

This slide shows the interrelationship between a typical new engine development schedule and the NASA Space Shuttle schedule as currently planned. Good agreement is seen providing a go-ahead on the engine development occurs early in the Space Shuttle vehicle program.

ENGINE DEVELOPMENT CYCLE



The types of engine tests required for a typical airbreathing engine qualification/certification program are shown on this slide. These tests are intended to demonstrate that all engine design requirements have been met prior to acceptance of production engines by the customer. Many of the requirements have evolved to meet military needs, and are not pertinent to the Space Shuttle. For example, infrared signature (IRS), and exhaust smoke measurement may not be of interest.

In the event that a partially developed or qualified engine is selected and modified for Space Shuttle, many of the specific tests will have already been completed reducing the extent of the required program.

The actual PFRT and QT test schedules have been devised to demonstrate engine performance and durability in aircraft service. Extensive endurance and cyclic operation are included, representative of aircraft duty cycles. The relatively brief Space Shuttle mission will require shorter life capability, but will place extreme emphasis on starting reliability. Hence, a new qualification concept with revised proof testing schedules would seem appropriate.

TYPICAL AIRBREATHING ENGINE

(QUALIFICATION REQUIREMENTS)

ENGINE TESTING

- SYSTEMS AND PERFORMANCE
- ENDURANCE - MECHANICAL INTEGRITY
- COMPATIBILITY - AIRCRAFT INTEGRATION
- ALTITUDE PERFORMANCE AND OPERATION
- ENVIRONMENTAL - HOT & COLD STARTING, INGESTION, ICING, ETC.
- SERVICE LIFE - MISSION ENDURANCE
- MISCELLANEOUS - OVERSPEED, OVERTEMPERATURE, NOISE, SMOKE, IRS, ETC.
- OFFICIAL PFRT
- OFFICIAL MQT

In addition to the engine testing requirements outlined in the previous slide, much of the required proof testing is completed by rig and bench testing. Major engine components such as the fan and compressor are run in test rigs, where greater operating flexibility is available for performance mapping. More extensive instrumentation is also possible, permitting thorough strain gage, and thermocouple surveys.

Controls and accessory components as well as built up subsystems are bench tested under simulated operating conditions. These tests are used to demonstrate that the many environmental and safety design requirements have beeh met. Bench testing ordinarily exceeds the total number of engine test hours, although the testing is far less costly.

TYPICAL AIRBREATHING ENGINE

(QUALIFICATION REQUIREMENTS)

MAJOR COMPONENT TESTING

- PERFORMANCE & COMPATIBILITY
- ENDURANCE - LIFE, STRESS, FATIGUE, ETC.
- SAFETY - OVERSPEED & OVERTEMPERATURE

CONTROLS & ACCESSORY - COMPONENT & SUBSYSTEM TESTS

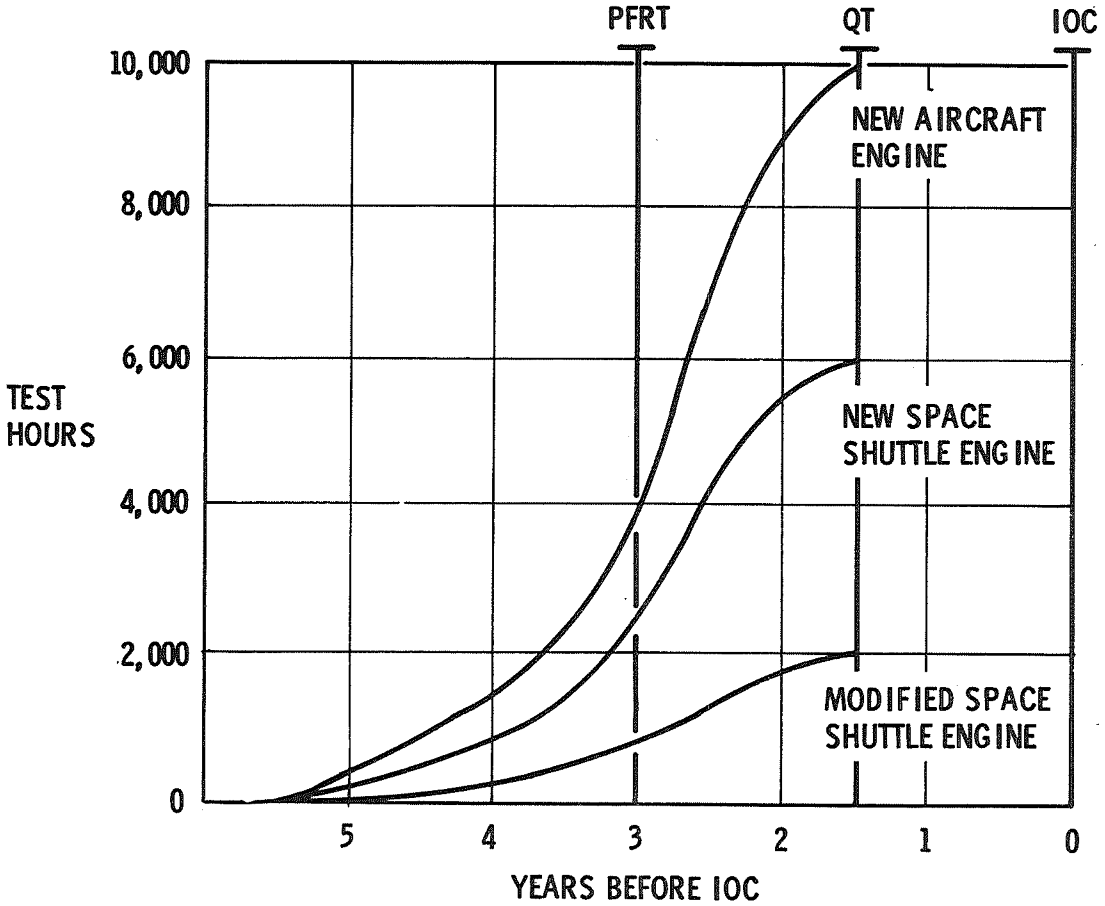
- FUEL SUPPLY & CONTROL SYSTEM
- LUBE & HYDRAULIC SYSTEM
- ELECTRICAL SYSTEM
- ENVIRONMENTAL - EMI, SALT CORROSION, FUNGUS, ETC.
- SAFETY - FIREPROOF, EXPLOSION PROOF, ETC.
- CRITICAL COMPONENT QUALIFICATION

This slide illustrates typical buildup of engine test hours in support of a qualification or certification program. The upper curve is typical of a military aircraft engine qualification. By eliminating the test elements not essential to the needs of Space Shuttle, it is anticipated that the total engine running hours can be considerably reduced. In addition, a further reduction is possible if the selected Space Shuttle engine is based on a developed aircraft engine with necessary modifications to the fuel system and lubrication system.

The experiemental flight test program is ordinarily started shortly after completion of the Preliminary Flight Rating Test. Unrestricted flight operation is contingent upon acceptance of the Qualification Test.

ENGINE TEST REQUIREMENTS

(APPROXIMATE TEST HOURS)



The approximate number of test hours necessary to complete the qualification program for an airbreathing engine are shown on this slide. The left column is typical of current aircraft engine programs. Because of the restricted operating envelope, lack of a combat environment, and reduced life requirements, the Space Shuttle engines can require less testing as indicated in the center column. Furthermore, if a developed or qualified engine is modified for Space Shuttle use, further savings can be made in the engine and major component test requirements.

Although the total number of test hours can be reduced by about half, compared to current aircraft standards, it is important that the modified engine approach achieves large reductions in the more expensive engine and major component test requirements. Therefore, the reduction in overall program cost will be greater than indicated by the total test hours.

ENGINE TEST REQUIREMENTS

(APPROXIMATE TEST HOURS)

	TYPICAL AIRCRAFT ENGINE	NEW ENGINE SPACE SHUTTLE	MODIFIED ENGINE SPACE SHUTTLE
ENGINE TESTING	10,000	6,000	2,000
MAJOR COMPONENT TESTING	50,000	40,000	5,000
C&A COMP & SYSTEM TESTS	150,000	100,000	100,000
TOTAL	210,000	146,000	107,000

CONCLUDING REMARKS

Warner L. Stewart

This discussion has reviewed some of the mission and environmental requirements facing the airbreathing engines for the space shuttle. Many of these requirements are new for gas turbine engines. These include the hydrogen fuel system and exposure to the launch, reentry, and space environments. Technology studies in these areas have been initiated by NASA.

Engine design studies being conducted by two contractors have the primary purpose of determining engine features and modifications required for the shuttle mission. Engines typical of those being considered for the shuttle vehicles will be selected for these design studies. The steady-state and transient operation of a hydrogen fuel system will be studied by analyzing, fabricating and testing such a system using an existing engine as a test bed. Studies associated with other components and systems will be conducted as required. The purpose of the technology studies is to provide a sound basis for the development of the airbreathing propulsion system for the shuttle.