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PROPULSION SYSTEMS TRENDS

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ABSTRACT

Propulsion systems as they exist today and some trends that are anticipated for aircraft that might be flying in the 1980's are presented. The number one trend for commercial engines is to quiet them to a level no louder than the normal background noise level of the environment in which they will operate. In military engines that are not so severely noise constrained, the possibility of stoichiometric gas turbine engines is within reach and will probably come into being whenever a military requirement provides sufficient motivation to develop such an engine. Very high bypass ratio engines are likely to find application in V/STOL aircraft while the evolution of variable geometry inlets and exhaust nozzles receives its impetus from supersonic airplanes. Both supersonic and V/STOL aircraft are prime candidates for digital computer control systems that will integrate the control of the propulsion system, the airplane, and its flight path. Multimode propulsion systems and supersonic combustion ramjets may one day be utilized in hypersonic cruise and boost aircraft while the first nuclear propelled aircraft most likely will fly at subsonic speeds.

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INTRODUCTION

The material presented in this paper is an updated version of reference 1 which incorporates many of the propulsion trends presented in reference 2. The intent of the paper is to present a rather broad review of airbreathing propulsion systems as they exist today and to indicate some of the trends that are anticipated for aircraft that might be flying in the 1980 to 1990 time period.

In this paper, the future technology trends in airbreathing propulsion are related to the aircraft of the future. These are shown in the first figure. On the left is a transcontinental jet. Jet transports that cruise below the speed of sound, or subsonically, service many of our major cities. These airplanes are powered by turbojet or turbofan engines and further advances in engine technology are likely to lead to better airplane performance and to lower fares. The helicopter in the middle of the slide is a reminder that, even now, helicopter service is available at a few cities to shorten trips within the city or to link the city with remote air terminals. High fares have hindered growth of this segment of air travel; but, again, further advances in gas turbine technology will do their part in lowering fares.

Since the speed and range of the helicopter are limited, it is likely that some type of V/STOL aircraft, shown at upper right, will be available for intercity traffic. Such an airplane could fly into and out of small new airports conveniently located in urban areas. The special demands made on any engine powering a V/STOL aircraft and the variety of propulsion systems being researched will be discussed.

At the lower right, an SST or supersonic transport is shown on its way over the ocean. Although military airplanes have been flying faster than the speed of sound for many years, the first commercial supersonic jets are just now being constructed. The demands on the engines for this aircraft are especially severe for a number of reasons that I will be getting into. Looking even further into the future, we can see rather dimly applications for airbreathing propulsion to the high supersonic or so-called hypersonic speed range. Here, a new airbreathing engine called a SCRAMJET is the sole candidate for very high speed cruise while a variety of multimode propulsion systems are being researched to handle noncruise phases of flight.

The types of advanced engines that are being used in supersonic and subsonic aircraft are shown in figure 2. The turbojet planned for the SST is similar to the engine that powered our first subsonic jet transports but has a far more complicated inlet and exhaust nozzle as well as an after-burner. The low bypass turbofan shown for the fighter aircraft incorporates an afterburner but is otherwise quite similar to the low bypass turbofan that quickly displaced the turbojets in subsonic commercial aircraft. The new commercial airplanes are all being powered by high bypass turbofans that are quiet, smokeless, and very economical in fuel consumption. The lift fan shown for V/STOL has an even lighter bypass ratio and must be very compact, very low in weight, and extremely quiet so that it can operate in small airports within business and residential areas.

SUBSONIC CTOL AIRPLANES

In a recent speech, Roy P. Jackson, National Aeronautics and Space Administration associate administrator for advanced research and technol-olgy spoke on the future goals of civil air transport and the government research and development support designed to meet them, including reduced noise and pollution levels. Aircraft noise abatement is given the highest priority, not only for the general public and the environment, but also because it is a key restraint to future aviation growth. The NASA goal is to show, by means of research and technology, how aviation noise can be reduced until it is no greater than the background noise where the aircraft operates. The principal effort is on reduction of propulsion system noise but NASA does have related work on noise reduction by flight procedures and on how people react to different types and levels of noise.

The first objective of NASA's work on design principles for quiet engines is an experimental conventional takeoff and landing (CTOL) engine and nacelle with 15 to 20 EPNdB less noise than the comparable JT3D class of engine in service today. The NASA Lewis Research Center and General Electric are working together on this program which began in 1969 and which will be completed by the end of 1972. The quiet engine with suppression is shown in figure 3. It has a single stage fan because it was learned that two-stage fans are about 6 dB noisier. The absence of inlet guide vanes and the considerable space between the far rotor and stator contribute to the engine having less whine. Notice that the walls of the inlet duct, the duct between the fan and compressor, the fan duct and the turbine duct are lined with acoustical material to suppress turbomachinery noise. Three splitters are installed in the inlet to provide more surface area for noise suppression material. The noise levels issuing from the fan and the core jet are controlled by proper selection of turbine inlet temperature, overall pressure ratio, fan pressure ratio, and bypass ratio (which is the ratio of the airflow through the fan duct to the airflow through the compressor).

If this engine is used to power a current CTOL transport of 300 000 lb gross weight the noise level heard by an observer 1000 ft from the airplane would depend mainly on the selection of fan pressure ratio as shown in figure 4. Notice that the suppressed fan machinery noise is about 15 dB lower than the unsuppressed level and that the suppressed fan and jet noise sources are pretty well balanced around a fan pressure ratio of 1.5, the ratio for which the Quiet Engine was designed. Noise is even lower at lower fan pressure ratios, but engine diameter increases and drag losses rise. The predicted noise level of 90 to 95 PNdB is about 10 PNdB below current FAA regulations for new CTOL aircraft. Production of an engine like this could begin in 1976 for retrofit or new aircraft. NASA plans to continue a vigorous research and technology program on noise reduction until the goal of a level no greater than normal background is achieved, hopefully in the 1980's.

When the noise constraint can be relaxed somewhat, for example in some military airplanes, it is possible to build a considerable lighter and more compact engine to produce a desired level of thrust. This can be done by designing for higher values of turbine inlet temperature which increases the thrust per unit airflow and by designing for higher rotational speed which reduces the number of compressor stages to produce the desired overall pressure ratio. The effect that rotational speed has on the performance of a single rotor is shown in figure 5. A blade tip speed of 1000 ft/sec is about right for the quiet commercial transports that were just discussed. Much higher pressure ratios can be achieved at higher tip speeds with only a slight drop in efficiency. At 1600 ft/sec, pressure ratio is about 2.0. An engine designed for 1600 ft/sec, while quite noisy, would require less than half the number of compressor stages as one designed for 1000 ft/sec.

Some very impressive reductions in the size of the burner have also been demonstrated in NASA research and these gains are applicable to all engines. Each of the three burners shown in figure 6 would result in the same thrust when installed in an engine. The middle burner that could have been used in the U.S. supersonic transport engine is over 40 percent shorter than the conventional burner shown at the top of figure 6. The bottom burner indicates that another 30 percent reduction in burner length might be possible. Not only is the advanced short burner itself smaller and lighter, but more importantly, the weight of the complete engine would be greatly reduced because of the shorter engine length. There would be a weight saving in the shafting connecting the turbines that drive the compressors, in the casing that encloses the rotating parts, and in the nacelle that houses the engine.

An advanced short combustor that was operated at 3600° F is shown in figure 7. A swirl-can modular combustor was used to achieve this high gas temperature. The NASA program aim is to evolve full annular combustors capable of performing with fuel-air ratios approaching stoichiometric values which means turbine gas temperatures of 4000° F and above. The initial results on these high-temperature combustors have been most encouraging: efficiency is close to 100 percent, pressure loss is comparable to that of conventional burners, smoke level was below the visible threshold even at 3600° F, there was no combination instability, and burner exit temperature profiles were acceptable. Future work will emphasize reduction of exhaust emissions (carbon monoxide, unburned hydrocarbons, and nitric oxide), durability and altitude relight performance.

The high temperature gas produced in the burner must be useable in the turbine. The past history and future projection of turbine gas temperature is shown in figure 8 (ref. 3). Up until 1967, the turbines were uncooled. The materials in the turbine had to be good enough to operate essentially at turbine gas temperature. When cooling was introduced, turbine metal temperature could be much cooler than the turbine gas temperature. This particular projection forecasts a turbine gas temperature of 3600° F in military engines by about 1980.

The progress in turbine/compressor disc material (ref. 3) is illustrated in figure 9. The use of graphite and boron composites is forecast for about the year 1990. Although Rolls Royce was not able to incorporate composite fan blades in their new high bypass ratio turbofan, they and others have made much progress in this area so that the future use of composites to reduce the weight of advanced engines (especially the high bypass ratio turbofans and propfans) appears promising.

If the high turbine gas temperatures are to be effectively used to achieve higher thrust to engine weight ratios, then the quantity of cooling air required to keep turbine metal temperature in bounds must be minimized. Some current and advanced cooling methods are indicated in figure 10. Today, convection is the principal cooling method and a local turbine inlet temperature of 2500° F is practical. The advanced cooling methods are full-coverage film and transpiration cooling. As indicated in the figure, they have the potential of allowing gas temperatures of 3500° F and above while maintaining the required coolant flow at or below today's level.

Stator blades fabricated to implement the three cooling methods are shown in figure 11. The convection cooled blade has a trailing-edge slot that allows the cooling air to rejoin the working gas stream. The blade with full-coverage film cooling has discrete holes in the blade surface that allows the cooling air to flow through the blade. The cooling air flows through a wire mesh porous skin in the transpiration cooled blade. One current deficiency of the advanced cooling methods is borne out in figure 12. The current-type blade with trailing-edge slots has a high level of turbine efficiency even when coolant flow is 7 percent. The porous blades, however, suffer a large drop in turbine efficiency. Ways to lessen this efficiency penalty are being investigated.

Before leaving subsonic aircraft, the revived nuclear-powered aircraft will be discussed. In the 1950's, we tried very hard to make a nuclear powered bomber, and we failed. I think Kelly Johnson of Lockheed summed it up very well when he said, "We tried to make it go too fast, too high, too soon." He probably should have added, "We also tried to make it too small." Eventually, we may have a large nuclear-powered cargo aircraft such as the one shown in figure 13. In many ways, it resembles a chemical fueled aircraft such as the promising new C5A being built for the Air Force by Lockheed. The C5A will carry a maximum payload of 220 000 lbs a distance of 3050 n mi. The motivation for a nuclear-powered airplane is, of course, that it could carry similar payloads and have essentially unlimited range. The advent of very large aircraft like the C5A and the possiblity of even larger aircraft in the future has led to a reexamination of the concept of nuclear-powered aircraft. Schematics of two closed loop nuclear propulsion systems are shown in figure 14. Both systems have a unit shielded reactor, a fan, compressor, and turbine. Unique features that are being examined in a technology assessment program are the heat exchanger that replaces the burner and long life fuel elements for the reactor that substitutes for the chemical fuel. Effort is also being directed to safety and reactor containment concepts.

V/STOL AIRPLANES

The driving requirements of vertical/short takeoff and landing (V/STOL) airplanes to the propulsion specialist are that they need much more thrust than CTOL airplanes and they must be much quieter. The STOL airplane requires twice as much thrust as the CTOL airplane and the VTOL airplane about four times as much. Both types should be about 25 dB quieter than the CTOL airplane because they will operate in and out of business and residential areas.

A STOL airplane that NASA is very much interested in because of its promise is shown in figure 15. This airplane achieves its short takeoff and landing capability by having the engine exhaust blow over the large double slotted flaps. One of the problems that NASA has uncovered in its research is that the interaction of the engine jet exhaust with the flap gives rise to a new source of noise. This is illustrated in figure 16. The dark band is the noise level of the jet exhaust when the flap setting is 0°. At higher flap settings required for takeoff and landing, the flap interaction raises the noise level about 5 dB. The third band in figure 16 is the suppressed turbomachinery noise of the fans. In order to meet the currently postulated goal of 95 PNdB at 500 ft, the fan pressure ratio should be about 1.2. The challenge is to build an engine light enough to result in an economically viable airplane.

The propulsion system for a second type of STOL airplane that NASA is researching is shown in figure 17. The engine is a two-spool turbofan with some special features. Notice that the air from the fan is ducted inside the wing and is discharged through a slot in the vicinity of the biplane flap. This results in augmentation of the lifting force on the wing which is good, but also results in quite a high level of noise which is bad. Ways to quiet this augmentor-wing noise are being investigated. A second special feature of this engine is the grid of airfoils ahead of the multistage fan. This is a choking mechanism that can reduce the fan inlet noise by 25 to 30 dB so that it is below the 95 PNdB level. Thus, the wing-slot noise dominates and quieting this remains as a challenge. Lining the flaps with acoustical material is expected to help.

Moving onto VTOL propulsion systems, the devices that can be used to produce the lifting thrust for vertical takeoff and landing capability are shown in figure 18. The turbojet is the most compact device. Its high thrust loading results from its high slipstream velocity which unfortunately makes it very noisy. As we proceed through the spectrum of devices from turbojet to fan to propeller to rotor, the size of the device increases and its slipstream velocity and hence, jet noise decreases.

Current noise levels are indicated in figure 19 along with two more major characteristics of these lift producing devices. The jets produce an intolerable noise level. Ear damage occurs at about 135 PNdB if the exposure is as little as 1 hour per week. At the other extreme, rotor noise is as low as 85 PNdB or 10 dB below the desired goal. The rotor also exhibits the lowest specific fuel consumption which explains why the helicopter is such a good aircraft for any application that requires extended periods of hovering. On the debit side, the rotor produces the least thrust per unit of installed system weight.

This is a principal reason the range of the helicopter is limited to a few hundred miles. Currently, the propeller offers an attractive blend of noise characteristics, moderate specific fuel consumption, and moderate system weight. Many planners seem to worry about the public's acceptance of propeller driven airplanes now that people have become used to flying jets. Another factor working against the propeller driven VSTOL transport is its rather limited cruise speed. Much of the NASA research program is concentrated on the fan family which includes shrouded prop, prop fan, and conventional turbofan. The future engines of this family will have to be quieter and lighter to meet the requirements of commercial VTOL transports.

The VTOL propulsion functions are illustrated in figure 20. Cruise can be accomplished with basically the same type of turbofan that the CTOL transport uses. The lift and control functions can be implemented with some rather specialized types of turbofans that are shown in figure 21. The type of fan drive distinguishes the engines.[4] The integral drive is conventional in that the fan and its driving turbine are mounted on the same shaft. Two types of remote drive are shown. In one, a turbojet generates hot gas that is ducted to a large scroll surrounding the lift fan. In the other, the bypass air from a turbofan is ducted to an auxiliary combustor that feeds hot gas to the scroll surrounding the lift fan.

The remote drive lift fan which is common to the gas generator and air pump system is shown in figure 22. The hot gas inside the scroll feeds a turbine mounted at the tip of the fan blades. The walls of the lift fan exit duct and a splitter surface are lined with acoustic material to suppress the machinery noise of the low pressure ratio fan.

The same acoustic treatment is applied to the integral drive lift fan shown in figure 23. It too has a single-stage low pressure ratio fan to keep noise level low. Notice that the turbine is fed by a reverse-flow combustor. This design feature is used to keep the engine short so that it can be better packaged in pods or in the wing of the VTOL transport. The noise estimates for a 100 000 lb gross weight airplane powered by 12 integral drive lift fans is shown in figure 24 as a function of fan pressure ratio. In order to meet a noise level of 95 PNdB at 500 ft, it appears that a fan pressure ratio of about

1.1 is required. Thus, the geared prop fans and shrouded props are of special interest for VTOL commercial transports.

SUPERSONIC AIRPLANES

A feature connected with supersonic flight that bears heavily on the airbreathing propulsion system is the large rise in the temperature and pressure of the air as it enters the engine. An advanced airbreathing propulsion system of the type planned for the Concorde supersonic transport is shown in figure 25. A large variable geometry inlet is included to efficiently slow down the air for the compressor. The air delivered to the compressor should be of uniform high pressure and have low turbulence. If either of these qualities gets out of hand (high distortion or high turbulence), there is danger the engine will surge. This whole area of distortion and turbulence and inlet-compressor interactions is a key research area receiving a great deal of attention. The inlet designers have taken a cue from the aerodynamicists and have successfully applied the use of vortex generators to this problem. The use of vortex generators in a reasonably long and gradual subsonic diffuser has provided to be a highly effective means in controlling steady-state distortion and also in reducing dynamic distortion (turbulence). This is illustrated in figure 26. Consider first the data on the left obtained without vortex generators. As engine speed is increased, the normal shock within the inlet moves from A to B. Total pressure recovery falls off and both steady-state and dynamic distortion increase rapidly. The 0.1 level of dynamic distortion is quite high, as the peak-to-peak amplitude of the fluctuations would be somewhere between 30 and 60 percent of the average compressor face pressure. The data on the right were taken with vortex generators installed on both the cowl and centerbody aft of the throat region. The generators pull high-energy flow from the main duct into the low-energy boundary layers. In these tests, the vortex generators were very effective in reducing steady-state and dynamic distortion over the entire pressure recovery range. Going back to figure 25, the compressor, burner, and turbine components look much the same as those components in a subsonic engine, but the temperature of the air coming out of the compressor could well be 1000° F. Since this air is used to cool the turbine blades, its high temperature definitely complicates the task of achieving reliable engine operation at high values of turbine gas temperature. Downstream of the turbine, we find an afterburner which is required to operate efficiently over a wide range of fuel flows. The high pressures that accompany supersonic flight require that a large variable geometry exhaust nozzle also be a component of this engine. The exhaust nozzle and inlet assume major roles, and their performance is strongly influenced by the installation of the propulsion pods on the airframe. This is especially true at transonic flight speed. Notice in the bottom sketch that the exhaust nozzle exit area is considerably reduced from its supersonic flight speed setting. This gives rise to important interactions between the exhaust nozzle internal and external flows.

The exhaust nozzle concepts that are being tested at the Lewis Research Center are shown in figure 27. For flight at Mach numbers near 2.7, each nozzle has an expansion ratio from the sonic area to the exit area of about 3.6. For good performance at subsonic speeds the expansion ratio must be decreased to a value near 1. The nozzle on the left achieves this with a divergent shroud made up of many overlapping flaps and seals so that it can be closed down at subsonic speeds. In the second nozzle, the multiple flaps do not close as far in order to simplify the flap mechanism while auxiliary inlets are opened to bring in additional air to help fill up the exit area. The conical plug on the right is a more recent concept that has not yet been used on a production engine. For low-speed operation, the exit area is decreased by translating the cylindrical shroud upstream. This kind of nozzle is harder to cool but has some advantages. It is easier to seal, requires simpler mechanisms that might be more durable, and some jet-noise tests indicate that it is inherently a little quieter than the other nozzles. All three nozzle concepts are being researched at the Lewis Research Center in a coordinated flight and wind tunnel program as depicted in figure 28. The isolated nozzle is tested in the 8- by 6-Foot Supersonic Wind Tunnel from Mach 0 to 2. To quantify the important airframe installation effects that occur at transonic speeds, small airplane models are tested in the wind tunnel. Nozzle shape is varied and also the position of the nacelle on the airframe in order to achieve best performance. The flight tests with the F-106 at Mach numbers from 0.6 to 1.3 correlate the wind tunnel and flight exhaust nozzle evaluations. Flights with the F-106 are also made at Mach 0.4 for noise fly-by measurements.

The control systems for supersonic propulsion systems and the V/STOL propulsion systems are becoming more complex. It is likely that the capabilities of current hydromechanical control will be inadequate and that fast, large capacity, flight worthy, digital computers will be developed and applied to propulsion system control. A possible configuration is shown in figure 29. The computer will manage the propulsion system for the pilot so as to achieve some desired performance criteria such as minimum specific fuel consumption. It will restore normal operation following the violation of a constraint such as a compressor stall or inlet unstart. Finally, the digital computer will provide a tighter control within known damage limits of operation and keep the engine in a stable and responsive mode of operation. The arrows labeled aircraft and external environment signify that the computer can be made more complex to control the aircraft as well as the propulsion system by taking into account information concerning air traffic control, weather, and aircraft performance. In this way then, the propulsion system and aircraft will be totally integrated through the use of digital computer control.

The high temperatures that come with supersonic flight give rise to yet another major propulsion problem — this one associated with the fuel. The fuel not only supplies energy to the engine, but it also acts as a heat sink cooling parts of the airframe and engine. Right around Mach 2.7, which was the design cruise speed of the Boeing supersonic transport, the cooling capability of conventional JP fuel becomes marginal so that great care had to be used in designing the fuel system. At some increase in fuel price, the cooling capacity of JP fuel can be increased. By keeping the oxygen content of the fuel very low, the heat sink capacity for cooling of engine components can be much greater than what is currently available. An inexpensive fuel which not only has greater cooling capacity but also a higher energy content is liquid methane, methane being the major constituent of natural gas. Studies at the

Lewis Research Center indicate that liquid methane has the potential of overcoming the cooling roadblock and of offering better airplane performance and lower operating costs. For a Mach 3 supersonic transport, the Lewis studies indicated a potential reduction in DOC of about 30 percent.[5] Because of its shining virtues of low cost, large cooling capacity, smoke-free combustion, and high energy content, liquid methane might well become the fuel of the future for all manner of airplanes from V/STOL types on up through advanced supersonic transports.

HYPERSONIC AIRPLANES

Hypersonic propulsion systems are being considered for application to hypersonic transport airplanes and also for use in recoverable first stages of orbital boost vehicles. For large scale delivery of men and materials to space stations, the recoverable concepts using airbreathing propulsion offer attractive operational and economic features.

As we move to higher supersonic flight speeds, a definite technology trend is toward airbreathing engines that operate in two or more modes. This is illustrated in figure 30. On the left, shown without their complicated inlets, are the two engines best suited to power Boeing's prototype supersonic transport at 1800 mph. At the right are two derivatives of these engines better suited for higher supersonic cruise speeds. They have in common the feature that above about Mach 3, the airflow to the fan or compressor can be shut off. The new mode of operation then allows air from the inlet to bypass the shut down rotating machinery and react with fuel injected into a burner component. Expansion of the hot high pressure gas through the exhaust nozzle produces the required thrust. This mode of operation is referred to as the subsonic combustion ramjet mode and is well suited for flight speeds between about Mach 3 and Mach 7.

It should not really surprise us that the rotating machinery can be shut down around Mach 3. After all, the function of the compressor-turbine unit is to provice high pressure gas that can be expanded through the exhaust nozzle. At a flight speed of Mach 3, the ram pressure rise is 3600 percent, so there is no longer a need for mechanical compression.

Turbojets and turbofans are not the only propulsion devices that can be used to accelerate an airplane up to ramjet takeover speed. Many other devices have been proposed and are being researched to a greater or lesser extent. The list of engines includes air turborocket,[6] fuel expansion engine, Lace, and ejector ramjet.[7] All of these engines are being considered for applications calling for a top flight speed up to about Mach 7.

Around Mach 7, however, the rising pressures and temperatures associated with the subsonic combustion ramjet mode of operation give rise to deteriorating performance and almost insuperable materials problems, so a new operational mode must be resorted to. This is called supersonic combustion ramjet operation and is illustrated in figure 31. The small sketches indicate the major difference between a ramjet engine and a scramjet. The scramjet is designed so that no internal shock slows the air down to subsonic speed within the engine. This greatly alleviates the high-pressure, high-temperature problems within the engine and promises very respectable engine performance. Even though specific fuel consumption of the scramjet is rising, the favorable effect on increasing flight speed maintains scramjet efficiency at a high level over the range of flight speeds shown.

NASA's research on the scramjet is focused under its Hypersonic Research Engine Project. The scramjet built for NASA by Garrett Corporation is shown in figure 32. The three fuel injector stations permit operation in either the subsonic combusion mode or the supersonic combustion mode. The engine will be tested to establish performance maps giving the effects of basic variables such as fuel-air ratio, simulated flight altitude, inlet contraction ratio, and fuel injection schedules. From these studies, important design information will be obtained on practical chemical kinetics and component interaction effects in a complete engine configuration.

CONCLUDING REMARKS

Many of the trends in airbreathing propulsion systems will benefit all types of aircraft. This is true of the push toward improved and new fuels and the reduction in size and weight of engine components such as compressors, burners, and turbines to produce a desired thrust. For commercial engines, the number one trend is to quiet the engines to a level no greater than the natural background noise level of the environment in which they will operate. Already, the NASA-industry efforts have made available engines that can better the current FAA regulation by about 10 dB. The noise constraints of commercial engines will undoubtedly slacken the trends toward higher turbine temperature and higher rotational speeds that shrink the size of the engine but generate more noise. In military engines that are not so severely noise constrained, the possiblity of stoichiometric gas turbine engines is within reach and will probably come into being whenever a military requirement provides sufficient motivation to develop such an engine.

Other trends in propulsion systems are applicable to specific types of aircraft. The very high bypass ratio prop fans are especially suitable for V/STOL aircraft. The evolution of reliable variable geometry inlets and exhaust nozzles characterize supersonic airplanes. Both supersonic and V/STOL aircraft are prime candidates for digital computer control systems that will integrate the control of the propulsion system, the aircraft, and its flight path. Multimode propulsion systems and supersonic combustion ramjets may one day be utilized in hypersonic cruise and boost aircraft while the first nuclear propelled aircraft most likely will fly at subsonic speeds.

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COMMERCIAL AIRCRAFT

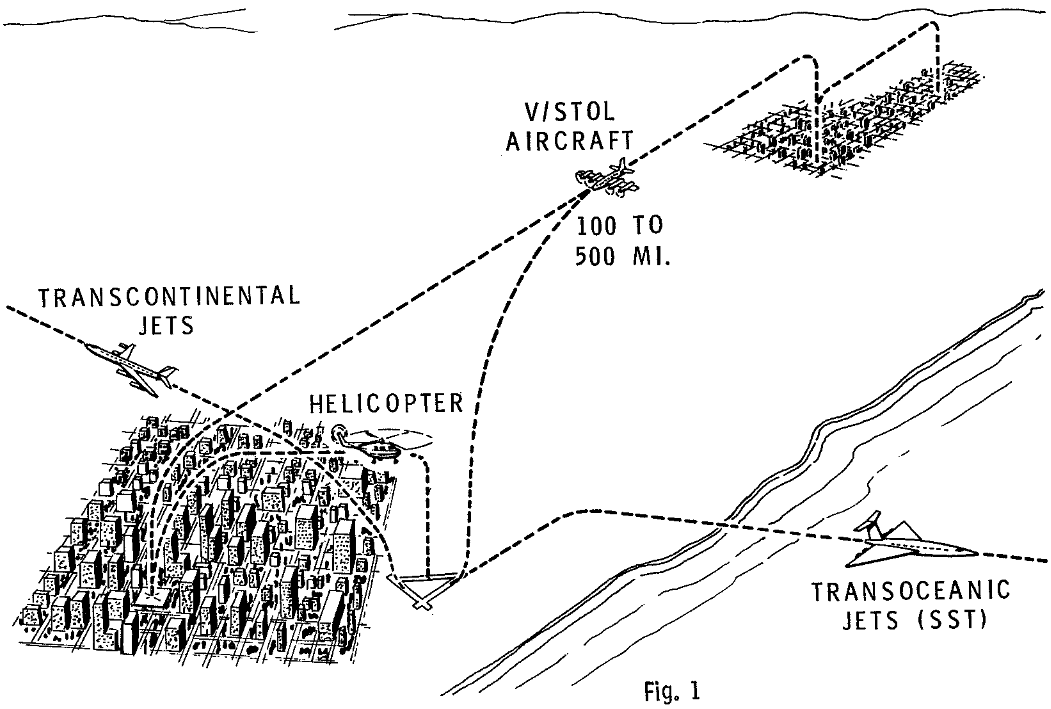

Fig. 1

TYPES OF ADVANCED ENGINES

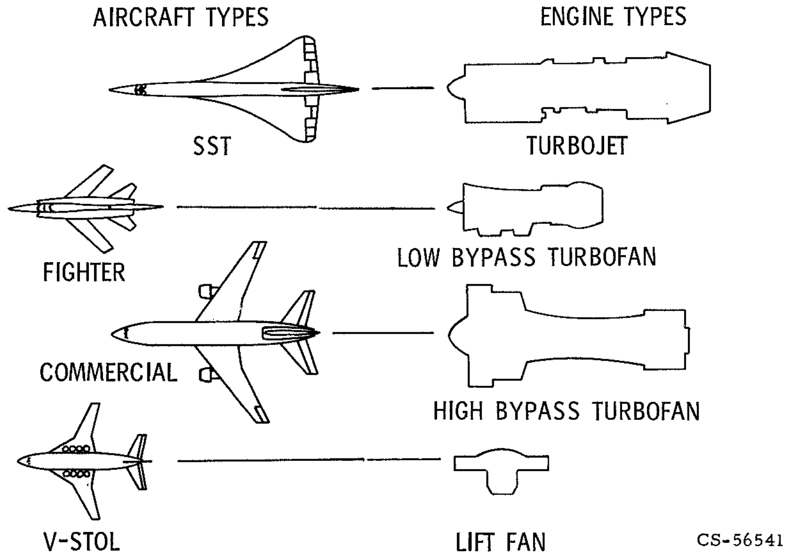

Fig. 2

QUIET ENGINE: WITH SUPPRESSION

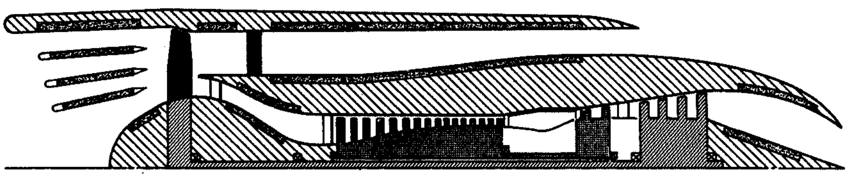

Fig. 3

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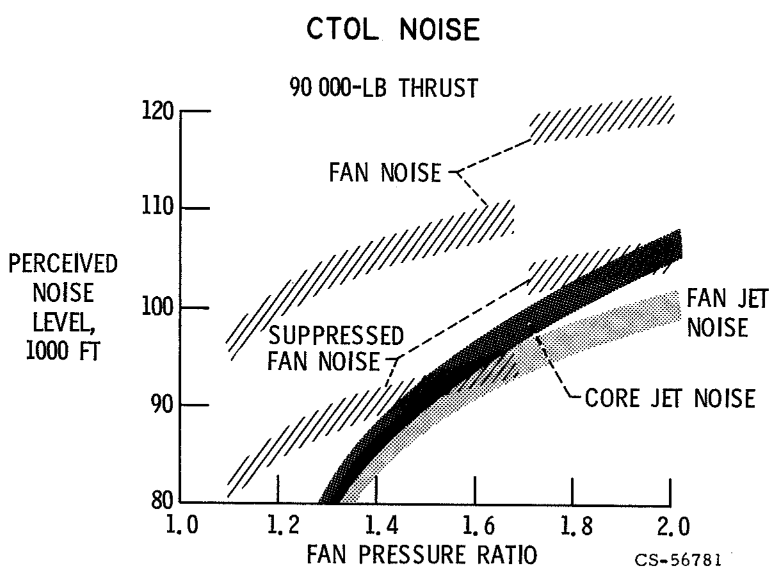

Fig. 4

EXPERIMENTAL TRANSONIC ROTOR PERFORMANCE

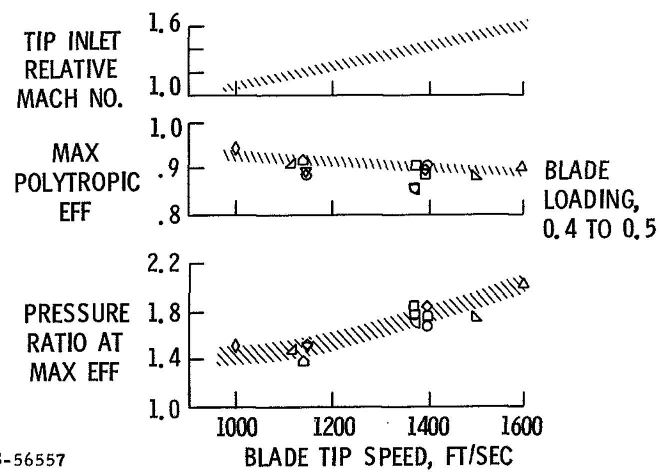

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Fig. 5

BURNER SIZE COMPARISON

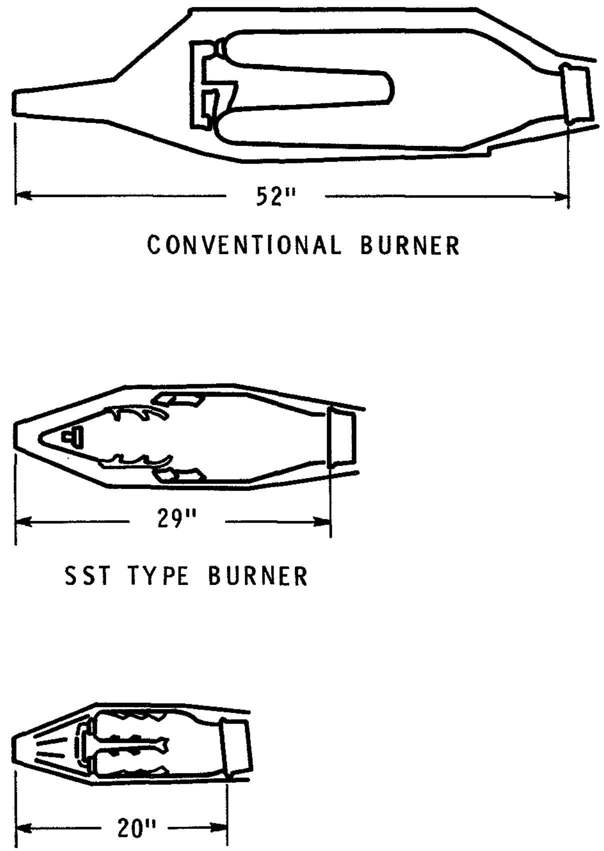

Fig. 6

HIGH TEMPERATURE COMBUSTOR AFTER 3600° F TEST

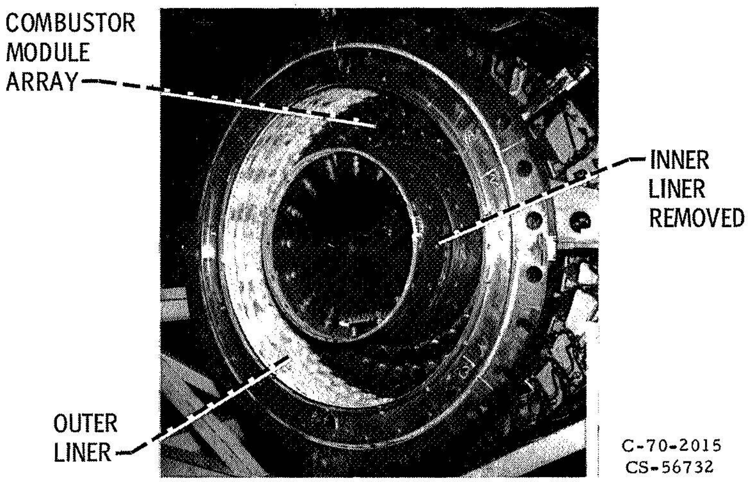

Fig. 7

TRENDS IN TURBINE GAS TEMPERATURE

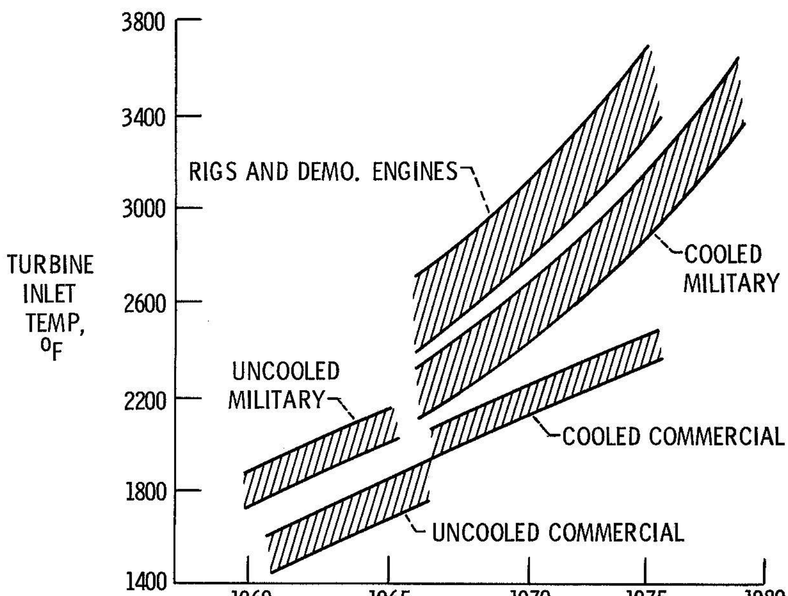

Fig. 8

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PROGRESS IN TURBINE/COMPRESSOR DISC MATERIALS

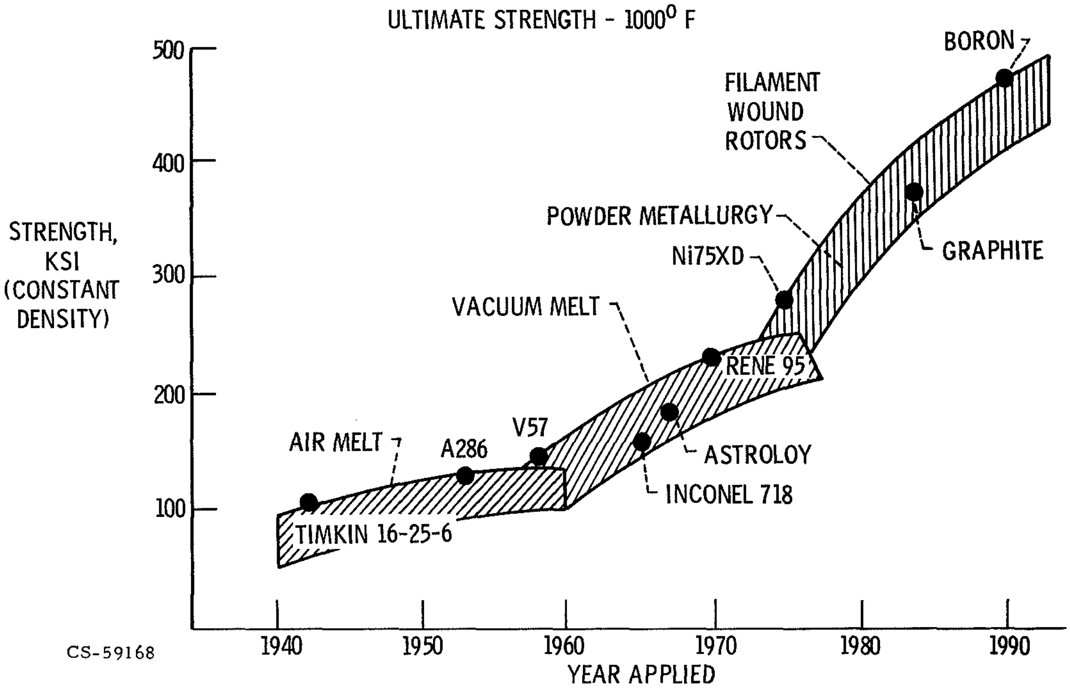


Fig. 9

POTENTIALS OF COOLING METHODS

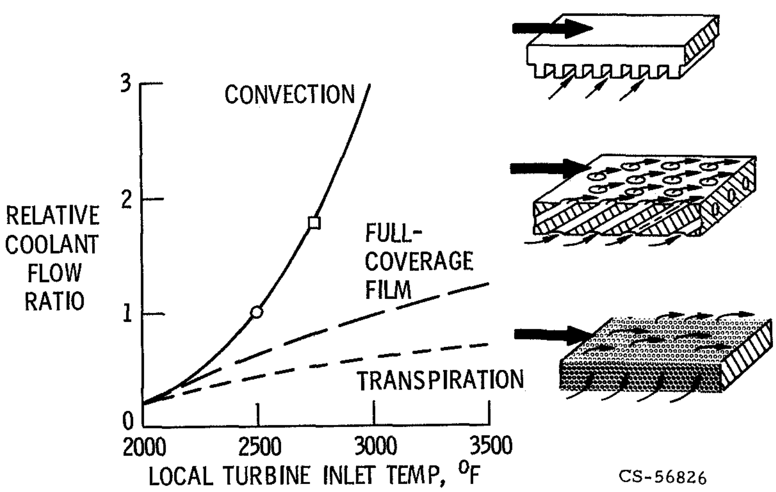
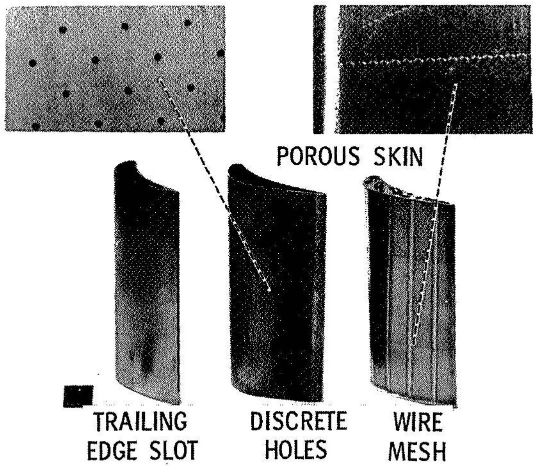


Fig. 10

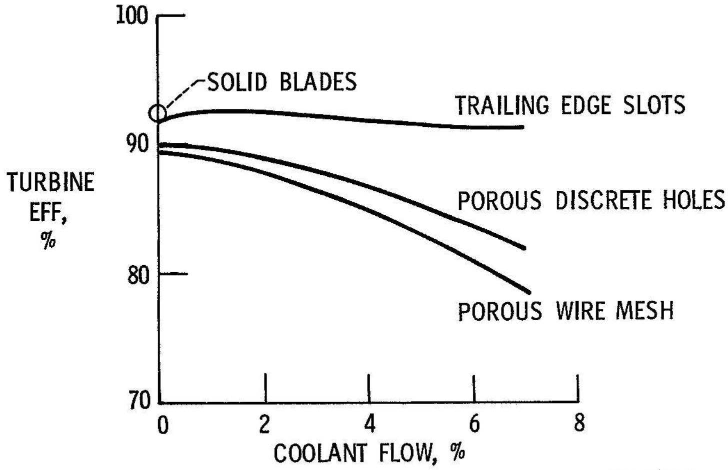
STATOR BLADES TESTED



C-70-551
CS-56680

Fig. 11

TURBINE STAGE EFFICIENCIES

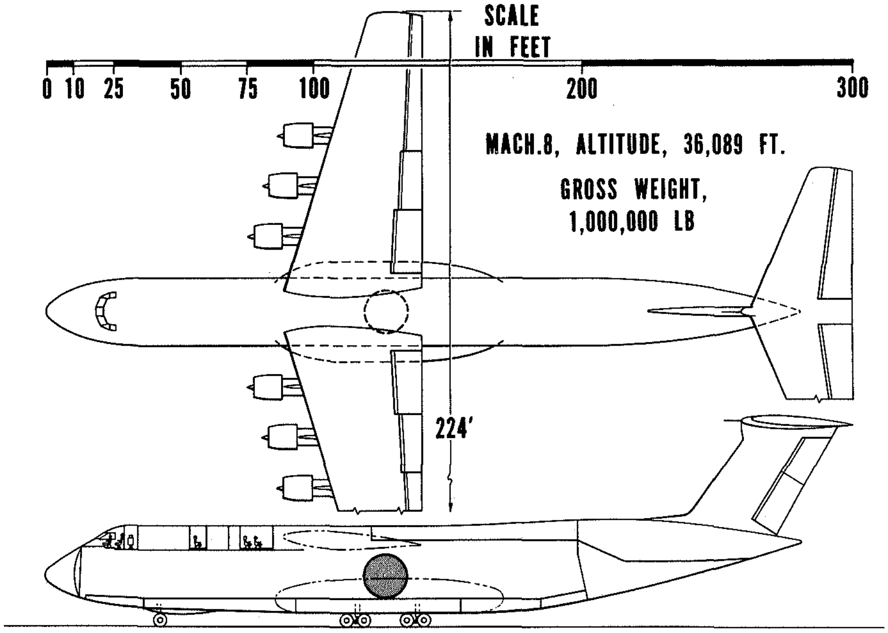


CS-56675

Fig. 12

E-6420

ATMOSPHERIC NUCLEAR TRANSPORT SYSTEM



9028-L

Fig. 13

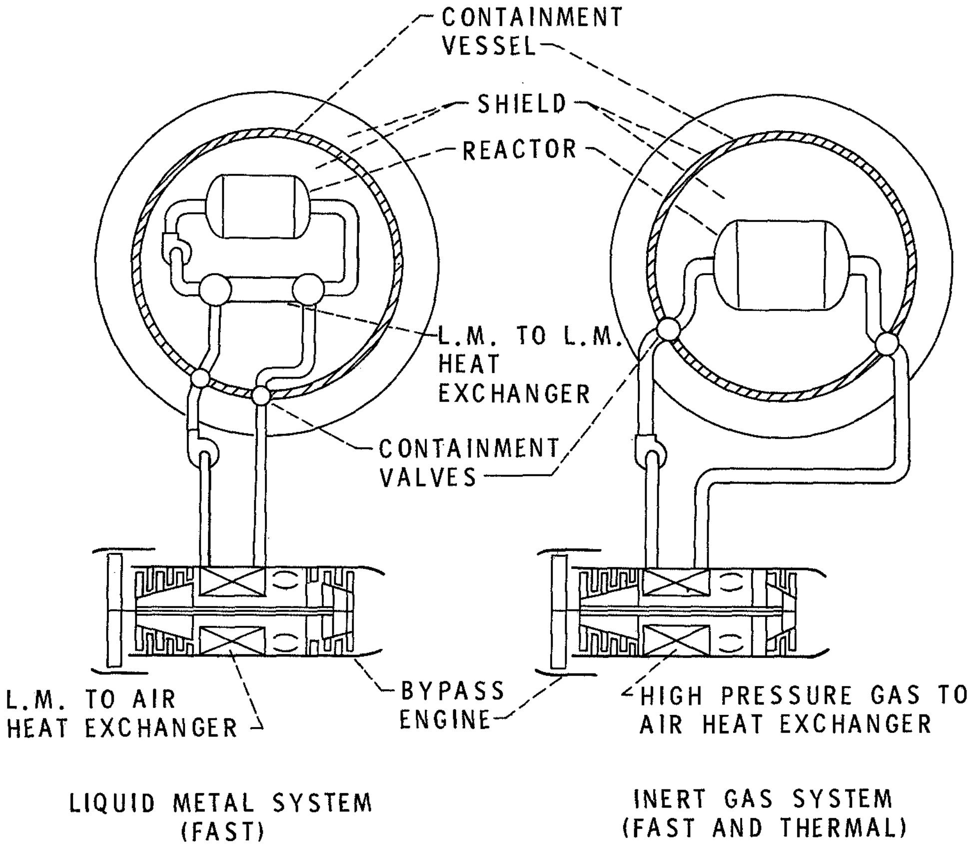

CONTAINMENT VESSEL
SHIELD
REACTOR
L.M. TO L.M. HEAT EXCHANGER
CONTAINMENT VALVES
L.M. TO AIR HEAT EXCHANGER
BYPASS ENGINE
HIGH PRESSURE GAS TO AIR HEAT EXCHANGER
LIQUID METAL SYSTEM (FAST)
INERT GAS SYSTEM (FAST AND THERMAL)

Fig. 14

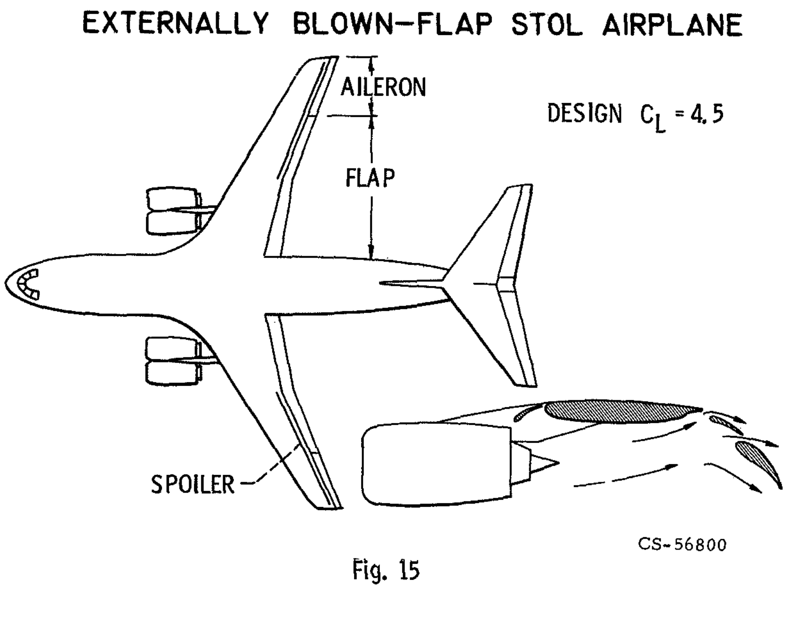

EXTERNALLY BLOWN-FLAP STOL AIRPLANE
AILERON
DESIGN $C_L = 4.5$
FLAP
SPOILER
CS-56800

Fig. 15

E-6420

NOISE ESTIMATES FOR BLOWN-FLAP SYSTEM - INCLUDING FLAP

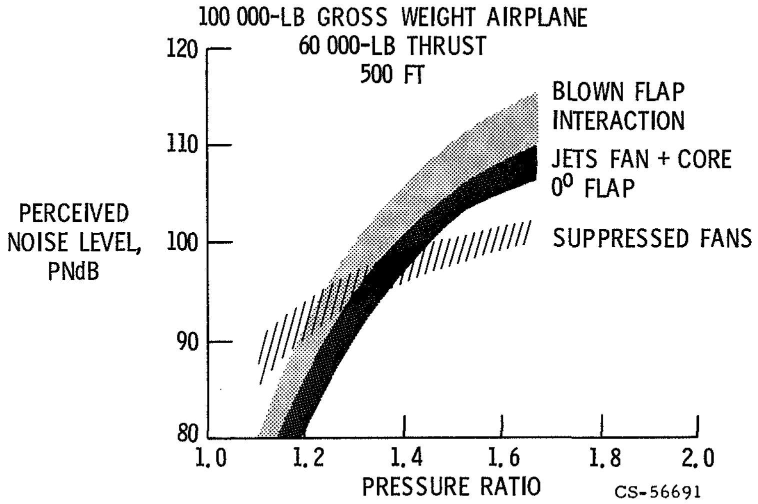


Fig. 16

AUGMENTOR-WING PROPULSION SYSTEM WITH CHOKED INLET

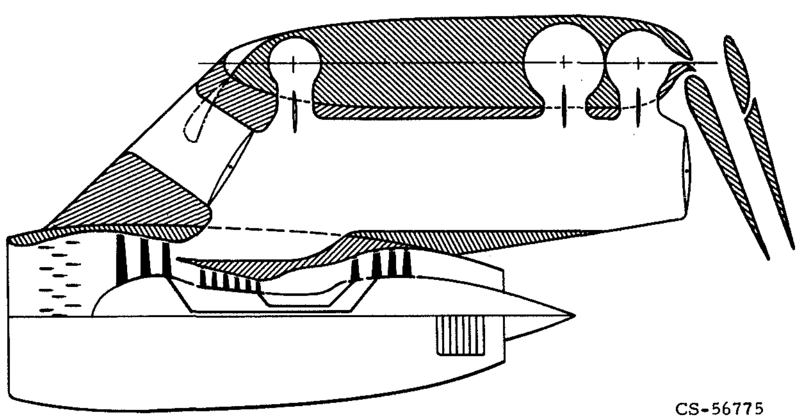


Fig. 17

LIFT PRODUCING DEVICES FOR VTOL AIRCRAFT

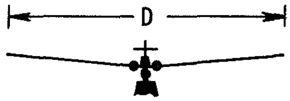
THRUST DEVICE		RELATIVE DIAM, D	THRUST LOADING, LB/FT^2	SLIPSTREAM VELOCITY, MPH
ROTOR		15	6-10	40-80
PROPELLER		5	10-90	90-200
DUCTED FAN		3	90-800	200-500
TURBOJET		1	900-10,000	900-1600

Fig. 18

VTOL LIFT SYSTEM CAPABILITIES

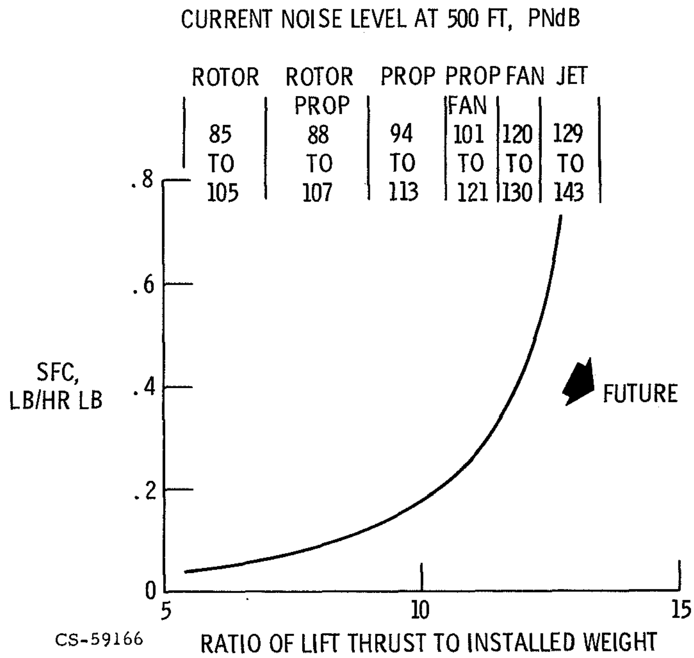


Fig. 19

VTOL PROPULSION FUNCTIONS

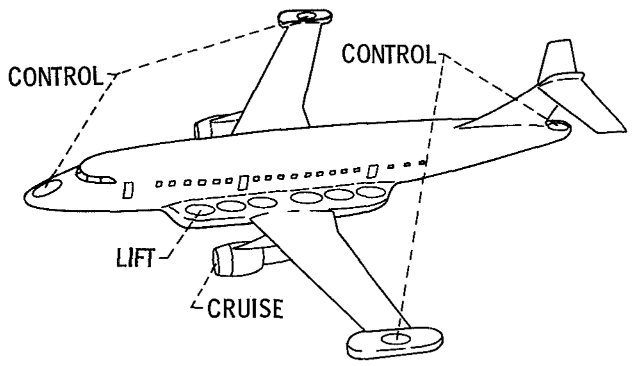
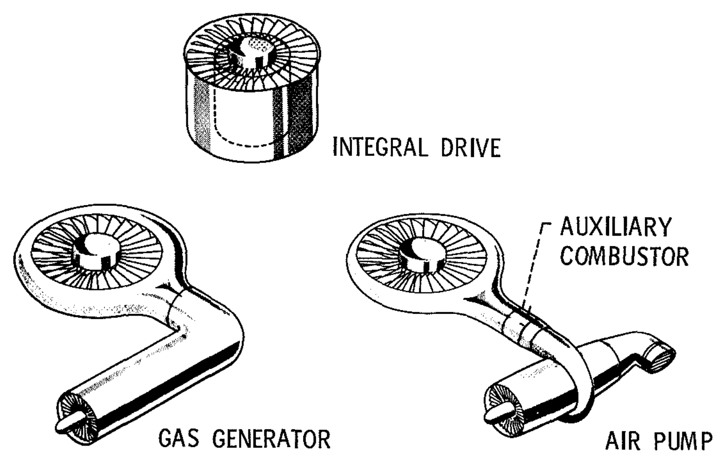


Fig. 20

CS-56798

FAN DRIVE DESIGNS



CS-56577

Fig. 21

REMOTE DRIVE LIFT FAN

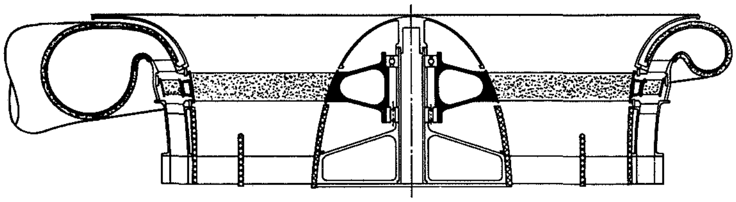
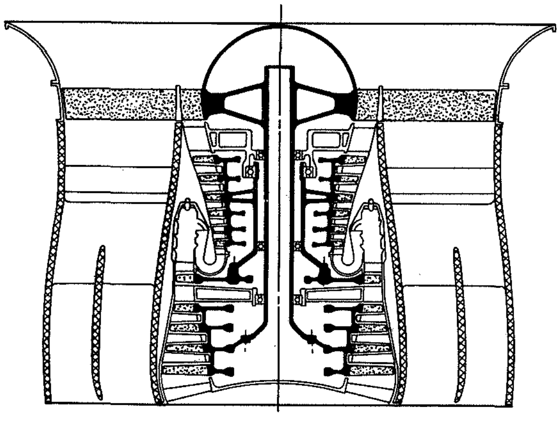


Fig. 22 CS-56574

INTEGRAL DRIVE LIFT FAN



CS-56578

Fig. 23

E-6420

NOISE ESTIMATES FOR VTOL PROPULSION

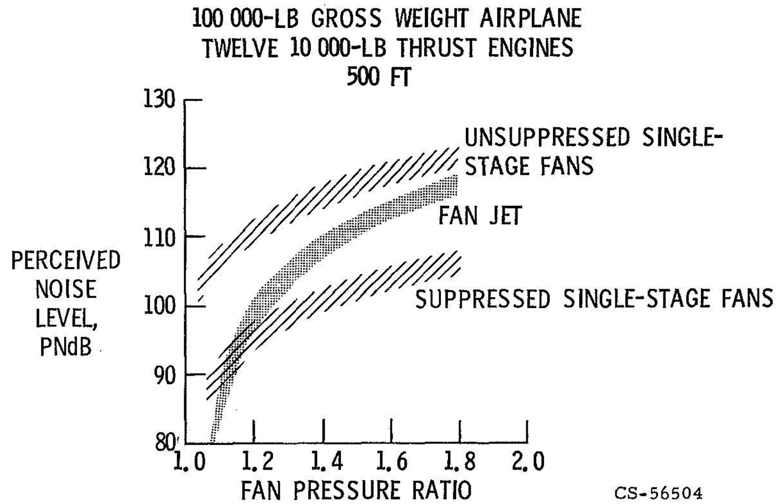


Fig. 24

SUPERSONIC AIR BREATHING PROPULSION SYSTEM

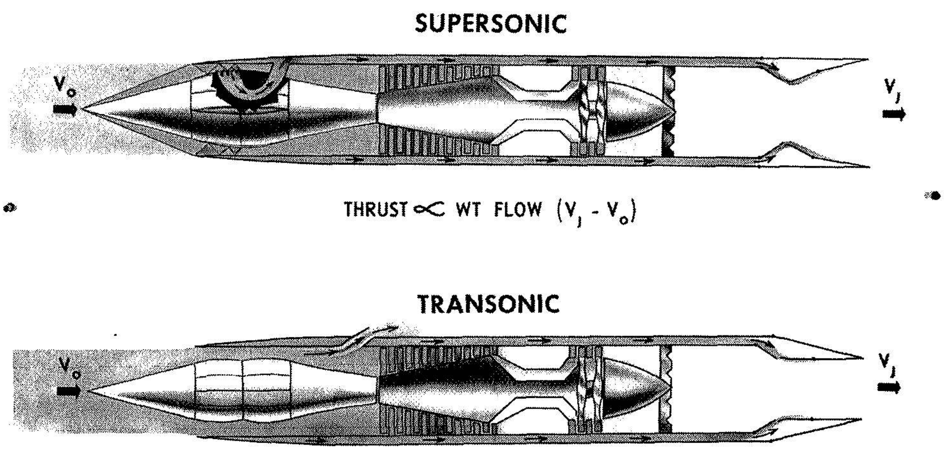


Fig. 25

EFFECT OF VORTEX GENERATORS ON DISTORTION

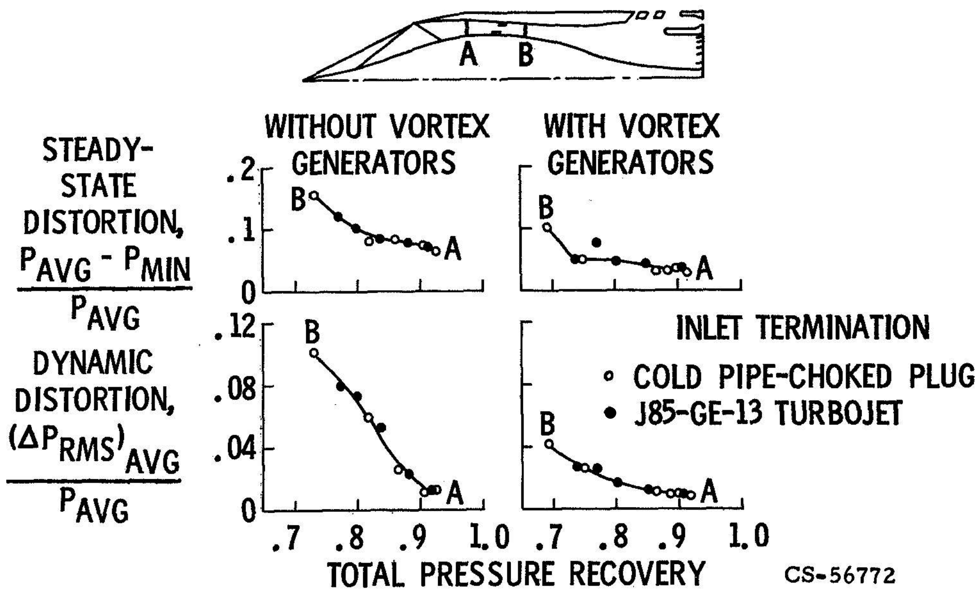
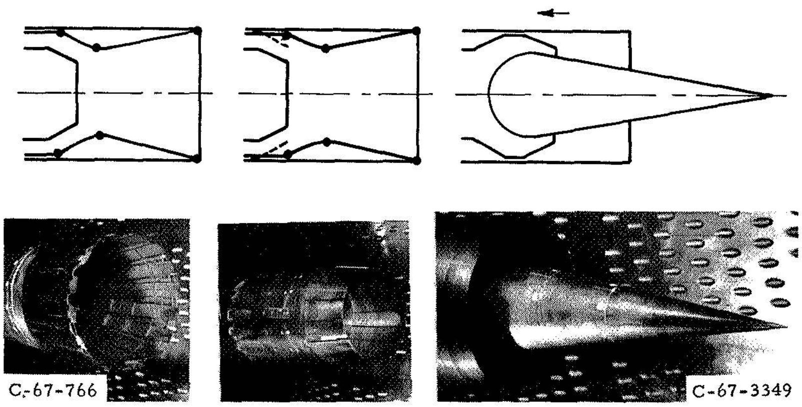


Fig. 26

EXHAUST NOZZLE CONCEPTS

SUPERSONIC CRUISE AIRCRAFT



VARIABLE FLAP EJECTOR

AUXILIARY INLET EJECTOR

PLUG

CS-56942

FIG. 27

E-6420

EXHAUST NOZZLE TEST PROGRAMS

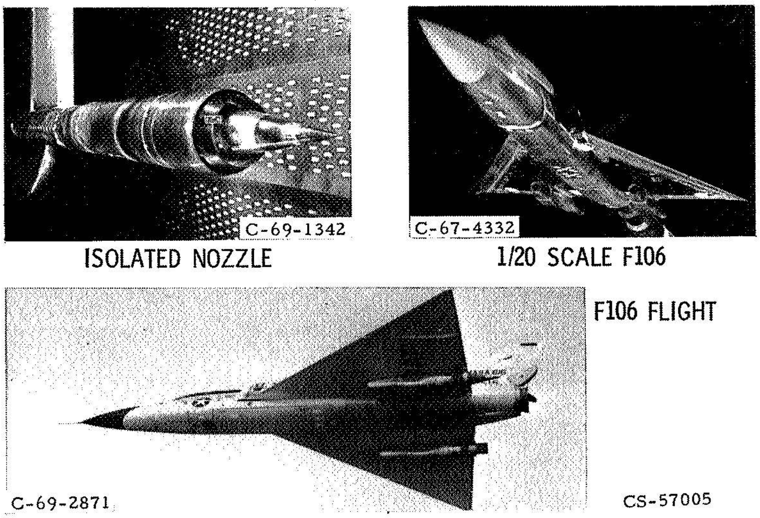
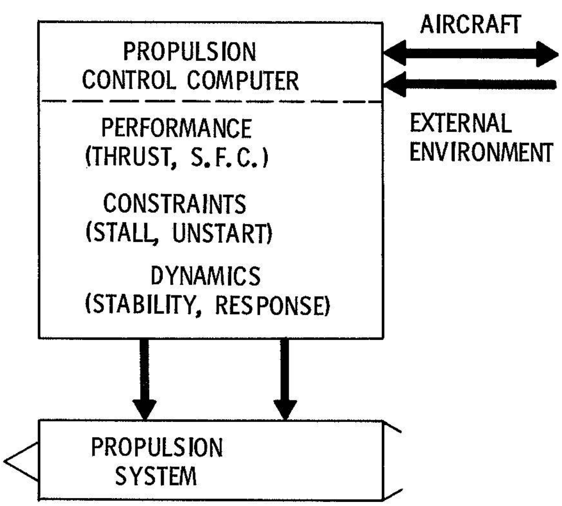


Fig. 28

DIGITAL COMPUTER CONTROL SYSTEM



CS-56919

Fig. 29

ENGINES FOR SUPERSONIC TRANSPORT

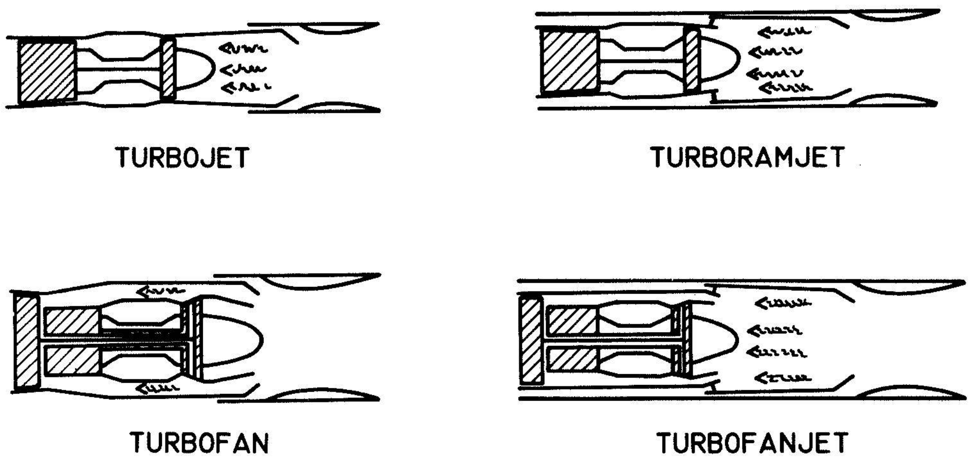


Fig. 30

HIGHER CRUISE SPEEDS WITH SCRAMJETS

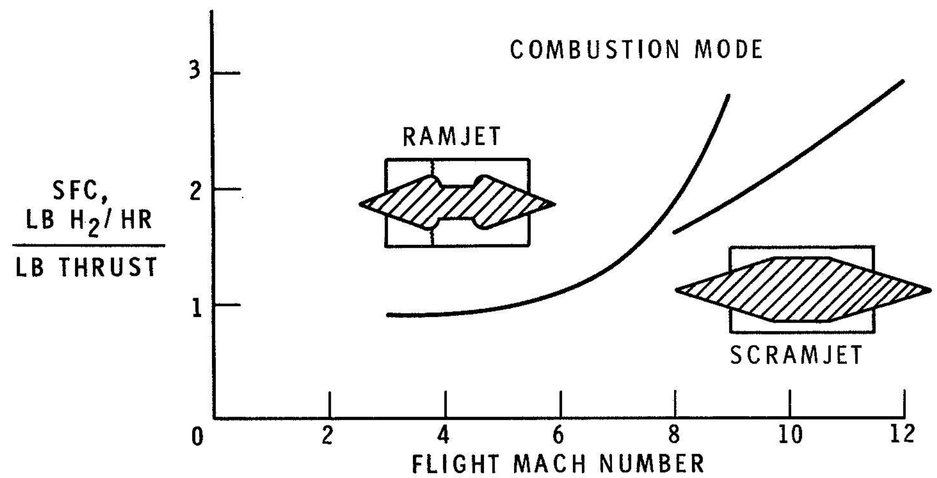


Fig. 31

E-6420

NASA-GARRETT ENGINE - HYPERSONIC RAMJET ENGINE PROJECT

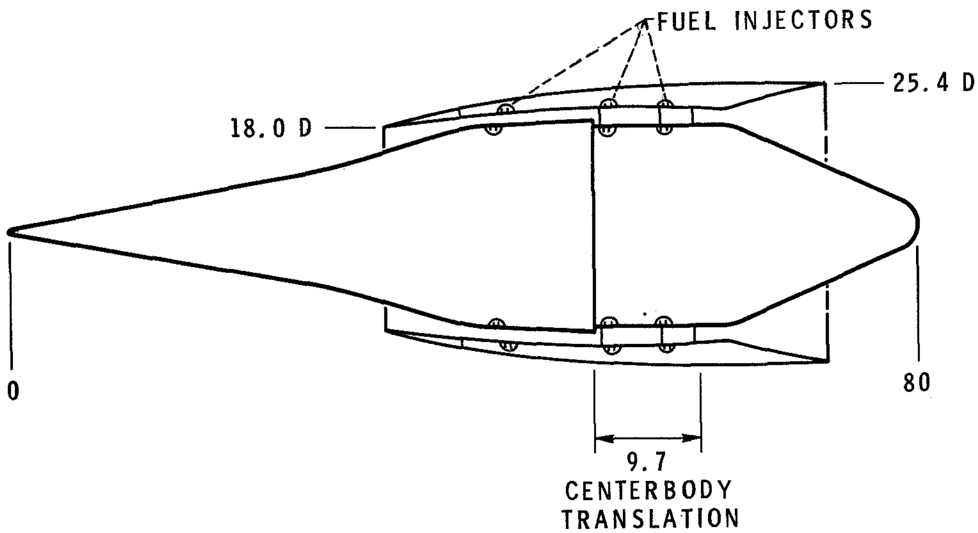


Fig. 32