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NASA Research Activities in Aeropropulsion

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Abstract

NASA is a civilian agency of the U.S. government, responsible for advancing technologies related to air transportation. This paper describes a sampling of the work at NASA's Lewis Research Center aimed at improved aircraft propulsion systems. Particularly stressed are efforts related to reduced noise and fuel consumption of subsonic transports. Generic work in specific disciplines are reviewed including computational analysis, materials, structures, controls, diagnostics, alternative fuels, and high-speed propellers. Prospects for variable-cycle engines are also discussed.

Introduction

Progress in aviation, dating from the Wright brothers on through today, has been largely paced by the performance of the propulsion system. This paper will describe the role of the National Aeronautics and Space Administration (NASA) and its efforts toward improved powerplants.

NASA was established as an independent, civilian, government agency in 1958, charged by Congress with the responsibility for advancing the technologies necessary for improved air transportation (in addition to the space activities that are more popularly recognized). Actually our aeronautics role is an uninterrupted continuation of the work of our predecessor agency, the National Advisory Committee for Aeronautics (NACA), which dates back to 1915.

In contrast to our space activities, where NASA is an operating agency that actually procures and controls space vehicles, our aeronautics responsibilities are much more limited. Through a combination of research conducted within our own facilities plus contracts with industry or universities, we attempt to make available the technologies that will be required for safer and more efficient aircraft. Emphasis is placed on the long-term, high-risk topics that industry is not able to undertake on its own. As a program approaches the point of technical readiness, we withdraw, leaving it to private companies to carry out product design, development, and production.

Within the specific area of propulsion our efforts are organized into two parallel, mutually supportive categories (Fig. 1): (1) a broad, ongoing generic research program in engine components, overall systems problems, and related basic sciences, and (2) a focused program that responds to the specific needs and characteristics of particular vehicle types. Examples of both categories will be described in this paper.

NASA's aeronautical research is conducted through a number of laboratories or field centers that are dispersed around the United States (Fig. 2). Of these, the Lewis Research Center, located in Cleveland, Ohio, on the shore of Lake Erie, is responsible for aeropropulsion (as well as related ground and space power). As shown in the aerial photograph of Fig. 3, this is a very substantial installation. The replacement value of our facilities is over 1-1/2 billion dollars; our staff of 2700 engineers, scientists, and support personnel has an annual research budget for aeropropulsion of about 125 million dollars. Some of our major test facilities are large, high-altitude engine test chambers (Fig. 4), several large subsonic and supersonic wind tunnels that can operate continuously with a running engine within them (Figs. 5 and 6), and noise test stands (Fig. 7).

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Systems Technology

The focused research activities at NASA/Lewis address the specific needs of all of the major classes of aircraft (Fig. 8). Rather than attempt to discuss our work in all categories, this section will concentrate on the subject of subsonic transports as an example, with only brief mention later of some other classes.

The principal concerns related to large commercial transports in recent years have been in the areas of environmental acceptability and fuel consumption (Fig. 9). The problem of exhaust emissions eventually was recognized to be rather minor relative to other, non-aircraft pollution sources, and diminished in public awareness once new combustor technology eliminated visible smoke. However, the noise and fuel problems are not so easily solved.

Noise Reduction

Anyone who lives or works near a large airport is very conscious of the airplane noise problem. Airport neighbors are becoming increasingly sensitive and militant about the intrusion of noise into their lives. In response, more and more airports are being forced to limit the unconstrained use of their facilities. As shown in Fig. 10, over a ten-year period the number of airports that impose some type of operational constraint (e.g., preferential runways or flight paths) has doubled. Additionally there has been a striking increase in the imposition of out-right curfews.

It is fortunate that technology has been able to offer some major reductions in engine source noise over the years to help alleviate this problem (Fig. 11).[1] The early turbojet engines were extremely noisy. Introduction of the first-generation low-bypass-turbofans (JT3D, JT8D) and the more-recent high-bypass-ratio engines (JT9D, CF6, RB 211) substantially reduced the core exhaust velocity and the associated jet noise. However, the fan generated a new source of noise, and only strenuous efforts in fan machinery noise suppression (e.g., blade spacing, reduced tip speed, wall treatment) have permitted the total noise to decrease as shown.

Fuel Consumption

The fuel normally constitutes the single heaviest portion of a long-range airplane. Consequently the performance of the airplane is very sensitive to engine fuel consumption, and reduction in this parameter has always been a goal of the engine designer. Thus, very substantial improvements in specific fuel consumption have been accomplished during the thirty years of commercial jet flight (Fig. 12). However, a new stimulus toward a more energy-efficient engine arose in the 1970's. The 1973 oil embargo awoke still-continuing concern about the long-term availability of petroleum-based fuel. And, even when available, a ten-fold cost increase (Fig. 13) has greatly increased the operating cost of aircraft and threatened the survival of many airlines.

The NASA response to this crisis, starting in the mid-1970's, had three principal elements (Fig. 14).[2] First was a near-term effort to relieve the immediate problem through modest improvements in the existing fleet of engines; a five-percent saving in fuel consumption was the goal here. Second was an all-new engine design, incorporating advanced technologies that would be available in the mid-1980's, with a potential fuel saving of as much as 18 percent. The third element was a search for unconventional, still-longer-term concepts, that might be substantially better than even the advanced turbofan. The result of this search was the advanced turboprop, with a potential fuel saving of more than 30 percent.

Engine component improvement (ECI) program. - The ECI program was performed through contracts with Pratt & Whitney Aircraft Company and the General Electric Company who manufacture the bulk of the engines in the present U.S. commercial fleet. This program is now completed and resulted in identifying practical means for improving the three major engines in current service by 4-6 percent (Fig. 15). Some of these techniques are economically practical to retrofit; others will be utilized in future production models.

In the JT8D engine, for example, Pratt & Whitney is already providing an improved outer air seal for the high-pressure turbine plus a more-effectively-cooled blade with bleed air discharged at the root. These two turbine changes reduce the specific fuel consumption (SFC) by about two percent. It is estimated that the corresponding fleet fuel saving during the remaining lifetime of this engine type will be 880 million gallons.

Another aspect of the ECI program involved obtaining an understanding of the causes of engine deterioration during service and determining ways to lessen or recover this decrement. As an illustration of the importance of this problem, it has been found that the JT9D engine, after 3000 flight cycles, typically worsens in SFC by about three percent. Normal maintenance of hot-section parts retrieves about one percent of this deterioration. Work under the ECI program has found that cost-effective refurbishment of cold-section parts can regain another 1 to 1-1/2 percent. Additionally it appears that the unscheduled engine removal rate is cut in half by this refurnishment.

Most of the other items noted on Fig. 15 are self-explanatory. Some that are not so obvious are explained below:

- Trenched compressor - an abradable material is applied to the compressor casing and is cut away or notched by the tips of the blades, so that running clearances are reduced and tip losses minimized.
- Stang fairing - the covering over the thrust reverser mechanism is redesigned to create less aerodynamic drag.
- Turbine ACC - active clearance control reduce tip clearances
- Turbine roundness - improved mechanical design and material selection reduces case distortion during throttle transients

Energy efficient engine. - The effort directed toward an entirely new, advanced turbofan is known as the E^3 program. It, too, is principally a contracted activity with P&W and GE, with in-house research support to help advance the necessary component technologies. After an initial period of analysis and component work, this program is now entering a phase of large-scale hardware experimentation and technology validation. The E^3 goals (top of Fig. 16) in fuel saving, economy, and environmental acceptability thus far seem to be achievable. The sources of the fuel benefit are indicated at the bottom of the figure. Discrete component improvements are the major contributor. A more advanced cycle (higher pressure ratio and bypass ratio) is important, and is feasible largely because of those same component advances. Forced mixing of the core and bypass streams is another significant factor.

The two E^3 designs are rather similar. Both have on overall pressure ratio (OPR) of about 37 and a bypass ratio (BPR) of nearly 7. The maximum turbine inlet temperature at sea-level takeoff (T, SLTO) is 100°-200° F higher than in today's engines. An example of the aggressive component technology is GE's compressor pressure ratio of 23 in only 10 stages, with a polytropic efficiency of over 90 percent. Active clearance control is used on both the compressor and turbine.

Advanced turboprop. - The fuel savings promised by E^3 are the result mostly of improved thermodynamic efficiency of the core. An entirely different approach is suggested in Fig. 17, which shows propulsive efficiency, that is, the efficiency with which core work is converted into useful propulsive force on the airplane. Note that the turboprops available back in the 1950's were very efficient. Their replacement by pure jet devices was not because of better efficiency but because of such things as higher speed and productivity, higher altitude for smoother, all-weather capability, etc. In our quest for ways to improve beyond the E^3 level of performance, we projected that modern technology would offer a new generation of propellers that again gave the high propulsive efficiency of the past but without sacrificing the high speed and high altitude we enjoy in modern airliners.

How this improvement is to be achieved will be discussed in the second part of this paper. If we accept the attainment of high propeller efficiency for the time being, the impact on airplane fuel saving is shown in Fig. 18. Depending on the range, an advanced turboprop should provide 15-20 percent fuel saving compared to an equal-core-technology turbofan. The potential reward for pursuing this approach is indeed great.

Commuter Airplanes

The preceding discussion has involved the type of airplane normally operated by major U.S. trunk airlines, i.e., large, high speed (Mach number, 0.8), long range (average domestic stage length, 700 miles). Recent deregulation of the airline industry has given these companies greater freedom to revise their route structures. In particular there is a tendency to withdraw from closely spaced, light-traffic city pairs that are ill-suited to their equipment. In their stead is a rapidly growing group of small airlines, which can more efficiently service these markets. These so-called commuter airlines share with their large cousins a desire for low noise and reduced fuel consumption. But their airplane needs are quite different: stage lengths are short (about 100 miles), which reduces the importance of high speed; hence, their typical propulsion system is a modest speed turboprop (Mach number, 0.4-0.6). Passenger load is rather small, perhaps 30-50 at most. They have less need (and less ability to pay for) sophisticated engines and airframes.

In order to address the needs of this type of user, NASA has a Small Transport Airplane Technology (STAT) program. This program is still in its initial, exploratory study phase.[3] Advanced airframe configurations are being considered at our other field centers (Fig. 19). At Lewis we have been assessing, with the help of the small-engine manufacturers, the potential improvements that foreseeable advanced-component technologies will afford (Fig. 20). Very significant benefits appear attainable in fuel usage, operating cost, reliability, and noise.

Component Research and Technology

A broad variety of research and technology activities are conducted at Lewis in the various generic component disciplines (Fig. 21). A number of these will be discussed in this portion of the paper, with particular emphasis on those aspects relevant to the subsonic transports considered earlier.

Computational and Analytical Research

In the past much of the progress in aeropropulsion was achieved through experimentation and empirical correlations. However, as pictured in Fig. 22, an almost revolutionary change in research techniques is now occurring. Vastly more powerful computers are permitting the analytical investigation of phenomena that were formerly too complex to treat except experimentally. Analysis of problems in structures, fluid mechanics, and combustion, both steady state and dynamic, is now becoming a discipline in its own right. In combination with benchmark and validation experiments, improved understanding of the underlying physics will enable us to more rationally design components in the future.

An important aid to generating confidence in the computational results is an ever-increasing ability to make precise experimental measurements. One important new tool for detailed mapping of complicated flow fields is the laser doppler velocimeter. This instrument can be employed for accurate, non-intrusive measurements of flow velocities within ducts and even within rotating blade rows. For example, Fig. 23 displays the measured velocities between the rotor blades of a high-speed compressor. Very good agreement is found with the calculated velocity contours shown on the left side of the figure.

Materials

The demanding stresses and temperatures within an aircraft engine, coupled with the requirements for light weight and long life, pose unique challenges to the materials researchers. Tremendous advances in material capabilities have been accomplished in the past, and imaginative new approaches promise still further progress.[4] As one example (Fig. 24), non-metallics and composites are now being evaluated for introduction into service. PMR polyimide, a Lewis development, appears very attractive as the matrix material in some composite applications in the cool parts of the engine. It has a temperature capability of 600° F. Composites have a bright future for achieving significant increases in component durability, reducing weight, and ultimately engine cost.

In the hot section of the engine, single crystal superalloys are just starting to be applied. A probable next step beyond that involves directionally structured materials, such as fiber-reinforcement or oxide dispersion (Fig. 25). New coating techniques will retard corrosion and oxidation, and can even provide thermal insulation. Uncooled ceramic blades are still beyond our grasp, but more modest usage of ceramics in nearer at hand. Intensive work is underway on ceramic shrouds to seal the gas path at the turbine blade tips. This alone has a potential to reduce fuel consumption by 2 to 4 percent.

A new concern that has surfaced in the materials field involves the cost and availability of vital elements that are used in high-temperature alloys (Fig. 26). Particularly critical are chromium, tantalum, cobalt, and columbium. These elements have experienced tremendous price increases in recent years. Furthermore, they are largely imported and subject to disrupted availability in times of political unrest. A new activity is, therefore, being initiated at Lewis called Conservation of Strategic Materials (COSAM).[5] This is a multi-pronged effort: (1) a near-term goal is to reduce reliance on these elements in current, high-usage alloys through substitution of less critical elements, (2) improved process technology (such as net-shape and tailored-structure processing) to reduce waste, and (3) development of new alloys based on materials highly available in the U.S. as a longer-term goal.

Engine Structures Research

Related to materials research, but treated as a separate discipline, is the issue of how best to design the various engine components within the capabilities of the available materials (Fig. 27). This field treats such topics as structural dynamics, fatigue and life prediction, fracture mechanics, and composite structure design.

A specific new program in this area is called Hot Section Technology (HOST). The intent of this program is to improve our understanding of all the factors that influence the durability of the hot parts of the engine (combustor, turbine blades and vanes). This long-term program will address improved instrumentation, advanced thermal and fluid-flow analysis, and advanced structural/life analysis methods. A comprehensive test program will help validate the analytical models and life-prediction tools that will be developed.

An example of the type of problem to be treated is given in Fig. 28. It is essential in the design of cooled turbine blades to be able to accurately calculate the local heat transfer rates along the surfaces. Small errors can result in inadequate cooling, excessive metal temperatures, and drastic reductions in blade life. The sketch at the left pictures the very complicated three-dimensional, non-steady flow phenomena that must be accurately modeled. The graph at the right shows the results of using two available theoretical techniques for predicting the chord-wise variation of heat transfer coefficient, accounting for the transition from laminar to turbulent flow. The experimental results, indicated by the squares, fail to confirm the theories by a wide discrepancy. This illustrates the challenges that this program will address.

<u>Controls</u>

The early gas turbine engines were all controlled by hydromechanical devices. As engines become more and more complex and controls are required to serve more functions, the hydromechanical approach becomes less practical (Fig. 29). Electronic controls are clearly the next step, and are just starting to see use in limited, back-up roles. The problem is largely one of reliability (Fig. 30). As long as there were only a few control variables, the hydromechanical system was acceptable. But with a greater number of variables, only the electronic system is able to cope. Fortunately, progress in improved reliability has been substantial, and there seems little doubt that they will be able to satisfy the requirements of even the most sophisticated future engines, including eventually a close interaction with the complete airplane and flight path. Full-authority digital electronic control (FADEC) has now been demonstrated on various engines such as the F100 (Fig. 31), and will appear on all future civil and military engines as the industry acquires sufficient confidence in this new technology.

Another advanced technology category involves digital-compatible sensors and actuators. As indicated in the figure, we anticipate extensive use of fiber optics, which has inherent advantages of simplicity, low weight, and passivity, as well as compatibility with the digital computer.

<u>Turbine Engine Monitoring Systems (TEMS)</u>

Another area where considerable progress is being made is that of engine diagnostics, commonly referred to as Turbine Engine Monitoring Systems (TEMS). This development has been precipitated by the concept of On Condition Maintenance (OCM), where the military is attempting to structure maintenance programs for engines around need rather than around engine flight hours. To implement OCM it is necessary to know and to be able to predict with reasonable accuracy the health of the engine and to isolate required maintenance actions down to the module level for field implementation.

Both the military forces and the commercial airlines have adopted various degrees of engine diagnostics into their operations. Perhaps the most ambitious program is being pursued by the Air Force where programs involving engines such as the J-85, TF34, and F-100 in airframes such as the T-38, F-5, and F-15 have been initiated. A current program involving the A-10/TF34 TEMS has been underway for several years and shows great promise for reducing maintenance costs and enhancing operational utility.[6]

The concept of TEMS is shown in Fig. 32. Data from both airframe and engine sensors are collected, stored, and processed by modern electronics onboard the aircraft. These data then feed a pilot display and a data collection unit. The display gives the pilot routine status and alerts him to out-of-tolerance conditions. The data collection unit is portable and can be directly plugged into a diagnostic console for shop maintenance at the operational unit, as well as providing inputs to appropriate management information systems.

The various levels of OCM have been defined in Ref. 7, and are listed below. Note that level 1 is the simplest, and more complicated levels correspond to higher numbers.

1. Simplest flight-line Go - No Go information, e.g., event recording such as limit exceedence, over temperature, or high vibrations.
2. Flight-line usage recording including cycle and time counting, combined with established thresholds for maintenance action.
3. Flight-line fault tree analysis to predict the time to correct deteriorating overall performance; e.g., fix by wash, trim, or carry out other maintenance actions.
4. Jet Engine Intermediate Maintenance (JEIM) inspection, fault tree analysis and replace components, e.g., faulty core and assembly of consistent life remaining engine.
5. Depot level trending to predict major overhaul, parts consumption, diagnose and replace modules, and life limit management.
6. JEIM diagnose and replace module.

Present technology is available to go to approximately level 4 above. If level 6 could be accomplished in a reliable fashion, considerable monies could be saved and operational capability could be enhanced for both military and commercial applications. The U.S. Air Force has taken the initiative in pursuing the research and technology required, and the NASA Lewis Research Center is just now embarking on appropriate projects to assist the Air Force and to provide the research and technology base for commercial applications. The most challenging tasks include sensor development for reliable performance under extreme environmental conditions, minimizing the number of measurements required consistent with good results, interpreting data by analytical or empirical means, reliable fault isolation, and trending. Progress in these very important areas could be of great benefit for future economical aircraft operations.

<u>Alternative Fuels</u>

Redesign of future engines for lower fuel consumption has already been discussed. Another aspect to this problem involves the type of fuel that will be available to be burned in future engines (Fig. 33). At the present the aviation industry is totally dependent upon petroleum as a source of jet fuel. Furthermore, only a limited fraction of each barrel of crude oil can be readily converted by distillation into jet fuel with its tightly specified properties. In the future it is highly likely that other fractions of the barrel may have to be utilized with a consequent increase in production cost. This will create pressure to modify and relax the specifications for jet fuel. Additionally, entirely different sources for fossil fuel may ultimately be developed, such as shale and syncrude produced from coal. Jet fuel derived from these sources might have to differ considerably from today's specifications to be economically feasible.

NASA has an effort underway to synthesize samples of these possible future jet fuels and to characterize their properties. It is probable that they will be higher in aromatic content, freeze more readily, and have poorer thermal stability. A related activity is, then, to study the impact of these broad-specification fuels on the design and performance of the engine and airplane systems. As one example, higher aromatics have reduced hydrogen content, which tends to increase combustor liner temperature and hurt durability. This is illustrated in Fig. 34, which shows the radiation energy and flame temperature of conventional jet fuel as compared to an experimental fuel having about two-percent lower hydrogen content. As shown at the left of the figure, the principal difficulty is due to the formation of fine carbon particles or soot in the combustion products. The soot persists in the secondary and tertiary combustion zones of the test combustor, and poses a major liner cooling problem.

A different type of problem is that higher fuel freezing point will hurt fuel pumpability after prolonged exposure of fuel tanks to the chill of high-altitude flight. Study of how to handle these types of problems will alow a balance to be struck with fuel cost and availability as affected by different fuel specifications.[8]

High-Speed Propellers

The great appeal of a high-speed turboprop engine has already been described, based on the presumption that a suitable propeller could be achieved. A major effort has been mounted by NASA to investigate the many technological problems that exist for such a device. Figure 35 shows the type of propeller that is evolving from this program. It differs considerably from conventional designs. In order to achieve high-altitude capability without excessive diameter, many blades are necessary. For good efficiency at high flight speed, the blades are very thin and are swept. Flow blockage near the hub is controlled through careful shaping of the spinner and nacelle. The unusual blade shapes will require advanced fabrication techniques to assure structural dynamic stability and light weight. Other problems that must be solved involve high-horsepower reduction gears, noise, and airframe aerodynamic interactions.

A number of alternative designs have been tested in small scale thus far, with very promising results. Propulsive efficiencies in the order of the 80-percent goal have been measured in the wind tunnel at Mach number 0.8. One model was installed atop the fuselage of a JetStar airplane and flight tested for noise. Preliminary results are that the measured noise was 10 dB less than expected. We hope soon to be ready to conduct large-scale acoustic and performance testing, both in wind tunnels and in flight.

A variety of alternative analytical methods are being explored for better understanding of these high speed, highly loaded propellers. A comparison of the predicted performance between two recently developed theories and experiment is shown in Fig. 36. Both analyses are of the curved lifting line type, but only the UTRC (United Technology Research Center) approach recognizes the actual shape of the spinner and nacelle. The more complicated theory does better in following radial variations (right side of the figure) but is actually poorer in predicting overall efficiency and power coefficient. Work is in progress to improve these analyses and other, more-elaborate approaches.

Variable-Cycle Engines

A very interesting new area has been developing in propulsion during the past few years that falls under the general title of variable-cycle engines. This refers to the fact that present aircraft engines are basically optimized for a single flight condition. However, there are new aircraft in the offing that generate unique demands for engine versitility. That is, these vehicles will operate in very different speed or altitude regions during a single flight. What is then desired in the propulsion system is an ability to modify its operating characteristics to best suit each region of flight. Several examples of these vehicles and associated variable engine concepts will be presented.

High-Speed Rotorcraft

Figure 37 pictures an advanced helicopter. The so-called "X-wing" rotates in the usual fashion for vertical lift. Later in flight the rotor is stopped and serves as a fixed wing. Forward thrust is provided by turbofan engines, and the top speed capability is about 400 knots. Bleed air from the engines is discharged through leading and trailing edge slots in the rotor blades to achieve good lift and drag characteristics.

The straightforward approach to powering such an aircraft is to use turboshaft engines to drive the rotor and then later to use turbofans for forward flight. An alternative approach is to use a single engine core for both purposes, alternately gearing the shaft output to the rotor or to a fan. An experimental program is now underway at NASA to investigate this type of system, which is usually termed a convertible engine. A modified TF-34 engine is being tested. The unique features involve the shafting, gears and clutches, and variable inlet and exit guide vanes on the fan. Additionally studies are being made of alternative, less conventional ways of achieving the desired convertibility. The benefit of the convertible system lies in the weight saving from using one, rather than two sets of engines in the aircraft.

Vertical Takeoff and Landing (VTOL)

Another type of aircraft with vertical takeoff capability uses jets instead of rotors (Fig. 38). Because there is no rotor, a VTOL airplane can fly much faster, even supersonically if desired. Because of the high power requirements of this type of vehicle, it is very desirable to be able to vary the characteristics of the engine between takeoff and cruise.

One approach, illustrated at the bottom of the figure, is called a tandem fan.[9] In an otherwise conventional turbofan engine with a two-stage fan, the fan stages are separated by an unusual long distance. Air-flow entering the first fan stage is discharged downward through an auxiliary nozzle. A separate airstream feeds the second stage through a second inlet located at the top of the nacelle. This stream emerges at the rear of the engine in the normal fashion, being deflected downwards for vertical takeoff. This layout essentially doubles the bypass ratio with little increase in frontal area. (The special problems inherent in these auxiliary inlets and nozzles are now being investigated at Lewis.) In a high-speed application of this device the auxiliary inlet and nozzle are closed, and air passes sequentially through the two fans. This device can, therefore, vary from a high-bypass-ratio, low-pressure-ratio turbofan (desirable for low-speed operation) to a low-bypass high-pressure engine (desirable for high-speed flight).

Another VTOL variable concept is illustrated at the top of Fig. 38. In the Remote Augmented Lift System (RALS), a large amount of air is bled from behind the first fan stage, ducted forward, heated in a burner, and discharged downward for lift. Later in flight all the air flows rearward through the engine in the usual manner. Although not shown in the sketch, a large number of variable-geometry features are also incorporated within the entire engine in order to achieve good performance throughout the flight spectrum.

Supersonic Transport

A civilian supersonic transport places great demands on the propulsion system. Low noise at takeoff and good subsonic capability usually requires a high-bypass-ratio engine similar to the previously discussed E^3. However, the essential, good supersonic capability is best provided by a turbojet-type of device. One variable-cycle concept that has been suggested for this application is pictured in Fig. 39. It is basically a duct-burning turbofan.[10] The ability to independently vary the exhaust temperatures of the two streams, coupled with some airflow variability provided by variable-geometry components, allows this engine to satisfy the varying needs of the airplane. Performance, acoustics, and exhaust emissions of this concept have been investigated with large-scale engine hardware within the past couple of years. Other candidate concepts have also been studied.

Concluding Remarks

Depsite the growing maturity of many areas of aeropropulsion technology, the continuing pressures for improvements in efficiency and the needs of new varieties of aircraft are being met by innovative advances in engine components and overall propulsion systems. The diverse research activities of NASA in both vehicle-focused systems and generic disciplines will support further major progress toward more effective air transportation in the coming years.

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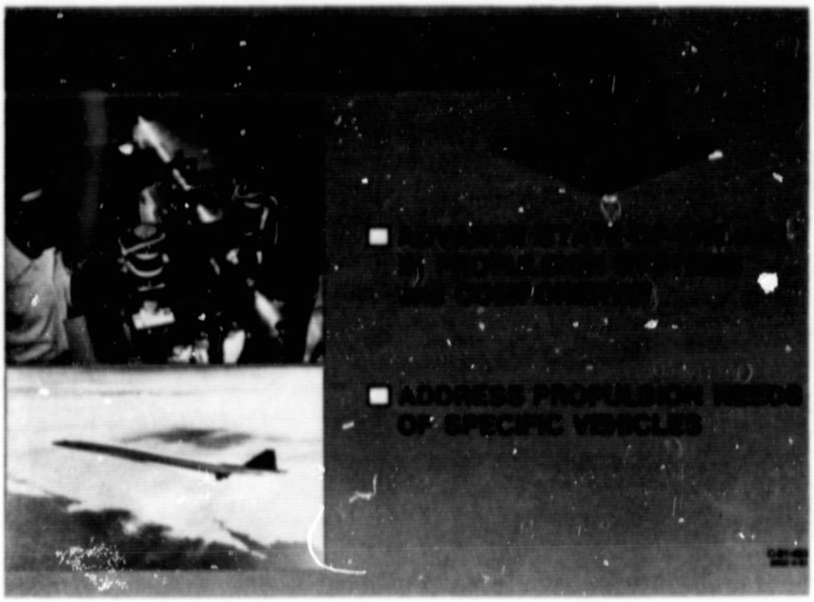

Figure 1. - Aeronautical propulsion.

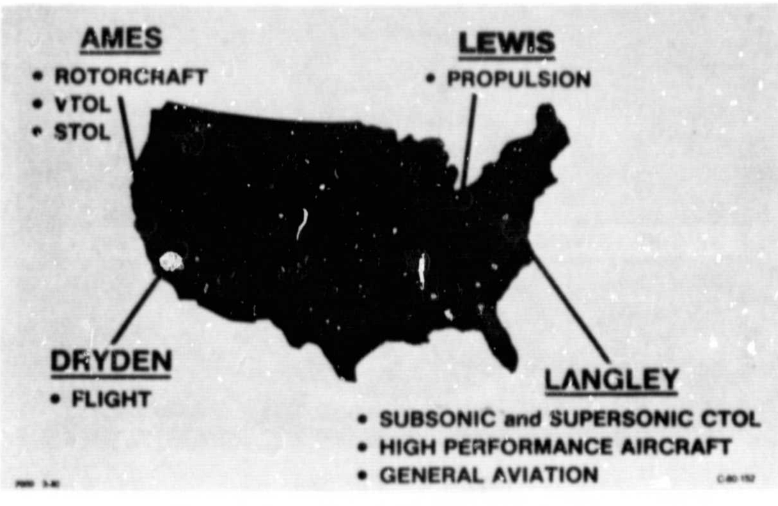

Figure 2. - Roles of NASA aeronautics field centers.

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Figure 3. - Lewis Research Center, Cleveland, Ohio.

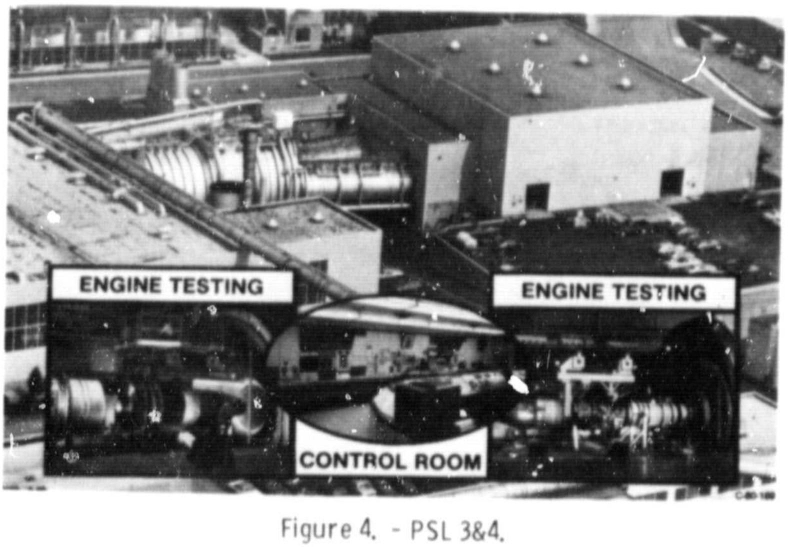

Figure 4. - PSL 3&4.

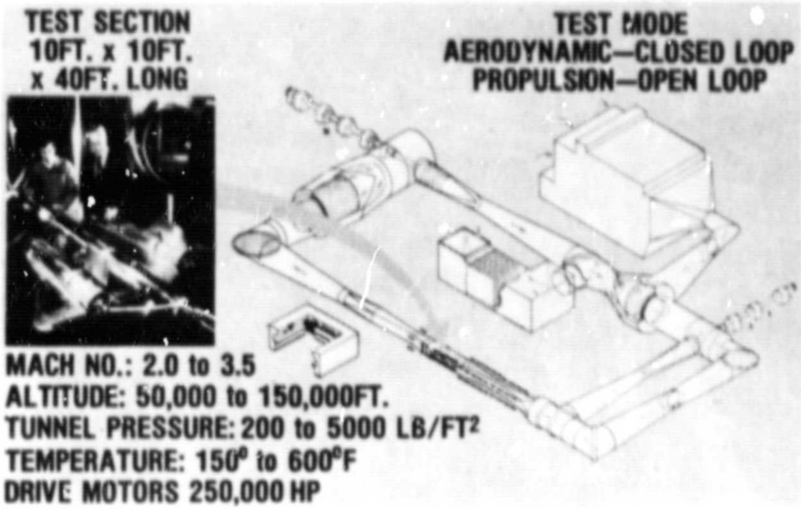

Figure 5. - 10x10 SWT.

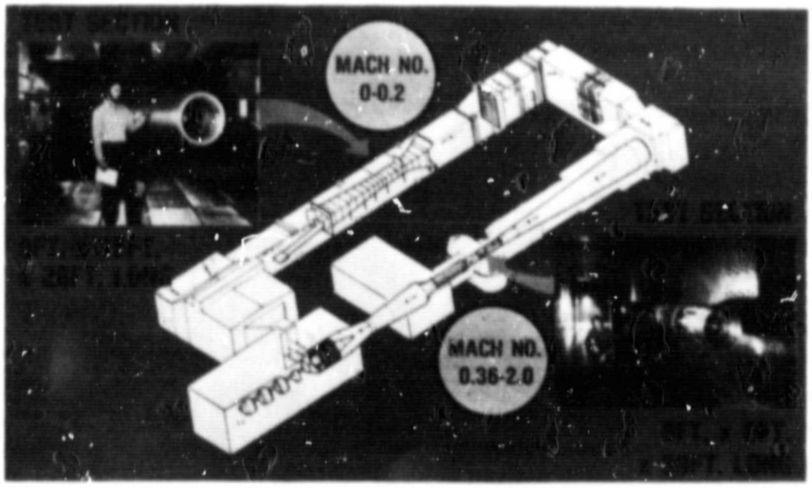

Figure 6. - 8x6 and 9x15.

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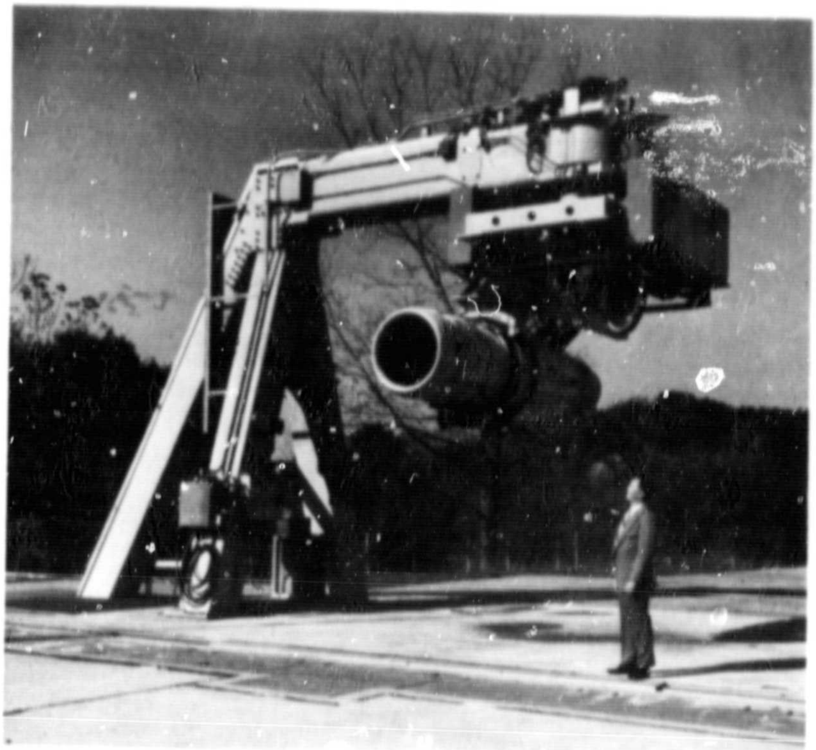

Figure 7. - QCGAT engine on VLF.

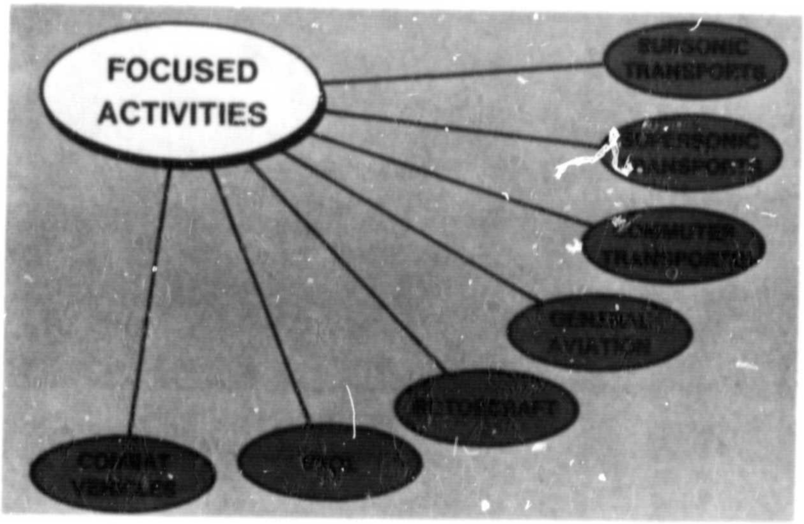

Figure 8. - Aero propulsion - vehicle specific.

ENVIRONMENT

- ■■ REDUCE NOISE
  - ■ REDUCE EMISSIONS

ENERGY

- ■■ REDUCE FUEL CONSUMPTION
  - ■ ACCELERATE USE OF BROAD PROPERTY FUELS

Figure 9. - Aeronautical propulsion - major areas of current national need.

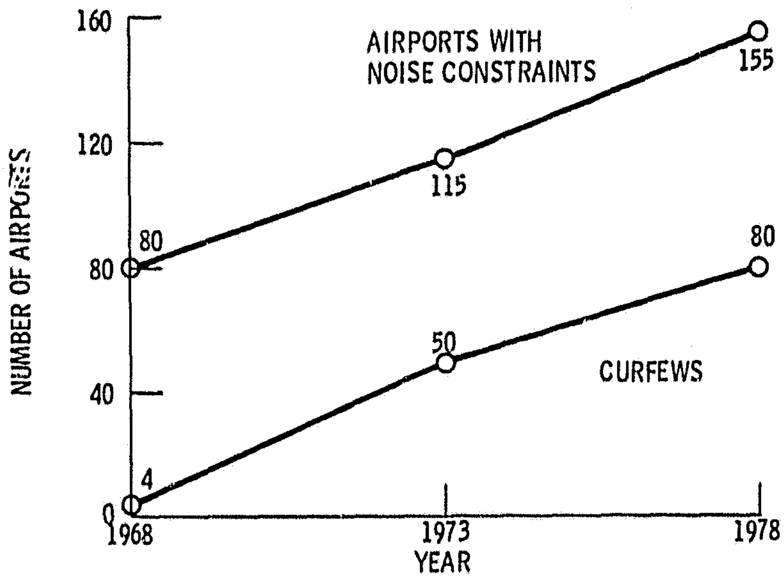

Figure 10. - Noise constraints at major world airports.

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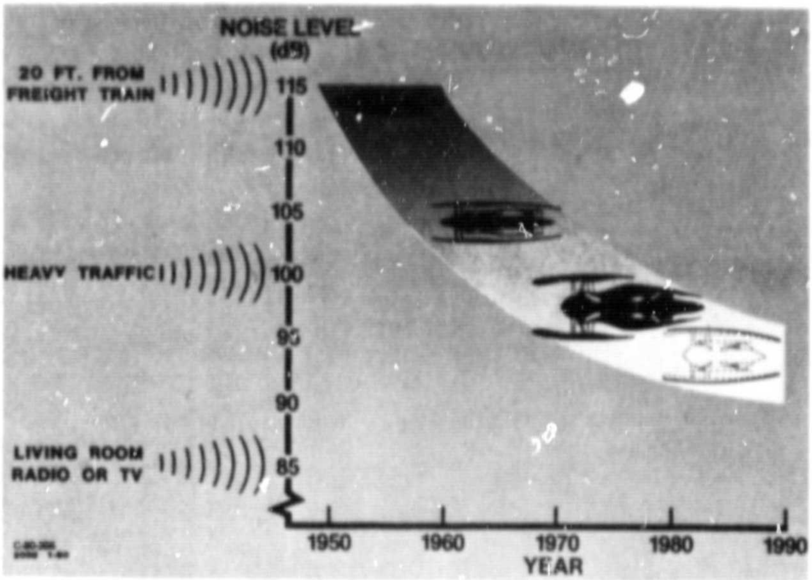

Figure 11. - Aircraft noise reduction.

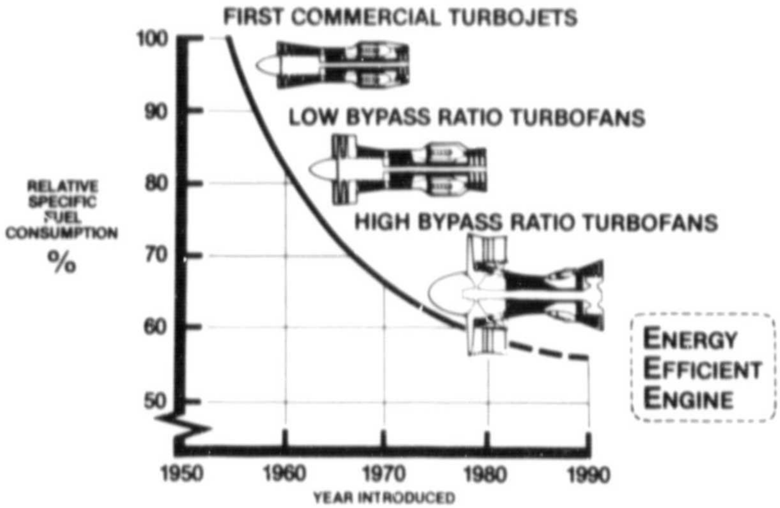

Figure 12. - Improvements in turbofan fuel efficiency.

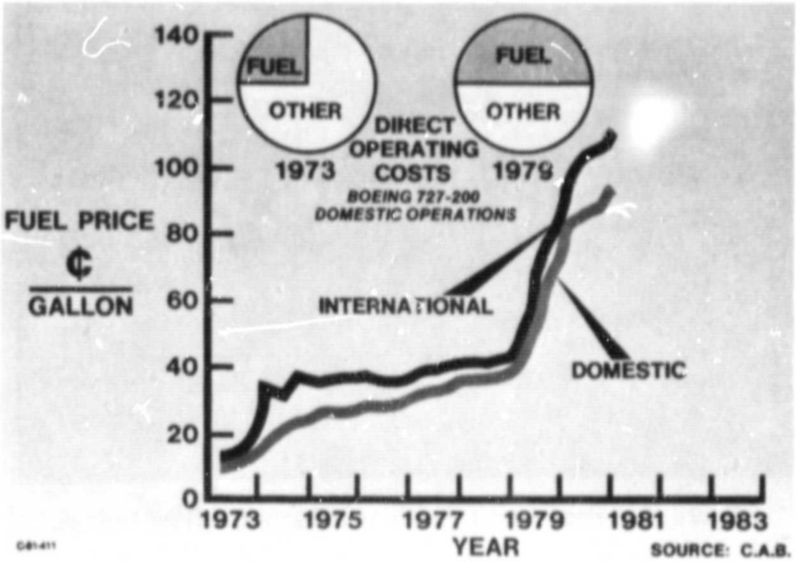

Figure 13. - U. S. airline jet fuel prices.

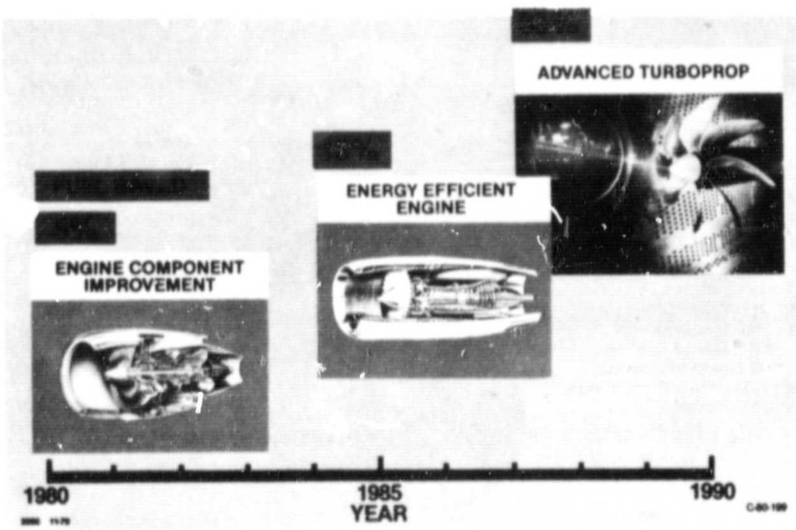

Figure 14. - Energy efficient propulsion technology.

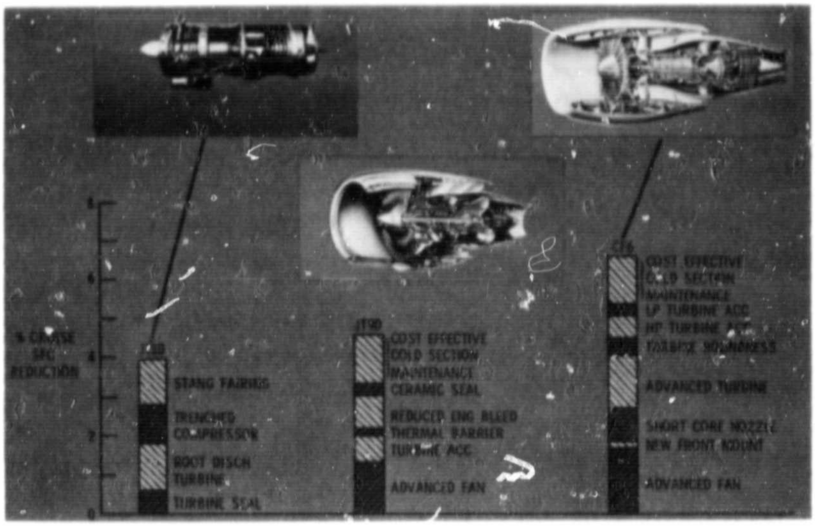

Figure 15. - Engine component improvement (ECI) fuel savings.

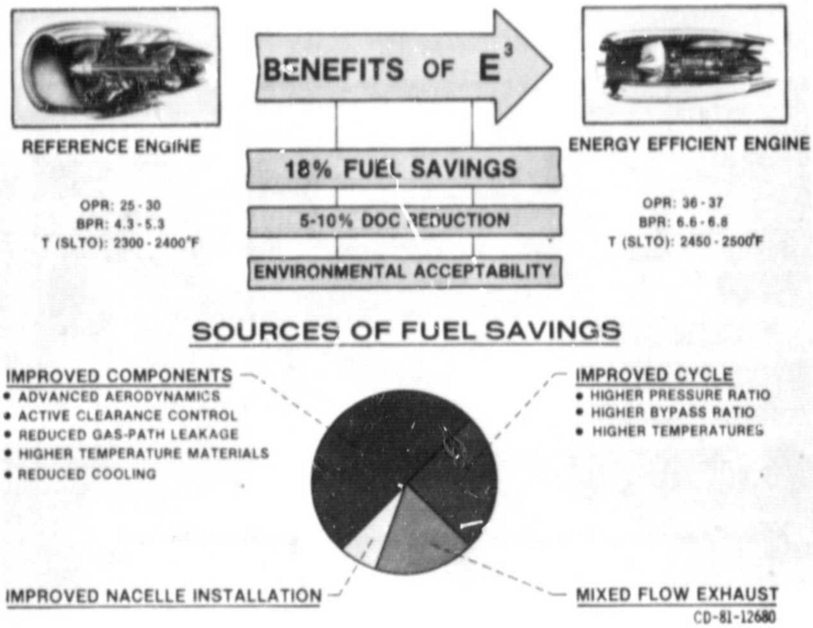

Figure 16.

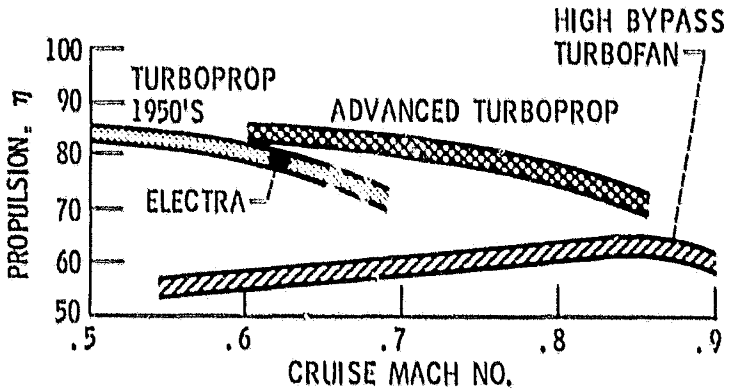

Figure 17. - Installed propulsive efficiency at cruise.

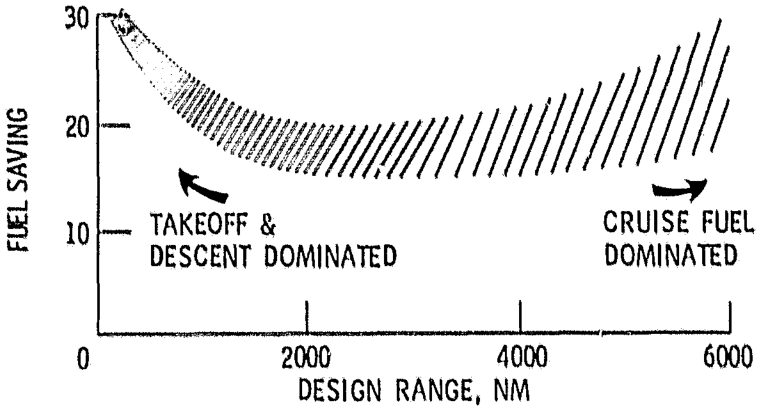

Figure 18. - Relative to turbofan-powered aircraft with same level of core technology.

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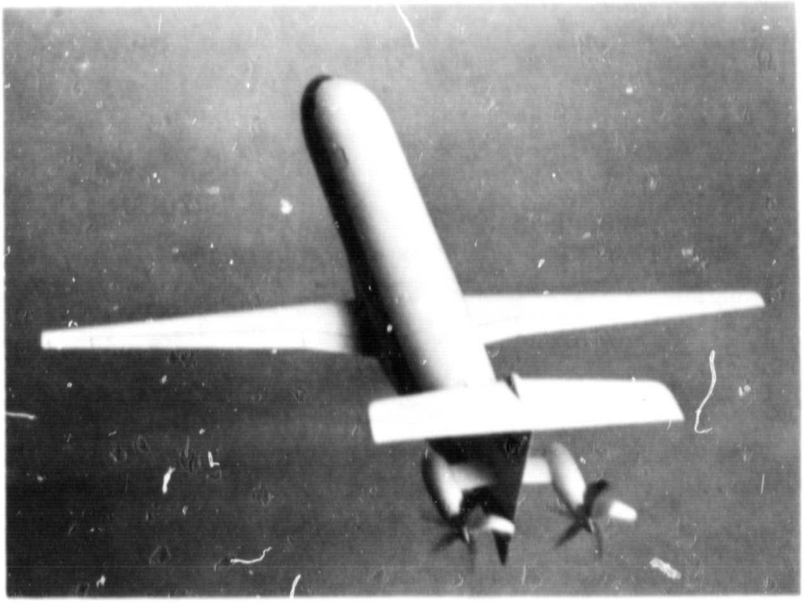

Figure 19. - Advanced commuter airplane.

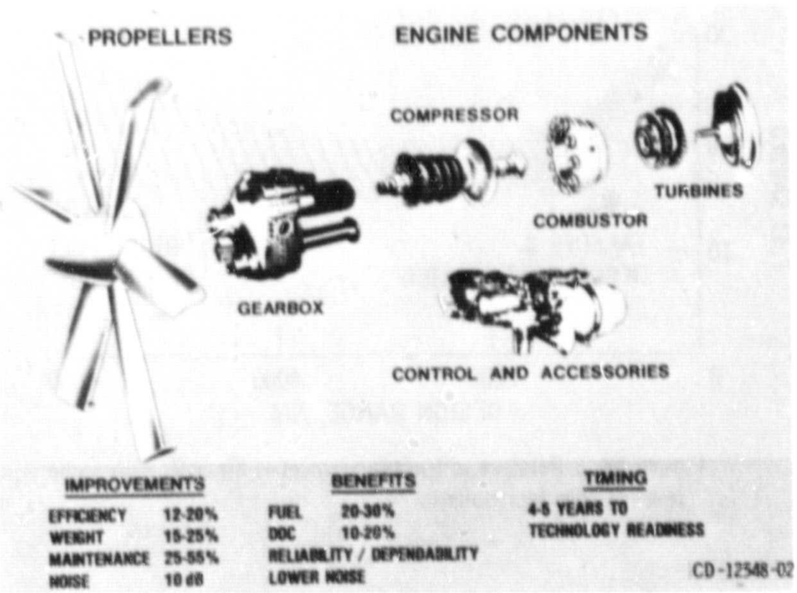

Figure 20. - Stat propulsion technology.

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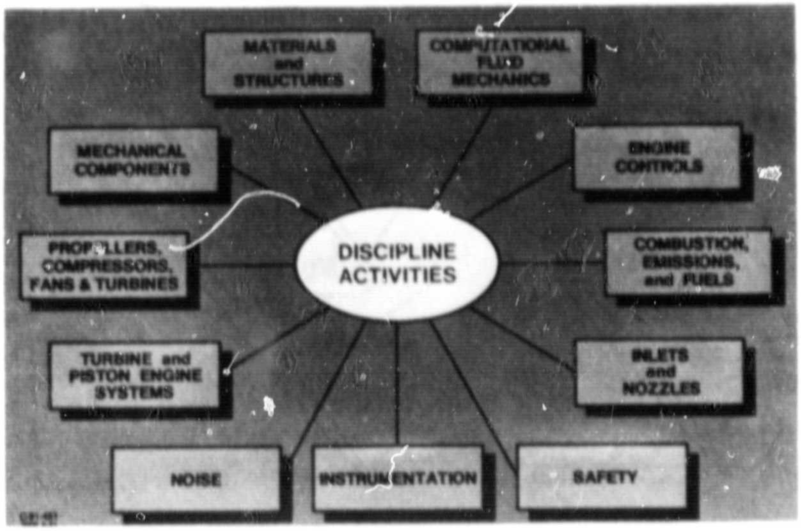

Figure 21. - Aeronautical propulsion.

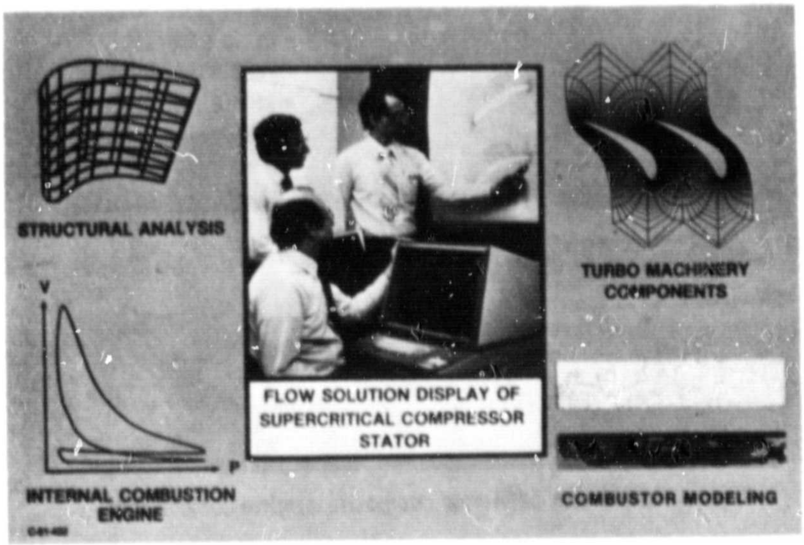

Figure 22. - Computational and analytical research.

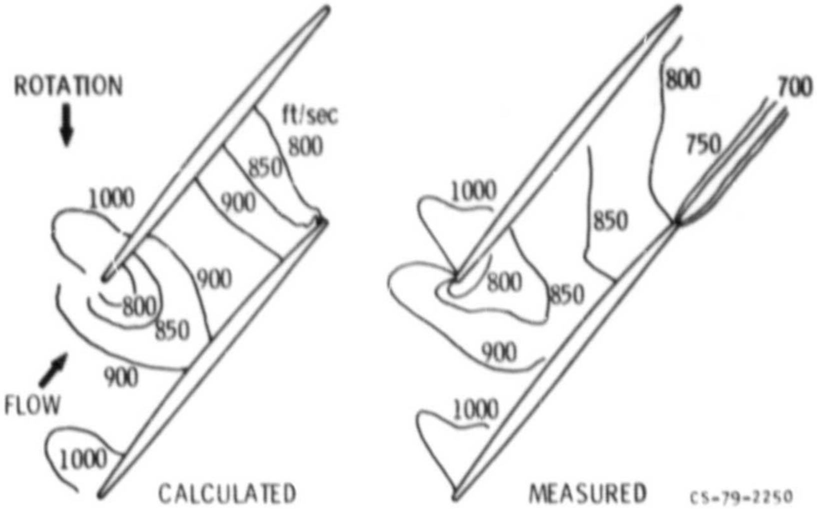

Figure 23. - Calculated and measured velocity contours.

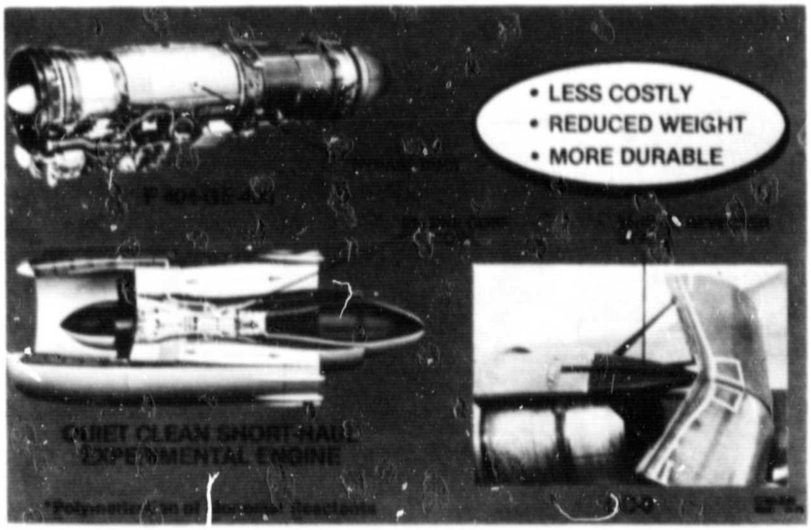

Figure 24. - PMR* polyimide composite engine components.

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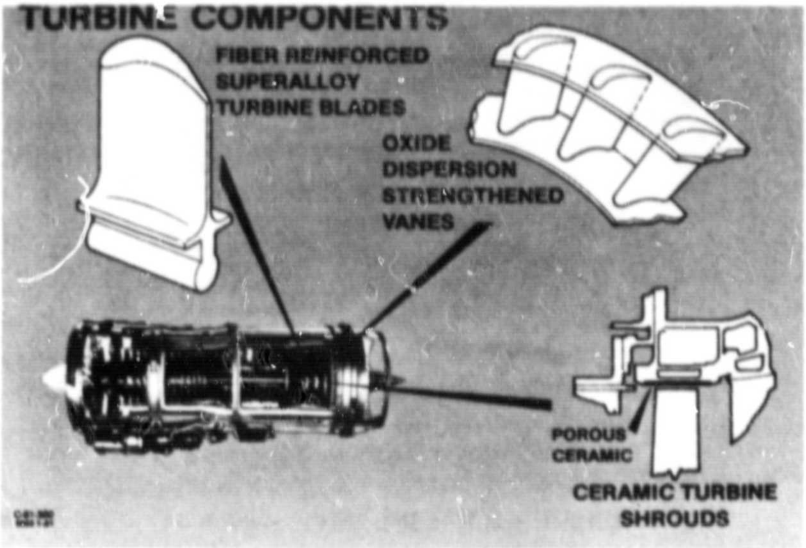

Figure 25. - Materials for higher temperature turbine components.

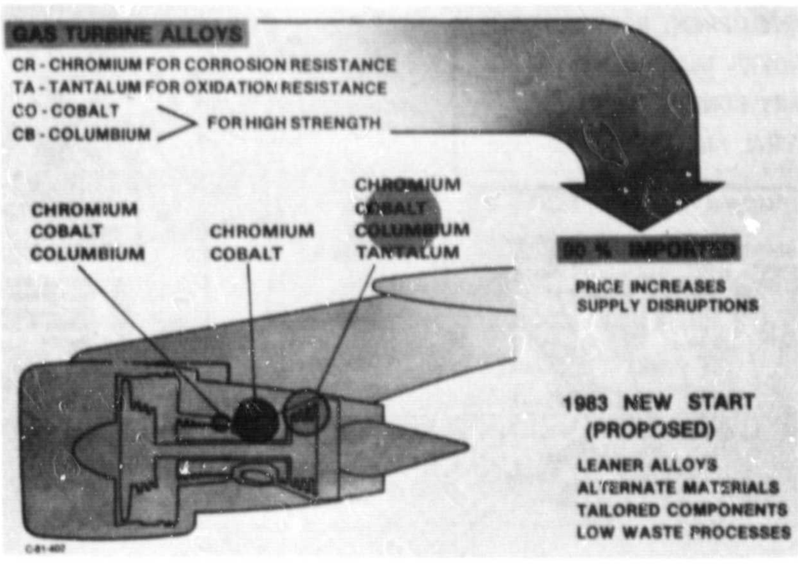

Figure 26. - Conservation of strategic materials.

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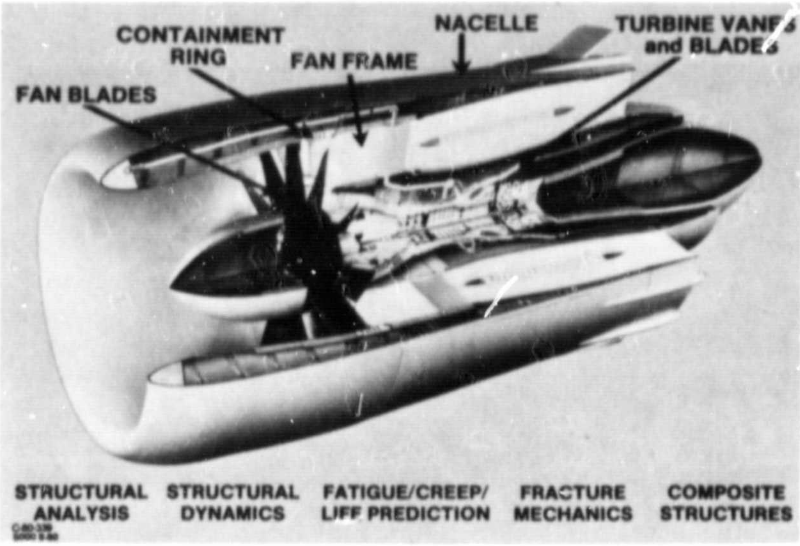
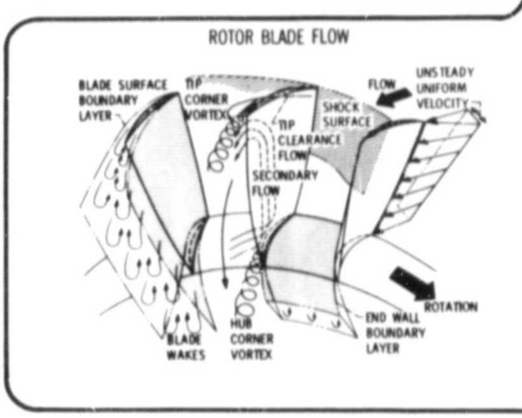


Figure 27. - Engine structures research.

TURBINE HEAT TRANSFER

DEVELOPMENT OF APPROPRIATE HEAT TRANSFER SCHEMES AND FLOW DEVELOPMENT ROUTINES WILL WILL PROVIDE MORE ACCURATE BOUNDARY CONDITIONS TO STRUCTURAL ANALYSTS.



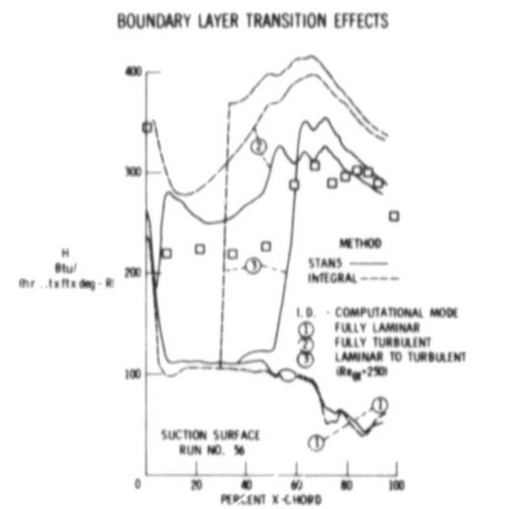


Figure 28. - Turbine engine hot section technology.

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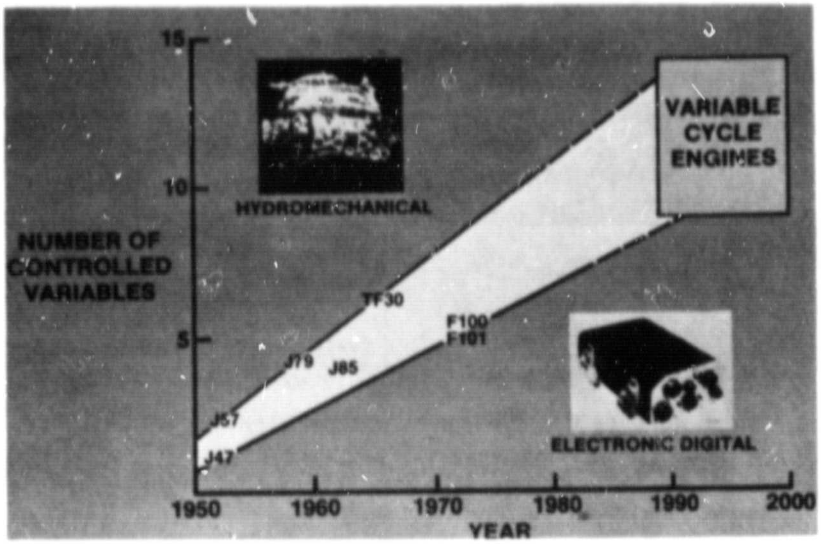

Figure 29. - Engine controls evolution.

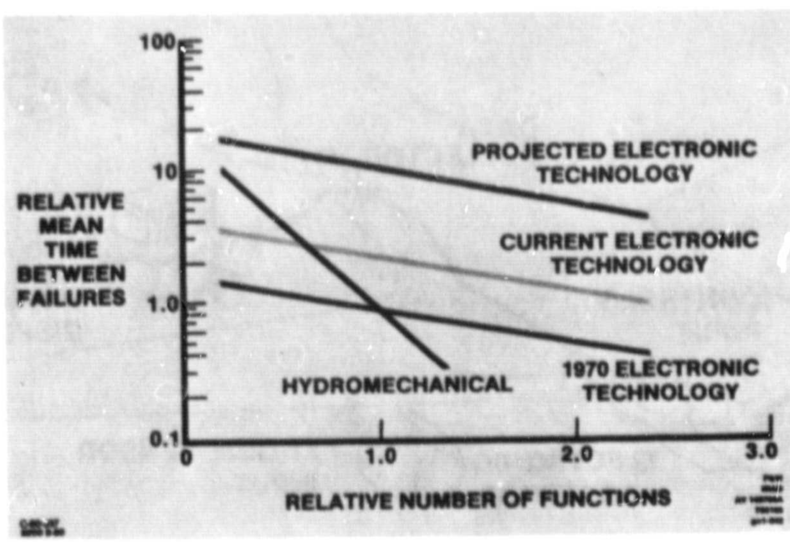

Figure 30. - Electronic control reliability.

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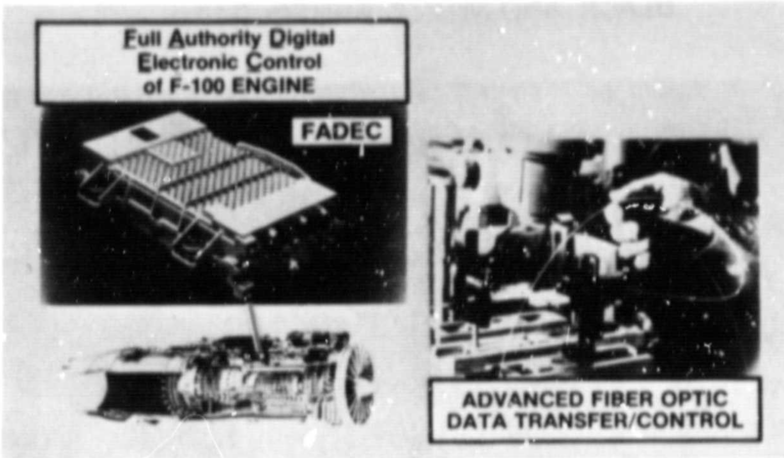

Figure 31. - Electronics and applied physics.

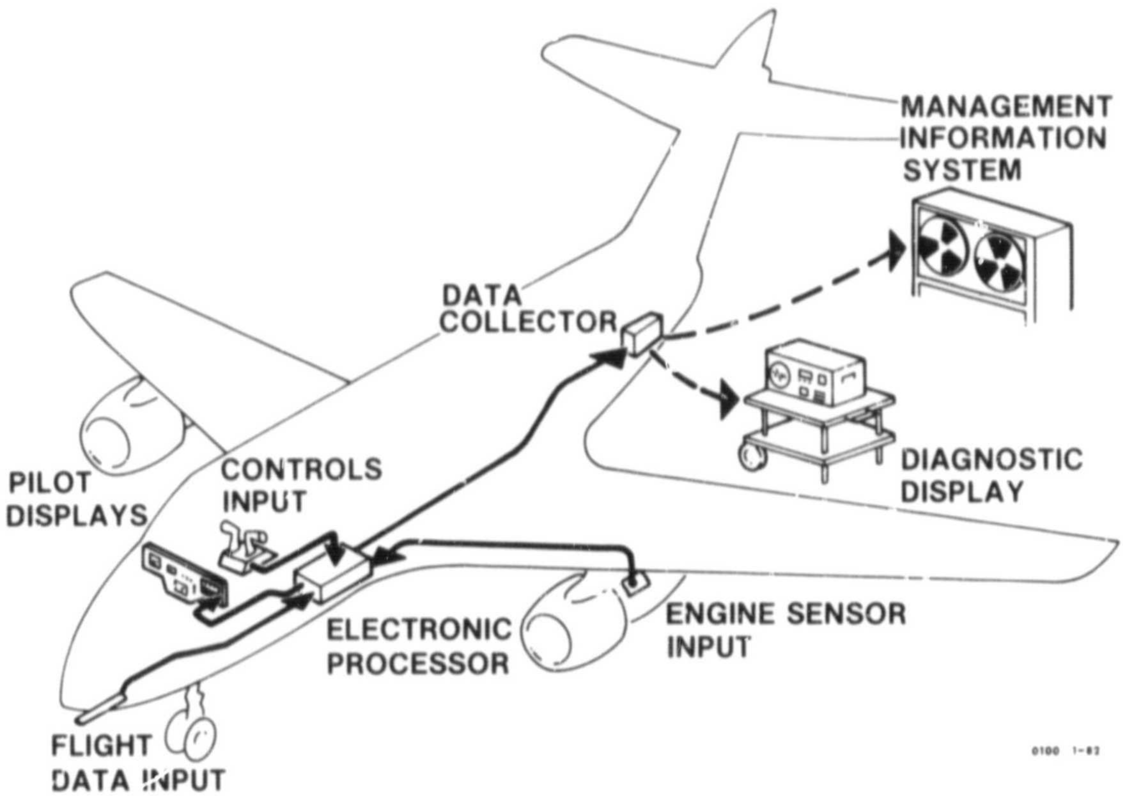

Figure 32. - Turbine engine monitoring system concept.

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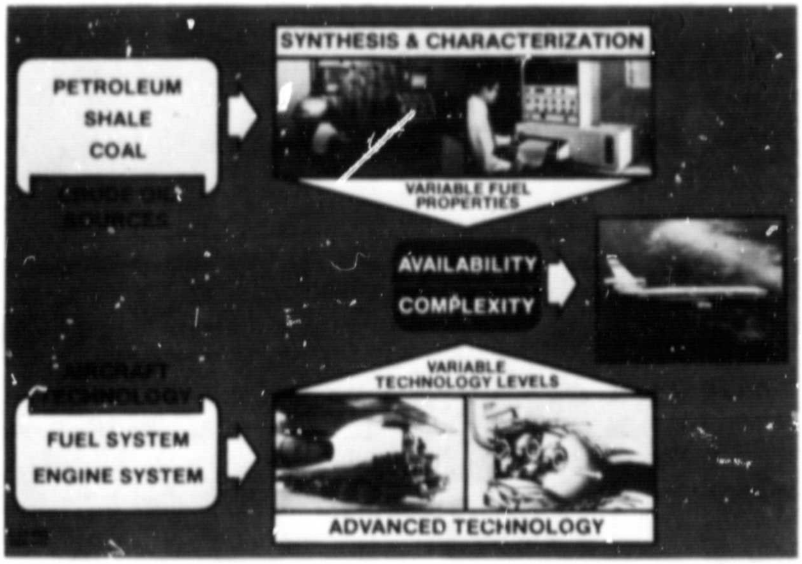

Figure 33. - Alternative fuels R&T.

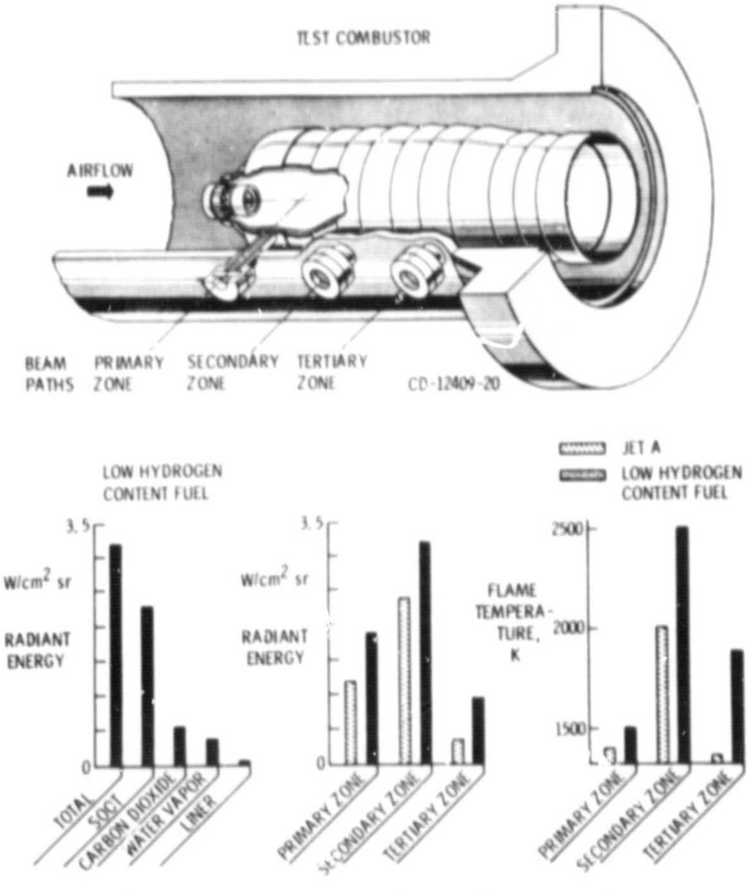

Figure 34. - Effect of fuel type on flame radiation.

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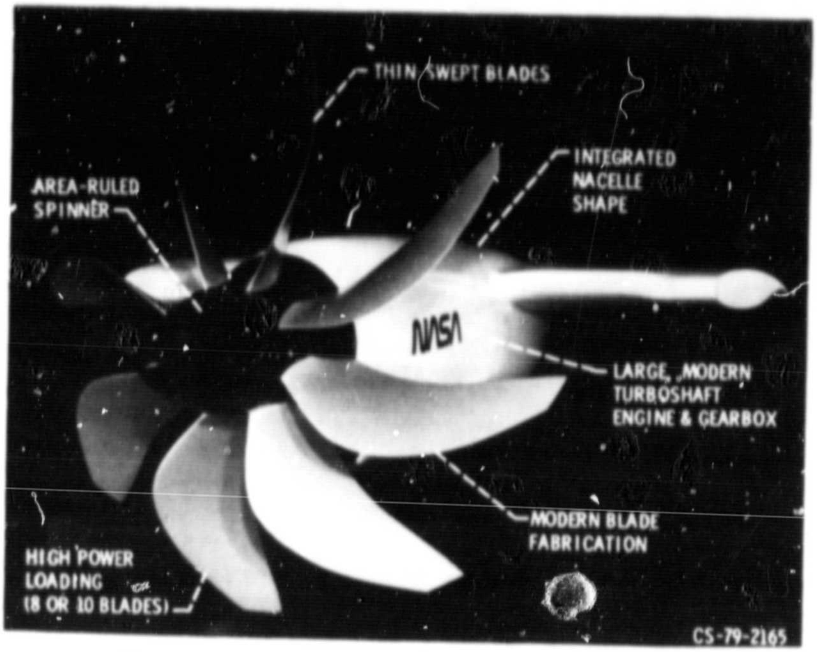

Figure 35. - Advanced turboprop propulsion system.

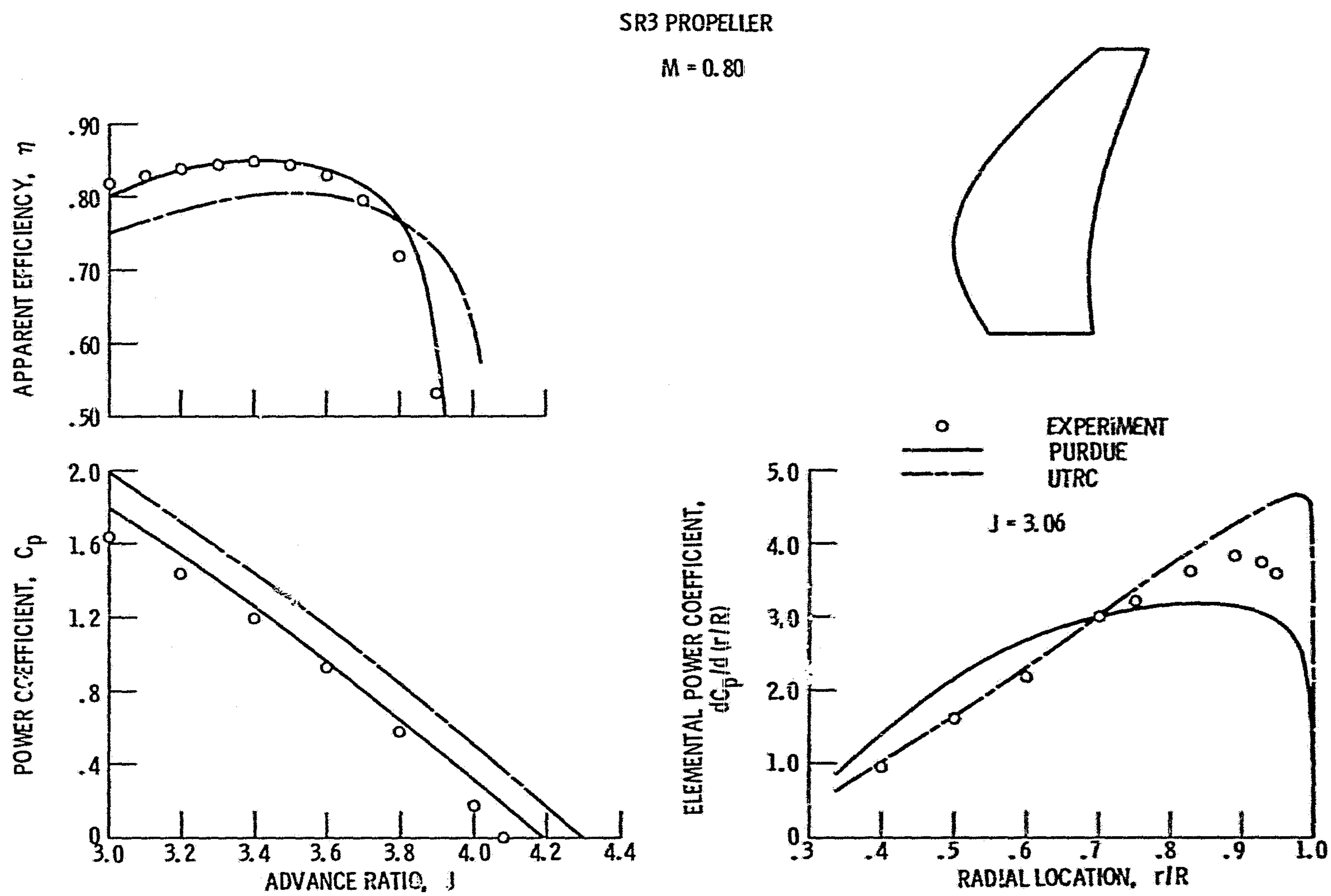

Figure 36. - Lifting line analysis results.

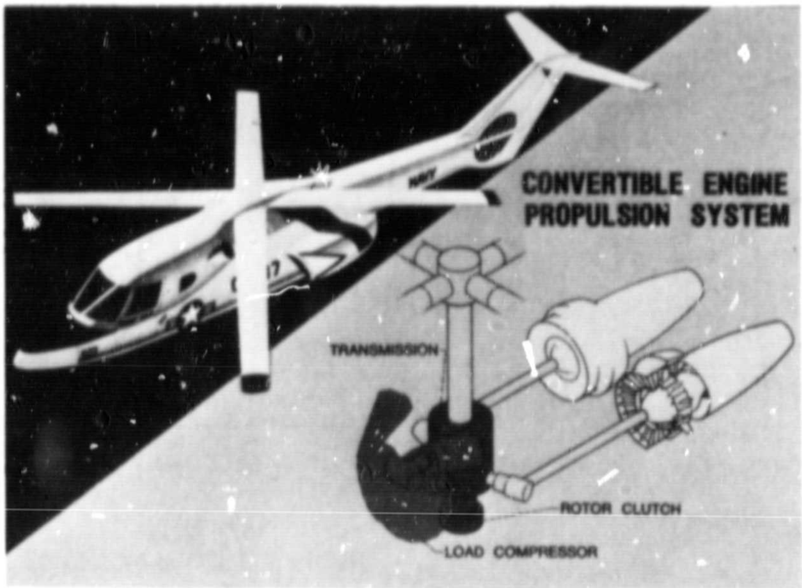

Figure 37. - Advanced high speed rotorcraft.

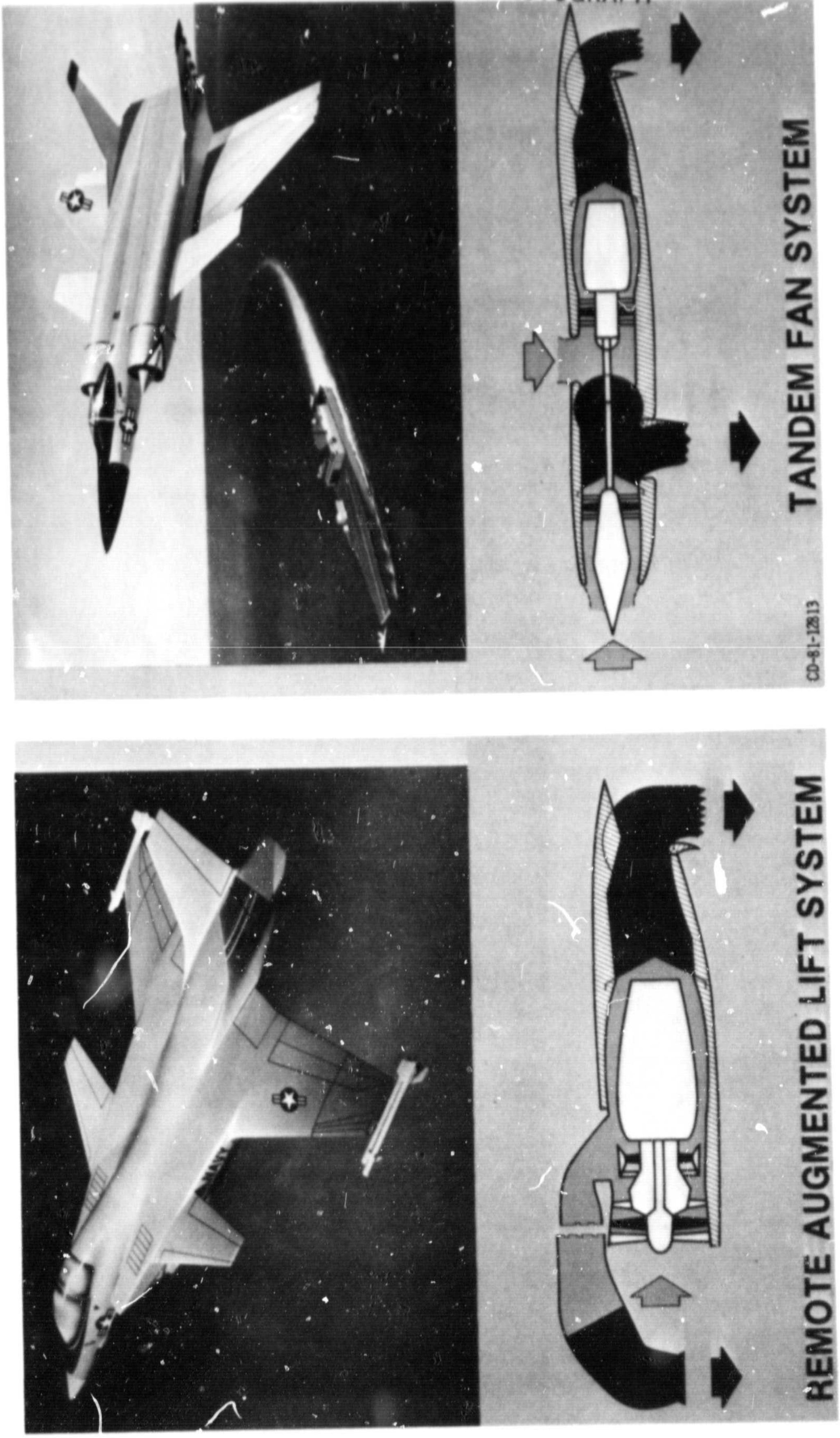

Figure 38. -V/STOL Propulsion.

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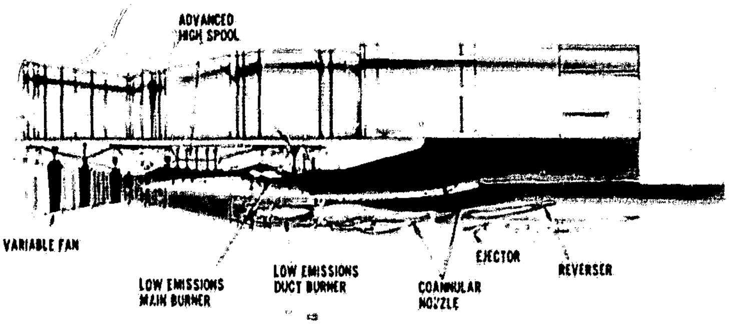

Figure 39. - Variable stream control engine.