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AEROPROPULSION IN YEAR 2000

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AEROPROPULSION IN YEAR 2000

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Abstract

Many advances can be anticipated in propulsion systems for aircraft in the next 20 years. This paper presents a sampling of probable future engine types, such as convertible engines for helicopters, turboprops for fuel-conservative airliners, and variable-cycle engines for supersonic transports. This is followed by a brief review of related technology improvements in propellers, materials, noise suppression, etc.

Introduction

The era has long passed when the forecaster of future aircraft developments could simply say "farther, higher, and faster." Diverse economic, societal, and military factors have imposed new needs that air vehicles must respond to. However, projecting to the year 2000 does not force supernormal prescience on the propulsion system forecaster. This is only 20 years hence, and since the development time for an all-new engine is usually in the order of 10 years, the shape of things to come is necessarily related to advanced concepts that are now under study in the laboratory. Accordingly, the approach of the present paper is to be guided heavily by the opportunities for improved engines that will be afforded by the advanced research that is happening now or expected in the next few years. This research takes place in many industrial and governmental laboratories, although lack of time to expand on the author's limited background has resulted in greatest reliance on work within NASA.

As noted, future aircraft and their associated propulsion systems are shaped by the needs of the user and the surrounding society. A present perception of significant technology drivers includes the following, self-explanatory factors:

- High price and limited availability of fuel and strategic materials
- Environmental protection (noise, emissions)
- National defense
- Enhancing corporate or national market competitiveness
- Higher productivity and/or lower cost
- Airline deregulation
- Airport congestion

Predicting exactly which propulsion developments will achieve flight status at any particular time is very speculative. And it is not my intent to review all on-going research programs to assure that nothing important is omitted. Rather, I will discuss a limited, but representative, number of advanced engine concepts that could be in operation in 20 years in response to the listed technology drivers. This will be followed by a review of selected technology elements that probably will be available for use in such engines.

Propulsion Concepts

This section presents descriptions of several advanced-propulsion systems that are applicable to expected future aircraft. They are arranged generally in order of increasing speed.

Rotorcraft

It is likely that future aircraft in this category will couple their vertical-lift capability with higher productivity in terms of greater range, size, and considerably higher speed (especially for civil applications). This will become feasible through advanced lift systems such as tilt rotors, the advancing blade concept (ABC), or stopped/stowed rotors. A promising propulsion approach for such vehicles is the convertible engine (Fig. 1), which can alternately drive the lift system at takeoff and a forward-thrust device during cruise, usually through the use of gears and clutches.

General Aviation

The conventional spark-ignition engine has served small aircraft well for many decades. Significant improvements have been offered throughout the years (e.g., fuel injection and turbocharging), and further advances are likely. A more radical step forward that is now receiving attention is to introduce a diesel cycle (Fig. 2). It is projected that a major reduction in specific fuel consumption can be obtained, while weight is competitive or even improved versus today's conventional reciprocating engines.[1] When installed in two "paper" airplanes of equal performance, the diesel conferred a reduction of 41 percent in fuel burned and 39 percent in 5-year operating cost.[2] A further advantage is relief from sole reliance on aviation gasoline. This very advanced, light weight, two-stroke-cycle concept requires major advances in technology, for example, ceramic-insulated ("adiabatic") combustion chamber, variable-compression piston, efficient high-pressure and high-temperature turbocharger.

Another alternative intermittent-combustion concept is the rotory engine. It has inherent advantages of smoothness, simplicity, compactness, and light weight. With the use of direct injection, stratified-charge combustion, it too has multifuel capability. For improved performance, it would also benefit from adiabatic combustion and turbocharging or even turbocompounding.

Of course, another possibility is to extend the use of turbine engines, already predominant in almost all other segments of aviation, down into the smaller, lower-powered classes of airplanes. Despite their appeal due to low weight, low vibration, and good durability, such engines have been impeded by the two barriers of high cost and poor performance in small sizes. However, a recent series of studies by several engine manufacturers has indicated that major improvements can be expected for turboprops in the 300 to 600 hp range.[3] A combination of low-cost design, improved technology, and high-volume manufacturing in a dedicated facility promises

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cost reductions of about 60 percent. Coupled with a specific fuel consumption improvement of about 20 percent, the benefit offered to the airplane is substantial (Fig. 3).

The availability of these alternatives for use in future aircraft is dependent on whether resources are expended, first for research, and later for development, certification, tooling, etc. However, it is clear that the potential for future general-aviation propulsion systems that are substantially better than those of today does exist.

Short-Haul Propulsion

The problems of increasing air congestion and ground access time to reach airports have led to suggestions that airplanes operating from close-in airports would offer a significant benefit to the nation's air transportation system. To be a good neighbor, these airplanes would have to be unusually quiet and probably would have to operate from rather short runways. Vehicles using the propulsion system to augment the wing lift are a possible way to achieve this goal. The QCSEE (Quiet Clean Short-Haul Experimental Engine) system sketched in Fig. 4 is an example of an engine suitable for such duty.[4] Although the QCSEE demonstration utilized an existing core, it is notable for the many advanced-technology features as shown, which will likely be incorporated in many futher designs.

Fuel-Conservative Turbofans

Low fuel consumption has always been a major goal for commercial air transports. However, the dramatic price increases and shortages of fuel in recent years have focused new attention on this characteristic of engine performance. NASA's E^3 (Energy Efficient Engine) program is presently striving for advances in technology that will demonstrate a reduction of at least 12 percent in specific fuel consumption (SFC). The design of Pratt & Whitney is pictured in Fig. 5. A picture of the General Electric design would appear quite similar. The most obvious feature that is different from current engines is the mechanical forced mixer. Other changes that are not apparent include moderate increases in bypass ratio, overall pressure ratio, and turbine-inlet temperature. The components incorporate such features as higher stage loadings and efficiencies, active clearance control, and better materials.

The E^3 technologies should be suitable for use in new engines that are developed during the latter 1980's. Still more-advanced designs will be attainable by 2000. It seems most likely that these designs will continue the evolutionary trends towards higher pressure ratios (reaching perhaps 45:1) and higher turbine-inlet temperatures (perhaps 2600° to 2800° F). The use of geared fans will also allow increases of bypass ratio into the 10 to 12 range.

Turboprops

The initial studies that led to the E^3 program also considered a large assortment of unconventional concepts that might represent improvements beyond the turbofan. The only one that seemed to merit further attention was the turboprop. The appeal of the device lies in its high propulsive efficiency compared to the turbofan (Fig. 6). It is hoped that the high efficiency that was available in the Electras of the 1950's can be combined with the higher speeds of modern turbofans through the use of advanced propeller technology (discussed later). It presently appears quite likely that this efficiency can'be achieved, which then can result in the 15-percent or more fuel savings indicated in Fig. 7. Additionally, there are difficulties associated with cabin noise and vibration, but these should be solvable in the coming years.

Improved turboprops will also find application in the smaller, lower-speed field of commuter airplanes, which have achieved new attention as a consequence of recent airline deregulation. The propulsion needs for this airplane category are not so much for performance as for better reliability, maintainability, and safety.

Supersonic Transport

The British-French Concorde has demonstrated the appeal of shortened trip time to a significant portion of the traveling public. By 2000 the technology should be in hand to offer an airplane that couples high speed with only moderately higher ticket cost (5 to 20 percent surcharge over economy class) and is as quiet as other passenger aircraft of that era. Noise is one of the principal constraints on engine design for this application. The variable-cycle engine is one interesting method for achieving low noise and also has further benefits in improved subsonic cruise and hold, which is a necessary requirement for practical operations. Figure 8 pictures a current concept by General Electric, which features two bypass streams, variable mixers to combine or separate the streams as desired in flight, and a flow inverter in the nozzle for noise attenuation. Other approaches are being studied by Pratt & Whitney and NASA.

Variable-cycle concepts will also find use in other vehicles that operate over a wide variety of conditions. These might include helicopters, VTOL, and several military missions. As always, the designer will have to balance the complexity and cost of providing varying degrees of flexibility against the benefit to the mission.

Military Applications

Many future military needs can be satisfied by the same technologies involved in the previously described civil engines. However, there are certainly a number of unique applications that must be addressed. For example, high-performance fighters require light-weight engines together with supersonic capability. It seems reasonable to project that future fighters will, in fact, attain true sustained supersonic cruising ability, rather than the brief dash ability of today.

Extrapolation of today's knowledge suggests that these future engines will not be too unlike those of today. Evolutionary progress from such military programs as ATEGG, APSI, and JTDE will no doubt continue the trend toward higher combustor temperatures, perhaps together with variable-geometry turbines. Continued emphasis on reduced life cycle costs will probably lead to extensive use of a common core for multiple applications, as stressed in the recently started ATES program (Advanced Technology Engine Study). New requirements such as reduced radar and I-R cross-sections or maneuvering thrust would influence inlet and nozzle designs. Unusually shaped and positioned inlets or deflecting two-dimensional exhaust nozzles can be anticipated (Fig. 9).

Any discussion of future aircraft must mention vertical takeoff, especially because of the intensive studies that are currently supported by the military (the Navy in particular). Since these vehicles are proposed for both subsonic and supersonic missions, a bewildering variety of propulsion concepts has been considered in the past. As a single example, Fig. 10 shows a fixed-nacelle airplane with a tandem-fan propulsion system. In this concept, each engine has two interconnected fans. Lift is achieved by deflecting the flow from the two fans and the engine exhaust.

Because of the weight and installation penalties associated with providing thrust capability considerably greater than airplane gross weight, plus the need for propulsive control of airplane attitude during takeoff and landing, any VTOL vehicle is apparently at an inherent disadvantage to its CTOL counterpart. The goal of the propulsion specialist in future years is to minimize this disadvantage, so that the VTOL option is available at a reasonable cost to the user.

The initial steps now being taken toward the use of cruise missiles will no doubt be well-established by 2000. Improvements in the technologies of small components will yield major improvements beyond today. Innovative concepts like Teledyne's Excentric Engine (Fig. 11) may help this trend. This scheme mounts the complete high-pressure spool off-axis to the rest of the engine. Since the high-pressure shaft then need not be hollow, the blade hub radius can be smaller, and the ultimate effect is higher compressor and turbine efficiency for small-sized machines. This benefit is compounded by the ability to now utilize high cycle pressure ratio without the usual component efficiency penalties.

Vulnerability considerations may well shift the use of future cruise missiles into the supersonic region. Inexpensive turbine engines are quite conceivable, but for still higher speed and possibly lower cost, ramjets appear to be desirable. This might be an extension of the present integral rocket-ramjet research. The probable directions for future improvements include variable-geometry inlets and nozzles, higher-temperature structures, and higher-energy fuels.

Still higher speeds, utilizing scramjets (Fig. 12) or other exotic engines, are conceivable. It is not presently clear that the demand will exist for such missions, even by 2000. However, the technology for these engines will probably be available, so that the option can be followed if desired.

Advanced Technologies

Propulsion systems of the types described in the preceding section will be able to profit from expected technological advances in many areas. It may be taken for granted that continuing evolutionary improvements will be realized in practically every engine component, both in aerodynamic and structural efficiency. This trend will be accelerated by the vastly improved computational and experimental techniques that are now becoming available. (As one example, an MIT-developed code allows analysis of three-dimensional flows with strong shocks in a rotating blade row that contains mid-span dampers. Calculated results are compared in Fig. 13 with experiments using a unique laser-fluorescence technique.) Related changes in design techniques will also enhance engine durability and maintainability.

Without trying to summarize the present state-of-the-art and all of the expected advances in each important propulsion discipline, the following sections will attempt to identify a number of specific improvements (or changes) that could have substantial impact by 2000.

Materials

Of all the various elements of an engine, materials are certainly the most pervasive and possibly the most important. They directly influence the weight of each component and, by limiting the pressures and temperatures, have a major effect on the overall engine thrust and efficiency. Looking ahead to 2000, we can foresee an increase of 500° F or so in the temperature capability of turbine materials (Fig. 14). In projecting the future use of such advanced materials as fiber-reinforced superalloys and ceramics, it is anticipated that they will become suitable in, not just temperature capability, but all the necessary practical aspects like resistance to thermal fatigue, oxidation, corrosion, and impact. The improved high-temperature materials will probably be supplemented by the additional benefit of thermal barrier coatings (Fig. 15). These insulating oxide ceramic layers increase the blade temperature capability by up to 600° F.

By 2000 the present research efforts in composites should be extensively utilized in cold section components, such as fan blades and frames. Their low density and high stiffness and strength will provide payoffs in lower weight and cost and even aerodynamic efficiency.

An additional motivation for the use of unconventional materials will be the probability of continuing shortages in certain critical metals, such as cobalt and chromium. Ceramics are especially desirable in this light, although alternative metal alloys will no doubt become available in the coming years.**

Fuels

To alleviate the problems associated with present cost and availability trends of petroleum, much of the future emphasis in commercial engine design will be on reduced fuel consumption. An alternative (or supplement) to this would be the use of different fuels from the kerosene or Jet A of today. The cryogenics (methane and hydrogen) have many virtues in terms of engine performance: higher heating value, better cooling capacity, lower radiant heat load on the combustor walls. However, they are disadvantageous in terms of insulation requirements, fuel tank volume, general difficulty of handling, and (probably) cost. For these reasons, coupled with the need for a radical change in the associated ground infrastructure, it seems unlikely that such

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**In general, further information on progress in this topic and most of the remainder of this paper may be found in the proceedings of the latest NASA Conference on Aeropropulsion.[5]

unusual fuels will be applied to aircraft in the next 20 years.

A more likely prospect is that kerosene-like fuels will continue to be used. But their characteristics will be somewhat different from the tightly controlled specifications of today, initially because of increasing competition for the limited fraction of crude oil that is most suitable for jet engines, and ultimately because of the use of such petroleum substitutes as shale oil and coal syncrude. Tradeoffs will be necessary between (1) the cost and energy consumption of producing the most desirable variety of turbine fuel and (2) the problems of designing engines to tolerate less-desirable fuels. These problems include:

- Combustion characteristics (reduced hydrogen content, lower volatility, and higher viscosity lead to increased carbon deposition and exhaust smoke, higher combustor liner temperature and hence lower durability, poorer ignition and relight capability (Fig. 15))
- Thermal stability (reactive constituents, especially nitrogen, auto-oxidize to cause fuel-injector deposits and consequent temperature nonuniformities)
- Pumpability (higher freezing point and viscosity interfere with fuel flow from the tanks to the engine; heated fuel tanks may be required (Fig. 17))

Noise

The community pressures to minimize noise annoyance are not apt to ease in the coming years. Accordingly, governmental regulations such as FAR Part 36 will continue to influence the design of future engines. Control of rotating machinery noise will be aided by better understanding of the effects of blade number, stage spacing, and wall suppression treatment. If necessary, unusual configurations such as swept blades may be utilized (Fig. 18). This concept reduces the normal component of the relative Mach number and eliminates much of the leading-edge shock system that is responsible for multiple-pure-tone noise.

During takeoff, especially for supersonic cruising airplane, jet noise is the predominant concern. The inverted coannular noise effect (i.e., placing the high velocity stream on the outside rather than the usual inside of a two-stream nozzle) has been demonstrated to be very helpful in reducing this type of noise (Fig. 19). Further advances in this technique can be anticipated, for example, eccentric nozzles.

Another approach to jet noise reduction is the recently discovered acoustic thermal shield (Fig. 20), in which a hot, but low velocity, jet is placed along the bottom sector of the exhaust nozzle, resulting in a noise reduction of 5 dB or so. And, of course, there is always the possibility of using advanced mechanical suppressors, either alone or in combination with these other approaches.

With techniques such as these, it can be expected that, by 2000, engine noise may be reduced to the level of that of the airframe itself, and airplanes will not be a noticeable contributor to the background noise of the surrounding communities.

Propellers

The technology of propellers for small, low-speed airplanes has been essentially dormant for many years. However, the coincidence of new design techniques, improved materials, and recent impetus for low noise plus better performance promise substantial change in the future (Fig. 21). It is estimated that improved propellers will provide trip fuel reductions in the order of 10 percent and reduce airplane cost by a similar amount. Substantial reductions in noise will also be obtained.

The great potential for fuel saving offered by high-speed propellers has already been mentioned in the turboprop section. The desire to achieve high efficiency without compromising the high speed and altitude capability of modern turbofan-powered airplanes leads to a quite-different design for the propeller (Fig. 22). So different, in fact, that some have given it a new name - prop-fan. At high altitudes, propeller diameter tends to become excessive. To prevent this, the power loading is greatly increased compared to conventional practice through the addition of more blades. The resulting device then starts to resemble the fan component of a turbofan, hence the name.

It has already been demonstrated in wind tunnels that high efficiency can be obtained through such aerodynamic concepts as reduced blade thickness, advanced airfoils, swept tips, and nacelle shaping. More gains can be anticipated, especially in the area of swirl recovery, perhaps through counter-rotation. More challenging may be the need to demonstrate low noise and vibration plus high safety and reliability. However, the urgency of fuel conservation will undoubtedly stimulate the solution of these problems in the next decade.

Controls

The ever-increasing complexity of modern engines has stimulated much work on the use of digital electronic controls rather than the traditional hydromechanical systems. Current engines are already starting to utilize this technique in varying degrees, and it seems clear that full-authority digital systems will become commonplace in both military and commercial use as reliability problems are resolved (Fig. 23). In addition to multivariable control, electronic engine controls offer new opportunities for automatic thrust rating, temperature limiting, self-trim capability, engine condition monitoring, fault tolerance, and communication with the other airplane systems.

Looking beyond the present electronic trend, there is a likelihood by 2000 that electro-optical devices will come into use due to their potential for higher reliability and speed. Engine-mounted optical computers with high-temperature capability can be combined with fiber-optical transmission lines and digital-compatible optical sensors.

Concluding Remarks

It is sometimes stated that aviation and its associated technologies are a maturing field, with the implication that further improvements will be minimal. There is some validity to this view, but the purpose of this far-from-complete survey is to point out that many exciting advances can still be anticipated in aeropropulsion by the year 2000.

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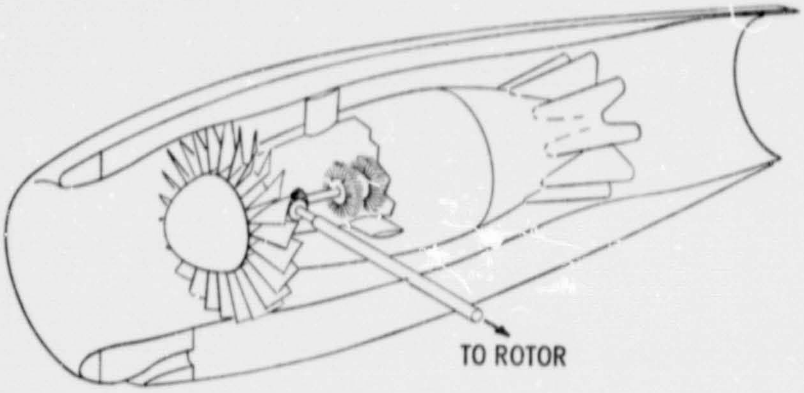
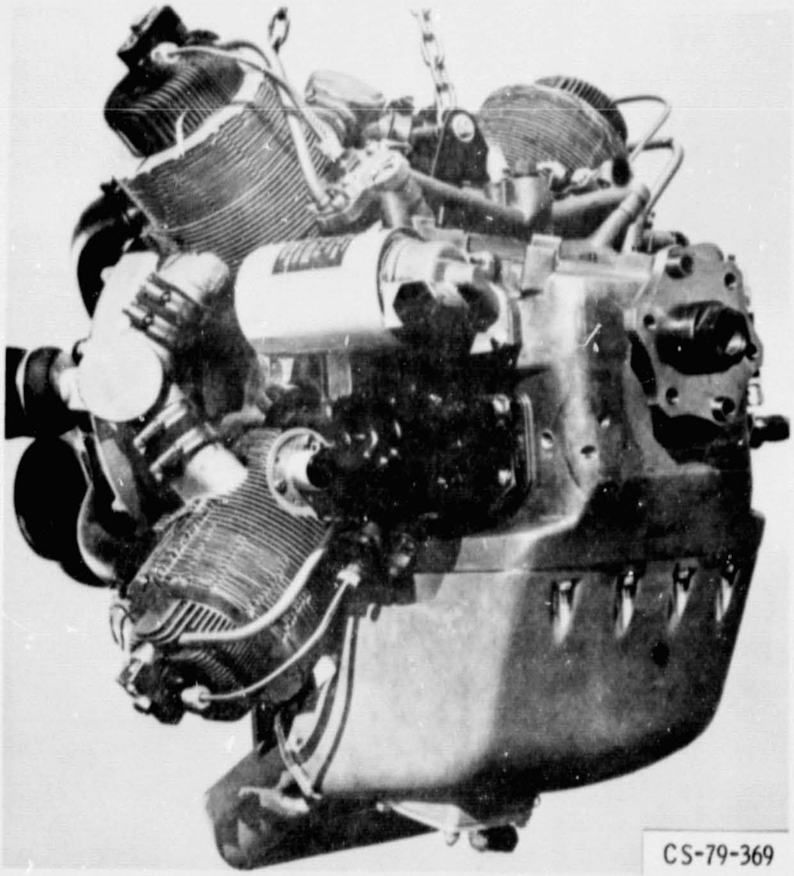


Figure 1. - Helicopter convertible propulsion system.



LONG-TERM TECHNOLOGY GOALS (1988)

BSFC: 0.32 - 0.35 lb/Bhp - hr; SP. WT: 1.2 - 1.5 lb/Bhp; EMISSIONS: MEET EPA '80; FUEL: DIESEL 2, JETA; COOLING: ZERO OR MINIMAL

Figure 2. - Lightweight diesel engine research.

10 - 15%	LESS GROSS WEIGHT	20 - 25%
5 - 15%	LESS FUEL BURNED	10 - 15%
10 - 15%	LESS INITIAL COST	15 - 25%
7 - 15%	LESS OPERATING COST	30 - 40%
8 - 15%	LESS LIFE-CYCLE COST	25 - 35%

HIGHER RELIABILITY
GREATER SAFETY AND COMFORT
QUIETER AND CLEANER
MULTIFUEL CAPABILITY

Figure 3. - Benefits relative to current reciprocating engine.

TAKEOFF CHARACTERISTICS

AIRFLOW, lb/sec	894
BYPASS RATIO	1.21
FAN P/P	1.27
FAN TIP SPEED, ft/sec	950
OVERALL P/P	14.3
THRUST, lb	17 400

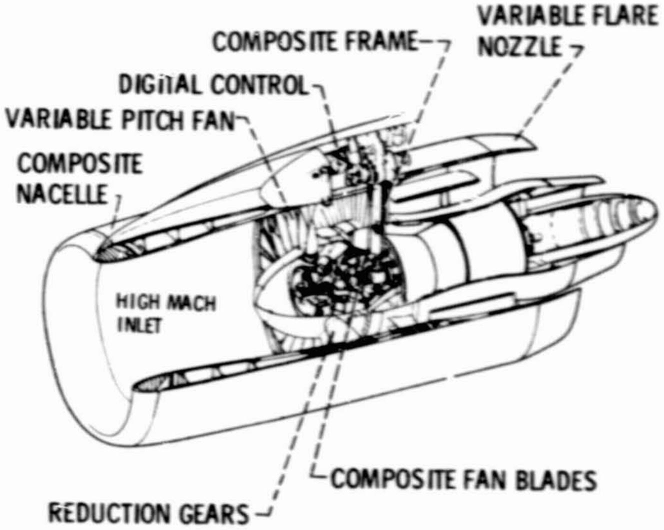


Figure 4. - QCSEE UTW engine.

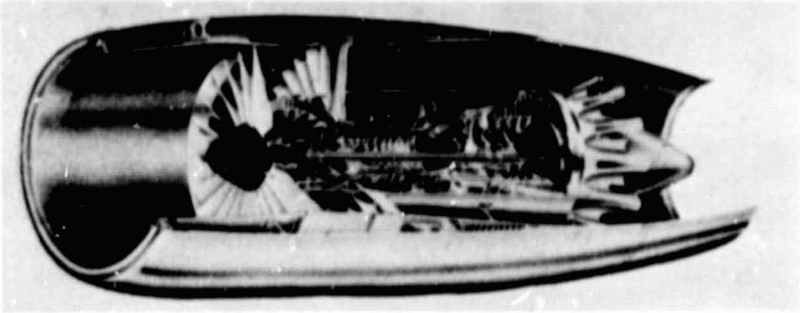


Figure 5. - Energy efficient engine configuration - Pratt & Whitney.

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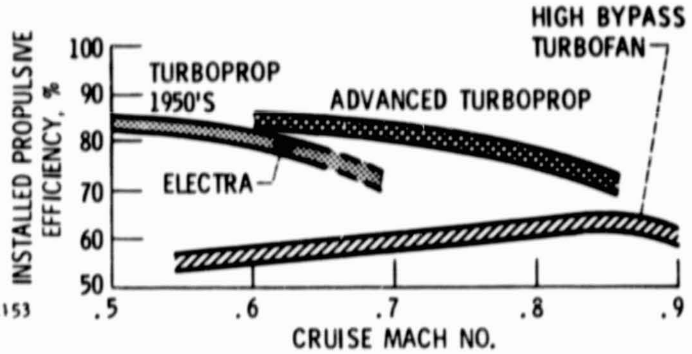

CS-79-2153

Figure 6. - Installed propulsive efficiency at cruise.

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Figure 7. - Trend of potential fuel savings for advanced turboprop-powered aircraft. (Relative to turbofan-powered aircraft with same level of core technology.)

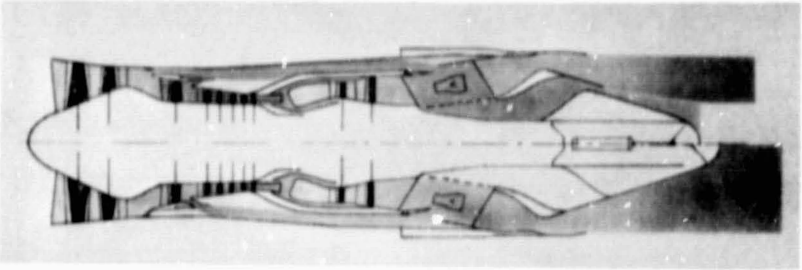

Figure 8. - Double bypass engine.

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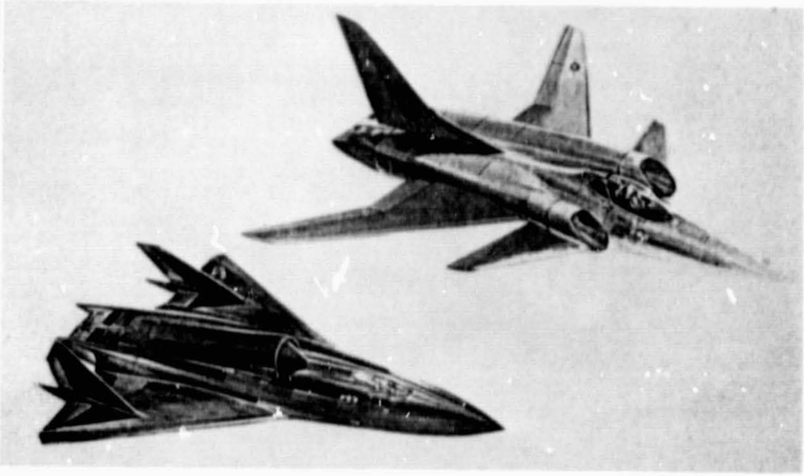

Figure 9. - Stealth configurations.

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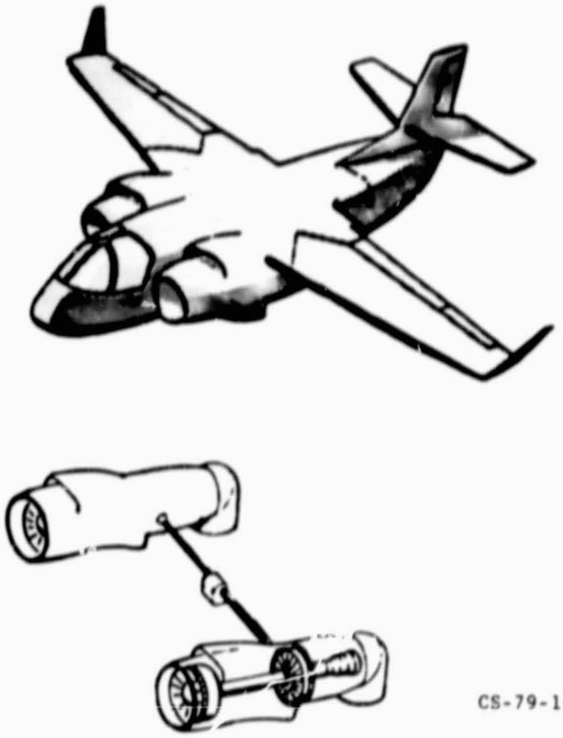

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Figure 10. - Representative fixed-nacelle VTOL aircraft.

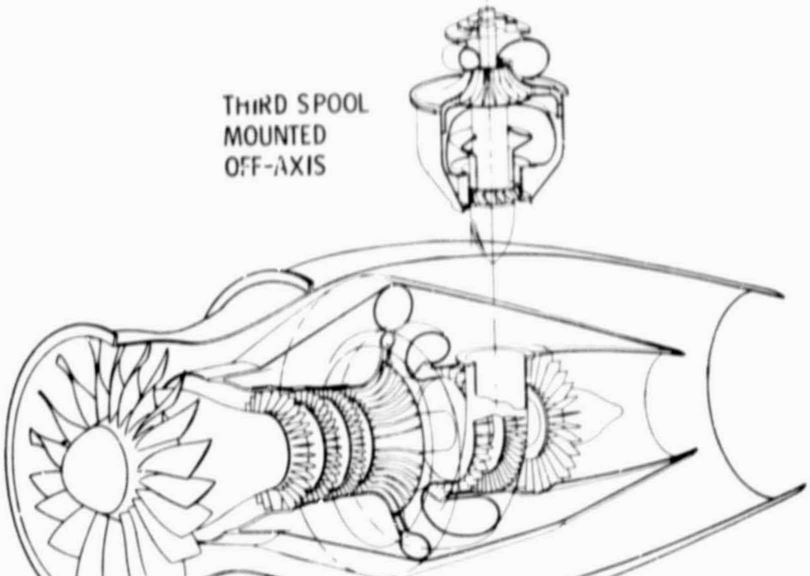

Figure 11. - Excentric turbine engine concept (Teledyne).

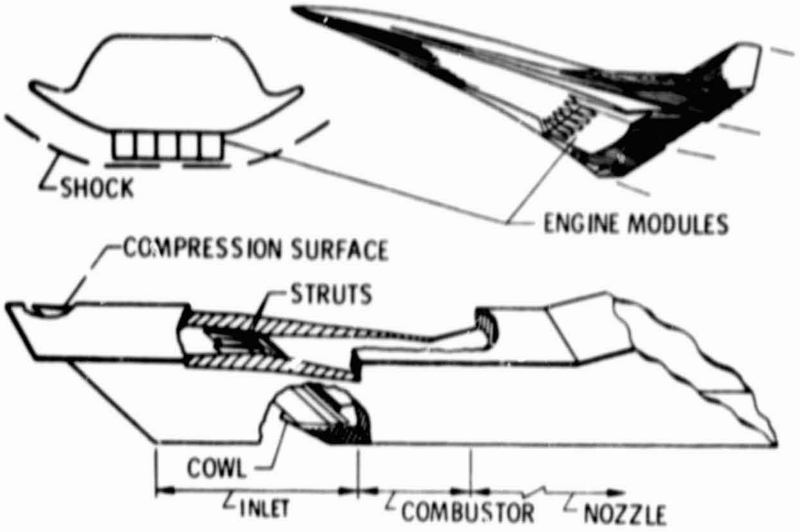

Figure 12. - Hypersonic propulsion.

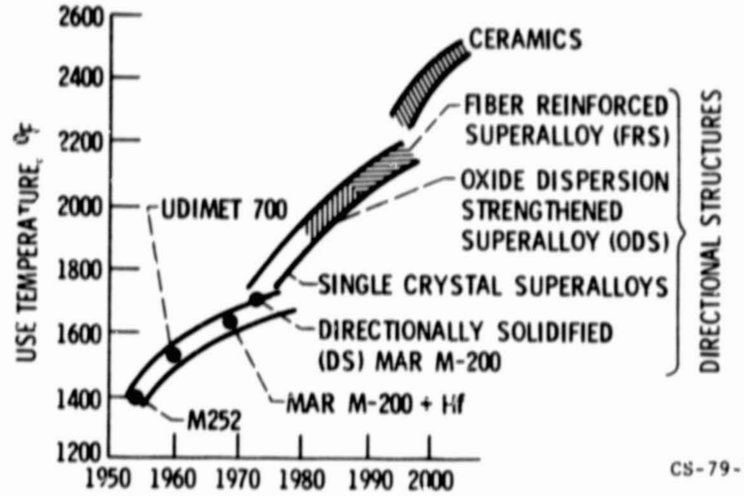

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Figure 13. - Projected use temperatures for turbine blade materials.

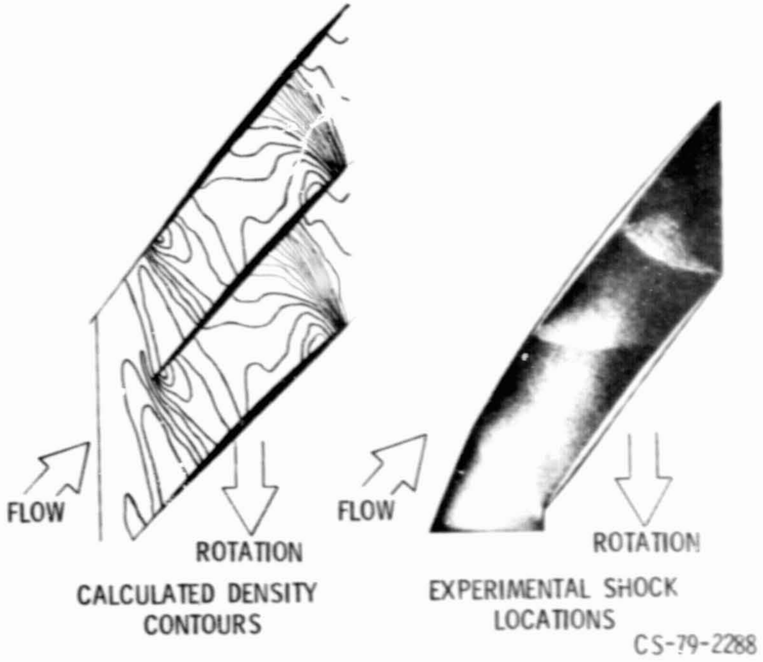


Figure 14 . - 3-D time marching method; 1600 fps rotor.

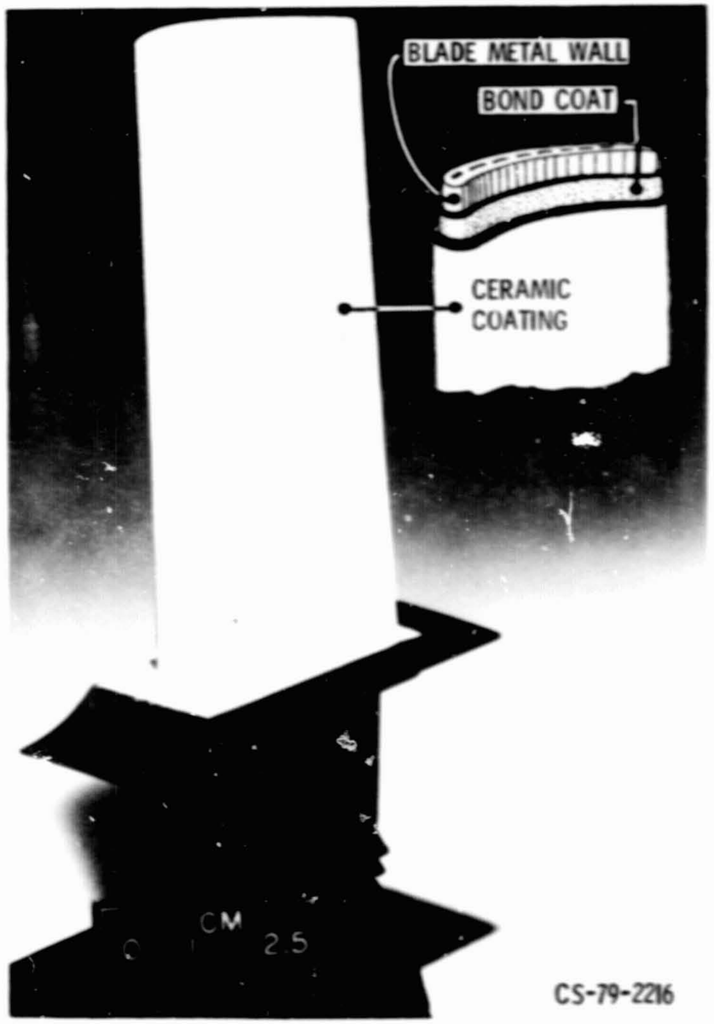


Figure 15. - Thermal barrier coated turbine blade.

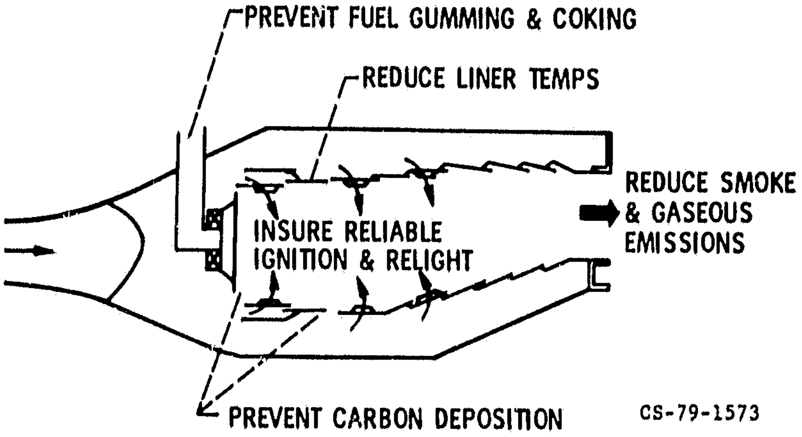


Figure 16. - Combustor technology required to use broad-spec fuels.

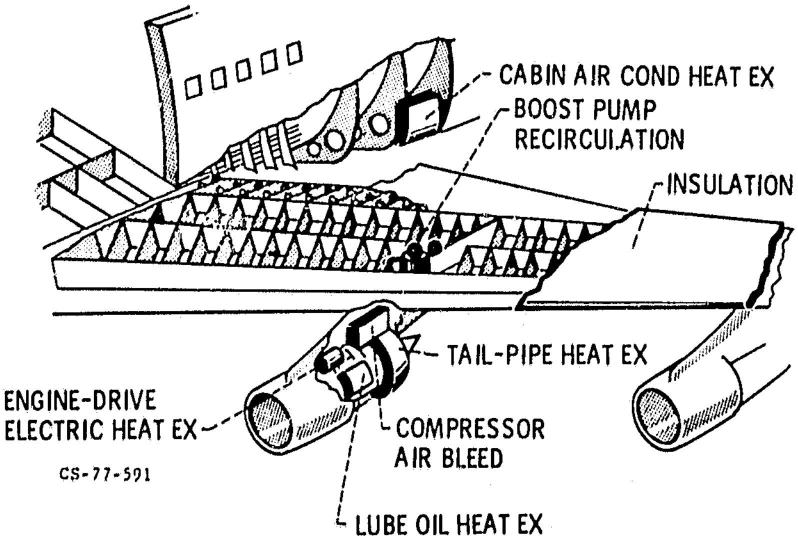


Figure 17. - Fuel tank heating sources.

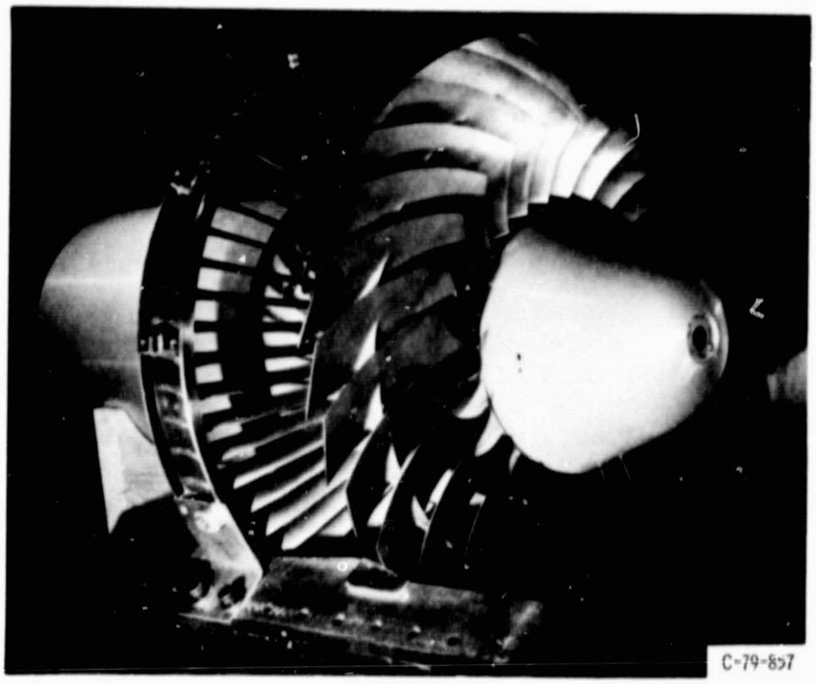
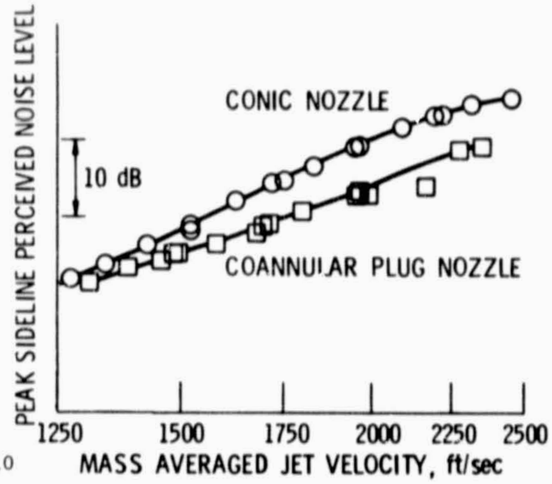


Figure 18. - Swept-rotor fan.



CS-79-1810

Figure 19. - Acoustic test data. (Scaled to full size and 2400 ft sideline.)

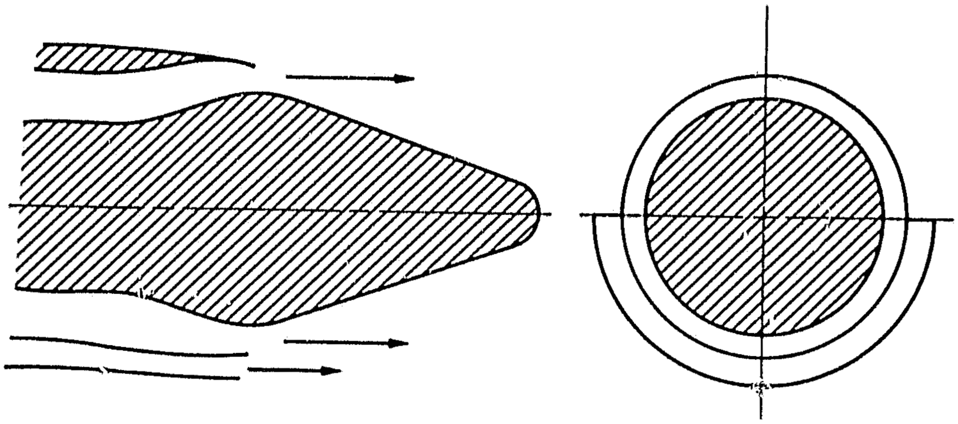


Figure 20. - Thermal acoustic shield.

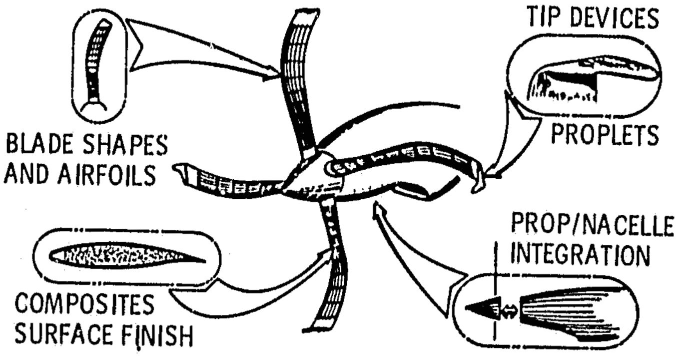


Figure 21. - Advanced technology concepts.

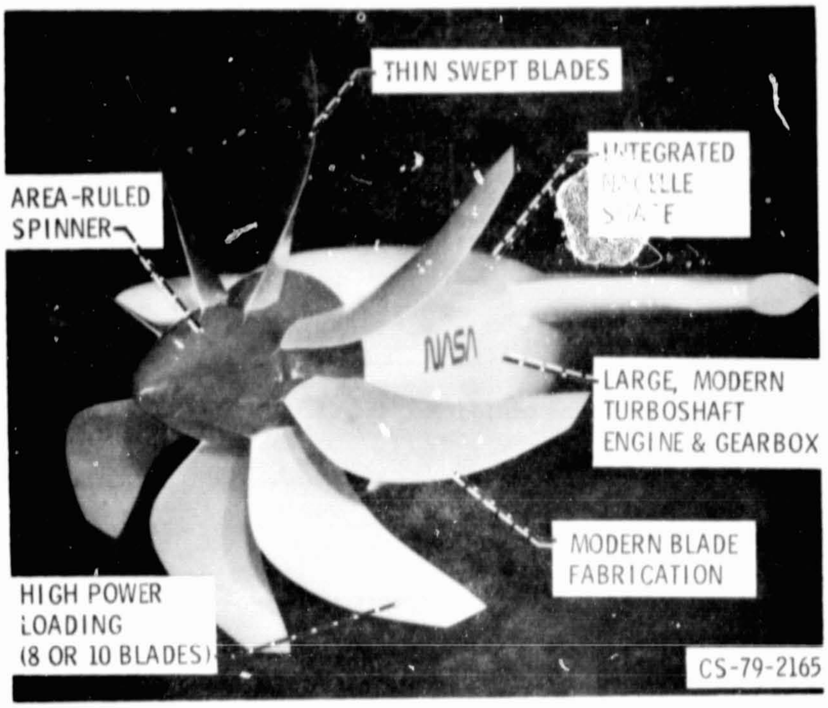


Figure 22. - Advanced turboprop propulsion system.

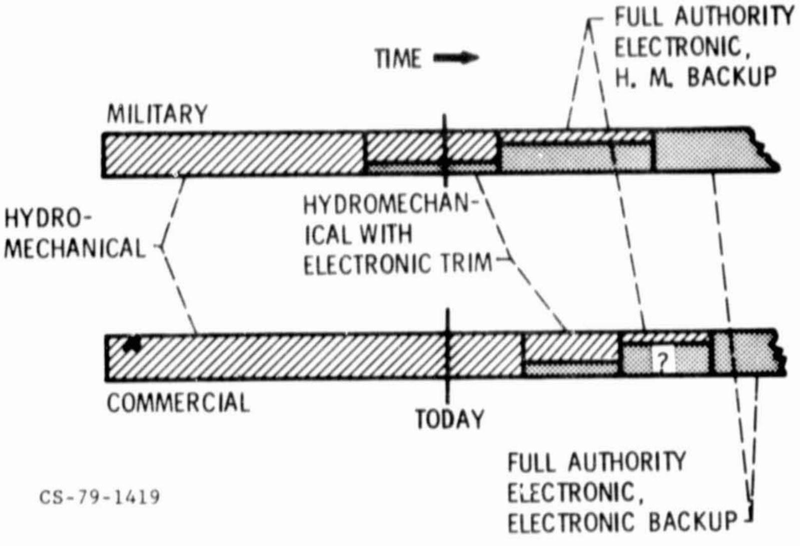


Figure 23. - Evolution of engine controls.

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15. Supplementary Notes

16. Abstract

Many advances can be anticipated in propulsion systems for aircraft in the next 20 years. This paper presents a sampling of probable future engine types, such as convertible engines for helicopters, turboprops for fuel-conservative airliners, and variable-cycle engines for supersonic transports. This is followed by a brief review of related technology improvements in propellers, materials, noise suppression, etc.

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