NASA Technical Memorandum 81559

SOME ADVANTAGES OF METHANE IN AN AIRCRAFT GAS TURBINE

(NASA-TM-81559) SOME ADVANTAGES OF METHANE IN AN AIRCRAFT GAS TURBINE (NASA) 18 p HC A02/MF A01 CSCL 21D
N80-29502
Unclas
G2/28 28454

Robert W. Graham and Arthur J. Glassman
Lewis Research Center
Cleveland, Ohio

Prepared for the
Aerospace Congress
sponsored by the American Society of Automotive Engineers
Los Angeles, California, October 13-16, 1980

NASA

SOME ADVANTAGES OF METHANE IN AN AIRCRAFT GAS TURBINE

by

Robert W. Graham and Arthur J. Glassman
NASA-Lewis Research Center
Cleveland, Ohio

ABSTRACT

Projections of the world's petroleum supply point to acute shortages by the end of this century which could impair air transportation. Synthetic fuels will undoubtedly be needed to relieve this shortage. One form of synthesized fuel will be liquid methane, which can be manufactured from any of the hydrocarbon sources such as coal, shale, biomass, and organic waste. Because there are so many potential sources of this fuel, including natural and synthetic sources, it should be considered as a petroleum replacement. In this paper a simple cycle analysis is carried out for a turboprop engine flying at Mach 0.8 and 10,688 meters (35,000 ft.) altitude. Cycle performance comparisons are rendered for four cases in which the turbine cooling air is cooled or not cooled by the methane fuel. The advantages and disadvantages of involving the fuel in the turbine cooling system are discussed. Methane combustion characteristics are appreciably different from Jet A and will require different combustor designs. Although a number of similar difficult technical problems exist, a highly fuel efficient turboprop engine burning methane appears to be feasible.

THE FUTURE OF FUELS FOR AIRCRAFT TRANSPORTATION is very uncertain. Some estimates suggest that petroleum reserves may run out sometime around the turn of the century. What year or even decade this will happen cannot be estimated. Many factors including pricing will establish exactly when petroleum becomes unavailable. Synthetic fuels will be introduced into the fuels market long before the depletion date. It isn't absolutely clear which synthetic will replace petroleum for aviation use, although fuels from syncrude most closely resemble the properties and handling characteristics of petroleum. A paper at this conference by Robert D. Witcofski (1)* concludes that synthetic kerosene appears to be the most logical synthetic fuel to replace petroleum-type aviation fuels. Notwithstanding, methane remains a viable candidate for an important role in aircraft transportation. There are so many potential sources of this fuel, including natural and synthetic possibilities (2), that its availability through an existing network of pipelines looks promising. It is one hydrocarbon fuel that can be produced from a renewable resource; namely, biomass.

Cryogenic-fueled aircraft have been studied many times over the past twenty years. Most of the studies have been devoted to supersonic flignt with both hydrogen and methane considered as fuel sources. These cryogenic fuels offer the potential of higher heating values than Jet A and an attractive heat sink capability (3, 4, 5). For example, in reference (6) the turbine cooling capability of methane was evaluated in several simple analytical cooling models for a Mach 3 aircraft. The heat sink capability of the fuel cooled the compressor bleed air in a heat exchanger before admitting it into the cooling passages of the stator and rotor blade rows. Another option that was analyzed was direct cooling of the blades by the fuel. However, it was recognized that direct fuel cooling poses many difficult practical problems, the most critical being leakage of the fuel coolant in the rotors. Direct fuel cooling of blades also poses problems of thermal stresses due to extreme temperature gradients

*Numbers in parentheses designate References at end of paper.

promoted by the cryogenic fuel coolant. As was pointed out in reference (5), an insulating material may be necessary in the construction of the first stage stator blades to reduce the internal thermal gradient. The author of reference (7) concluded that fuel cooling of the compressor bleed air would yield greater potential for turbine cooling than improvements in cooling design or cooling method alone.

To illustrate some of the advantages of methane in a turbine engine, we have elected to use a turboprop engine as a model for the cycle analysis instead of a turbofan. There has been a resurgent interest in the turboprop due to advances in high speed propeller design. As discussed in reference (8), propulsive efficiency at subsonic speeds may be increased on the order of 20% above that of a turbofan engine. It will be assumed that the turboprop engine cruises at Mach 0.8. Using a simple cycle analysis, comparisons of the engine performance will be rendered for cases in which the compressor bleed air used in turbine cooling is cooled or not cooled by the methane fuel. In addition to turbine cooling heat transfer, mention will be made of a few ancillary topics pertaining to the use of methane as an aircraft fuel.

SOURCES OF SYNTHETIC METHANE GAS

Methane can be produced synthetically from several sources including coal, shale, tar sands, organic wastes and plant biomass. The technical feasibility of making methane from these sources has been under investigation for a long time. Process research and pilot plant activity have been vigorously pursued under both private and governmental sponsorship. Although commercialization of these processes hasn't yet been achieved, with proper incentives and favorable markets, they could become active sources of methane for domestic and commercial users. There is optimism that a large supply of methane can be made available from synthetic sources (2). A comprehensive discussion of the viability of such a commercial methane-producing industry is beyond the scope of this paper. However, some comments pertaining to the availability of each of the major synthetic sources of gaseous methane is appropriate. The anticipated magnitude of these sources give indications of their availability for transportation fuels. It must be recognized that these basic hydrocarbon sources are in competition as feedstock for all types of synthetic fuels in the overall energy market. Undoubtedly, priorities will have to be established to meet the demand for the various forms of synthetic fuels derived from these feedstocks.

COAL - Generally, it is recognized that coal is the most abundant feedstock for synthetic fuel production (9). One of the prevailing uncertainties about coal as a feedstock is how the sulfur content affects the conversion process. Another major uncertainty regarding coal is the national capacity to mine it. In the last two decades, the mining industry has suffered losses in manpower and very little has been done to upgrade the technical equipment used in mining. If coal is available in sufficient abundance, conversion plants can be operated to convert it to methane. NASA-sponsored studies on alterante fuels have reported that two known commercial processes, HYGAS and CO_2 Acceptor, appear attractive for the production of methane from coal (10). In the HYGAS process, heated coal particles react with hydrogen-rich gas in a high pressure (67 atm), high temperature (1100 K) reactor vessel. About half of the methane is produced directly in this reactor; the other half comes from methanation of the remaining effluents of the reactor. In the CO_2 Acceptor process, steam and coal particles are reacted in the main gasifier. Much of heat supplied comes from a reaction of dolomite and CO_2. About 37% of the methane is made in the gasifier; the remainder by methanation of effluents from the gasifier. Both the HYGAS and CO_2 Acceptor processes are more efficient than the process for making liquid fuels from coal (1). The HYGAS process exhibits the best conversion efficiency (63%). In the liquification process, approximately 11% of the gaseous methane production would be needed as an energy source. Preliminary cost estimates indicate that liquid methane from these processes will cost about eight to nine dollars per gigajoule, which is about the same as is estimated for coal-derived Synjet, which ranges in cost from six and a half to nine dollars per gigajoule. 1979 prices for Jet A were six dollars a gigajoule or 75 cents a gallon.

SHALE - Shale or shale oil has been looked on as a source of synthetic oil. Pilot plants have been operated to extract the hydrocarbon, "kerogen", from the shale and to make it into a synthetic crude oil as feedstock for a refinery. This synthetic crude oil can be gasified. It is also possible to gasify directly the kerogen in the shale, but relatively little has been done to develop the latter process. A principal problem with shale conversion is its impact on the environment. The mining operation and ensuing land reclamation is a formidable environmental concern. In the process of extracting the kerogen from the shale, the actual volume of the rock residue increases significantly creating a surplus disposal as well as a reclamation problem.

BIOMASS - In the mid 70's the first author participated in a systems study on the feasibility of deriving hydrocarbon fuels from biomass and organic waste reported in reference (11). For biomass, a promising source in the continental United States appeared to be silvaculture (tree farming), with slash pine the most favored species. Approximately, the fuel-energy equivalent of 54 gigajoules (51 million Btu's) could be realized from an acre of land per year. Non-cultivated forest land could be used for this enterprise.

The waste organic source could vary drastically depending on the incentives to collect this material. The disposal of waste is a severe urban problem so its conversion to needed fuel is an attractive option. From organic waste alone, the fuel energy equivalent of 5% of the total energy consumption of the country is a possibility. If that were possible, fuel derived from waste alone could replace the fuel now consumed by aviation transportation.

The biomass source of methane has the added attraction of being a renewable source. Through an organized program of planting and harvesting, it would be possible to have a renewable supply. From estimates in reference (11), 27 million square hectometers (67 million acres) could yield sufficient harvest for the equivalent of 3 to 4% of our national energy use. This is approximately the acreage now devoted to commercial wood products.

It is obvious that the combined fuel production from biomass and waste organics could reach almost 10% of our total energy use or approximately 20% of our current use of petroleum. As is the case for all synthetic fuels, their estimated cost is above the current market price for the natural fuels.

The market price does depend on the credit received for disposal of the waste organics because it is presumed that both waste organics and biomass will be blended as feedstock.

METHANE COMBUSTION

An extensive full scale combustor research program using natural gas was carried out at the Lewis Research Center during the early 1970's. The natural gas used in these tests was 93.5% methane, so the results can be interpreted as typical of methane. This research revealed that natural gas or methane exhibited comparable combustion performance to kerosene for design combustion operating conditions as encountered in ground starts, take off and cruise. However, off-design performance of methane is appreciably poorer (12). This is particularly true of altitude blowout and ignition limits, and there is also a greater tendency toward combustion instability with methane. This inferior combustion performance is attributed to the greater stability of the methane molecule. The larger, long chain molecules that are found in kerosene are chemically less stable and enable combustion over broader limits. A redeeming feature of the chemical stability of methane is its ability to absorb heat without decomposing. Jet A or Synjet decompose readily and can't be used to cool the compressor bleed air without severe coking occurring on the heat exchanger surfaces. In the combustion studies of methane, it was established that increasing the fuel temperature greatly improved the altitude combustion performance. At fuel temperatures of 800 K, relight was achieved at the same airflow condition as blowout. Thus it would be advisable to utilize the fuel as a heat sink in order to improve its off-design combustion characteristics.

If methane is to be used as an aircraft fuel, NASA research (13, 14, 15) shows that some development effort will be required to establish a satisfactory combustor geometry and its associated control system. Avoiding altitude blowout appears to be the most critical problem. It should be added that one of the attractive features of methane combustion is the reduced carbon-based emissions compared to Jet A. However, methane combustion does yield more water vapor than Jet A.

CYCLE COMPARISONS

In order to make an assessment of the effect of the fuel as a heat sink on the engine cycle performance, a turboprop engine configuration was chosen and some elementary cycle calculations were rendered. It was assumed that the turboprop would incorporate an advanced propeller design similar to what was reported last year at the SAE Conference on Business Aircraft (16). A photograph of such a highly swept blade propeller design is shown in Figure 1. Efficiencies of approximately 80% were measured at Mach 0.8 in wind tunnel testing. More research and development is required before this propeller concept can be considered ready for commercial application. The engine configuration chosen was based on the Energy Efficient Engine two spool by-pass concept (17). The two spool bypass configuration was converted to a turboprop by removing the fan and adding a low pressure compressor and output shaft to the driven end of the low speed spool. A schematic of the engine configuration is shown in Figure 2. The thermodynamic cycle calculations were performed for a standard day cruise condition of Mach 0.8 at an altitude of 10,688 meters (35,000 ft.). The cruise marks the condition wherein most of the fuel would be consumed and thus any significant changes in the thermodynamic performance would change the fuel overall consumption for a flight mission dramatically. At the cruise condition, the cycle pressure ratio is 36 and the combustor exit temperature is 1530°K (2760°R). This temperature was held constant throughout the entire analytical exercise. The core compressor, which provides a pressure ratio of 22, is driven by a two-stage cooled turbine. The low speed spool is driven by an uncooled multistage turbine.

As a means of establishing a comparison for the cycle analysis, a reference case was selected initially. For the reference case, shown in Figure 3a, the bleed air from the compressor entered the cooling passages of the turbine at the compressor exit temperature. The comparative cases (Figure 3b) assumed that the compressor bleed air passed through a fuel-cooled heat exchanger that dropped the bleed air temperature by 111K, 222K, and 333K (200°R, 400°R, 600°R). A fourth case was run in which the cryogenic methane was circulated through the stator blades to effect the cooling (see

Figure 3c). The turbine efficiency and the relative coolant flow fraction, relative specific power and relative specific fuel consumption (SFC) were compared among the five cases calculated. Table 1 summarizes the results from the cycle analysis, which used the methodology described in reference (18). The algorithm for turbine cooling flow found in reference (19) was employed in the analysis. The information presented in the second, third, and fourth columns of Table 1 is normalized with respect to the no cooling of coolant reference case. The higher heating value of methane causes the SFC for methane to be approximately 13% less than the SFC of the kerosene fuels. Throughout the analysis, the bulk metal temperatures of the vanes and rotor blades were held to 1200K (2160°R), respectively.

The most obvious change noted in the Table is the reduction in coolant flow required to maintain the blade material at the maximum surface temperature when fuel cooling is employed to reduce the compressor air bleed temperature. Appreciable effects of this reduced bleed air flow are observed in the specific power column. By reducing the cooling air temperature 333°K (600°R), the specific power was increased by 10%. The real significance of this increase isn't directly obvious from the values of this Table. The improved specific power realized through fuel cooling means that lower engine mass flows or smaller engines could be used for the same flight mission. Smaller and lighter engines would have a cascading effect on the total aircraft structural design and total weight. An assessment of the changes in the total aircraft design and weight is beyond the scope of this paper. It is clear that fuel-cooling the turbine cooling air could bring about some improvements in the payload or range capability of the aircraft. The analysis also showed that reduced coolant temperature for the same coolant flow would result in lower bulk metal temperatures. One-hundred degrees reduction in coolant temperature would yield 50°-70° drop in bulk metal temperature.

An examination of the specific fuel consumption (SFC) column reveals a small improvement when fuel cooling is introduced. Within the limitations of the simplified cycle analysis, all of the energy that is exchanged between the fuel and the turbine cooling air is conserved and appears as thermal energy at some station in the cycle. Apparently, this movement of quantities of energy causes only small changes in the SFC. The maximum difference between the reference case SFC and the most highly cooled case ($\Delta T = 333K$) SFC was about 1%. A similar modest decrease in SFC was computed in reference (20) for a hydrogen engine in which the fuel was used to cool the turbine coolant air.

The potential benefits discussed above show fuel-cooling of the compressor bleed air to be desirable. A mission analysis of an aircraft incorporating this turboprop engine would be required to quantify the benefits. As a coolant, methane appears attractive because of its inherent thermal stability and heat sink capacity. It is definitely superior to Jet A in these respects. The design of a compact heat exchanger which won't add appreciable bulk or weight to the power plant seems feasible. There are opportunities for clever innovation in the design of the heat exchangers and the cooling schemes for the blades. Regarding the latter, there are no unique heat transfer problems for the turboprop engines considered in this analysis that aren't already being considered in other advanced engine concepts. There are some difficult challenging fundamental problems relevant to air-cooling the turbine blades. Some of the internal cooling problems include impingement cooling, film cooling, passage curvature, three-dimensional conduction, and centrifugal effects. Prediction of the external surface heat transfer is complicated by another list of difficult fundamental problems (21) which pertain to all advanced turbine engines.

Direct fuel cooling of the stator with no cooling of the rotor coolant air (bottom row on Table 1) yielded an additional small SFC improvement over cooling the coolant air. If the rotor coolant had passed through a heat exchanger, the SFC reduction would be a little more. Such a system would involve fuel cooling of the bleed air, as well as direct fuel cooling of the stators. Direct cooling of the stator would introduce mechanical design problems associated with circulating the cryogenic fuel through the stator row. As was discussed in reference (4), direct fuel cooling could necessitate the introduction of insulation in the stator wall so as to avoid excessive thermal gradients. This is an example of one of the design complexities that might be introduced by direct cooling.

AIRFRAME AND SAFETY ISSUES

This paper is limited to discussing some of the technical issues relevant to using methane in an aircraft engine. The potential use of methane as an aircraft fuel raises a host of issues including aircraft design, airport fueling, fuel supply systems, safety systems, and overall airport design. The cryogenic nature of liquid methane is largely responsible for the complexity of these issues. An appreciation of the overall cryogenic fuel problem can be obtained from an examination of references (20 and 22). These reports are devoted primarily to use of cryogenic hydrogen in aircraft but cryogenic methane poses similar problems. As an example of one problem area, the location and geometry of the fuel tanks is a significant structural change in the airframe design. Cryogenic tanks must be approximately spherical to minimize heat loss and must be independent structures--not an integral part of the airframe. A sketch of the possible cryogenic tank locations is shown in Figure 4. The bulkiness of the tanks and the greater volume requirements of methane compared to Jet A will cause the fuselage cross section to be larger than current aircraft.

It should be recognized that a liquid methane fuel system poses safety problems which are different from those associated with Jet A. Methane possesses rather narrow flammability limits which contribute to its safe handling but there are unanswered questions regarding the hazards of fuel spills which require more investigation.

CONCLUDING REMARKS

In view of the impending depletion of petroleum sources, studies of aircraft alternate fuels are warranted. Recent discoveries of large amounts of natural methane, such as the geopressure zones along the Gulf of Mexico, indicate promising future supply. Methane as a synthetic fuel, will be available from several hydrocarbon sources including coal, shale, biomass and organic waste. Preliminary estimates of the cost of liquid methane made from coal by commercial processes indicate that it will be somewhat more expensive, but comparable to Synjet on a cost per unit energy content basis. NASA estimates show synthetic liquid methane to be 30 to 50% more expensive than Jet A based on 1979 information.

A simplified cycle analysis of the performance of a methane-fueled turboprop engine was carried out. The analysis showed that fuel cooling the compressor bleed air used in turbine cooling could lead to smaller more compact engines. Such engine weight savings would impact the total structural design of the airframe and the gross weight of an airplane. The cycle analysis showed small gains in SFC (approximately 1%) through this application of fuel cooling. Direct fuel cooling of the first stator, while yielding a small additional gain in SFC, would introduce design complications. The analysis also revealed that reduced cooling air temperatures for a given coolant flow rate, could lower the bulk metal temperatures of the blades significantly. Such a system will also give improved cooling margin to allow the turbine inlet temperature to be raised. Only one fixed gas inlet temperature was considered in this analysis.

From combustion research with methane, it has been shown that methane burns more cleanly than Jet A or the proposed Synjet. Its narrow flammability limits do pose a severe problem in altitude relight. This deficiency will require redesign of the combustor.

The higher heating value of methane compared to Synjet and its heat sink capability are advantages in considering liquid methane for aircraft turbine engines.

REFERENCES

1. Robert D. Witcofski, "Rating Liquid Hydrogen as a Potential Aviation Fuel." SAE Congress and Exposition, October 1980.

2. "New Lease on Life for Gas." Energy, June 1979, pp. 15-17.

3. C. L. Joslyn, "The Potential of Methane as a Fuel for Advanced Aircraft Aviation and Space Progress and Prospects." ASME, 1968, pp. 351-355.

4. Jack B. Esgar, "Cryogenic Fuels for Aircraft." NASA SP 259, pp. 347-420.

5. Raymond S. Colladay, "Thermal Feasibility of Using Methane or Hydrogen Fuel for Direct Cooling of a First Stage Turbine Stator." NASA TN D-6042, October 1970.

6. David G. Evans, Keith A. Furgalus, and Francis S. Stepka, "Turbine Aerodynamic and Cooling Requirements for a Turbojet Powered

Mach 3 Transport Using Methane Fuel." NASA TN D-5928, 1970.

7. Francis S. Stepka, "Consideration of Turbine Cooling Systems for Mach 3 Flight." NASA TN D-4491, 1968.

8. James F. Dugan, Jr., Bernard S. Gatzen, and William M. Adamson, "Prop-Fan Propulsion--Its Status and Potential." SAE Technical Paper 780995, Aerospace Meeting, San Diego, November 27-30, 1978.

9. J. Gilson, "Aviation Fuels from Coal." Proceedings of an Anglo/American Conference Organized by the Royal Aeronautical Society and the American Institute of Aeronautics and Astronautics, London, December 5-7, 1978.

10. Robert D. Witcofski, "Comparison of Alternate Fuels for Aircraft." NASA TM-80155.

11. Robert W. Graham, Thaine W. Reynolds, and Yih-Yun Hsu, "Preliminary Assessment of Systems for Deriving Liquid and Gaseous Fuels from Waste of Grown Organics." NASA TN D-8165, February 1976.

12. Jerrold D. Wear and Robert E. Jones, "Comparison of Combustion Characteristics of ASTMA-1 Propane and Natural-Gas Fuels in an Annular Turbojet Combustor." NASA TN D-7135, January 1973.

13. Donald F. Schultz, Porter J. Perkins, and Jerrold D. Wear, "Comparison of ASTMA-1 and Natural-Gas Fuels in an Annular Turbojet Combustor." NASA TM X-52700, 1969.

14. Nicholas R. Marchionna and Arthur Trout, "Turbojet Combustor Performance with Natural Gas Fuel." NASA TN D-5571, February 1970.

15. J. S. Goldsmith and G. W. Bennett, "Hydrogen-Methane Fuel Control Systems for Turbojet Engines." NASA CR-121247, October 1973.

16. Robert J. Jeracki, Daniel C. Mikkelson, and Bernard J. Blaha, "Wind Tunnel Performance of Four Energy Efficient Propellers Designed for Mach 0.8 Cruise." NASA TM-79124, 1979.

17. "Energy Efficient Engine, Preliminary Design and Integration Studies." NASA CR-135444, September 1978.

18. Arthur J. Glassman, "Computer Program for Thermodynamic Analysis of Open-Cycle Multishaft Power System With Multiple Reheat and Intercool." NASA TN D-7589, March 1974.

19. J. W. Gauntner,"Algorithm for Calculating Turbine Cooling Flow and the Resulting

Decrease in Turbine Efficiency." NASA TM-81453, 1980.

20. G. D. Brewer, et. al., "Study of Fuel Systems for LH_2-Fueled Subsonic Transport Aircraft." NASA CR-145369, July 1978.

21. R. W. Graham, "Fundamental Mechanisms That Influence the Estimate of Heat Transfer in Gas Turbine Blades." NASA TM-79128, Presentation to National Heat Transfer Conference, San Diego, California, August 5-8, 1979.

22. G. D. Brewer, editor, "LH_2 Airport Requirements Study." NASA CR-2700, October 1976.

Table 1 - Methane Turboprop Engine Cycle Analysis

Case Cooling Air Condition	Turbine Eff.	Coolant Flow Ratio	Specific Power Ratio	Specific Fuel Consumption Ratio
No cooling of coolant air	0.885	1.0	1.0	1.0
-111K (200°R) Cooling	0.892	0.7226	1.047	.99[illegible]6
-222K (400°R) Cooling	0.895	0.5597	1.079	.9906
-333K (600°R) Cooling	0.897	0.4511	1.100	.9891
Direct use of fuel to cool stators	0.893	0.4494	1.106	.9755

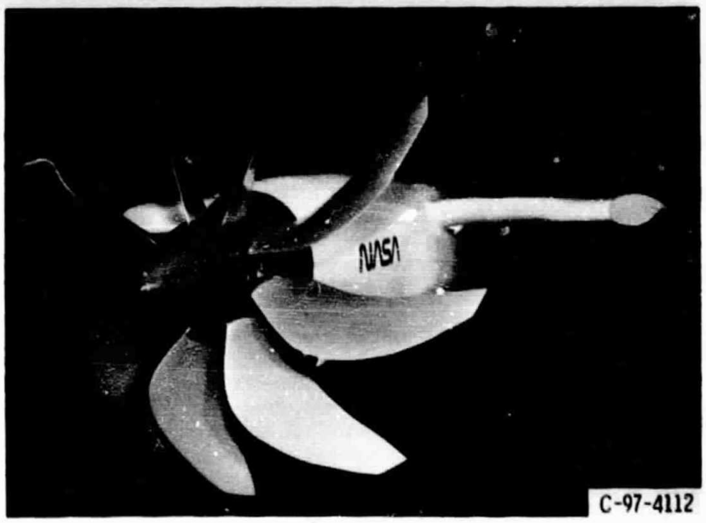


Figure 1. - Advanced propeller.

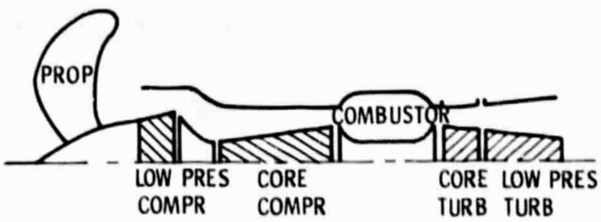
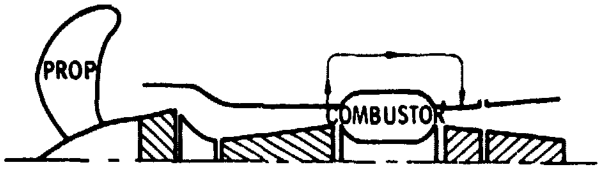
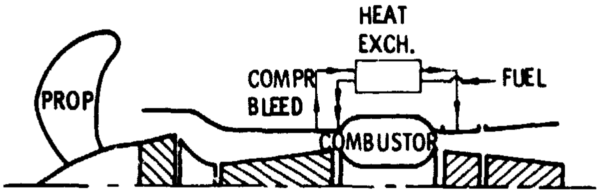


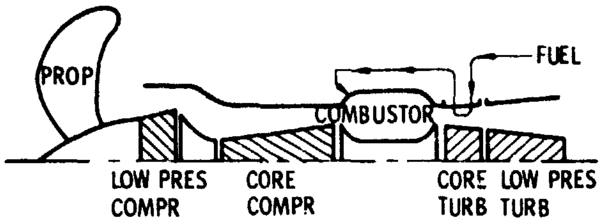
Figure 2. - Schematic of advanced turboprop.



(a) REFERENCE CONFIGURATION - NO USE OF FUEL FOR COOLING.



(b) FUEL-COOLED COMPRESSOR AIR BLEED.



(c) DIRECT FUEL-COOLING OF TURBINE.

Figure 3. - Turboprop configurations used in cycle analysis.

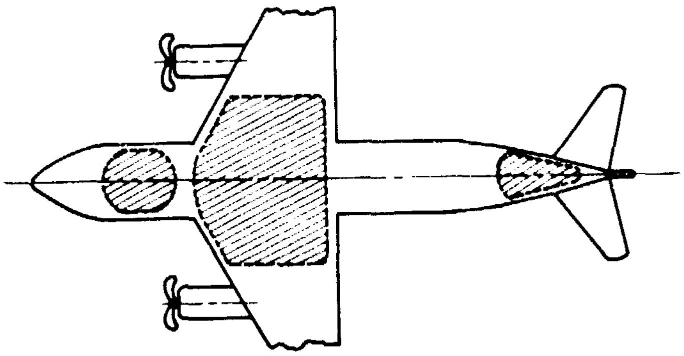


Figure 4. - Possible cryogenic tankage locations in aircraft.