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AN AIRLINE STUDY OF ADVANCED TECHNOLOGY REQUIREMENTS FOR ADVANCED HIGH SPEED COMMERCIAL TRANSPORT ENGINES

I - ENGINE DESIGN STUDY ASSESSMENT

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AMERICAN AIRLINES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

The results of an airline study of the advanced technology requirements for an advanced high speed commercial transport engine are presented. This report is one of a series of three reports developed as a part of the NASA Advanced Transport Technology Program. This report presents the results of the American Airlines Phase I study effort and covers the following areas:

    a. Statement of an airline's major objectives for future transport engines

    b. An airline's method of evaluating engine proposals

    c. A decription of an optimum engine for a long range subsonic commercial transport including installation and critical design features

    d. A discussion of engine performance problems and experience with performance degradation

    e. The trends in engine and pod prices with increasing technology and objectives for the future

    f. A discussion of the research objectives for composites, reversers, advanced components, engine control systems, and devices to reduce the impact of engine stall

    g. A discussion of the airline objectives for noise and pollution reduction

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SUMMARY

This report presents the results of an airline study of the advanced technology requirements for an advanced high speed commercial transport engine. This report is one of a series of three reports developed as a part of the NASA Advanced Transport Technology Program. This specific report covers the results of American Airlines' Phase I study effort which includes the following:

a. An airline's major objectives for future transport engines are presented including the major challenges faced in subsonic commercial aircraft propulsion technology.

b. An airline method of evaluating engine proposals is discussed to provide insight into the relative importance of various engine design and installation factors.

c. A discussion of engine performance problems, experience with performance degradation and the results of a number of programs undertaken to reduce the increase in specific fuel consumption that occurs with time.

d. The trends in engine and pod prices with time and complexity and the validity of current economic assessment tools in estimating the maintenance cost of advanced engines.

e. A discussion of the research objectives in five major technology areas where improvements could produce economic benefits. Current experience and cost impact data are presented as the basis for a discussion of the research objectives for composites, reversers, fuel controls, advanced components and for control of engine stall.

Introduction

The overall intent of NASA Lewis Research Contract NAS3-15572 with American Airlines was directed at obtaining a comprehensive airline review of the studies conducted by Pratt and Whitney and the General Electric companies covering the engine requirements for advanced technology transport aircraft. These studies were directed at determining the technological areas that had the greatest potential for signficant benefits to society through reduced pollution and noise, and improved aircraft/engine economics by the application of advanced research. To this end airline input, with its inherent differences in perspective, could provide additional information upon which to base and plan advanced projects.

In addition it was expected that the airlines might have general long-standing problems which could provide additional areas for the meaningful expenditure of research effort to advance the general state of propulsion technology. The airline industry has grown to where it is a vital part of the national transportation system and the sale of commercial aircraft to foreign countries a vital part of national trade. The continued success of the sales of U.S. manufactured aircraft and engines to foreign countries/airlines is to a large extent dependent on the ability to produce a more efficient product. This contract was considered as part of an initial probe and an innovative attempt towards improving the research planning process.

The information covered in this report is directed at fulfilling Task I of the above mentioned contract.

This report is divided into four major sections.

I. The first section presents a description of an optimum engine for an advanced transcontinental and intercontinental near sonic commercial transport. It contains a description of the engine cycle, the critical design features, the installation concepts, the estimated engine and

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propulsion system price, and pollution and noise requirements for such
an engine.

II. The second section details the engine performance and economic ex-
   periences that have occurred with the introduction of new engine types
   into American Airlines service. This section provides information
   that is pertinent to the emphasis placed on these two factors in the
   selection of an optimum engine.

III. The third section details airline experience and objectives in five
   major technology areas which are felt to be the most productive areas
   for advanced research effort.

IV. The last section is a comprehensive review of the ATT Engine Study Con-
   tractors Phase 1 Study Reports and an airlines view of the contractors
   recommendations.

A. Objectives for Future Commercial Engines

The airlines continue to desire improved engines with improved performance.

At the same time the environmental concerns of the nation place emphasis on re-

ducing the impact of aircraft and airports on surrounding communities to an ac-

ceptable level while maintaining the economic soundness of each new design.

The emphasis of the past for improved performance has reduced in relative im-

portance while noise, pollution, maintainability and reliability have in-

creased. The technology for subsonic aircraft engines has arrived at a point

that further advancements of the order of magnitude achieved in the change from

jets to low bypass ratio fans and then high bypass ratio fans is not readily

foreseen. This does not mean however that improvements cannot be achieved, but

that the expenditure of effort into perhaps more productive areas heretofore

overlooked is expected to be more productive. The cost of modern engines and

aircraft emphasizes the requirement for high utilization. To have an aircraft

delayed in service for an hour due to a faulty switch or indicator and thus incur

a loss of thousands of dollars is patently ridiculous if the reliability could

have been improved by the investment of a few more dollars, or if rapid fault

isolation could have been provided and rapid changeout effected. In total the

problems facing the airlines is achieving the proper balance of all factors with the

final objective of producing efficient transportation at a profit. The decision-making tools for this increased complexity have not yet been constructed to provide the data for such decision-making processes. Experience and intuitive feel are necessary and are the prime factor in decision-making at this time.

It should be understood that significant advancements in specific fuel consumption and thrust to weight performance are required for supersonic aircraft and for STOL and VTOL propulsion systems. The noise constraints for these aircraft types will produce heavy penalties unless the technology is found to reduce the noise efficiently. The technological fallouts from effort in these areas will produce benefit in conventional subsonic aircraft but research effort in the fundamental areas to produce more thrust at less total weight and better fuel consumption are most appropriately directed at these latter aircraft types mentioned above.

B. Airline Approach to Engine Evaluation

American Airlines like others formally evaluate each new engine proposal in great depth. Propulsion represents 20 to 25% of new aircraft prices. Engine maintenance is 48 to 50% of the total aircraft maintenance expenditure. The following provides the general headings and descriptions of the significant points of evaluation and the type of considerations made during recent evaluations.

1. System Characteristics and Installation Compatibility

This area of evaluation includes the general design concept of the engine in terms of the number of spools, bearings, blades, cooling provisions, variable geometry, bleeds, combustion chambers and fuel nozzles, customer bleed provisions, overall weight, length, diameter and the flexibility and complexity of the resulting engine installation. Included in this area is the engines ability to meet the bleed and power extraction demands.

2. System Operation and Safety

   This area of evaluation includes the engine operating envelope, stall

   margin, transient performance, idle thrust level and variation with

   temperature, engine control system capabilities to produce the rated

   performance and prevent overspeed and overtemperature conditions as major

   items. In terms of safety the foreign object ingestion capability and

   probable resulting secondary damage, fire hazard and heat rejection from

   the case, and air restart capabilities are assessed along with blade

   containment provisions.

3. Propulsion System Performance, Pollution (Air Pollution and Noise) and

   Growth Potential

   In evaluating the performance commitment for the engine several major areas

   are assessed in addition to the direct comparison of uninstalled perform-

   ance between contending engines. The performance of the engine is cal-

   culated from cycle data provided and an attempt is made to determine the

   amount of margin available for failure to meet component performance ob-

   jectives. Using the best information available on the state-of-the-art in

   compressor, fan and turbine design, the performance of the engine can

   be calculated. This level versus quoted guaranteed level provides

   some indication of the risk associated in achieving guaranteed per-

   formance. Strong preference is given to comparing the installed engine

   performance at off design point operating conditions since aircraft

   normally use altitudes and airspeeds for cruise that vary widely from

   an isolated design point. Long term performance is a key issue in these

   evaluations. Design features which are critical to achieving the engine

   performance must be maintainable over the life of the engine. Con-

   tractor commitments in terms of smoke and noxious gas emission levels

   are compared as are the projected noise levels commitments. As a final

   item the ability of the engine to achieve easy growth is assessed to

insure that major design changes which would effect the pod or basic engine structure are avoided and that there is assurance that if the aircraft grows during the development cycle that aircraft performance can be maintained without water injection or significantly reducing engine life. Good growth potential is necessary to maintaining a sound economic engine development and production program over many years.

4. Power Plant Package

The willingness of the contractors to undertake a large part, if not all, of the total power plant responsibility is evaluated. Until recently the majority of engine contractors provided only the bare engine. Engine performance is critically affected by inlet and nozzle performance and engine life by the power extracted from the engine based on aircraft instrumentation. The position traditionally taken is no longer acceptable to the airlines. This assessment includes the complexity, design concept, accessibility and maintainability of the engine as installed. The reverser design, cost, life and maintainability are also items for consideration.

5. Engine Design and Subsystem Requirements

The total engine design assembly by assembly is reviewed for repairability, maintainability, and reliability. The fuel system, oil system, flanges, rotor design, bearing design, thrust balance, seal design, etc. are reviewed for compliance with airline needs. Particular attention is paid to the integrity of structural members, repairability or replaceability of high wear areas, applicability for wide scope sectionalization of the engine, inclusion of on-the-wing inspection and diagnostic aids, simplicity or justifiable complexity for assembly, maintenance and repair, and high cost components and repair potential. The estimated repair costs for high cost items are used as one of the many comparisons. Further, the disassembly and assembly elapsed and total manhour estimates are reviewed and compared.

The other areas evaluated are the reliability program, the maintenance and repair procedure development programs, materials and airline experience therewith, engine developmental test program with particular emphasis placed on cyclic testing for low cycle fatigue, the development risk, economics (price/delivery/financial terms), warranty programs and content, and technical and spare part support based on past experience.

Airline evaluations place heavy emphasis on engine economics. Repairability, maintainability, reliability and long term performance retention are the keys to a successful commercial engine. This report is directed at defining the objectives for advanced engines. The current airline state-of-the-art in achieving the key parameters listed above is discussed to provide an improved understanding of the basis for the many requirements presented.

Description of a Recommended Optimum Engine for a Future Mach No. 0.98
Commercial Transport Aircraft

A. Introduction

The engine selection process must consider a multitude of factors in ar-
riving at a final "optimum" selection. These factors include technical,
economic, environmental, reliability and maintainability considerations
as well as an assessment of risk. The engine described herein was selected
as optimum for a Mach No. 0.95 to 0.98 aircraft on the basis of including
a moderate level of risk. Commensurate with a late 1970 decade introduc-
tion the selection was based on the data provided in the ATT engine con-
tractor reports and internal American Airlines sources.

The overall mission requirements of the ATT Engine Study included both
intercontinental and international range aircraft where engine specific
fuel consumption is of high importance. Further, the objective of re-
ducing aircraft noise below current FAR Part 36 limits places an additional
heavy burden in arriving at the selection of an engine cycle.

The airlines desire continued advances in the state-of-the-art but are cautious
of involving more than one or two relatively new advancements in any new
engine. The failure to achieve guaranteed performance levels or needed
engine life and reliability involve both customers and contractors in
expensive problems (poor scheduling reliability, late aircraft delivery, etc.)
which can ill be afforded. The environmental problems faced and their solu-
tions must not penalize the aircraft economics so greatly that the new air-
craft represents little if any advantage over older aircraft. Progress in
noise and pollution reduction must be tempered with these practical con-
straints while producing continued reduction in the environmental impact
of each succeeding aircraft and engine type. Lastly, engine price and

maintenance cost must be minimized to the maximum extent possible. In-corporation of many technological advancements in a single new engine in-variably increases both first cost and the cost of maintenance.

B. Recommended Cycle for an Optimum Engine for an Advanced Mach 0.95 to 0.98
     Transport Engine

The recommended optimum engine for a Mach 0.95 to 0.98 commercial transport

of both domestic and international range capability would have the follow-ing cycle characteristics:

Bypass Ratio	- 4.5 to 4.7
Fan Pressure Ratio	- 1.80 to 1.85
Overall Cycle Pressure Ratio	- 26 to 28
Turbine Inlet Temp. at Cruise Condition ISA + 10°C	- 2300° to 2350°F
Non-mixed flow with nominally coplaner nozzles	

This single cycle design point was selected based on the following con-siderations.

1. The cycle is near optimum for either long range or domestic

    aircraft and produces the largest core engine to meet the

    aircraft customer air bleed and horsepower demands.

2. The cycle represents the lowest bypass ratio consistent

    with realistic single stage fan state-of-the-art performance

    projected for the envisioned time period. (This is an

    identifiable area of risk and the envisioned fan would use

    composite blading.)

3. The aircraft is expected to make full use of operating pro-

    cedures to reduce noise and to have a heavier aircraft thrust

    loading as a result of a minimum of 37,000 ft. altitude start

    of cruise ceiling objective at maximum takeoff gross weight.

    The cycle therefore represents a good balance to achieve the

    takeoff and approach noise objectives.

4. The modest increase in turbine inlet temperature selected assures early margin for growth as engine durability is demonstrated or if early aircraft growth requires. The thermal efficiency advantages produced by higher temperature are insufficient to justify the inherent risk of short life in high pressure turbine and combustor parts. Further, the lower temperature and modest pressure ratio are consistent with reducing the formation of nitrogen oxides (NO_x) since combustor design technology should produce reduction of a significant magnitude without the use of water injection.

5. The anti-icing bleed air demands for inlet acoustic treatment and engine handling qualities can be more easily satisified with a larger core engine (low bypass ratio).

6. It is inescapable that conservatism produces better life and operational efficiency. Engine manufacturers have extreme difficulty in finding risk capital financing. The commercial engine development programs have been of shorter duration (fewer total hours) with more limited developmental testing than is normally planned for high technology military developments. Further only one engine would be developed to fulfill both aircraft requirements so that a suitable total market would be provided.

7. The fan, advanced combustor for pollution control, and noise control features represent the major risk areas. The compressor pressure ratio and turbine inlet temperature are more conservative in relationship to the advancements required. It is essential that the objectives for future compressor development be directed at minimum complexity, minimum cost, excellent stall margin and long term performance and for turbines improved turbine cooling effectiveness, improved materials and cooling concepts, and long life seal clearance control.

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The selected cycle is compatible with this objective.

8. Although engine size was not selected as it is relatively unimportant at this point, the maximum neutral quick engine change configuration must not exceed 96 inches (8 feet) in diameter to permit unrestricted over-the-road transportation by truck. The lower bypass ratio is in the direction of more easily satisfying this requirement

C. Recommended Installation Concept

1. General Configuration - It is recommended that the installation consider the use of a long duct nacelle. This configuration is compatible in concept with both wing and body installation positions and with mixed flow or non-mixed flow final nozzles. This configuration also provides the opportunity for using the total powerplant on several aircraft types. The following paragraphs discuss additional factors which are applicable to this concept.

2. Inlets - The desired inlet would have a length to diameter ratio exceeding or equal to 1 with a fixed lip and no acoustic rings. The acoustic treated barrel section of the inlet would be the structural load carrying member of the inlet transmitting all loads to the fan case front flange. The barrel section acoustic treatment should be replaceable in sections. Acoustic inlet rings are specifically not desired, however, if they are mandated they should be stowable/retractable for cruise and climb conditions. The engine bullet nose/spinner should be acoustically treated and considerably longer, perhaps 0.640 of the max diameter, to preclude the need for two splitters by providing a lower passage height and thus a proper L/H ratio for acoustic treatment effectiveness. Early R&D is necessary to integrate the total inlet designs and fan aerodynamic designs into an optimum performing system.

3. Fan Cowl - Externally mounted accessories, mounted external to the core engine, are required. The fan cowl should provide the enclosure, with appropriate access doors, for the accessories if fan case mounted. If the engine is mixed flow external mounting is obviously required. In both cases the cowl should be supported by the pylon and remain with the aircraft during engine change.

4. Pylon - The pylon, whether for wing or body mounted engines should be designed to transmit thrust loads from the fan frame to the structure. Services should be segregated with electrical, instrumentation and pneumatics at a higher elevation than fluids (i.e. fuel and hydraulic).

5. Long Cowls/Fan Ducts - For non-mixed flow engines the long cowl-fan ducts should be an integral assembly split and supported from the pylon. Preferably the fan nozzle, reverser assembly, ducts, and acoustic treatment would be an integrated assembly of the lightest possible weight consistent with the overall 30,000 hour minimum life requirements. Long life sealing of the ducts to preclude overboard leakage of fan airflow is a critical design item.

6. Final Nozzles - Final nozzles shapes should be consistent with minimum afterbody drag, long term performance and should be easily adjustable to maintain proper area for best average engine performance versus time. The allowable maximum afterbody boattail half angles are estimated to be no greater than 7° on the upper quadrant and 9° on the lower quadrant (underside). This feature must be validated by powered model testing.

7. Reverser - Strong preference is given for a hydraulic actuated, single target type reverser which will reverse both streams of a non-mixed flow engine and is recommended for mixed flow engine. The design performance objective should be 45% of the takeoff gross thrust with a

minimum acceptable level of 40%. Noise levels in maximum reverse
thrust must not exceed the sideline takeoff thrust noise require-
ments. This approach is consistent with minimum weight, first
cost and continued maintenance cost. The cost for maintaining the
reverser should not exceed 0.5 dollars per flight.

8. Acoustic Design - The above stated recommendations are consistent with
   meeting the noise treatment requirements of future aircraft. Long
   ducts provide for aft fan noise suppression treatment and the pos-
   sibility of improved mixing noise control from non-mixed flow
   engines. The long inlet and long bullet nose should preclude the
   need for more than one acoustic splitter. Requirements for turbine
   noise treatment can be met with inner nozzle wall treatment.

9. Position Mounting - The recommended configuration requirements are
   consistent with wing and side body mounted engines. The center engine
   position for a three engine configuration differs only in that the
   longer inlet, either DC-10 or L-1011 configurations, precludes the
   need for acoustic splitters. Special position builds are to be
   avoided. The need to dress an engine differently for right or left,
   inboard or outboard or tail installation position requires additional
   spares support and increases costs for maintenance and ownership.

D. Installation Power Extraction Requirements

The following are general recommended guides to the power extraction re-
quirements for advanced transports and should be considered estimates.
Final detailed levels should be established from test and final aircraft de-
sign. However, if errors are to be made in original estimates it is im-
portant that they be on the side of too great an extraction demand.

1. Bleed Air - The requirement is established as 22 to 25 cubic feet
   per minute of fresh air per passenger or an estimated 3 pounds per

second interstage bleed per engine for engines in the 40 thousand pound thrust class. This level is consistent with increasing public pressure for segregation of smokers and non-smokers and for non-mixing of the airflows to insure minimum airflow recirculation. In addition the following additional bleed/flows are estimated single engine extraction levels for inlet and aircraft anti-icing.

	Sea Level	25,000 Ft.
Inlet Duct	2.0 lb./sec.	1.5 lb./sec.
Inlet Duct & Splitter		
Single	2.5 lb./sec.	2.00 lb./sec.
Double	3.25 lb./sec.	2.75 lb./sec.
Wing	2.75 lb./sec.	2.0 lb./sec.

Note: Engine anti-icing is not included in the levels estimated above.

The compressor must be designed to provide these bleed flows with minimum losses. Air conditioning bleed is always provided and the design should consider bleed air from the outset. Further, a sufficient number of engine bleed air positions on the compressor should be provided to eliminate the need for a precooler providing weight and possibly cost advantages. Fan bleed for the CSD*oil heat exchanger and the air conditioning system precooler is required if air conditioning bleed air exceeds 450°F. The precooler if required shall not be mounted on the engine.

2. Mechanical Power - Initial designs should provide for a minimum of 200 horsepower extraction sufficient to drive the CSD/Alternator, two hydraulic pumps, 1 fuel vapor eductor pump.

E. Engine Mechanical Design

The following lists a number of design items which are considered critical in the design for future engines:

*Constant speed drive.

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1. Compressor Case Temperatures - The compressor case temperatures
    should be maintained at less than 550°F for fire safety. Al-
    ternatively case insulation or double walling of flammable
    fluid lines must be provided.

2. Compressor Bleeds - A preference is shown for providing all customer
    air bleed from a single port at each of the required compressor stations.
    Such bleed air should be tapped from the inner diameter of the compressor
    to avoid contamination. Strong preference is also given for locating
    the compressor bleeds in such a way as to eliminate the need for a
    bleed air precooler. The proper location and sizing of bleed ports
    as well as the stage or stages of the compressor from which bleed air
    should be taken requires careful and early consideration in compressor
    design.

3. Engine Windmilling Power Extraction - Unless adequate windmilling power
    is available to drive the aircraft hydraulic system, alternative sources
    such as drop out generators, or battery driven hydraulic systems must be
    added to the aircraft. This requirement comes from the powered controls
    of modern aircraft and the need to insure aircraft control under an all
    engine out condition. Design provisions to insure the availability of
    high pressure rotor rotation of sufficient speed to extract hydraulic
    power should be provided.

4. Compressor and Turbine Tip Clearance Control - Compressor and turbine
    performance is dependent upon clearance control and control over
    extraneous leakage. Long life in current designs has not been achieved
    and early performance loss has been the result.

5. Rotor Support and Bearing Location - Many advanced engine designs employ the concept of supporting the high pressure turbine on the low pressure turbine shaft. This concept permits a lighter engine than would otherwise be possible. The problems foreseen with this design approach is that wear of the bearing surfaces will play a large factor in turbine tip clearance control and that bearing failure could have potentially disasterous effects. As such American wants nothing to do with this type of design at this time. It is possible that a reversal of opinion can be obtained if the design concept is proven over a long period of time in military operation and that long endurance testing of a large number of samples proves safety and reliability. This possibility is not foreseen however and alternate design approaches are preferred even at the expense of weight. As part of any design the turbine must never be capable of spinning to destruction. The design must provide for rearward move-ment upon shaft failure such that the turbine engages the static structure and brings the turbine to an all but instantaneous stop.

6. Case Flanges and Leakage - Case flanges must have special provisions for long term sealing, restoration of surfaces and extra material for such restoration. Flange leakage with age and the use of different cases in assembly must be taken into consideration in the initial design.

7. Rotating Assemblies - The use of dowel bolts for alignment and carrying centrifugal loads in rotating assemblies is not acceptable. Rabbeted joints are preferred. Reference surfaces not subject to wear shall be provided on all required parts for use in checking alignment.

8. Provisions for Internal Inspection -
Unobstructed access for borescoping all stages of the compressor, com-bustor and turbine shall be provided. Additionally the use of radio isotope and X-ray techniques for inspection should be considered in

the initial design.

9. Fire Protection - The possibility of case burn through must be considered in the initial design. Means for detecting such a burn through need to be developed. The use of acoustic or vibration sensors must be investigated as possible means of detection. Generally, it is expected that a liquid nitrogen fire extinguishing system will be used. The seriousness of the exposure of hot cases, etc. to LN_2 needs investigation.

10. Oil System - The design of the oil system must consider minimizing the possibility of internal oil leakage due to mis-assembly of parts. To this end O-rings on internal oil transfer tubes are forbidden as are brazed connections. Mechanical connections are required on all internal tubing.

11. Fuel System - The fuel control system must be fully capable of managing engine performance throughout the engine operating envelope. It must provide the capability of allowing full throttle takeoffs without exceeding the rating scheme and provide climb and cruise power at fixed throttle position without regard for the temperature lapse rate with altitude or airspeed. Additionally, the control must prevent overspeed and overtemperature of the engine.

12. Engine Starting - The engine must be equipped with a starter that will provide a thirty-second start after 4000 starts for minimum pollution control.

F. Propulsion System and Engine Prices

There are many factors which affect the price of a new engine, not the least of which is the amount of development work that must be undertaken and the number of basic and variant engines which are projected to be sold. These factors plus the competition in the market place have perhaps the largest

bearing on prices. Pod system prices have not been as openly competitive in the past and are normally buried in the price of the aircraft. Emphasis was placed on requiring the engine manufacturer to be responsible for the total power plant during the recent competition for the DC-10/L-1011, and comparison of the engine prices was expanded to include total pod prices. This pressure and the quoted pod prices came as a revelation to the engine manufacturers and to the airlines.

The major cost elements in the pod are the inlet and nozzle system. The nozzle system includes the reverser. The overall price level has increased versus time as emphasis has been increased on the structural design life of these items from their original level of nominally 2000 hours to in excess of 30,000 hours. The reverser must be designed for the same time between major maintenance objectives as the engine. Reverser nozzle assemblies in the past appear to price at approximately 100 dollars a pound of weight. The addition of acoustic material will increase the price upward toward 150 dollars per pound for future designs. For all practical purposes the inlet systems should be considered to cost approximately 150 dollars a pound when acoustically treated with wall treatment alone. Price increases towards the two hundred dollar a pound level are anticipated. Basic cowling runs 90 to 100 dollars a pound. The largest element of these prices is the engineering and tooling non-recurring write-off that occurs over the first production airplanes, up to the production breakeven point. The costs for the pod are therefore written off over a very small number of units in comparison to the traditional method employed in the past for writing off engine development costs. The objective for future aircraft is to design a power package that is usable on many aircraft models so that these high non-recurring costs need not be repeated for each new aircraft type.

Reviewing past engine prices in an effort to produce cost estimating trends has been quite unproductive because of the large variations in circumstances which existed at the time the development started. The existence of a developed core engine from which the new engine can be developed is perhaps one of the largest development cost savings. The major development cost area lies in high pressure compressor development followed closely with high pressure turbine development cost. Poor experience or development problems in other component areas can and have escalated development cost far above projections and can change this general rule of thumb.

In reviewing advanced technology to determine the potential rewards that can be achieved by increasing engine temperatures, pressure ratios or bypass ratio it is at best quite difficult to assess the effects of these changes on engine price. The following general expressions, however, are used by American Airlines for long range planning purposes and for taking a first cut at comparing the prices quoted by manufacturers for realism. Increasing overall cycle pressure ratio tends to increase the price of an engine by the cube root of the design pressure ratio divided by a base level of twenty $(OCPR/20)^{.33}$. Increasing turbine inlet temperature has the unexpected effect of reducing engine price as the thrust increase produced by the temperature increase is more rapid than the price increase for combustion chamber and turbine parts. However maintenance cost which tend to be dominated by turbine and combustor hardware replacement on repair costs is adversely affected. For the future this relationship of reduced first cost due to turbine temperature increases is not expected to hold. The basis for this projection is that the manufacturing and material costs are expected to increase more rapidly than in the past as higher and higher levels of turbine cooling effectiveness are sought to minimize cooling airflow losses. The relationship for the effect of turbine inlet temperature increases on engine price has in the past been following the cube root of the design temperature

in degrees Rankine divided into $2260°R$, $(2260/TIT)^{.33}$.

The effect of varying bypass ratio on engine price is to increase the price with increasing bypass ratio as larger blades and cases and more low pressure turbine stages are required. The relationship of price to bypass ratio is that the price increases approximately as the fourth root of the design bypass ratio divided by 4, $(BPR/4)^{\frac{1}{4}}$. The cost changes associated with two stage fan engines are roughly 108% of the single stage fan engine price for the same takeoff thrust.

The overall equation for estimating engine price in terms of dollars per pound of takeoff thrust is as follows for a base level 40,000 pound thrust engine flat rated to $90°F$ at sea level static conditions.

$$\$/lb_{Fn} = x \cdot y \cdot \left(\frac{OCPR}{20}\right)^{.33} \left(\frac{2260}{TIT}\right)^{.33} \left(\frac{BPR}{4}\right)^{.25}$$

where x = 1.00 single stage fans and 1.08 for two stage fans

and y = 20.5 for low risk development programs where all components are demonstrated and an available core engine of the proper size is in hand

y = 22.5 for medium risk programs where scaling of core engines and modest changes to other components are required

y = 26.5 for high risk programs requiring a new core engine or more than two new undemonstrated components

Scaling of the engine price to fit other engine thrust classes can be accomplished between 25000 lb. and 65000 lbs. of thrust by multiplying by the following factor $\left(\frac{40000}{Fn_{T.o.}}\right)^{.33}$

The engines for an ATT are expected to be priced at $950,000 to 1 million per engine. The total powerplant at 1.4 to 1.5 million. However strong pressure will be placed on driving the price for the complete powerplant to $25 per pound of installed thrust.

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G.   Noise and Pollution Design Requirements

The noise level objectives which must be guaranteed are a function of the
projected state-of-the-art. "Guarantees" and "technical objectives" however
are different. The technical objective is to incorporate all known noise
reduction features that can be economically installed. The guaranteed noise
levels are normally higher by 3 decibels than the level which is technically
judged reasonable to achieve. The following is the expected guarantee noise
level requirement related to Appendix C of FAR-36 and the introductory year
of aircraft operation.

Year	Level
1975 to 1978	FAR 36 minus 5 EPNdB
1978 to 1981	FAR 36 minus 8 EPNdB
1981 to 1984	FAR 36 minus 11 EPNdB

The achievement of these levels will require the use of operating procedures
to minimize noise. Equally the design of the aircraft to avoid a high drag land-
ing configuration is essential. The major overall objective will continue to
be the reduction of the area enclosed by the 100 EPNdB contour in a uniform
manner until the contour is completely within the airport boundary. Considera-
tion must be given to the noise level produced by reverse thrust operation
on the ground which must not exceed the sideline levels covered by the re-
quirements stated above. The noise and pollution emission produced by the
auxiliary power units must equally be controlled. The noise level at the
cargo doors caused by APU operation must be controlled to a maximum of 80 dBA
for the future and the internal noise level within the cabin during flight
must be reduced slightly from the current levels in terms of speech interfer-
ence (SIL).
The main challenge in pollution control will be to reduce the formation of
emission at the source and to further control emissions by proper oper-
ating procedures. Starting characteristics are considered important in odor
formation. To this end rapid flame propagation and high stability

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of the combustion process are important during starting as is an adequate

engine starting system to produce quick starts. Automatic starting systems

should be considered for future engines. There must be no overboard drains

from future engines with the exception of the false start combustion chamber

drain. Specific design attention must be given to oil vapor and bearing

seal drains of the engine and accessories to minimize this source of pollu-

tion. Heavy engine breathing during initial operation which allows the escape

of oil mists must be more closely controlled. The NASA stated targets for

carbon monoxide and hydrocarbon are reasonable "technical goals", however the

forthcoming Environmental Protection Agency Rules will be the required

"guarantee levels" for future engines. High idle thrust levels and the use

of water injection as pollution control devices are considered to be a last

resort measure only. High idle thrust, a level that exceeds approximately 6%

of the takeoff thrust, involve ramp safety problems and general brake wear

problems that are undesirable. Water injection for nitrogen oxide control

is effective but only while the water is used. The objective must be set on

advanced combustion system designs which insure a more realistic solution

and provide benefits throughout the operating envelope of the aircraft.

SECTION II

Engine Performance and Costs

A. Introduction

This section addresses historical propulsion system performance problems
and maintenance costs in an effort to provide a better appreciation for
the effects of technology as observed from an airline engineering point
of view. The performance and cost history is the experience of American
Airlines and it should be expected that other airlines would produce data
which differed in minor ways. The experiences however are representative
and an understanding of the trends is vital to understanding why airlines
take a conservative position on introduction of advanced technology; and
the reasons behind the strong current emphasis placed on engine reliability
and economics.

The general conclusion that has been drawn from this review is that specifically
for an advanced subsonic commercial aircraft the avenues open to improve air-
craft power plant operating economics are not the traditional areas of im-
proved specific fuel consumption and engine weight. It will be far more
cost effective to place research emphasis on achieving a propulsion system that
utilizes those features to improve performance that are consistent with the
overall objectives of very high reliability, low maintenance costs, minimum
pollution and excellent long term performance retention. It is unfortunate
that the current methods of assessing aircraft economics do not provide means
for indicating the tangible benefits associated with these objectives.

There is every indication that the trends in engine performance deterioration
and in maintenance cost have increased exponentially with improvements in
technology. While it is recognized that the total experience with the new

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high bypass engines is less than would be desirable to draw firm conclusions, and that the current problems can and will be resolved by the manufacturers and airlines; there is sufficient indication that unless a high level of effort is placed on reversing these trends during the initial design process the airlines can ill afford "advanced technology."

B.   Problems with Engine Performance Development and Retention

Records associated with the problems of achieving engine performance during the development of JT3C/J57 series engines widely used on commercial aircraft have not been maintained. Early records from the military will undoubtedly disclose that serious problems existed in achieving performance with this new two spool engine. The commercial JT3D turbofan version of the engine was developed from the J57 by applying the first two stages of the ANP demonstrator engine to the low pressure spool and adding low pressure turbine stages (switching to the T57 turbo prop low pressure turbine). Considerable performance experience was in hand before contractual commitments were made on what the engine should produce. The JT8D engine was derived from the J52 military developed engine. Engine performance levels were guaranteed before the engine was well in hand and extreme difficulty was faced in achieving the stated performance. The aft fan version of the J79, the CJ805-23, developed for the Convair 990 produced performance as required but was short of life and it was not until the engine was essentially derated in-service that engine life was brought to a reasonable level. Performance of the JT9D engine was committed long before real development started and the performance guarantees were set at a level that proved impossible to meet with early production engines. The inability to deliver early engines with performance margins produced engines which operated above planned temperatures and resulted in shorter lives than would otherwise be expected. These characteristics are costly to the airlines and the manufacturers in terms of high engine removal rates and high replacement parts costs. The engines of the future must be committed to realistic

guarantees with sufficient "margins for errors".

1. <u>Rigs to Engine</u> - Normally it is the practice of U.S. engine manufacturers
   to base proposed engine performance guarantees on projected and demon-
   strated component rig performance. This practice is not used by foreign
   manufacturers as traditionally the time available to develop an engine
   and the funds available to do so are more restricted. They follow instead
   the practice of debiting each engine component rig performance level by
   a minimum of one percent in efficiency. Experience has
   indicated that they have been unable to generate rig performance in the
   finished production engine within the time and budget limitations that
   existed.

2. <u>High Bypass Ratio Engines</u> - The current generation of high bypass ratio
   engines at first engine run all operated at a point roughly 15% above
   their engine specific fuel consumption guarantees. The TF-39, the parent
   of the CF-6, is addressed here as being the appropriate point of reference.
   The RB-211, JT9D and TF39 programs all reached an equivalent point of
   about 4% over commitments in about 15 months of development effort. The
   TF39 eventually reached its committed performance, the JT9D did not and
   missed performance by about 2%. The RB-211 story is not yet complete.
   Certification performance levels will be presented shortly and there is
   a strong possibility that the engine will be initially placed in service
   as a derated engine. It is probable that early RB-211 engines will be
   above the required specific fuel consumption performance by approximately
   two percent just as the early JT9D engines were. Heavy continuing ex-
   penditures of research and development funds are required when the initial
   engines are short on performance. Traditionally early service experience
   will produce requirements for design changes that will adversely affect
   performance. Such factors as combustor life may demand higher pressure
   drop to provide adequate cooling for longer life, and turbine nozzle and

blade cracking will require increased cooling airflow. Perhaps the most difficult problem to face is the presence of inadequate stall margins presenting the requirement for additional bleeds, revision to bleed schedules, or restrictions on throttle movement and use of reverse thrust.

3. Production Variation

Normal production engines have varied 1½% in airflow and 2% in specific fuel consumption. The average production engine must therefore be at least 1½% better in performance than specification minimums to avoid high production rejection rates. In addition there must be a large temperature margin between the worst production engine and the redline limit on measured temperature. A 90°F tolerance is historically the minimum for good operating flexibility. Production variations in spool speed and thrust at minimum power setting parameter are all part of production tolerenaces that are expected. Figure 1 indicates the variations seen from reasonable production size samples of engines.

4. Service Experience with Engine Performance

The development of engines to achieve their design performance commitments is a difficult job with many hours spent with component rigs to finally achieve each components objectives or to determine whether a given component can carry the deficiency of another. The maintenance of engine performance over long periods of operation has not been a problem faced by the military services with the exception of those elements that conduct their operation in a commercial airline fashion. Mechanical problems usually preclude long hours of operation of military engines designed to achieve maximum performance. The deterioration of engine performance with time is a serious problem to the airlines. Efforts to correct performance problems in the past have been short term and sporadic in nature and directed at getting

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Figure 1

The Average Variation for Production Engines
at Constant Sea Level Static Takeoff Thrust

	JT3D	JT8D	Spey	JT9D	CF6-6D
$N_1/\sqrt{\theta}_{T_2}$ (rpm)	± 85	± 95	± 50	± 40	± 25
$N_2/\sqrt{\theta}_{T_2}$ (rpm)	± 98	± 159	± 90	± 44	± 90
EGT/θ_{t_2}	± 17°C	± 13°C	± 15°C	± 12°C	± 22°C
$W_f/K_c \delta_{t_2}$	± 2.1%	± 1.4%	± 1.5%	± 1.0%	± 1.5%
$EPR (P_7/P_2)$	± .017	± 0.017	Not Available	± 0.006	± .10*

$$* \ P_t/P_2 = 5.1$$

out of a specific problem. The science of achieving performance from old parts in the most cost effective way has really been under development for only the last three years. Progress in this field has been hampered by a number of real problems.

The deterioration of performance on a total industry basis appears to be as follows: a) the early JT3C, JT4C turbojet powered aircraft have lost roughly 8% of their specific range capability at this time. Early turbofan (JT3D, Conway) powered aircraft have lost between 4 and 5% and newer aircraft have lost 2.5 to 3% of their range capability. There are no technical features that would indicate that these later engines are superior to the early turbojets and that they will not deteriorate to the 8% or greater level as they continue to accumulate time. Early indications are that the new breed of high bypass ratio engines are worse, if anything, in terms of the rate at which performance deteriorates.

Performance loss in terms of aircraft specific range, a portion or all of which is due to engine deterioration, is not the only problems faced as engines grow older in service. Engine stall margin also deteriorates and compressor reblading programs have been necessary to return engine stall margin to a satisfactory level. Experience with the new breed of engines gives little confidence that the newer technology has done anything to improve the loss of stall margin with time. While production engines have normal performance variations, the installation of the engines with real aircraft nozzles, bleed systems, and instrumentation also produce real and imaginary variations in the observed engine performance. Age and use further produce losses and changes in performance through wear of seals, erosion of blading and changes in aircraft airconditioning system performance to name but a few. None of these changes in observed engine performance are uniform from engine to engine or are isolated to a given engine component. As an example, although by design there is uniformity

in the amount of bleed air taken from each engine, in practice there is a hogging of bleed air from one engine and a non-uniformity of off-take from engine to engine on an aircraft. Figures 2, 3 and 4 show the trend of aircraft and engine performance versus time. Introduction of new engines of later-build-standard have helped to maintain the aircraft fleet performance at a lower deterioration rate than would be produced if all the engines were of the same age. When an airline's fleet has reached its maximum size and the flow of new engines stops, the average deterioration rate would be expected to increase. Figures 5, 6 and 7 show the average change in performance, for engines returned to service, using new production engine performance as the base. Similar curves for JT9D and CF-6 engines are not yet available due to lower total service time accumulated to date. An unknown portion of aircraft performance deterioration may be attributable to changes to inlets, nozzles and bleed flow rates. The average installation effect for new production engines and pods; and the effects observed with old hardware are shown for the JT3D and JT8D in Figures 8 & 9. Figures 5 & 6 are test cell changes to which the installation effects of Figures 8 & 9 must be added to obtain the observed change. In general this data produces more questions than answers. Research effort into this area of performance losses through deterioration. could produce design guides for the future.

5. <u>Experience with Performance Recovery in Spey Engines</u> - A performance recovery program was launched on the Spey engine to determine if some of the average loss of specific fuel consumption could be regained. A series of repairs were undertaken to determine the effects of each individual repair on total engine performance.

FIGURE 2

AIRCRAFT AND ENGINE PERFORMANCE TRENDS
BASED ON AIRCRAFT PERFORMANCE AUDITS AND
ENGINE CONDITION MONITORING DATA SUMMARIES

B707-123B/720B
JT3D-1,MC6,MC7

FLEET PERFORMANCE AUDIT

ENGINE CONDITION MONITORING DATA SUMMARIES
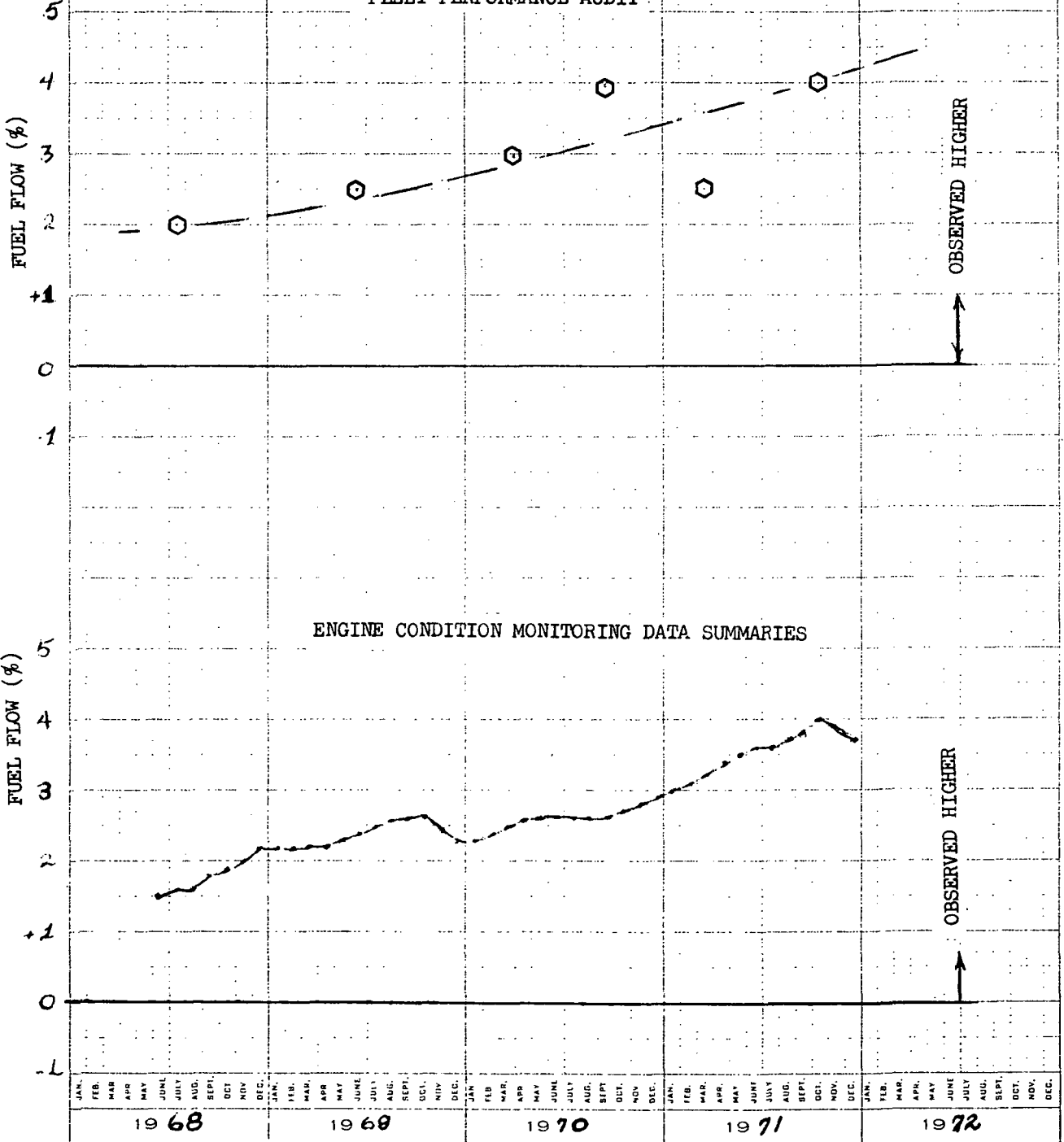
FIGURE 3

AIRCRAFT AND ENGINE PERFORMANCE TRENDS
BASED ON AIRCRAFT PERFORMANCE AUDITS AND
ENGINE CONDITION MONITORING DATA SUMMARIES
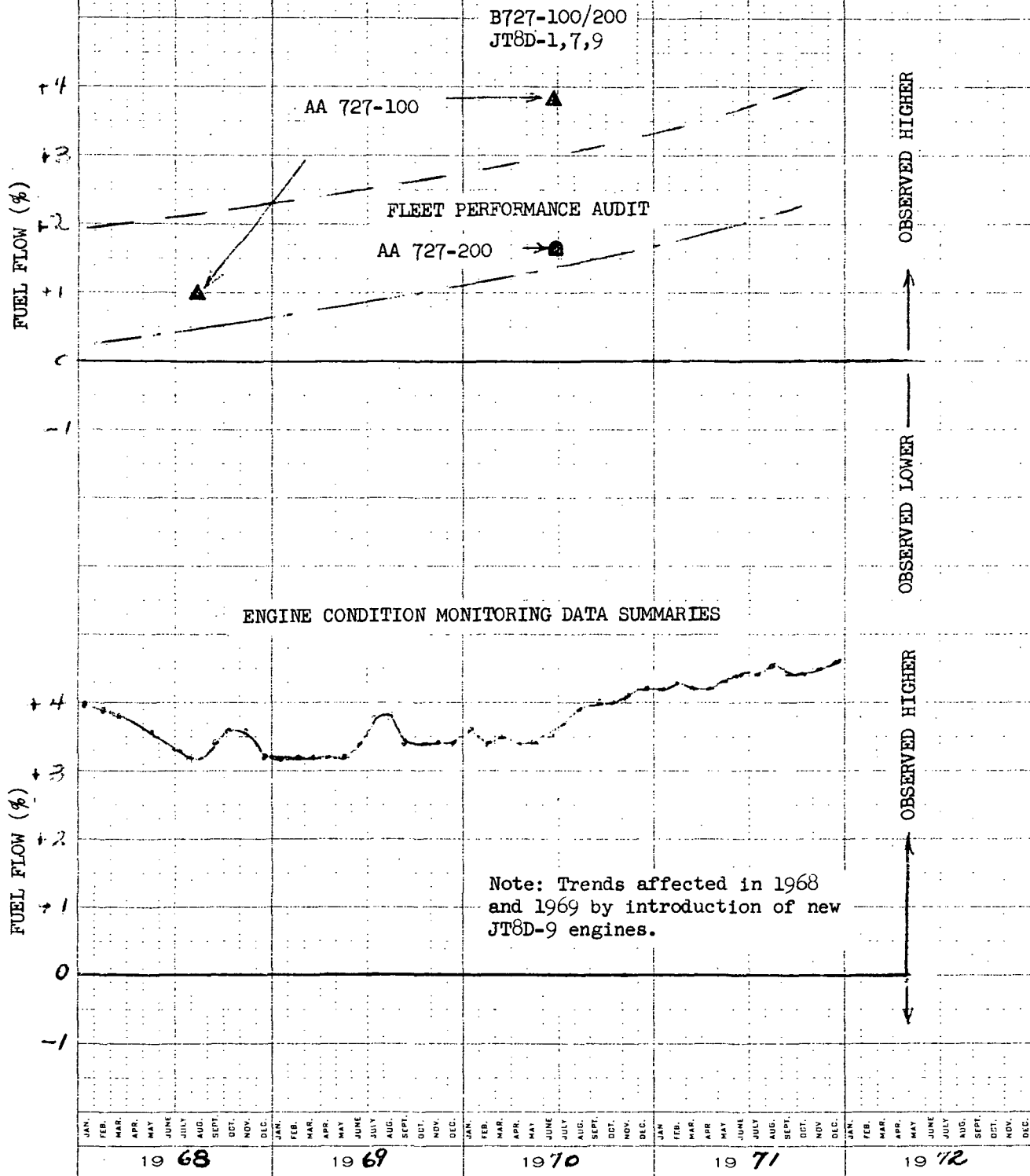
FIGURE 4

AIRCRAFT AND ENGINE PERFORMANCE TRENDS
BASED ON AIRCRAFT PERFORMANCE AUDITS AND
ENGINE CONDITION MONITORING DATA SUMMARIES

B707-320B/C

JT3D-3B

FLEET PERFORMANCE AUDIT

AA 707-320B/C

ENGINE CONDITION MONITORING DATA SUMMARIES

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Figure 5

Average Engine Performance Referenced to Average New Production
Performance and One Sigma Bands at Takeoff Power

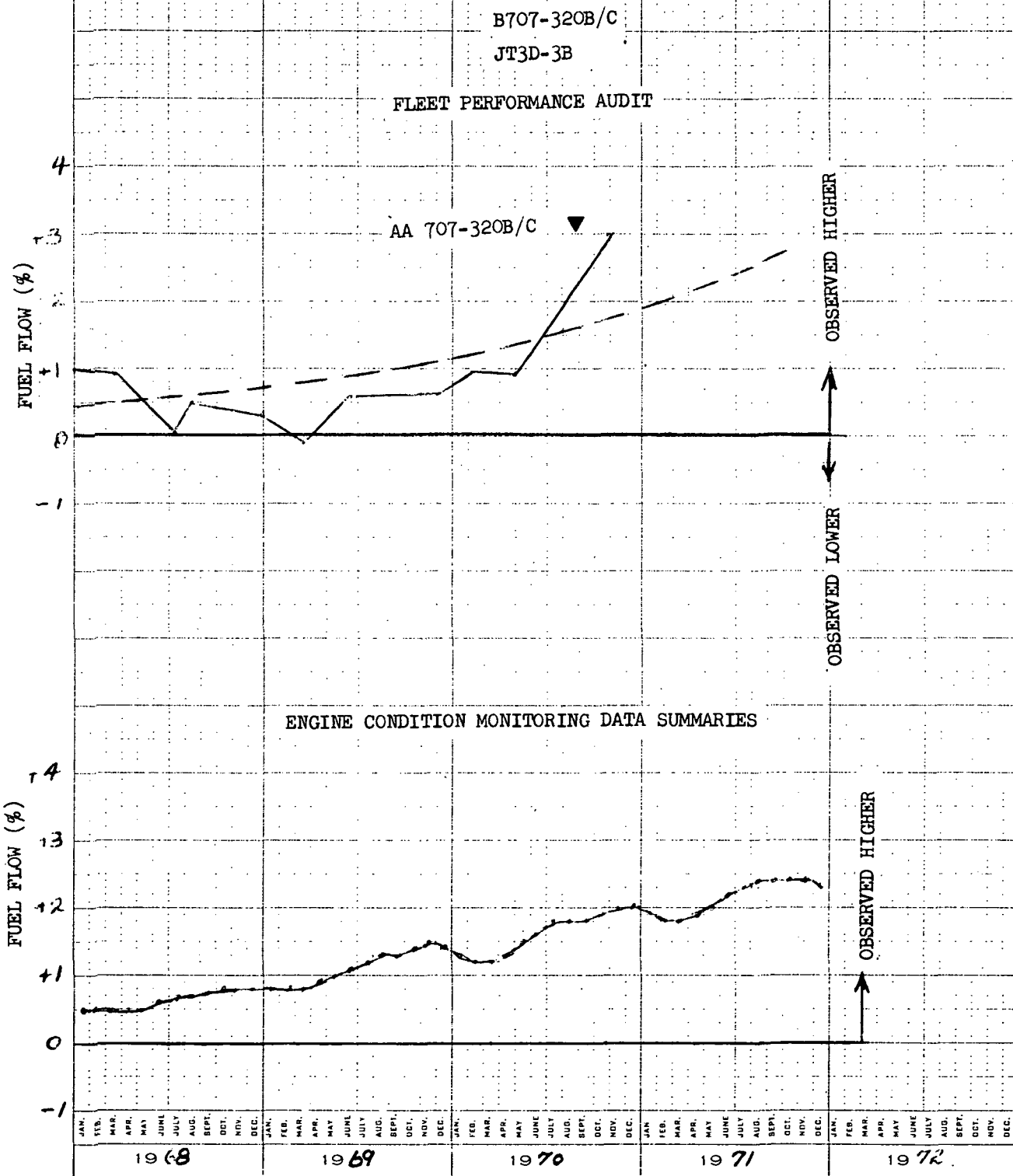|	JT3D-1, MC6, MC7	JT3D-3B
ΔW_f (lb/hr)	+ 260 ± 130 (3% ± 1 5%)	+ 250 ± 110 (2.6% ± 1.2%)
ΔEGT (°F)	+ 38° ± 12°	+ 25° ± 13°
$\Delta N_1/\sqrt{\theta}_{t_2}$ (rpm)	+ 10 ± 50	- 20 ± 20
$\Delta N_2/\sqrt{\theta}_{t_2}$ (rpm)	+ 90 ± 45	- 40 ± 50
$\Delta P_{s_3}/P_{t_2}$ (%)	+ 1.5% ± 1.3%	- 1.4% ± 1.4%
$\Delta P_{s_4}/P_{s_3}$ (%)	+ 1.2% ± 2.8%	+ .6% ± 2.0%
$\Delta P_{s_4}/P_{t_7}$ (%)	- 1.5% ± 1.2%	- 1.5% ± 1.8%

Figure 6

Average Engine Performance Referenced to Average New Production
Performance and One Sigma Bands at Takeoff Power

	JT8D-1/7	JT8D-9
ΔW_f (lb/hr)	+ 170 $\pm$ 80	+ 280 $\pm$ 90
ΔEGT ($^\circ F$)	+ 26$^\circ F$ $\pm$ 10$^\circ F$	+ 36 $\pm$ 14
$\Delta N_1/\sqrt{\theta_{c_2}}$ (rpm)	+ 25 $\pm$ 40	+ 5 $\pm$ 30
$\Delta N_2/\sqrt{\theta_{c_2}}$ (rpm)	- 15 $\pm$ 65	0 $\pm$ 50
$\Delta P_{s_3}/P_{c_2}$ (%)	+ 1.4% $\pm$ 1.8%	+ 1% $\pm$ 1%
$\Delta P_{s_4}/P_{s_3}$ (%)	- 1% $\pm$ 2%	- 1.5% $\pm$ 1.3%
$\Delta P_{s_4}/P_{c_7}$ (%)	0 $\pm$ 1%	- .7% $\pm$ 15%

Figure 7

Average Engine Performance to Average New Production
Performance and One Sigma Bands at Takeoff Power
Spey MK 511-14

ΔW_f (lb/hr)   + 450 $\pm$ 25

ΔEGT (°F)   + 50 $\pm$ 10°F

$\Delta N_1 / \sqrt{\theta_{t_2}}$ (rpm)   + 50 $\pm$ 40

$\Delta N_2 / \sqrt{\theta_{t_2}}$ (rpm)   - 10 $\pm$ 50

$\Delta P_{t_3} / P_{t_2}$ (%)   0% $\pm$ .7

$\Delta P_{s4} / P_{t_3}$ (%)   + .3% $\pm$ .8%

$\Delta P_{s4} / P_{t_7}$ (%)   - .5% $\pm$ 1.5%

Figure 8

Installation Effects Observed Based
on Correlation of Test Cell and Installed Engine
Data at Takeoff EPR plus 1 Sigma Data Scatter

JT3D-1 (Average)   JT3D-3B (Average *)

ΔW_f (lb/hr)   + 675 $\pm$ 325   + 300 $\pm$ 300

ΔEGT (°F)   + 10° $\pm$ 40°F   + 0 $\pm$ 40°F

ΔN_1 (rpm)   + 200 $\pm$ 100   + 200 $\pm$ 100

ΔN_2 (rpm)   + 50 $\pm$ 100   + 70 $\pm$ 100

*Large Suck-in Door Cowl

JT3D-3B Average**

ΔW_f (lb/hr) + 480 $\pm$ 400

ΔEGT (°F) + 20 $\pm$ 40°F

ΔN_1 (rpm) 230 $\pm$ 100

ΔN_2 (rpm) 100 $\pm$ 90

**Small door cowl

JT3D-3B Flight Test Data - New Engines Large Door Cowls

ΔW_f (lb/hr) + 200

ΔEGT (°F) - 21

ΔN_1 (rpm) + 75

ΔN_2 (rpm) 0

Figure 9

Installation Effects Observed Based
on Correlation of Test Cell and Installed
Engine Data at Takeoff EPR plus 1 Sigma

	JT8D-1/7 (Average)	JT8D-9 (Average)
ΔW_f (lb/hr)	+ 200 ± 300	+ 350 ± 250
ΔEGT (°F)	+ 8 ± 32°F	+ 12 ± 38°F
ΔN_1 (rpm)	+ 115 ± 100	+ 80 ± 60
ΔN_2 (rpm)	+ 80 ± 100	90 ± 70

Flight Test Data with New Engines

	JT8D-7	JT8D-9
ΔW_f (lb/hr)	+ 100	- 100
ΔEGT (°F)	+ 27	+ 12
ΔN_1 (rpm)	+ 80	0
ΔN_2 (rpm)	+ 50	- 60

Based upon test cell data and installed performance trend monitoring programs the fuel flow of the average Spey engine had increased by 3.5% above that demonstrated by the engine as new. That level of increase represented an increased annual expenditure of 350,000 dollars based on a fleet of approximately 30 aircraft. Recognizing that modifications had been incorporated in the engine to improve life and that some of these modifications had an adverse affect upon performance there was still the possibility that a sizeable portion of the loss could be recovered. The average time on the engines at the time the program was initiated was 5000 hours with a few engines having a service time accumulation of 6000 hours. The first modification undertaken to the evaluation engine was to recontour the leading edges of the low pressure compressor/fan blades. This modification reduced the fuel flow by 0.5%. The second modification was to repaint the low compressor with Nubelon -S Paint. This action improved the fuel flow by slightly greater

than 1% and two additional engines were produced with these two bills of work. The improvements noted were 1.3% and 2% lower takeoff fuel flow. The low pressure compressor of the Spey engine has alumunium blading and it is evident that blade erosion caused a significant loss in airflow and efficiency. The restoration of the leading edges and smoothing of the blade surfaces by the application of paint brought the airflow presumably back to the original level and improved the efficiency. The next bill of work done on the test engine was to strip and repair the high pressure compressor area and combustor. The repairs were made in accordance with the overhaul

manual and no significant change was noted in performance. The incorporation of an improved first stage turbine blade which was known to cause a performance loss was tried next and evidenced the expected loss. The second stage turbine turbine seal areas were reworked to minimum clearances and the turbine flow area was closed by three percent. The first change improved the fuel consumption by 1/3% and the second reduced the part power fuel consumption although it had no significant effect on takeoff power. The total program produced a reduction in fuel flow of about 2.5% with the major contribution coming from the low compressor rework and turbine improvement, i.e. minimum turbine seal clearances. Starting from a base of an average of 3.5% up on performance the improvements were considered signficant. Until this point in time the airflow capacity of individual engines had not been measured as a routine practice. Neither calibrated bellmouths or airflow instrumentation existed for the purpose. The manufacturer estimated that at that point in the service life of the engine the average engine had lost 2 to 2½ percent of the original airflow capability in the low pressure compressor. Titanium blading would probably have slowed the rate of deterioration. However, little is known about air flow losses in current engines to be certain that the blade blending practices used to remove nicks are not the major factor in airflow losses and that titanium blading in current engine do not suffer from a similar problem.

6. Experience with Performance Recovery in the JT3D - An earlier program of a similar nature was run on a JT3D engine. The performance recovery program was a joint effort with Trans World Airlines investigating the hot components and American investigating the compressor and fan components. This work is reported in SAE Paper No.700329. The American program required 18 months to complete due to the production nature of the overhaul and repair operation taking precedence. Therefore long periods of time went by between discrete

engine runs. Further, the test cells instrumentation was not suf-
ficiently accurate to produce highly detailed performance data nor
were the engines configured for accepting additional instrumentation
in a manner to permit this type of research. Lastly the engine test
cell fuel system was poorly designed and not sufficiently accurate for
this type of work and was replaced as a result of the indications of this
weakness. Nonetheless the program produced useful results in terms of
telling American more about what was not known about engine performance
and what had to be learned if future programs were to produce results.

A summary of the observed results and the results speculated from the data are
as follows:
The most significant effect of deteriorated compressor parts was the loss of
high compressor stall margin. It appeared possible to use blading eroded
to 0.040 in. without encountering stall problems on engines equipped with
twelfth stage bleed systems. There was no definable trend in performance that
would indicate that a performance loss had been encountered using blades of
this type. Beyond this point no firm conclusion was possible. Over the
period of time which elapsed the test cell undoubtedly shifted slightly in
calibration. One cannot be sure from the records that the same identical
bellmouth and reference tailpipes were used on each test, the fuel system was
known to be inaccurate, and airflow was not taken so that changes in fan and

compressor airflow capacity remain unknown. The TWA program was run more
quickly from May to October of 1969. The test work conducted by TWA on
the JT3D-3B provided the following information. Utilizing a new engine
rebuilt with only aged combustion system parts and first stage nozzle
and turbine blades, the performance loss in terms of specific fuel con-
sumption was determined to be 1.5%. The effect of eroded blades alone

was determined to be 0.3% of the total and produced a 50 rpm decrease

in high rotor speed and an increase of 5°F in EGT. The rest of the

losses can be explained by turbine tip clearance changes and slight

changes in turbine area. Turbine tip clearance increases affect SFC

approximately 0.4% per 0.010 inches increase over minimum. Nominal

tip clearance is 0.062 to 0.089 inches with replacement required when

the clearance exceeds 0.100 inches of radial clearance. First stage

turbine clearances run to the high side can obviously produce 1.5% loss

in SFC by themselves. Modest changes in turbine area of the order of

1.3% (2 classes) can affect SFC by 0.6%. It should be further explained

that an increase of turbine tip clearance to the maximum causes a severe

loss in low pressure compressor stall margin. Referring to Section III and

figure 19 of this report, the effects of the loss of low pressure turbine

performance through aging are more important than other components. It

is unfortunate that this fact was not recognized at the time this work

was done. The effects of turbine efficiency appear to be far more power-

ful upon specific fuel consumption than are small changes in high pres-

sure compressor efficiency.

7. Performance Problems with the JT8D - A preliminary review of the per-

formance of fifteen JT8D engines after engine repair and reintroduction

into service is provided below as an indication of the efforts that

were undertaken to understand engine performance. Fifteen engines were

compared to JT8D-7 Specific Operation Instruction performance levels.

It was assumed for this analysis that all engines had the one-piece

burners, air cooled HPT vanes and original D-7 HPC. For the newer

engines (653 and 654 series) reference was also made to their individual

final acceptance performance levels.

As a diagnostic guide the following performance parameter shifts at constant thrust were used to indicate the specific area of component performance loss.

(a) Fan O.D. - Low rotor speed increases with increased levels of Ps3, Ps4 (% Δ Ps3 $\approx$ % Δ Ps4) and N2.

(b) LPC (including I.D. of fan stages) - Ps3 and Ps4 decreases (% Δ Ps3 $\approx$ % Δ Ps4) with a decreased level of N2 but no change in N1.

(c) HPC - Ps3 increases with an increased level of N2 but no change in N1 or Ps4.

(d) Burner - No change in N1, N2 or Ps3. Ps4 could increase or stay the same.

(e) HPT vane bow - Ps4 decrease but no change in N1, N2 or Ps3.

(f) HPT - Ps3 increase with a decreased level of N2 but no change in N1 or Ps4.

(g) LPT - Ps3 decrease with an increased level of N2 but no change in N1 or Ps4.

Bleed leakage and reverser leakage were not considered, since tests were run with bleed ports capped and a reference tailpipe. In general, shifts of less than 1% in Ps3 and Ps4 or 50 rpm in N1 and N2 were considered insignificant. Various combinations of the losses mentioned above can be assumed to explain combination of parameter shifts. This analysis only considered fairly straight forward effects and should not be considered as the only interpretation possible from the data.

The parameter shifts are one type of guide but should be integrated into a complete analysis involving observed condition of engine parts and previous engine modifications as well.

Results

Engine	Comments
654708	N2 up 100 rpm relative to acceptance. If engine configuration had not been modified too much, would be indicative of a HPC problem. The current level of N2, however, was within normal limits.
654671	Performance levels satisfactory.
654376	TSFC and EGT levels satisfactory. However, N2 was up 100 rpm relative to acceptance and the normal limits.
653847	N1 up 120 rpm relative to acceptance. If engine configuration had not been modified too much, would be indicative of fan O.D. damage. The current level of N1, however, was within normal limits.
653696	Ps3 up 3 to 4% relative to either acceptance or normal level. Indicative of high spool damage (more than likely HPT).
653852	Data was unrealistic.
649699	N2 up 150 rpm relative to normal level. Indicative of a HPC problem.
649661	N1 up 100 rpm relative to normal level with corresponding increases in Ps3 and Ps4. Indicative of fan O.D. damage.
649278	N1 up 60 rpm and N2 up 130 rpm relative to normal level with Ps3 and Ps4 increases corresponding to N1 increase. Indicative of a combination of fan O.D. damage and HPC problems.
649087	No shifts in speeds or pressures. Indicative of a burner section problem.
648989	N1 up 100 rpm relative to normal level with no Ps3 or Ps4 change. Indicative of fan O.D. and LPC problems.

648978   Ps3 up 4% relative to normal level. N2 has slight tendency to be low. Indicative of a HPT problem.

648852   No shifts in speed or pressures. Indicative of a burner section problem.

648837   N1 down 80 rpm and N2 up 130 rpm relative to normal level. N1 should be good for engine. N2 indicative of a HPC problem.

648764   No shifts in speed or pressure. Indicative of a burner section problem.

Notes:

The TSFC increases noted agreed with the EGT increases indicating that the shifts were real and not just measurement problems.

No single component stood out as the reason for the TSFC and EGT increases. A tabulation of the components mentioned in the analysis is shown below.

     i   Fan O.D. - 4 cases

     ii   LPC - 1 case

     iii   HPC - 4 cases

     iv   Burner - 3 cases

     v   HPT - 2 cases

The burner section (diffuser, fuel nozzles, burner cans, transition ducts, etc.) have been a source of considerable performance deficiencies. There is no shift in any performance parameter that can be used to detect most cases of burner deficiency. Ideally, a combustion efficiency change would only affect fuel flow and leave EGT unchanged. In practice, the deviation that caused the efficiency change usually changes the burner temperature pattern as well. A loss in combustion efficiency, therefore, could be present in any of the twelve engines that indicated TSFC and EGT losses to some degree.

9. Causes and Unknowns Concerning the Loss of Performance Over Time -

There are obvious factors that effect the loss of engine performance versus time of service use. The uncertainty lies in the amount of loss associated with each factor and the cost of recovering the performance lost. New production engine performance can be achieved if all of the worn parts are restored or replaced to the original drawing tolerances and finishes. The cost of such a repair philosophy has been more than the airlines have been willing to pay. It is equally true that the continued usage of old parts until they become unsafe for further service involves increased costs in terms of fuel consumption losses heretofore only partially realized. The science of obtaining performance from old parts has not been developed to the degree required to do the cost benefit tradeoffs necessary to implement another course of action. Progress has been made in determining the cost of recovering performance and will continue to be made as time goes by. However, the effects of parts aging should be taken into account in the design process. It should be possible to design an engine such that the majority of performance can be recovered inexpensively. The efforts of the airlines to achieve recognition of this problem will be seen in the requirements for performance guarantees that apply through the first four thousand hours of operation. If original engine performance has to be achieved by very fine design details such as very accurate control of seal clearances, tip clearances variable geometry rigging tolerances, area tolerances, etc. then the original performance as delivered will not last. Airlines fly on used engines and average engine performance. The objective in the original design must be to achieve long life both in parts and in performance and to provide the repair and maintenance procedures that make the retention of performance economical. Current problems are briefly summarized below.

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a. Blade Erosion Effects on Flow Capacity and Efficiency - The effects
    of blade erosion are more noticeable in the compressors and fans
    than in turbine. The effects of erosion on stall margins have been
    determined by experience and through experience the airlines have
    normally wound up in a major campaign to reblade compressors on an
    expedited basis. The sensitivity of engine stall margin to inde-
    pendent blade and vane conditions is an unknown. There are indications that
    compressor stall margin is more sensitive to vane condition than blade
    condition at least in the case of the JT3D high pressure compressor.
    American is currently testing suspect JT8D engines for stall margin
    because of the sensitivity of the JT8D to stall in the center position
    of the Boeing 727. Engine selection criteria have been developed to
    preclude a stall-sensitive engine from being installed in the center
    position but sufficient data has not been developed to indicate how
    the engine should be rebuilt economically to remove this constraint.
    Rework of the fan component of the Spey engine gave strong indication
    that engines were experiencing a loss of airflow capacity with age and
    that recontouring and resurfacing the blades restored the compressor to
    close to the original capability.

b. Maintenance of Minimum Clearances
    Maintaining minimum clearances in turbine seals is extremely effective
    in retaining performance of current engines. The effects that JT8D
    and JT3D compressor tip clearance have on efficiency and stall margin
    have not yet been documented and remain an unknown to the majority
    of airlines.

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c. Foreign Object Damage

The current practice of blending nicks in blades caused by foreign object damage is expected to continue. The larger fan blades for high bypass ratio engines make the continuation of the practice necessary as the per unit price per blade exceeds 1000 dollars. As advanced blading is employed such as multiple circular arc blading the effects of blending nicks on the aerodynamic performance are expected to become more severe. Currently, decreased solidity of up to 10% occurs locally as the result of heavy blending to recover blades damaged by FOD. The absence of highly accurate airflow measuring capability has precluded much progress in defining performance losses in this area.

d. Case Flange Seals

The higher pressure ratio engines produce case flange seals which are difficult to maintain, particularly when engine parts are scrambled. The amount of leakage that exists to date from this mixing of case pieces of current engines is an unknown to American's knowledge. No airline has taken the time to check for case seal leakage variations from engine to engine.

e. Final Nozzle Area/Contours and Thrust Reverser Leakage

Current aircraft engine nozzles have no provisions for trimming the final area. The criticality of local nozzle contours to overall engine performance has not been defined and maintenance handbooks are less than definitive on the allowable variation in contour, surface roughness and out of round limits. Reverser seal designs and replacement practices allow the discharge air to escape to ambient. While sea level static testing can indicate oversized nozzles by trends in engine operating characteristics the escape of high pressure air at the beginning of the fan cowl boatail probably produces a drag penalty

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which exceeds the loss measured statically. It is the normal practices to test engines with reference hardware and aircraft nozzles and reversers are not installed for separate testing.

C. Cost of Performance

It is often tacitly assumed that an advancing technology produces improvements in performance which are worth the purchase cost. In reviewing advanced engine cycles for an ATT type aircraft it is apparent that little can be gained in terms of engine thrust-to-weight ratio and specific fuel consumption benefits over the current generation of advanced high bypass ratio engines. Further it is evident from internal airline studies that the tools employed to evaluate the economic benefits of future aircraft and engines are sufficiently vague that the tolerance for error is obscuring real trends. It is equally important that there has been little if any assessment of what benefits have been actually achieved from past investments in advanced engines.

This section of the report is directed at isolating engine costs within actual fleets while showing not only trends but relationships with certain key parameters. From these relationships it is the further aim to present the value of historical achievements as well as give some insight to future engine research objectives.

1. General Cost Relationships - The benefits of improved engine performance have traditionally been assessed in terms of increased aircraft range or payload. These benefits were specifically related to fuel consumption and engine specific weight or that which can be termed technical advancements. Based on estimated engine costs and aircraft utilization, projected aircraft direct operating costs (DOC) and return on investment (ROI) are calculated for newly purchased or planned aircraft.

The number of assumptions made in calculating DOC & ROI are subject
to errors which are perhaps larger than the estimated performance im-
provements.

Procedures for roughly estimating engine production prices have been
previously discussed in the Section I. The procedures to estimate engine
maintenance cost developed by the ATA is described below and are taken
from ATA Standard Method of Estimating Comparative Direct Operating
Costs of Turbine Powered Aircraft of December 1967.

· **Labor — Engine** (includes bare engine, engine fuel control, thrust reverser, exhaust nozzle systems, and
augmentor systems) (includes gear box, but does not include propeller on turboprop
engines) (Figure 3)

$$C_{am} = \frac{K_{FH_e} \, t_f + K_{FC_e}}{V_b \, t_b} (R_L)$$

Where: $K_{FH_e} = (0.6 + 0.027 \, T/10^3) \, N_e$ = Labor manhours per flight hour (turbojet)

$K_{FH_c} = (0.65 + 0.03 \, T/10^3) \, N_e$ = Labor manhours per flight hour (turboprop)

$K_{FC_e} = (0.3 + 0.03 \, T/10^3) \, N_e$ = Labor manhours per flight cycle (jets and turboprop)

T = Maximum certificated takeoff thrust, including augmentation where applicable and at
sea level, static, standard day conditions (Maximum takeoff equivalent shaft horsepower
at sea level, static, standard day conditions for turboprop).

R_L = Labor rate per man-hour $4.00

N_e = Number of engines

· **Material — Engine** (includes bare engine, engine fuel control, thrust reverser, exhaust nozzle systems and
augmentor systems) (includes gear box, but does **not** include propeller on turboprop engines)

$$C_{am} = \frac{(C_{FH_e} \, t_f + C_{FC_e})}{V_b \, t_b}$$

Where: $C_{FH_e} = 2.5 \, N_e \, (C_e/10^6)$ = Material Cost — $/Flight Hour (For Subsonic Airplanes)

$C_{FC_e} = 2.0 \, N_e \, (C_e/10^5)$ = Material Cost — $/Flight Cycle (For Subsonic Airplanes)

$C_{FH_e} = 4.2 \, N_e \, (C_e/10^5)$ = Material Cost — $/Flight Hour (For Supersonic Airplanes)

$C_{FC_e} = 2.9 \, N_e \, (C_e/10^5)$ = Material Cost — $/Flight Cycle (For Supersonic Airplanes)

N_e = Number of engines

C_e = Cost of one engine

The distribution of the elements in direct operating cost for the recently entering service new technology aircraft can be compared at this point in time with the older generation for a point of reference. The total direct operating cost can be broken into pie segmented graphs and appear below for both an old generation aircraft and a new aircraft type. Engine costs impact the areas of depreciation, insurance, maintenance and fuel and oil. Although not conclusive, because early cost data on the 747 does not show a decernible trend, it appears that engines represent a larger portion of the maintenance costs. The overall maintenance cost is a greater percentage of the total while the fuel and oil represents a smaller segment when compared to the 707 aircraft. More will be said about these major items later.

747
Depreciation
  12.2%

Obsolete Parts
  0.26%

Maintenance
  22.4%

Flying Operations
      65%

Taxes

CREW

OTHER

AIRFRAME C 4%

ENGINE 6.2%

FUEL & OIL 21%

OTHER

INSUR.

707-300
Depreciation
   8.3%

Obsolete Parts
   0.7%

Maintenance
   20.9%

Flying Operations
      70.4%

Taxes

CREW

OTHER

A/E 4.5%

ENG 4%
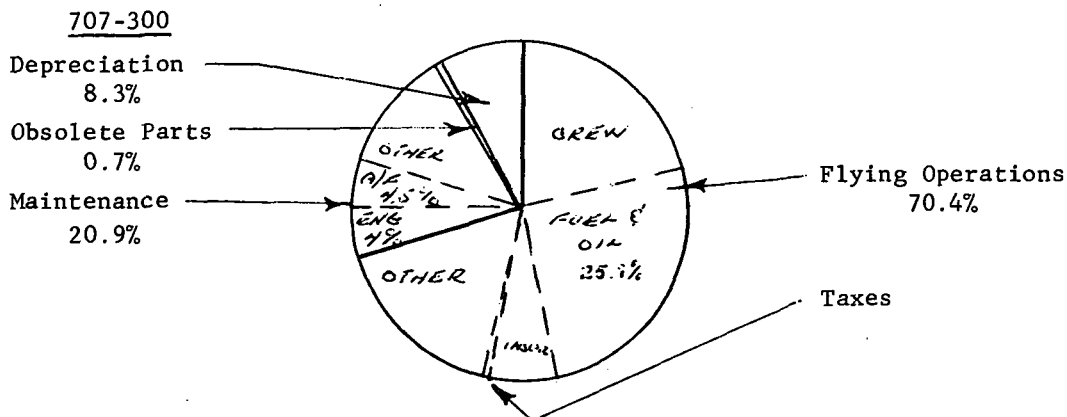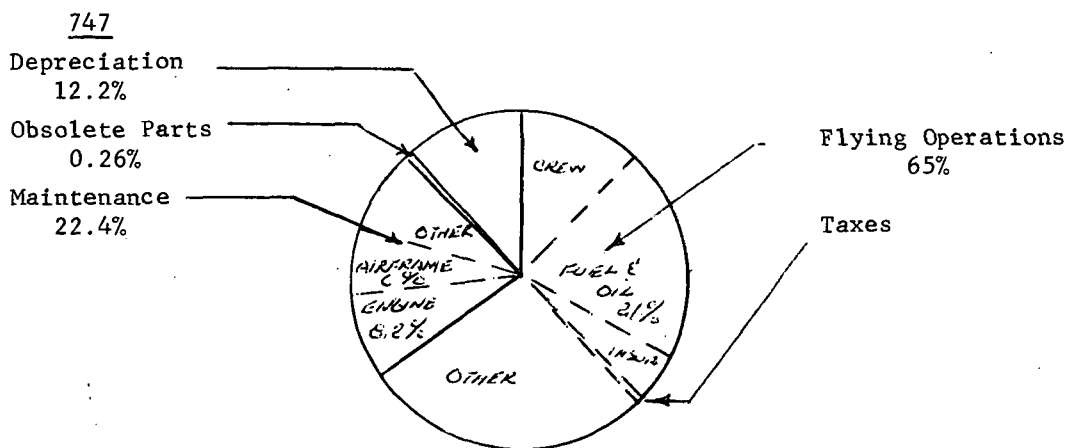
FUEL & OIL 25.5%

OTHER

INSUR.

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Figure 10 is a comparison of actual engine maintenance costs versus the
cost which would be calculated from the listed ATA equations and
shows the divergence of real cost versus ATA projected costs. Indicated
on the figure is the direction costs have taken with advancing technology.
The trend or relationship between projected and actual should be expected.
The elements of any forecast are dependent on fore-knowledge of technology
trends. It can therefore be expected that as advancements in engines are
achieved the cost relationships will not necessarily follow. There is no
attempt here to change the ATA coefficients nor to criticize the methods
outlined. It is the purpose of Figure 10 to acknowledge that ATA cost
relationships should not be relied upon for cost projections.

Figures 11 & 12 show on a relative basis the actual maintenance, material
and labor, costs with reference to turbine inlet temperature without any ad-
justment for engine size, price, or flight cycle. Sufficient parts usage
experience with the highest temperature engine has not been obtained as of this
writing and a reduction in maintenance cost is anticipated. The straight
line suggests the probable relationship based on past experience and it is an
effort to estimate dampened maintenance cycle trends.

Figures 13 & 14 show an indication of current engine prices per pound of
thrust and per pound of weight. The cost of a pound of engine weight and
maintenance as related to thrust to weight (T/W) are covered in
Figures 15 and 16 respectively. While it is apparent that advanced technology
has permitted advancements in engine performance at essentially no change in
basic purchase costs per pound of thrust, in current dollars (also no reduc-
tion in cost per pound of thrust), the effects of technology on maintenance cost
have been quite profound. It should be pointed out that all referenced costs
relate to vehicles with approximately the same utilization.

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It is normal to expect as turbine temperatures increase so will compressor
pressure ratios. The effects that increasing high pressure compressor
pressure ratio have had on compressor maintenance material costs is depicted,
on a relative basis, in Figure 17.

As discussed in the preceding section engine performance deteriorates with
time. Maintenance practices have not recovered this loss in performance
so that over the years of use there has been a gradual accumulation of
SFC losses. The maintenance cost which have been shown here should be
considered as those costs necessary to maintain a mechanically
reliable engine which complies to all manufacturers requirements and
Federal regulations pertaining to engine maintenance. The additional
costs and benefits of maintaining a minimum level of engine specific fuel
consumption performance loss have not been assessed nor can it be with
todays limited information. However it is obvious that if engine specific
fuel consumption were maintained close to the original production level an
increase in material and labor cost would accrue.

Historical maintenance costs variation for several engines are plotted
versus service time in years in Figure 18. The data for each engine have
been normalized on the basis of the first year cost.

Early costs tend to be high due to premature failures and "infant" mortality.
Large portions of these could be avoided or greatly reduced by operating
the engine at a reduced power setting during early introduction. This
management procedure also tends to reduce the demands for early spare engines
and the expenses associated with their purchase. Large portions of first year
expenses may fall within warranty coverage; Although the values shown reflect
actual expenses it must be remembered that warranty recovery credits are
included.

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FIGURE 10

ATA ESTIMATED MAINTENANCE COST
VERSUS
ACTUAL MAINTENANCE COST
(LABOR AND MATERIAL)

Note: Labor rate used in
ATA equation were 1971
rates and flight durations
were from the same time
period.

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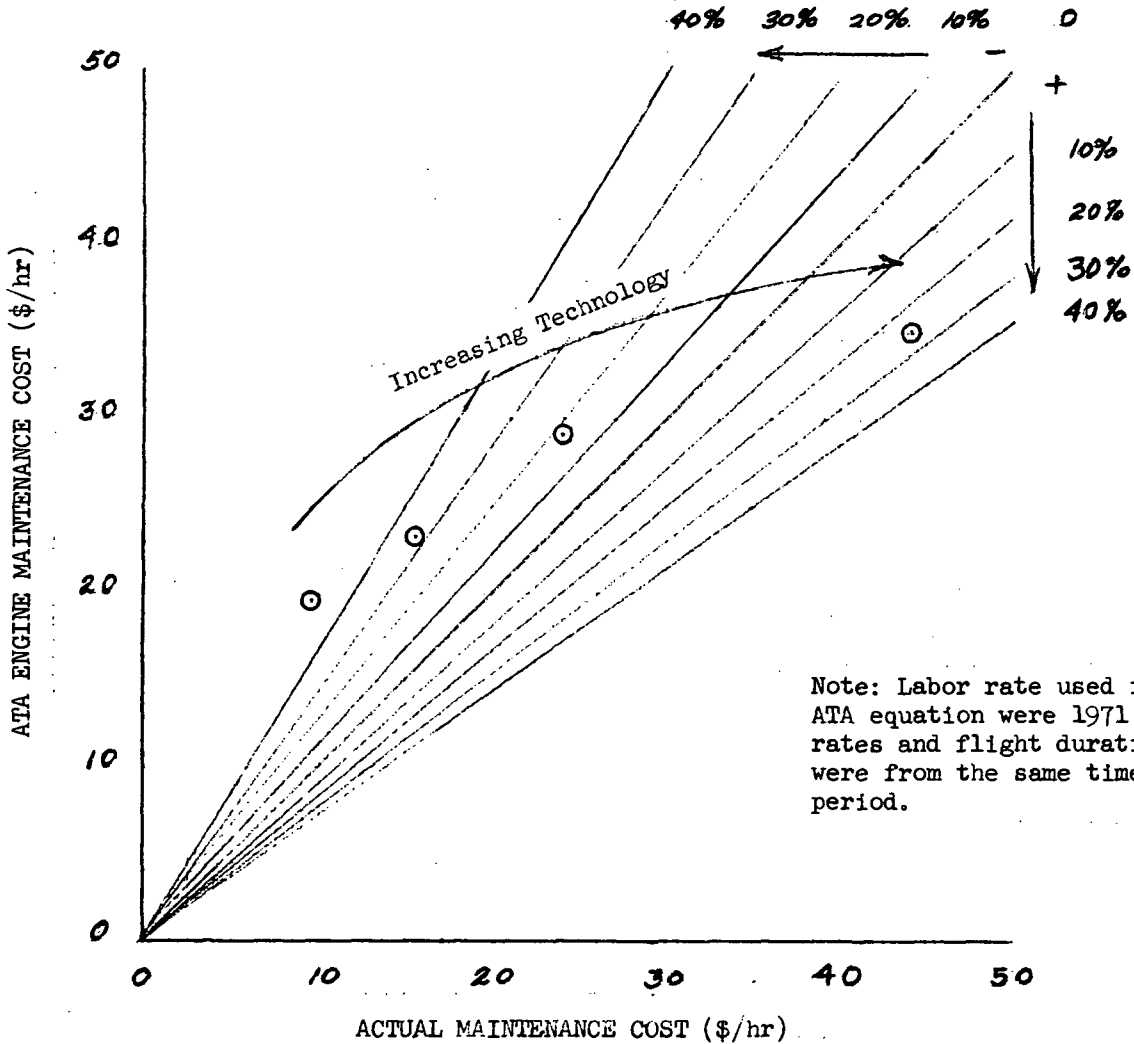
FIGURE 11

RELATIVE MAINTENANCE MATERIAL COSTS
VERSUS
TURBINE INLET TEMPERATURE AT TAKEOFF
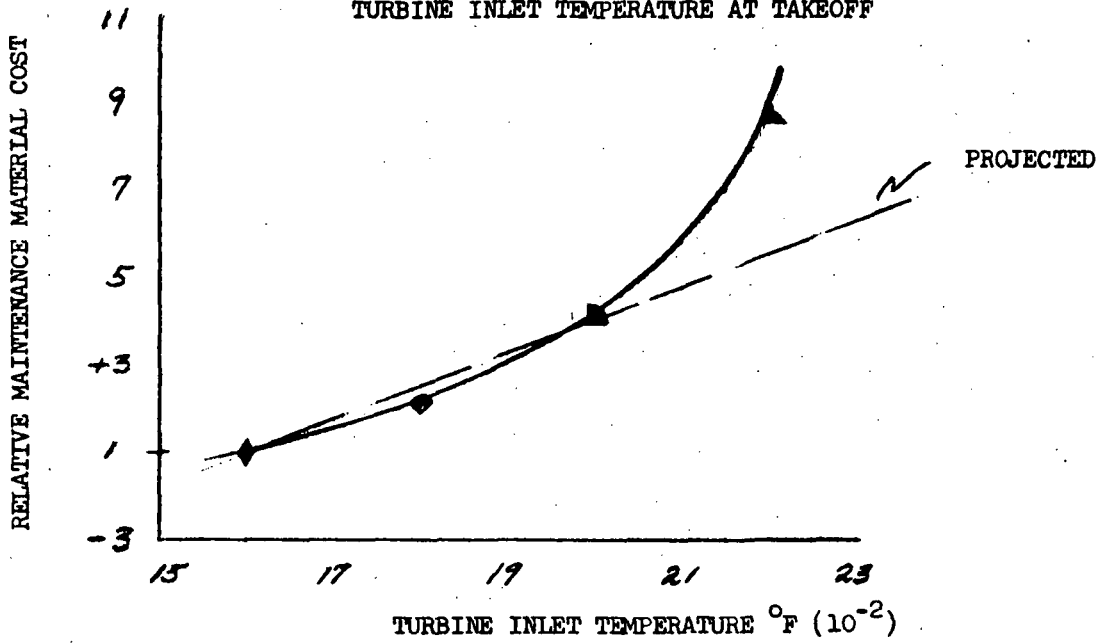
FIGURE 12

RELATIVE MAINTENANCE LABOR COSTS
VERSUS
TURBINE INLET TEMPERATURE AT TAKEOFF

55
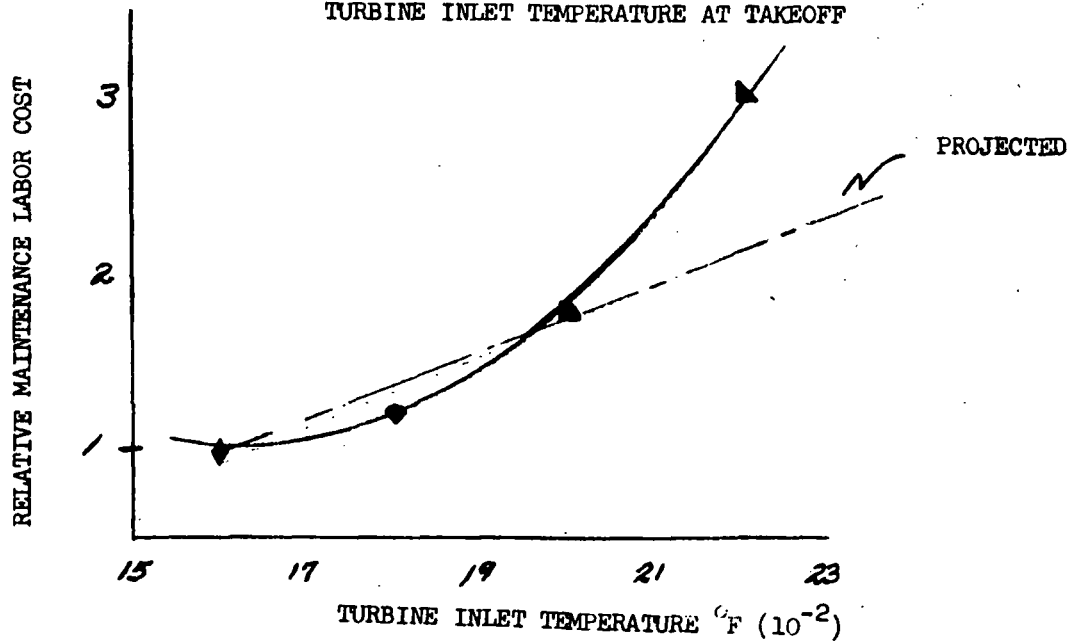
FIGURE 13

ENGINE COST/PRICE IN DOLLARS PER POUND OF
TAKEOFF THRUST VERSUS SEA LEVEL TAKEOFF THRUST

$/lb ENGINE THRUST

THRUST (lb x 10^{-3})
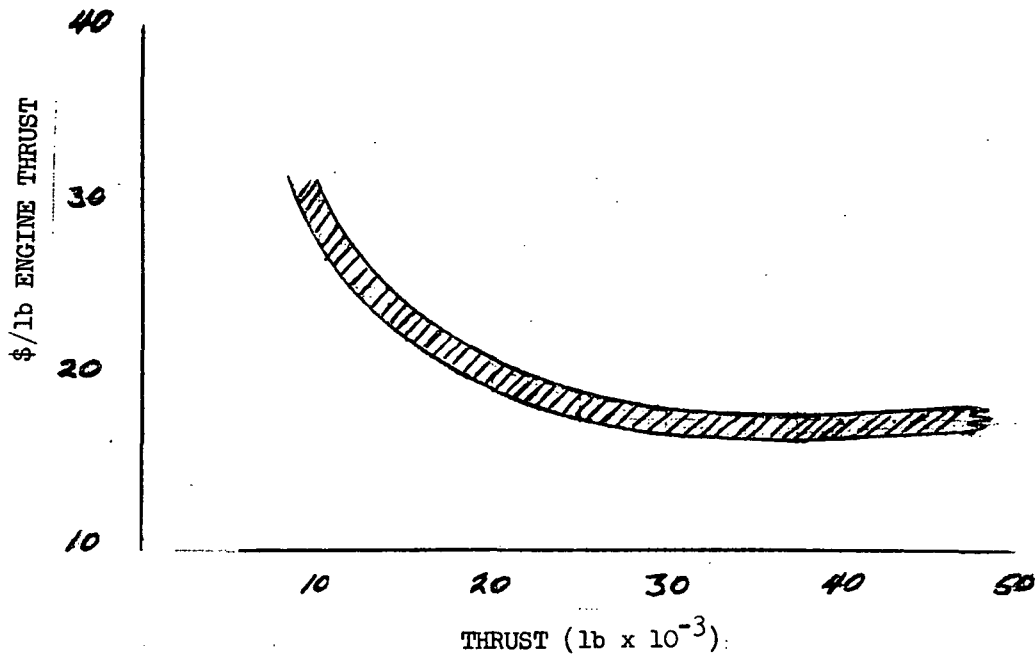
FIGURE 14

ENGINE COST/PRICE IN DOLLARS PER POUND OF
ENGINE WEIGHT VERSUS SEA LEVEL TAKEOFF THRUST

$/lb ENGINE WEIGHT

THRUST (lb x 10^{-3})

56
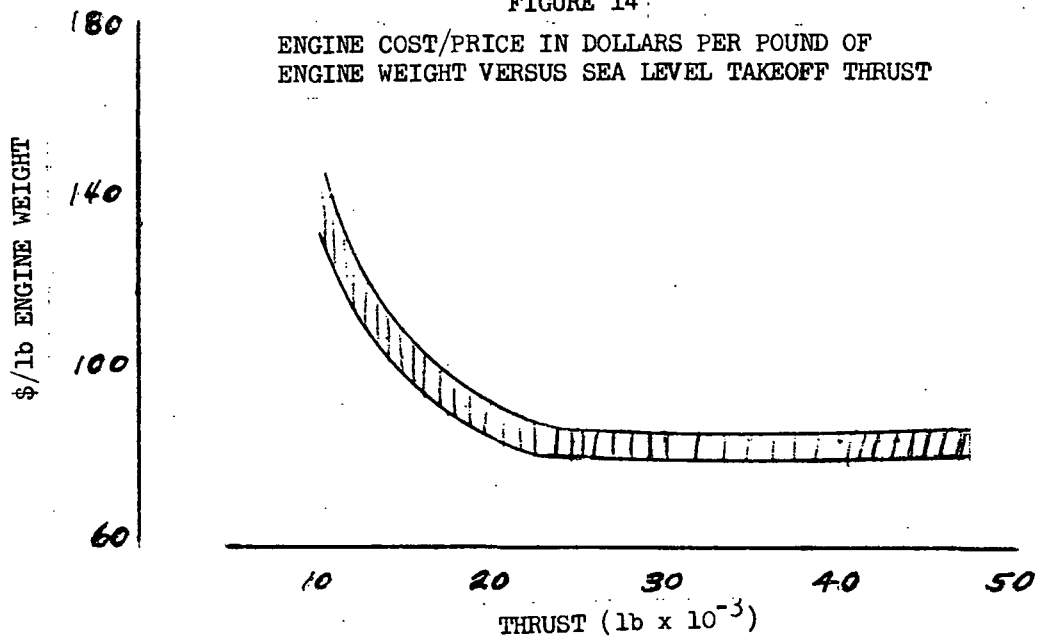
FIGURE 15

ENGINE COST/PRICE
VERSUS
THRUST TO WEIGHT RATIO

$/lb of ENGINE WEIGHT

LOW BYPASS

PROJECTED HIGH BYPASS
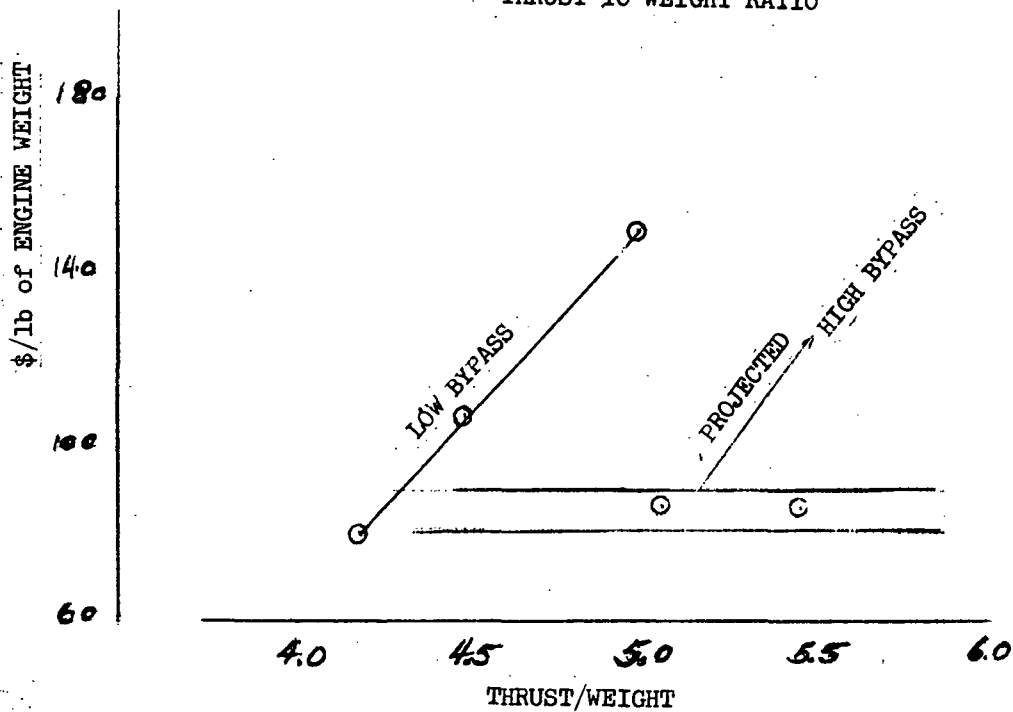
THRUST/WEIGHT

FIGURE 16

RELATIVE ENGINE MAINTENANCE COST
VERSUS
THRUST TO WEIGHT RATIO

RELATIVE MAINTENANCE COST (LABOR & MATERIAL)

MAX.

PROJECTED MIN.

THRUST/WEIGHT

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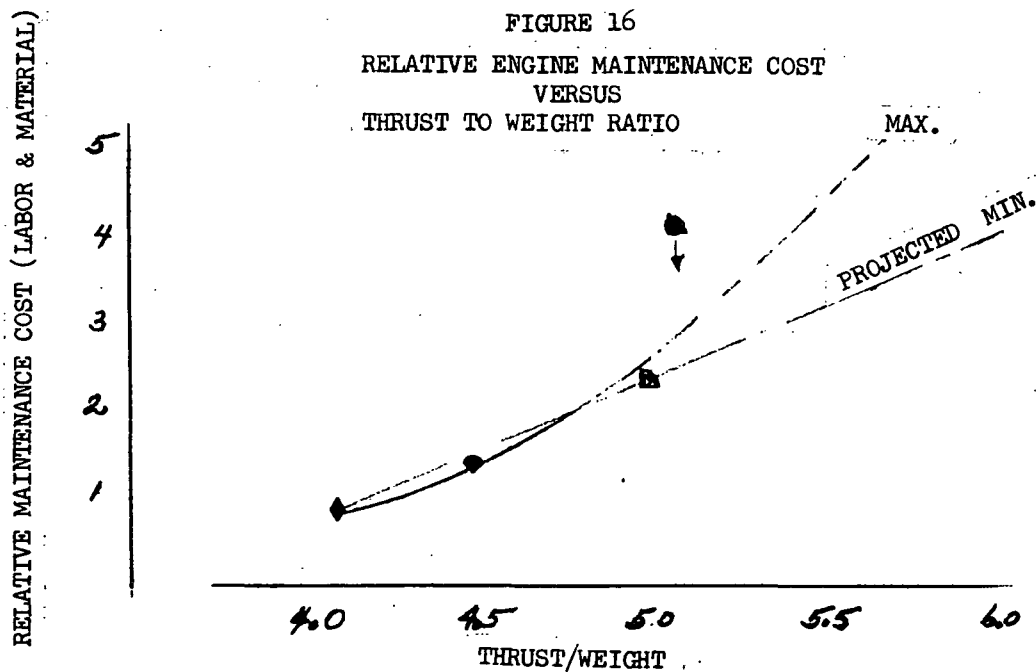
FIGURE 17

RELATIVE HIGH COMPRESSOR MAINTENANCE COST FOR MATERIAL
VERSUS
HIGH COMPRESSOR PRESSURE RATIO

FIGURE 18

RELATIVE MAINTENANCE COST VERSUS
YEARS OF SERVICE FOR SEVERAL
ENGINES NORMALIZED ON THE BASIS
OF THE FIRST YEAR OF SERVICE

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During the second and third year the first round of disk and life limited
parts replacements occurs and unexpected low cycle fatigue problems cause
an increase in maintenance costs. The gradual improvement of the engine
to further life through modification tend to reduce maintenance cost until
the next round of life limited assemblies has to be removed. Again the
capitalized modification costs are not included. Only those costs actually
expensed were reported. Inadequate development is seen in early expenses
for modification to achieve life. The investment for life in the JT3D
has been estimated to be 10% of its purchase cost. The investment for
life in the JT8D was on the order of 30% of the first cost, the JT9D ap-
pears to require much the same level of investment to bring it to a standard
where adequate life is in hand.

2. Alternate Method of Evaluation - A way of looking at the Cost of Performance
   is to proceed with a value added or cost performance benefit accrual from
   technology advancements. To achieve this end, the operation costs of two
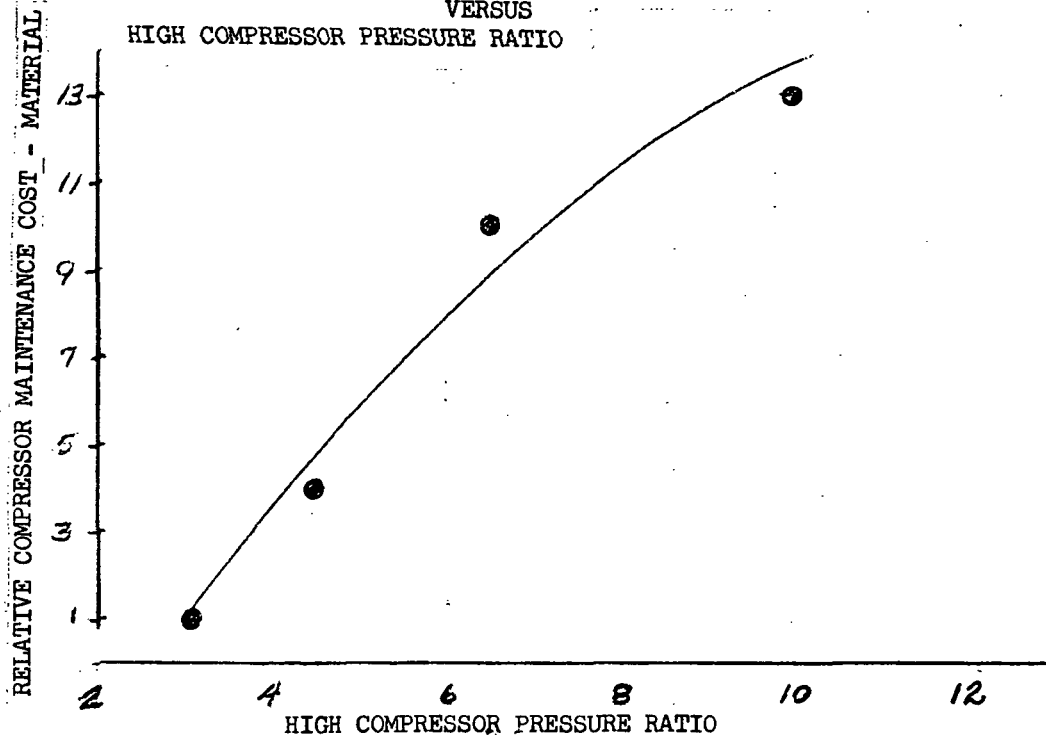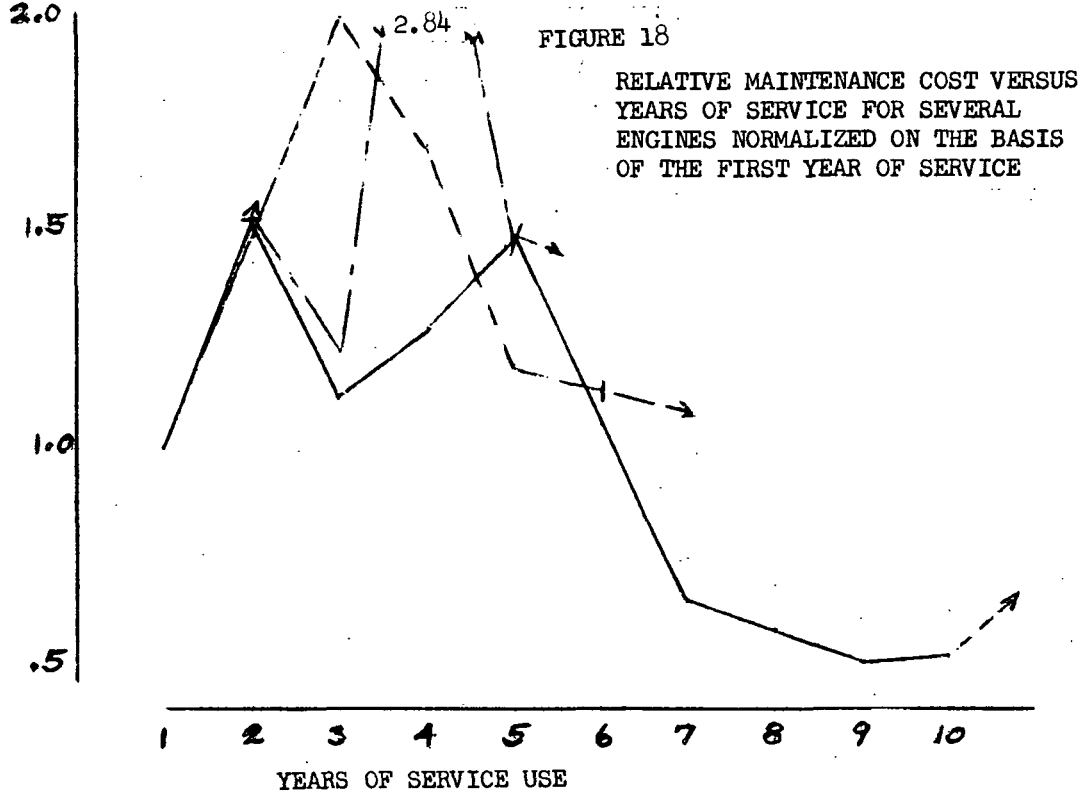   engines, significantly different in technological advancement, were com-
   pared. The major costs were isolated into fuel, material, and depreciation
   categories. Costs were compared for the same time period with cyclic
   effects deflated. For representative cruise conditions the following normal-
   ized costs are found.

	Operating Costs $/Engine - Hour	
	Old Technology Engine	New Technology Engine *
Depreciation	$ 11	$ 32
Fuel	70	115
Material	8	41
Total	$ 89/Eng-Hr.	$188/Eng-Hr.

*This engine has a 20% improvement in SFC reflected in the fuel cost.
Labor costs were eliminated from an initial comparison or relationship
between the two technologies. The labor rate influence at present is on
a three to one basis. Since it is difficult to substantiate this trend,

all comparisons were made with the less volatile cost elements as shown.

All of the costs listed are based on an average annual utilization for actual fleets of aircraft. The new technology engine can be generally described as a larger higher bypass type. The primary or major parameter relating the two engines is thrust. Thrust ratings, in a simple ratio, for both takeoff and cruise can be used as correlation factors. The thrust ratios, as multiples of the Old Technology Engine (OTE) produce expected or projected New Technology Engine (NTE) cost levels. These projected cost levels are $192/Eng.Hr. and $215/Eng.Hr. based upon cruise and takeoff ratios respectively. If the common "square/cube" rule is applied to material and depreciation, while the direct ratio of cruise thrust is used for fuel, a $185/Eng.Hr. can be projected. Based on the aforementioned ratios it can be concluded that a cost level projection from OTE values fall in the neighborhood of from $185 to $192/Eng.Hr. in the absence of labor costs. The costs for the Old Technology Engine and new technology engine are therefore quite comparable.

The specific fuel consumption performance for the ATT engine is not projected to be greatly improved over current high bypass ratio engines. The trend in maintenance and purchase costs with increased technology, are such that very little economic benefit from advanced technology engines can be foreseen unless significant effort is placed on controlling and hopefully reducing these costs in the future.

3. Recommendations - The objectives for the future engines must be improved economics which places greater emphasis on first cost and long term maintenance cost, while maintaining or improving performance consistent with the major objectives of low noise and pollution. There is every indication that the next round of "advanced technology" engine could cost more than

the performance improvement would be worth unless significant attention

is given to the technology of lower cost, longer parts life and high

propulsion system reliability.

Technology Areas of Major Importance

A. Introduction

There are five major areas where the airlines feel that advanced research efforts would prove most productive. These areas are composite materials, advanced reverser systems, component development for long life, compressor and fan stall, and advanced engine control systems. The following discussions are directed at explaining the needs and cost implications and objectives in the areas mentioned above and are specifically applicable to the ATT aircraft. These discussions are factored into the description of the optimum engine as are the discussions of Section I of this report.

B. Composite Materials

The airlines were quite excited by the proposed use of composite material for the fan blades and early stages of the low pressure compressor of the RB211 engine. The material promised many qualities that had the potential of producing real benefits in terms of lower containment weight, lower secondary damage from element failure, possibilities for field repair of minor damage, better stall margin, lighter engine weight and lower engine cost.

1. Advantages - The projected advantages of using composites as proposed were reduced weight due to the low density and high strength properties of the material, and reduced cost due to virtual elimination of component machining. On large fans a low-weight blade means a signficantly lighter disk and blade containment structure. Additional reasons for preferring the composite fan blade were:

a. Better engine handling could be achieved because the low density and high strength of composites permitted a wide-chord (low aspect ratio) fan blade design. Rig tests indicated that such blades would have better surge margin than the narrow-chord blades made necessary by the use of

titanium. This higher surge margin gives an engine with greater flexibility of acceleration and deceleration, and which is less sensitive to engine inlet distortion.

b. Because of its wide chord and greater stiffness the composite fan blades do not need the mid-span shrouds that are required on the narrow-chord titanium fan blade to prevent flutter. The composite fan blade would avoid the loss of efficiency and mechanical, production and maintenance problems associated with mid-span shrouds.

c. Composites, particularly the carbon filament reinforced plastics, have a high degree of internal damping. When subjected to conditions which induce a resonant vibration, the composite blade will vibrate at a much smaller amplitude than a titanium blade and decay rate is higher when the excitation is removed.

d. The composites did not suffer from sudden fatigue failures like titanium and other metals. With an increasing number of stress reversals a gradual reduction in frequency occurs, and this characteristic enabled a simple reliable test to be used as a means of assessing life of a blade during service. Scrapping of blades due to life limits could be reduced.

e. The multi-filament structure of composites is near to "fail-safe." Failure of a fiber in the close-packed matrix results in the transference of the load, which will be shared by the adjacent whole fibers in the region of the break. Mechanical damage such as may be caused by foreign objects would result in the load following alternative paths, without giving rise to the high local stress concentrations which lead to rapid fatigue failure of a metal blade.

f.   The composite fan blades could be repaired to restore the aero-
dynamic form - important to maintain performance in a high by-
pass ratio engine. Erosion or minor ingestion damage to a
blade can be repaired in the field. Depot repairs appeared easier
and to require much less expensive equipment than for titanium
blades.

g.   The projected price for a composite blade would have been less
than a corresponding blade in titanium.

h.   Lastly, if a portion of a composite blade becomes detached, the
fibrous nature of the material would cause far less damage to
the rest of the engine than a similar failure in a titanium
blade.

2.   Unresolved Concerns - While there were many advantages to the composite
material proposed there were unresolved problems. The effects of erosion
both rain and grit, and impact from pebbles and large birds were the areas
of concern. Various forms of protective coatings were investigated as
were the development of leading edge laminates and metalic coverings.
These approaches produced the majority of protection needed but failed to
provide the capability to withstand a large bird strike as required by the
certification requirements without essentially producing a solid metal
blade. The consequential adoption of a titanium blade was required. Blade
retention, another early concern, was satisfactorily resolved early in the
program.

3.   Other Applications - The uses for composites which can be foreseen are in
static structural elements such as fan cases and associated fan ducts, fan
and low pressure compressor blading and in stator blades and exhaust
struts. Opportunities exist for reducing the weight of blade containment
provisions both due to lighter blade weight and from perhaps case winding
for high strength. Further possibilities for application are in the area
of disk burst protection through the application of composites wound

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around the disk to preclude or reduce the consequence of a disk failure. Composites are in use today for aerodynamic fairing and for acoustic treatment, and expanded use in these areas is probable. Perhaps a more dramatic improvement is available from an investigation of the use of composites for nacelle structures such as inlets and cowlings, provided that the cost to produce such components are reasonable. Pylon structure and skins offer additional areas for application with the objective of reducing weight. Information about the use and experience with boron filament reinforced plastics or aluminum is scanty. This material offers similar but not all of the benefits projected for carbon filament based composites. The airlines concern over erosion and foreign object damage effects upon such boron filament materials, as well as repair procedures, must be resolved.

4. Recommendations - The chief objectives for the application of composites in commercial engines in order of priority are:

   a. Improved safety and reduction of the consequences of blade and disk failure.

   b. Lower cost for engine procurement and maintenance.

   c. Lighter engine/propulsion system weight.

C. Improved Reversers Performance

Thrust reverser systems in use today are satisfactory in terms of converting forward thrust into a rearward retarding force. Typically on four engine aircraft the power on the outboard engines must be reduced during the early portion of the landing roll to prevent surging due to hot gas ingestions; and the inboard engines must be reduced later in the roll, typically no lower than 60 knots to prevent foreign object damage and stall from reingestion. The three and two engine powered aircraft also must reduce power to avoid reingestion or foreign object damage between 60 and 80 knots.

Reverser performance can be addressed in many ways and from different points of view. Reverse thrust has not been used to establish aircraft landing distances under the Federal Aviation Administration rules. However, in a real sense the use of reversers to shorten landing distance and reduce runway occupancy time are important as are the improved stopping characteristics in foul weather conditions. The real requirement for reversers are the latter and there are real weight, cost, and maintenance implications for the advantage of having a reverser.

1. Background on Reverser Design & Development - Reversers have been traditionally designed and certified by the aircraft manufacturer. There has been a few notable exceptions in that Pratt & Whitney designed and provided a reverser for one of the DC-8 series of aircraft, and Rolls-Royce for the Spey/BAC 1-11 to name two. The DC-8 reverser was heavy and costly and caused Pratt & Whitney to decline any other such undertaking up until the present. On the positive side however the reverser was quite reliable and trouble free. The same cannot be said for many of the other reversers produced for American manufactured aircraft. The best reverser experience to date has been with the target reverser on the DC-9 and American's experience with the Spey reverser designed by Rolls-Royce for the BAC 1-11 aircraft. Reverser performance is equated by the airlines as cost to maintain a level of reliability with respect to reports of discrepancies, premature removals and aircraft delays.

2. Requirements for Future Reversers - A firm requirement for improved reverser performance in the traditional sense of higher effectiveness does not appear justified for the ATT aircraft. The performance level of current reverser designs under static test conditions are fairly uniform (approximately 40 to 45%) while the actual installed reverser performance recognized is subject to additional factors. Recirculation and engine stall sensitivity have set the lower ground speed boundary at 60 knots or higher for discontinuing the use of reverse thrust. The

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effects of the fan and gas generator flow fields upon wing and flap performance have also effected the actual installed performance of the reverser system. Several factors are important for an ATT type aircraft. The reverser design employed must be integrated into the nozzle assemblies such that a light weight, low noise, low cost, reliable design can be achieved. The design must not contain elements which produce aircraft delays and premature removals as current designs have done. A review of the impact of reversers on aircraft delays and cost for maintenance is provided below as well as a review of 727 reverser problems during a 9 month period to provide emphasis to the requirements stated above. The overall objectives for the performance of a thrust reverser system for the ATT are as follows:

a. The noise levels at maximum reverse thrust shall not exceed the sideline noise limits set for the aircraft under FAR-36.

b. The thrust reverser system shall provide the maximum practicable. reverse thrust force level consistent with safe, efficient aircraft operation, giving full consideration to the need to use reverse thrust at low speed during wet or icy runway conditions and the need for functional check of reverser while static.

c. Consideration shall be given to the use of reverse thrust or partial reverse thrust for controlling aircraft speed and flight path during two-segment approaches for reduced noise. (A tradeoff between the aircraft flap and gear positions required for high angle of descent approaches and the use of lower flap settings and modest reverse thrusts should be made. Additionally the weight increase for quick acting reverser controls and actuation systems including the change in noise radiation pattern within reversers deployed should be studied.)

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d. The reverser system should not cost more than 90 dollars per pound
    of weight and should have a maintenance cost of less than 0.50
    dollars per flight.

e. The reliability of the reverser should be such that the entire system
    produces no more than 0.2 delays per 1000 aircraft departures.

3. Current Reverser Performance Trends - The performance (reliability) of
    current reversers in operation in American's fleet can be listed in
    terms of delays per 1000 departures. The Spey reverser has never been
    a noticeable delay problem during its operation and the reliability has
    been excellent. The Boeing 727 reverser currently produces about 10
    departure delays per month for a rate of .6 per 1000 departures. The in-
    troduction of modifications to this system has signficantly improved its
    performance from that achieved in 1969 and early 1970 to the point where
    the reverser is currently the 5th largest cause for aircraft delays.
    (The 727 reverser is slightly more complex than the Spey reverser but less
    complex than the 707 reverser.) The JT3D Boeing 707 reverser system (core
    and fan reversers) produce an average of 16 delays per month for an average
    rate of 1.8 delays per thousand departures and is ranked 4th highest cause
    for aircraft departure delays. The Boeing 747 reverser currently causes an
    average of 6 delays per month for an average rate of 5 delays per 1000
    departures and normally ranks between first and 4th in the cause for aircraft
    delays. The Boeing 747 reverser is the most complex and newest and its
    mechanical reliability will be improved with time.

    A review of the problems associated with the 727 reverser during the period
    of July 1969 to April 1970 is summarized below to indicate the
    types of problems encountered and the relative cost of maintenance.

a. 727 Reverser Operational Problems

A review of thrust reverser problems as denoted by Pilot Reports and Maintenance Reports for the period between 7-1-69 to 4-12-70 revealed the following problems.

Problem	Qty.	Comments by Maintenance Crews
Unable to unreverse	218	All were pilot report and were corrected by "cleaned and lubed."
Link Bolts Loose*	164	Fleet Base Check - 140 were repaired by "tightened loose nut."
Actuator Fairing - Attach screws missing	137	
Position indicating light "flickers or on in flight"**	67	All corrected by switch adjustment or repairing wiring.
Actuator Fairing Cracked	48	
Broken Links	45	
Deflector Door Damage	11	
Reverser Rig Problem	9	
Directional Valve Leaking	1	
Total Number of Write-ups	700 - 2.5 per day	

Notes:

*   Maintenance Reports
"Off-Set Jam-Nut Loose"	58
"Drive Link Jam-Nut Loose"	23
"Jam Nut Loose"	36
"Link Bearing Worn"	16
"Fwd Link Bolt Support Bracket Loose"	9
"Linkage Loose"	5
"Pivot Bolt Loose"	15
"Deflector Door Attach Nut Loose"	2
	164

Notes (Cont'd):

** "Lite Out"
Loose or
Broken Wires
On T/R Switch

**"Lite on in Flight"
Switch Adjusted or Cleaned

June	2		1
July	2		4
August	4		4
September	2		5
October	3		6
November	2		2
December	3		7
January	3		5
February	2		1
March	1		5
April	1		2
	25		42

b. Maintenance Costs for 727 Reversers

During the calendar year of 1969, the following costs were charged

to the 727 (all types) thrust reversers.

1969 Calendar Year 727/023 and 223: ATA 78

	Material	Labor	Other	Total
Overhaul Depot*	$330,000	$434,000		$764,000
Field	$ 33,000	$ 30,000 60,000 4,000	$ 2,000 21,000	$150,000
Other			$ 6,000 36,000	$ 42,000
Total	$363,000	$528,000	$54,000	$956,000

Unscheduled Costs $145,000

Scheduled Costs   811,000
                  Total $956,000 or $3.97/aircraft hour
                              or $1.45/engine/landing

*Based on 300 shop visits

Note: Replacement of reverser parts is often entirely due to wear
       induced by engine vibration of the reverser in the stowed
       position.

Because of these trends towards higher delays with increasing complexity and the impact that such delays have on aircraft productivity the airlines tend to place heavy emphasis on simplicity. On a relative basis related to the highly reliable Spey reverser, the current cost of JT8D reverser maintenance is more expensive by a factor of 3, the JT3D a factor of 4 and the JT9D a factor of 12. The JT9D reverser is of course suffering normal early problems, nonetheless a factor of 8 in cost is probably representative for the future.

The design concept for the ATT should approach the simplicity of the Convair 990 and DC-9 target reversers. As a last item current reversers are subject to leakage from internal seals which could have serious adverse affects on nacelle drag. Other design requirements beyond those objectives mentioned earlier are described below.

D. General Design Requirements for Future Reverser-Nozzle Systems

1. Exhaust Nozzles -   Nozzle shall be made of corrosion resistant alloys. The exhaust nozzles shall be designed to easily accommodate modest changes in exit areas by trimming, tabbing or extending the exit cone.

2. Noise Suppression Treatment - The exhaust and thrust reverser systems shall be acoustically treated to provide an appropriate portion of the overall, installed engine noise suppression requirement including suppression of the noise in reverse thrust.

3. Thrust Reverser System

    a. The reverser system may be two positional, without modulation except by adjustment of the engine thrust setting.

    b. The system shall be designed to minimize thrust loss and/or specific fuel consumption increase with the reversers in the forward thrust position and shall not cause engine surge, flameout, overspeed, or engine operating condition outside the engine limits while in any position from fully stowed to fully deployed.

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c. Actuation time for the reverser system shall not exceed 2.0 seconds in either direction.

d. As installed on the airplane, the thrust reverser system must provide the maximum deceleration force to the airplane taking into account changes to the airplane drag due to reverser operation. In addition the reverser operation must not cause serious deterioration of airplane control.

e. The reverser effectiveness should be as a minimum 40% of engines gross thrust at sea level static conditions.

f. The reverse effectiveness performance must be maintained at speeds from 120 knots down to 60 knots at maximum continuous power. From 60 knots to static condition the reverser will be left deployed to supply as much additional braking impulse as possible. The contractor will specify the levels of reverse effectiveness and power achievable over this lower speed range without causing flame-out or damage to the engine.

g. Blockers will be required in the reverser system to limit exhaust air impingement on the ground for the wing mounted installation and on the control surfaces for the aft mounted installation. The blocking or redirectional devices must be easily removable and replaceable for Quick Engine Change (QEC) buildup of either wing or tail mounted pods.

h. Normal operation of the thrust reverser system for ground braking shall not result in significant loss of aircraft directional control.

i. The reverser system shall be so constructed that if accidentally deployed at maximum cruise speed or if already deployed and speed is increased to the maximum design dive speed, no serious damage shall occur, after which it shall be capable of being stowed when speed is reduced to 200 knots.

j. The system shall be designed such that no single failure shall result in unintentional operation of the system.

k. Thrust reverser system position indication shall be provided. The system shall provide a signal to energize a light when in reverse and a similar and separate signal showing the reverser is not stowed or in transit. All light(s) shall be out when the reverser system is stowed and latched in the forward thrust position.

l. Means shall be provided to secure the reverser and spoiler in the stowed position, both by use of mechanical latches and by over-centering of the actuating linkages. The latches shall not be affected by failure (false signal, etc.) of the hydraulic or pneumatic selector valves or their operation mechanisms.

m. A means shall also be provided for securing the reverser system in a fixed position for safety of ground personnel during maintenance.

n. Means shall be provided for securing an inoperative reverser in the stowed position while airplane is on the ground to permit dispatch with the reverser inoperative. Means shall be provided for inspection of the "stowed" position of the latches and over-center linkages. The latch inspection means shall be readily visible.

o. The system shall be designed so that, in the event of loss of motive force, the reverser will:

    . While in the reverse position - remain in reverse position

    . While in the forward thrust position - remain in that position

p. The system shall be designed with maximum freedom from asymmetric operation. Where failure can cause asymmetric conditions, the system (including engine mounts) shall be designed to accommodate the resultant loads.

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q. An interlock shall be provided in the reverser control system to limit application of thrust to approximately reverse idle until the reverser is in the reverse position.

r. Ground functional check provisions shall permit operation of reverser without engine operation.

4. Reverser System Control

a. The system on each engine shall be completely independent of the system on other engines for normal operation.

b. The system shall be directly controlled by the engine power lever. The motive power for operation of the system shall be independent of the airplane hydraulic and/or pneumatic systems. Actuation of the system shall not be dependent upon application of the engine power.

c. The system must be designed to provide maximum simplicity. For proper operation every effort shall be made to avoid the need for sequencing mechanisms in the control system.

d. All components required for actuation of the reverser system, e.g., actuators, valves and accumulators, shall be supplied by a single contractor whether or not installed in the nacelle. This does not apply to piping and support bracketry for components installed in the airframe.

e. The system shall include the incorporation of feed-back of position into the control system, which will prevent inadvertent movement of the engine power lever beyond the minimum reverse thrust position unless the reverser buckets are in the reverse thrust position. In addition, if while in reverse thrust the buckets can inadvertently open to forward thrust position, this feedback system or "throttle" interlock shall return the engine thrust level to idle detent thrust.

D. Advantages & Disadvantages of High Performance Components

Engine performance improvements other than those achieved by basic changes to engine cycle characteristics must be derived from performance improvements in component state-of-the-art. Higher stage loadings and work factors, high efficiency levels and annulus flow rates are the traditional approaches to achieving lighter weight, higher performance engines. These improvements have produced the high technology engines of today which have provided improvements in aircraft range and payload. In every visible respect all of these improvements have been worthwhile, however, they have been achieved at a price. Continued pursuit of the traditional path for component research is worthwhile but an additional dimension should be considered. This dimension for lack of a better word is realism. From the following review there are indications that as technology has improved the sensitivity of component performance to small changes in mechanical condition has increased, and further the dependence of the overall engines performance on retaining the high efficiency of each components has equally increased. The loss of 1% in compressor efficiency has a modest effect on a JT3D and a more serious effect on the JT9D. The effects of blade tip clearances on the JT3D do not appear to be as signficant as they are on high bypass engines.

The majority, if not all, of component performance development done by manufacturers and government agencies is undertaken using new parts and is conducted over a relatively short period of actual component running time. Historically there has been little information obtained on the effects of variation in blade surface condition, variation in blade leading and trailing edge contours and variation in blade tip or seal clearances. The experience that is gained in the development process is normally only recorded for use on a temporary basis to determine the course of action for subsequent testing to improve component performance.

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The efficiency of every component is affected by clearances, contours, leakages, and surface conditions and the ability to maintain these mechanical conditions is not adequately considered in the design process. There are practical constraints to the ability of even a sophisticated repair facility to maintain shapes, fits and clearances to higher standards than currently employed. The costs for maintaining improved levels of contour, fit and tolerance control have never been assessed. The costs of not maintaining such control is apparent in the more rapid deterioration of higher performance engines. It is apparent that each new technology component is requiring a level of control greater than its predecessor and this control may not be achievable in practice.

1. Influence/Fault Coefficients - The airlines have used influence/fault coefficients as an aid to determine the cause of measured performance changes in both in-service and overhauled engines. Influence coefficients are determined by artifically changing a component performance parameter by one percent and calculating the effects of such a change on other components measured performance parameters (i.e. a change in the low pressure efficiency by one percent changes the fuel flow, exhaust gas temperature, rotor speeds, pressure ratios, etc.). Influence coefficients are helpful in understanding the relative importance that each component parameter plays in the overall performance of an engine. There are several factors however that are important and have hampered the usefulness of influence coefficient for determining the source of performance deterioration.

    a. The first factor is that rarely has a single component caused the shift in performance measured. Normally several components are responsible and the influence of one component masks or distorts the effects of another. To provide a basis to distinguish the component or component most probably responsible for the major portion of the shift in performance, a computer program has been utilized which identifies

the most likely component in descending order of probability. Additional techniques are currently being developed to iterate the performance, using a computer model, of an average production engine until the performance duplicates the actual engine under test. By comparing the production standard versus the data for the engine under test a complete analysis of the location(s) of the deficiencies can be established at the major component level.

b. The second factor that prevents full utilization of these techniques is even though the problem components may have been identified, there is little information on what must be done to restore the performance. To undertake restoring the component's performance the sensitivity to roughness, clearance, shapes, etc. individually and in combination needs to be understood. Lacking this information, economical repairs have been identified only by trial and error. The replacement of worn parts with an all new component or parts is too expensive to be warranted except in the case of engine stall.

c. Lastly the ability to instrument engines beyond the level of instrumentation normally required for engine operation is extremely difficult. Access ports for pressure and temperature instrumentation have not been provided until the most recent high bypass engines. The performance improvements achieved by a given rework to a specific component are therefore difficult to assess

2. <u>Changes in Influence/Fault Coefficients with Advancing Technology</u> - Figures 19 through 23 are the influence/fault coefficients for current engines. A complete review of these figures will not be presented but characteristic trends with changes in technology are discussed which are pertinent to research on advanced components.

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Figure 19

Fault Coefficients at T.O. Power

JT3D

Component Fault	Magnitude of Change%	JT3D Coefficients					
		N2 %	EGT %	N1 %	Wf %	P_{s3} %	P_{s4} %
L.P. Compressor Eff	-1	+0.2823	+0.5755	-0.2308	+0.4997	-0.2872	-0.1138
H.P. Compressor Eff	-1	-0.6701	+0.3438	-0.0718	+0.3402	+0.5133	-0.0379
L.P. Turbine Eff	-1	+0.1900	+1.0400	-0.3000	+1.1600	-0.8700	-0.1400
H.P. Turbine Eff	-1	-0.7200	+0.3400	-0.0800	+0.3200	+0.5400	-0.1800
H.P. Turb Area to Large	+1	-0.4000	+0.2200	+0.0100	+0.3600	+0.3600	-0.9000
H.P. Turb Area to Small	-1	+0.4500	-0.0400	+0.1000	+0.1300	-0.1800	+1.2900
L.P. Turb Area to Large	+1	+0.8100	+0.4200	-0.1500	+0.4800	-1.1600	+0.0500
L.P. Turb Area to Small	-1	-0.8900	-0.1900	+0.0800	-0.2000	+1.0200	-0.1000
Fan Eff	-1	+0.0646	+0.1918	-0.1179	+0.3579	-0.3178	-0.0742
Combustion Eff	-1	+0.0000	+0.0000	+0.0000	+1.0000	+0.0000	+0.0000

Figure 20

Fault Coefficients at T.O. Power

JT8D

Component Fault	Magnitude of Change%	JT8D Coefficients					
		N2 %	EGT %	N1 %	Wf %	P_{s3} %	P_{s4} %
L.P. Compressor Eff	-1	+0.2666	+0.6333	-0.2666	+0.4000	-0.2000	+0.0666
H.P. Compressor Eff	-1	-1.1333	+0.4333	-0.2333	+0.3333	1.7666	-0.0666
L.P. Turbine Eff	-1	+0.2666	+0.8000	-0.3666	+0.7333	-0.1333	-0.4000
H.P. Turbine Eff	-1	-1.5666	+0.6666	-0.3333	+0.7666	+1.1000	-0.2000
H.P. Turb Area to Large	+1	-0.2000	+0.1333	+0.0000	+0.3666	+0.0000	-0.9333
H.P. Turb Area to Small	-1	+0.2000	-0.1333	+0.0000	-0.3666	+0.0000	+0.9333
L.P. Turb Area to Large	+1	-0.4000	+0.5000	-0.1333	+0.3000	-0.8000	+0.1666
L.P. Turb Area to Small	-1	-0.4000	-0.5000	+0.1333	-0.3000	+0.8000	-0.1666
H.P. Comp Air to F.D.	+1	+0.1333	+1.5000	-0.1666	+1.6666	-0.3000	-0.6333
8th Stg Air to F.D.	-1	-0.1000	+1.3000	-0.0333	+0.6000	-1.2000	-0.3333
6th Stg Air to F.D.	-1	+0.2666	+1.2666	+0.0000	+0.7333	-2.6666	-0.3333
Dirty N2 Comp.	-1	+0.7000	+0.3500	+0.3700	+1.0000	+0.0000	+0.8300
Fan Eff	-1	+0.1000	+0.1666	-0.1333	+0.3333	-0.2666	-0.0666
Combustion Eff	-1	+0.0000	+0.0000	+0.0000	+0.0000	+0.0000	+0.0000

Figure 21

Fault Coefficients at T.O. Power

SPEY

Component Fault	Magnitude of Change%	Spey Coefficients					
		N2 %	EGT %	N1 %	Wf %	P_{T2} %	P_{s3} %
L.P. Compressor Eff	-1	+0.2900	+0.3500	-0.2000	+0.6400	-0.1200	+0.2900
H.P. Compressor Eff	-1	-0.5800	+0.9600	-0.2600	+0.8700	+0.1400	-0.4100
L.P. Turbine Eff	-1	+0.0600	+0.3700	-0.2200	+0.5300	-0.1400	+0.1500
H.P. Turbine Eff	-1	-0.6800	+1.2500	-0.2900	+1.0000	+0.1400	-0.5800
H.P. Turb Area to Large	+1	-0.2300	+0.2500	-0.0800	+0.2500	+0.0700	-0.9200
H.P. Turb Area to Small	-1	+0.2300	-0.3300	+0.0900	-0.1700	+0.0000	+1.1000
L.P. Turb Area to Large	+1	+0.2800	-0.1400	-0.0430	+0.0000	-0.1200	+0.3000
L.P. Turb Area to Small	-1	-0.2300	+0.1200	+0.0200	+0.0000	+0.1500	-0.2500
Bleed Valve Open	+4	+1.0300	+2.4900	-0.7900	+2.7500	+0.1400	-1.1600
L.P. Comp Air Flow Capacity Down	-1	+0.1200	+0.2200	+0.7900	+0.4400	-0.0200	+0.1800
H.P. Comp Air Flow Capacity Down	-1	+0.6400	+0.1400	-0.0600	-0.1500	+0.1000	+0.0600
L.P. Comp Air O/B	+1	+0.3000	+0.4400	+0.8200	+0.6800	-0.3000	+0.2300
H.P. Comp Air to F.D.	+1	-0.0100	+0.9000	-0.3000	+1.0400	+0.0800	-0.5200
Combustion Eff	-1	+0.0000	+0.0000	+0.0000	+1.0200	+0.0000	+0.0000

Figure 22

Fault Coefficients at T.O. Power

JT9D

Component Fault	Magnitude of Change%	$\% \Delta w_f'$	$\% \Delta N_i$	$\% \Delta N_2$	$\% \Delta P_3/P_2$	$\% \Delta P_{t/3}$	ΔT_{c6} °F	ΔT_{t7} °F
Fan Eff	-1	0.24	-0.22	0.06	-0.48	0.47	2.5	2.5
L.P. Compressor Eff	-1	0.16	-0.10	0.13	-0.09	0.07	4.5	4.0
H.P. Compressor Eff	-1	0.85	0.01	-0.30	0.67	-0.81	14.5	12.5
H.P. Turbine Eff	-1	0.86	0.02	-0.41	0.84	-1.20	15.0	12.5
L.P. Turbine Eff	-1	-0.10	-0.41	0.06	-0.83	0.61	0.0	5.5
H.P. Turbine Area	+1	0.14	0.01	-0.12	0.11	-1.07	2.5	2.0
L.P. Turbine Area	+1	-0.52	-0.44	0.35	-1.37	-1.39	-7.5	-0.5
Core Nozzle Area	+1	1.66	0.63	0.22	0.70	0.39	10.0	4.0
Fan Nozzle Area	+1	-0.08	0.11	-0.02	0.24	-0.21	-1.0	1.0
VSV Open	1°	-0.20	0.0	-0.50	-0.15	0.20	-3.5	-3.0

Figure 23

Fault Coefficients at T.O. Power

CF-6

Component Fault	Δ	% ΔF_n	% ΔN_2	% ΔW_f	% ΔEGT	% ΔP_s	% ΔT_3
Fan Eff	-1	+ .21	+ .22	+1.02	+ .42	+ .69	+ .19
H.P. Compressor Eff	-1	+ .11	- .36	+1.0	+1.45	- .31	+ .53
H.P. Turbine Eff	-1	+ .18	+ .2	+1.07	+ .48	+ .62	+ .16
L.P. Turbine Eff	-1	+ .13	- .42	+1.15	+1.64	- .48	- .13
Combustor Eff	-1	0	0	+1.06	0	0	0
Fan Nozzle Area	-1	+ .46	+ .14	+ .87	+ .27	+ .69	+ .18
Core Nozzle Area	-1	+ .21	+ .07	+ .35	+ .16	+ .20	NEG
Fan Air Flow	-1	-1.78	- .41	-2.13	- .76	-1.55	- .42
Core Air Flow	-1	0	+ .40	0	0	0	0
VSV Closed	-1$^\delta$	0	+ .40	0	0	0	0
Combustor ΔP	+1	+ .06	- .14	+ .51	+ .72	+1.01	+ .19
H.P. Turb Area	-1	- .02	+ .11	- .17	+ .26	+1.13	+ .31
L.P. Turb Area	-1	- .01	- .34	NEG	+ .57	- .61	- .17

Control Parameter = N_1 = Constant

a. Fan efficiency loss is not relatively as important in terms of
    advanced engine performance as are other components. Stall sensi-
    tivity and airflow retention are however extremely important. The
    effects of leading edge shape and surface roughness on fan airflow
    have not been documented. The performance of advanced blading of
    the multiple circular arc design after erosion by normal use and the
    effects of leading edge removal of up to 0.5 inches of the chord must
    be assessed. The performance of the fan in terms of noise may also
    be affected by normal deterioration and maintenance practices. It
    can be assumed that for large fan engines of the future fan efficiency
    retention will not be relatively more important than it is today.

b. Low pressure compressor performance has considerably more impact on
    the overall engine performance of early turbofan engines than of the
    new high bypass types. What is significant is the fact that low
    compressors are easier to remove and maintain than high compressors.
    It is assumed that low compressor blade tip clearances have little
    effect on flow capacity or efficiency and that surface roughness is
    equally less important in the newer engines. The effect of increased
    tip clearances and surface roughness on low pressure compressor stall
    margins is probably small; however, the importance of L.P. compressor
    condition on H.P. compressor stall margin performance is unknown.
    The knowledge about these factors is unsatisfactory.

c. As technology has progressed the pressure ratio of high pressure com-
    pressor components has been increased while maintaining a high level
    of efficiency. To accomplish these advances improved blading and
    variable vanes have been employed as well as closer control of seal
    and tip clearances, leakages and secondary flow. The sizes of air-
    foils have decreased slightly and there are more noticeable Reynolds No.
    effects on overall performance. The effects of the loss of high

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pressure compressor efficiency is becoming more pronounced in terms of overall engine performance. Clearance limits on older high compressor blades nominally run plus or minus .010 inches (.060 to .080) and replacement limits .015 inches greater clearance than the largest tolerance value (.095). On newer engines however the effect of a change of .010 inches in tip clearance can cost 1% in efficiency and 1% in specific fuel consumption and serious loss of stall margin. Economic means to recover high pressure compressor blades from serious effects of erosion have not been developed. The high pressure compressor for the future engines will be targeted for a minimum of 90% polytropic stage efficiency. Therefore great care must be exercised in the design of advanced compressors, and increases in efficiency and pressure ratio beyond those levels in use today should not be undertaken without a better understanding of the ability to economically maintain the performance achieved. The effects of usage on high compressor stall margin is causing considerable concern today particularly for the more modern engine.

d. The presence of a loss of combustor efficiency or change in pressure drop are extremely difficult to determine. The combustor chamber pressure drop has been increased on several engines from when delivered by modifications to improve burner durability. The main effect discovered to date concerning combustor deterioration has been shifts in temperature profile. These shifts can affect blade life and gives an artificial indication of loss of SFC. However, knowing what to do about the condition is something entirely different, as is knowing precisely what design or mechanical feature is causing the loss.

e. Just as with compressors the blading of turbines change due to erosion, corrosion and contamination during operation too. There are three predominant causes for performance loss surface roughness, loss of seal clearances and changes in turbine blade tip clearances. The relative importance of HP turbine efficiency increases with pressure ratio and technology. The method of re-introducing cooling air into the main stream is also extremely important. The effects of first turbine blade erosion on the JT3D has been measured at 0.3% increase in SFC. The effects of .031 increase in tip clearance was a 1.2% increase in SFC or roughly .4% per 0.10 inches. The effects of first turbine blade roughness on the high bypass engines have not been determined but the effect of a .010 inches increase in tip clearance is nominally a 0.7% loss of SFC and a similar loss in low pressure compressor stall margin.

The effects of seal clearance deterioration depends obviously on the increased flow rate through the seal and where the flow goes. The smaller the seal diameter the less sensitive it is in terms of overall performance. High pressure seal clearance control in the HP turbine area however have the greatest effects on performance.

3. Conclusion - In summary as components and engines have been improved the performance effects of small differences in mechanical condition have increased. There is little advantage to advanced components if there per-

formance cannot be maintained at a realistic cost. There has been a

general lack of definitive data provided in the entire area of per-

formance retention such that the airlines have had to develop much of

the data in use today. This situation is not expected to improve unless

serious research is undertaken into the effects of aging. The only

recourse available to the airlines at the moment is to insist that the

technology programs for the future contain the requirement to determine

the effects of aging and to require engine manufacturers to guarantee the

performance of their product to be good for extended periods, such as

4000 hours. The ATT engine could have higher pressure ratios, higher

temperatures, etc. but if the performance degrades rapidly or depends

on non-maintainable design features of what value are the advances? It

would certainly be an improvement if the most sensitive components were

the most accessible components. A highly critical high compressor is

the way to economic disaster for the airlines.

E. Cost Impact of Compressor Stall Sensitivity

Compressor and fan flow instability with distortion is a prime example of an

area of technology that requires additional effort. Many military engine

programs and commercial engine programs have had significant delays or in-

creased development costs solely attributable to compressor stall. The in-

troduction of the Boeing 747 was marred by three incidents of engine stall at

idle power during the first few days of service. Only a brief review of the

costs of engine stall on a series of commercial engines is included below. The

requirement for any new engine for commercial aircraft is that it shall not

stall (unless the engine has experienced a failure). Engine manufacturers

must guarantee that the engine as installed will not stall during any opera-

ting mode of the aircraft whether normal or abnormal. <u>Engine stall is too ex-

pensive to be tolerated</u>.

1. <u>JT3D</u> - In 1965, American Airlines experienced an off-idle stall problem that was considered associated with deteriorated high compressor blades which had an average total operating time of 12,000 hours. At that time, most of the engines involved were of the 9th stage bleed configuration, and the only known way to regain stall margin was to buy new compressor blades. This was done at a cost of $1.14 million. The 9th stage bleed configuration stall margin did improve, but not enough. In 1967, P&W offered a further improvement in off-idle stall margin with a 12th stage bleed configuration. American Airlines elected to incorporate the Mod at a cost of $2.68 million. This has virtually eliminated the off-idle stall problem.

    However, another type of stall is being encountered today - high altitude decel stall. This problem results from the opening up of first stage nozzle guide vane area as time between major repair on turbines is increased. The increased area cause the high compressor to slow down and the low compressor to speed up. During a decel, the N1 maintains a higher speed longer due to its greater mass. When the mismatch is great enough, the stall occurs. On the average, eighteen engines are removed for this cause each year and the test cell performance program rejects an additional 12/year which would stall when put on an aircraft. This results in an annual cost to American Airlines of $170,000.

2. <u>JT8D</u> - The major stall problem on the JT8D occurs at high power and particularly in the No. 2 position on the 727 aircraft. The average time on the engines is approximately 10,000 hours, during which a significant amount of hardware deterioration has taken place resulting in reduced stall margin. On the average, two engines a month are removed for this cause with a cost impact estimated to be $43,800/year. The cost impact would be

much higher except it is known that an engine that stalls in the No. 2 position will operate satisfactorily in a No. 1 or 3 position. A computer program has been developed which predicts those engines that would stall in the No. 2 position so those engines are restricted to an outboard position. Based on January production, American could expect an additional 4 engine removals per month if this program was not in effect. This would bring the annual cost to $131,000/year.

As of this time the airlines do not know where to spend their money to recover the stall margin. However, American is currently accomplishing a series of "Bills-of-Work" to an engine out of which it is hoped can be determined the action required. The testing program will cost roughly $50,000.

3. JT9D - The JT9D has a basic compressor instability problem with susceptibility to stall in crosswind conditions and reversing operations. There is also a long history of inflight flame outs. Costs attributable to these problems have reached $1.5-2.0 million since beginning of AA operation. These costs are based on the average repair cost of engines removed for stall and overtemp. It is estimated that an additional $1.3 million will be required for upgrade modifications to finally correct the problem. However, the effects of erosion and deterioration in general remain unknowns. The costs borne to date or planned represent in excess of 5% of the total price paid for all of the JT9D engines American procured .

4. Conclusions - It is probable that if all American's records were reviewed that engine stall has cost American in excess of 8 million dollars. The cost to the U.S. airlines for engine stall is reasonably estimated to be in the neighborhood of 80 million dollars. Several factors should be considered as goals for future engines.

   a. A complete understanding of the effects of erosion on compressor blading and stall margin needs to be achieved.

b. Economical means for the recovery of compressor stall margin must be developed as well as general performance recovery maintenance procedures and practices.

c. Design guidelines must be developed which provide the compressor designer with information which will permit a new design to be compatible with a and b above.

d. Compressor instability under normal operating procedures during early introduction of an aircraft must not be allowed.

F. Basic Requirements for an Advanced Technology Transport Aircraft Engine Control System

The complexity of engine fuel control systems have increased markedly with the passage of time. The introduction of high bypass ratio engines have added further complexities not only to the control system but in terms of engine rating systems and power management procedures. The desire for auto-throttle systems for use with advanced autoland systems has added additional requirements which cannot be optimumly accomplished with current or projected hydromechanical controls. The poorer acceleration characteristics of high bypass engines have required multiple idle settings, and altitude deceleration stall characteristics as well as avoidance of thermal shock during deceleration have required additional fuel scheduling features. These complexities when added to the higher thrust lapse rates of high bypass engines have produced thrust setting procedures which require significantly higher workloads for the crew. To avoid the constant referral to tables or hand held calculators the development of TAD-EPR computers which displays the proper power setting value was undertaken and these computers are in use.

Perhaps the largest single problem with current controls is associated with the inability to compensate for non-standard altitude - temperature lapse

rates particularly during climb. Because high bypass engines have a higher altitude and speed thrust lapse rate the aircraft becomes climb thrust critical. The inability of the control to independently correct and maintain the proper thrust level with differences in temperature lapse rate requires a re-adjustment of climb power every few thousand feet during climb. Very often it is possible to over boost the engine during climb due to rapid changes in speed, temperature lapse rate etc. As a result of these current control limitations an additional annual cost on the order of 1/2 to 1 percent for fuel and an estimated 25 to 33% for engine material parts cost has already been encountered. The airlines requirement for the ATT engine is for an advanced control beyond the capabilities of current hydromechanical controls.

1. <u>Objectives for Engine Controls Systems</u> - It should be possible for the pilot to establish a given power setting and have the engine control system maintain that setting regardless of aircraft speed, altitude, or attitude. In addition, the engine control system should be capable of providing sufficient engine fuel to meet all engine design and operation criteria, i.e., start, accelerate, decelerate, and shut down, without incurring unnecessary engine hardware distress or operating malfunction.

   To achieve this control, the fuel control system needs several of the following signal inputs:

       a. All Engine Rotor Speeds
       b. Ambient Air Pressure and Temperature
       c. Core Engine Compressor Discharge Pressures
       d. Engine Pressure Ratio
       e. Core Engine Discharge Pressure (P_b)
       f. Core Engine Turbine Inlet or Exhaust Gas Temperature
       g. Power Lever Position Input

   The preferred basic signal reference for the control system would be core engine speed modulated by the other parameters to achieve the constant speed requirements at each preselected power lever position.

To achieve the desired accuracy of speed control necessary to permit uniform and symmetrical thrust, maximum fuel economy and maximum engine parts utilization, it is essential engine speeds be controlled accurately and synchronized to within $\pm$ 0.2% between engines and to within $\pm$ 0.2% of the set parameter. This is not feasible with current hydromechanical fuel controls and it is necessary to add on such items as auto-throttle computing system at approximately $45,000/aircraft and an automatic engine trim system at $30,000/aircraft.

2. Design Requirement - The ideal engine control system should contain the following features:

   a. Central Computer

   1) An automatic thrust rating computer system incorporating the ability to preset, select and maintain a selected number of power control modes (takeoff, maximum climb, maximum cruise as a minimum).

   2) The ability to select, synchronize and maintain all engines to within $\pm$ 0.2% of the selected thrust setting parameter (N1 for large bypass fan engine; EPR or equivalent for pure jet engines) regardless of aircraft speed, altitude or attitude.

   3) The provision/capability to maintain constant aircraft speed as the prime parameter.

   b. Engine Control

   In addition to the normal control functions the following should be provided.

   1) The engine control system should have the ability to automatically trim individual engines $\pm$ 5% to achieve the desired power setting. Outside of this range, the system should incorporate a failure warning device to indicate engine control system malfunction.

2) The engine control system should be designed such that air is easily purged from the system without the use of additional systems or components. The introduction of air into the system should be precluded except as a result of fuel tanks either becoming depleted of fuel or the opening of a fuel supply line.

3) The engine control system should be packaged as a modular assembly permitting either the changing and checkout of the total system or any specific major module, i.e., pump, fuel control, electronic control package, etc. In addition, any portion of the engine control system shall be readily accessible with the engine cowls open and component or system change times of not more than 1 hour duration shall be easily accomplished.

4) The engine control system should incorporate a separately manually operated fuel cut-off device or system between the control function and the fuel distribution manifold.

c. Reliability

Reliability goals for the control system should not be less than 30,000 hours MTBF*and 25,000 hours MTBUR** In addition, the reliability of the system should not rely on such items as critical torque settings for electrical connectors, etc.

d. Self Test

The correct functioning of any portion of the electronic system shall be capable of either being checked out using built-in test equipment or pre-programmed ground support test equipment.

* Mean time between failure
**Mean time between unscheduled removal

Evaluation of Phase I Advanced Transport*
Technology Engine Study Contractor Reports

The following recommendations and conclusions are based on an assessment of

the oral and written reports presented by General Electric and Pratt & Whitney

in accordance with Contract NAS3-15544 and NAS3-15550 respectively. A critique

of both contractors reports is provided in detail in subsequent paragraphs of

this report. The first section is addressed to the general conclusions and recom-

mendations which are drawn from both reports. The criticisms included herein are

intended to provide an airline perspective on the requirements for future power

plants.

GENERAL REVIEW & RECOMMENDATIONS

I. Cycle Studies

A. Both contractors exercised the required range of cycle variables to

insure a good first approximation of the optimum engine for both a

domestic and international range Mach No. 0.98 aircraft. Their assump-

tions concerning installation effects were identical with similar factors

being excluded from these early studies. The optimum engine of both

contractors lay between 4 and 5 in bypass ratio with nominal pressure

ratios between 25 and 30 with a modest increase in turbine inlet

temperature over the level that is in operation today in the advanced

high bypass ratio engines. An independent assessment using in-house

parametric data confirms these selections. The domestic range aircraft

favors the lower bypass ratio mentioned above and the

international aircraft the higher bypass ratio. A near optimum for

both aircraft would center at a bypass ratio of 4.5 with essentially

*This reflects the previous submittal format.

neglible penalty to either aircraft. The effects of increased engine

bleed due to the demands for better isolation of smoking and non-

smoking passengers has been taken into consideration in this analysis

where it was not specifically covered in the contractors studies.

B. The contractors made different assumptions concerning the aerodynamic

requirements for the nacelle and the flow conditions desired at the

mixing plane for mixed flow engines. The subsequent division in the

opinions of the two contractors are based on the differences brought

about by these assumptions. Neither contractor provided supporting

data for these assumptions and it should be recognized that, particularly

with respect to nacelle aerodynamics, very little data exists upon which

to make firm conclusions. The proper afterbody shape for mixed and non-

mixed flow engines for the Mach No. 0.9 to 0.98 speed region is in need

of a thorough wind tunnel test program with powered models. Secondly,

the effects of single and two stream engine nozzle configurations on

aircraft noise is not well understood and data from existing aircraft

indicates that there are effects that can be significant in efforts to

reach the target noise levels desired for future aircraft. The noise

impact of various nozzle configurations must be determined by test as the

effects can only be estimated today.

C. The preliminary installation configuration drawings of both contractors

indicated that aircraft and engine accessories would be driven from a

core mounted gearbox. This configuration is totally unacceptable to the

airlines as it hampers maintenance and helps to defeat the objectives of

modular engine construction. The labor to dress and strip the installa-

tion and accessory assemblies from a similarly configured engine is a

large percentage of the maintenance costs and totally defeats the ob-

jective of rapid fault isolation and repair.

The aerodynamic impact and costs for other accessory installation schemes must be considered. Until such time as data is provided that proves that core mounting is necessary it should be avoided.

D. The weight and performance benefits associated with composites are significant and were recommended for use in fan blades and related assemblies. In addition to the weight and performance benefits the airlines see great potential for decreasing the danger associated with fan blade failure and a reduction in the seriousness of downstream secondary damage. It should be pointed out that a previous program ran into difficulty with ingestion of large birds which are part of the certification requirements. Clearly additional research is warranted in this promising area.

E. The contractors reports did not include information pertinent to investigation of the effects of variable bypass ratio features, variable geometry turbines or the effects of variations in engine rating schemes or engine control features. These studies need to be undertaken to determine the potential vehicle performance improvements possible from such features.

F. The contractors economic studies are first order and are not sufficiently definitive to produce more than general guidance. Maintenance cost is not a simple function of thrust size and initial price nor are the manufacturer's price estimating procedures sufficiently accurate for determination of more than general trends as discussed in Section II of this report. These shortcomings present perhaps one of the greatest challenges in determining where research can be most effective. The profit motive of the airlines puts great emphasis on lower first cost and low continuing cost for maintenance.

Opportunities exist for improving both with the application of technology to reduce the total propulsion system cost. The general trends produced by the contractors are believed reasonable with respect to the effects of various levels of noise treatment but with the range of tolerances expected are not sufficiently accurate to determine a preference for mixed flow versus non-mixed flow or for the selection of cycle characteristics within $\pm$ 0.5 in bypass ratio, $\pm$ 2.5 in cycle pressure ratio or $\pm$ 100°F in turbine inlet temperature.

II. Noise

A. Results of fan component noise tests have not yielded sufficient evidence to warrant a single approach to fan design. Instinctively the airlines lean toward low tip speed single stage fans. However, single stage high and low tip speed and low tip speed widely spaced two stage fans should be considered in research programs.

B. It is noted that the results of the two contractors studies were quite similar when the 5 EPNdB lower source noise assumption of GE's is excluded. Pratt & Whitney's interest in aircraft noise abatement operating procedures, to reduce the noise levels to below FAR 36-10 EPNdB, is due to their reluctance to make a similar assumption. The GE study however shows the importance of a 5 EPNdB fan noise source reduction in achieving the low noise levels desired. The approach noise level goal is the most difficult to reach. A re-assessment of the noise objectives using footprints will show that takeoff noise dominates the largest amount of land area.

C. It is important that the effects of various noise abatement operating procedures be assessed as well as the effects the utilization of such procedures have on the optimum engine. Further it is recommended that noise footprints be used to assess the overall benefits around the airport and the relative importance of reducing takeoff, sideline and ap-

proach noise levels individually.

D. Neither of the contractors assessed the performance impact of inlet splitters or variations in design approaches to inlet splitters, or variations in design approaches to inlet noise suppression. It is recommended that effort be expended in this area. Further the effects of various nozzle configurations, exhaust stream velocity ratios and thrust reverser designs should be studied for information as to the best integrated design approach.

E. The sideline noise levels during thrust reversal and approaches to acoustically treating the reverser system should be studied.

III. Pollution

A. It is suggested that the study contractors review the Environmental Protection Agency's rules governing aircraft emissions and determine what effects the rules will have on engine design or cycle characteristics. At the current time these rules are four months behind schedule and there release is indefinite. This recommendation however might be carried out in subsequent efforts.

B. The suggestion by Pratt & Whitney that a high idle thrust level be used as part of the solution to the idle emission problem is unsatisfactory. The higher jet velocity and large air mass from these engines present serious safety problems in the terminal area.

C. It was noted that Pratt & Whitney used an estimated relationship between carbon monoxide (CO) and hydrocarbon (HC) emission levels at idle of 4 parts CO to 1 part HC using CH_4 as the basis for quoting levels. General Electric utilized a generalized curve of CO and HC versus combustion efficiency using C_6H_{14} as the base for reporting hydrocarbon emission levels. More authoritative data and uniformity in reporting would be helpful in assessing the difficulties in achieving the target

pollution emission levels.

D. The use of water injection to reduce NOx emission is not viewed favorably. This approach does not correct the emission into the upper atmosphere and hence a design solution that produces reductions throughout the operation of the aircraft is needed.

IV. Summary

The major areas requiring additional study are summarized below for NASA's consideration.

A. The impact of nacelle aerodynamics on engine cycle selection and mixed versus non-mixed flow configuration needs to be defined.

B. The noise reductions achieved should be assessed by the use of noise footprints as well as FAR 36 procedures.

C. The contractors should evaluate the impact of using noise abatement operating procedures on the choice of an optimum engine.

D. Engine economic trends in terms of first cost and maintenance cost with increasing cycle pressure ratio, temperature, etc. should be assessed to determine points of emphasis for future research. Additional approaches to assessing the economics of the various engine configurations is required.

E. Alternate accessory gearbox configurations should be studied to improve accessibility and maintainability.

F. Variations of bleed air and horsepower extraction requirements including anti-icing of inlet splitters should be examined for their influence on optimum engine selection.

CONCLUDING REMARKS

This report presents an airline's view of the significant design and installation features for the next generation high speed subsonic commercial transport propulsion system. A number of airline problems related to the selection of the performance goal for such an engine have been presented with the objective of providing guidance for advanced research projects. It is suggested that major improvements in specific fuel consumption and engine specific weight will be difficult to achieve and that as a consequence improvements in direct operating cost must come from other technology areas. Several technology areas where reductions in direct operating cost might be obtained have been presented. The economic data presented by the engine study contractors indicate significant economic penalty for achieving the noise and pollution goals established. It is American Airlines' opinion that the economic assessment tools used to study the impact of various design features and technology levels is not providing adequate guidance. Recognizing that noise, pollution and total operating economics will be the driving forces in propulsion system design for the forseeable future strongly suggests that a program be initiated to develop the necessary economic assessment tools to provide more accurate guidance for the future.

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