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# Wide Speed Range Turboshaft Study

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## Summary

NASA-Lewis and NASA-Ames have sponsored a series of studies over the last few years to identify key high speed rotorcraft propulsion and airframe technologies. NASA concluded from these studies that for near term aircraft with cruise speeds up to 450 kt, tilting rotor rotorcraft concepts are the most economical and technologically viable. The propulsion issues critical to tilting rotor rotorcraft are: 1) high speed cruise propulsion system efficiency, and 2) adequate power to hover safely with one engine inoperative. High speed cruise propeller efficiency can be dramatically improved by reducing rotor speed, yet high rotor speed is critical for good hover performance. With a conventional turboshaft, this wide range of power turbine operating speeds would result in poor engine performance at one or more of these critical operating conditions.

This study identifies several wide speed range turboshaft concepts, and analyzes their potential to improve performance at the diverse cruise and hover operating conditions. Many unique concepts were examined, and the selected concepts are simple, low cost, relatively low risk, and entirely contained within the power turbine. These power turbine concepts contain unique, incidence tolerant airfoil designs that allow the engine to cruise efficiently at 51% of the hover rotor speed. Overall propulsion system efficiency in cruise is improved as much as 14%, with similar improvements in engine weight and cost.

The study is composed of a propulsion requirement survey, a concept screening study, a preliminary definition and evaluation of selected concepts, and identification of key technologies and development needs. In addition, a civil transport tilting rotor rotorcraft mission analysis was performed to show the benefit of these concepts versus a conventional turboshaft. Other potential applications for this technology are also discussed.

## Introduction

### Background

Over the past several years, NASA-Ames has sponsored a series of rotorcraft company studies to identify the key technologies and development needs for high speed rotorcraft (HSRC) for both civil and military applications. GEAE has been participating in NASA-Lewis studies to define propulsion systems to support the NASA-Ames studies, and to determine the critical engine technologies for this type of aircraft. The four Ames sponsored aircraft companies (Bell Helicopters, Boeing Helicopters, McDonnell Douglas Helicopters, and Sikorsky Aircraft) studied a wide range of HSRC concepts, including tilt rotor (fixed and variable diameter), folding tilt rotor, tiltwing, locking rotor, and fan-in-wing. GEAE defined propulsion system concepts for each of these rotorcraft types, and estimated performance, assessed risk, and defined development needs for each of the selected engine concepts. As a result of these studies, NASA has chosen to focus its available resources on tilting rotor rotorcraft. NASA believes that for cruise speeds of 450 kt or less, tilting rotor rotorcraft concepts present the lowest risk for near term applications.

### Tilt Rotor Propulsion Issues

GEAE has identified two key propulsion issues for tilting rotor rotorcraft. The first propulsion need is the ability to hover safely with one engine inoperative (OEI). This will undoubtedly be a requirement for civil applications, and a desirable quality for military aircraft. The other critical issue is the overall propulsion system efficiency during high speed cruise. Cruise efficiency is key to achieving an economically viable high speed rotorcraft design.

The main obstacle to achieving good propulsive efficiency in cruise is the losses due to the high helical tip Mach No. of the proprotor. For flight speeds in the 350 to 450 kt range, rotor tip Mach Nos. can become transonic, resulting in high losses and poor proprotor efficiency ($\eta_{prop}$). Reducing rotor tip speeds (Vt) to levels significantly below typical rotorcraft hover values can dramatically improve cruise $\eta_{prop}$ and reduce rotor induced noise. On the other hand, high Vt is required to hover on one engine, as rotor lift is proportional to $Vt^2$. Unfortunately, with a conventional turboshaft, this wide range of proprotor operating speeds would result in poor engine performance at one or more of these critical operating conditions. Most rotorcraft companies set Vt to about 750 ft/s for good hover performance, and try to trade off proprotor and engine performance at cruise by reducing Vt to ~80% of the hover value.

Studies of tilting rotor rotorcraft by both NASA Ames and McDonnell Douglas (MDHS) indicate cruise $\eta_{prop}$ can be improved 15% to 22% by reducing cruise rotor speed from the typical 80% down to 50% of the hover value. (See Figure 1.) The potential for dramatic improvement in cruise performance is why NASA has chosen to investigate the feasibility of a turboshaft concept that could operate efficiently over a wide range of rotor speeds.

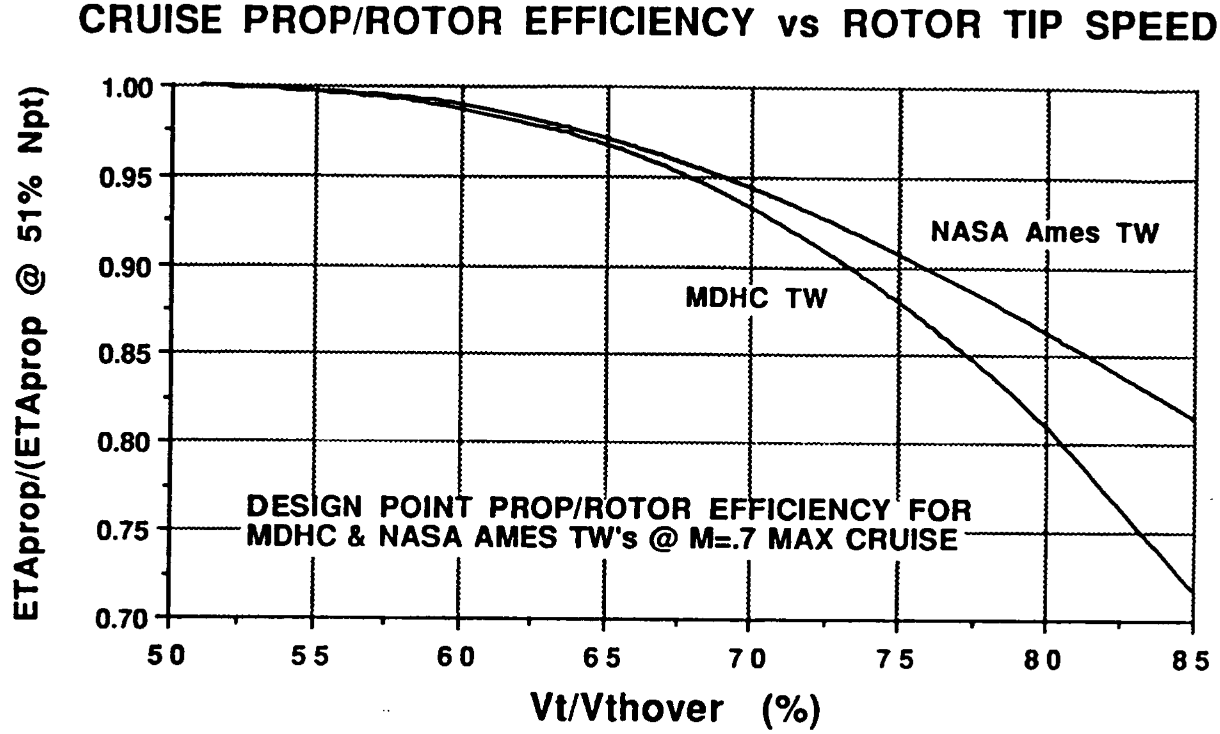


Figure 1. Need For WSR Turboshaft.

## Wide Speed Range Turboshaft Study: Objectives And Methodology

There are three main goals to this study. The first is to define engine concepts that cruise efficiently at significantly reduced output shaft speed ($N_{PT}$), yet retain good full speed hover performance for OEI emergencies. The second study goal is to evaluate these wide speed range (WSR) turboshaft concepts versus a conventional turboshaft to define their potential benefits to tilting rotor rotorcraft. The third goal is to identify the enabling technologies and development needs of the most promising WSR concepts.

This study was divided into several tasks. The first task was the establishment of a suitable set of propulsion requirements for a WSR turboshaft in a high speed tilting rotor rotorcraft application. Next, concepts with potential to enhance operation over a wide range of operating speeds were identified. These concepts were screened for suitability for this application, and the most promising ones were selected for further definition. Performance models and preliminary designs were established for the selected engine concepts, as well as a baseline conventional turboshaft. The selected WSR engine concepts were then evaluated against the baseline turboshaft using the established propulsion requirements. In addition, GEAE chose to perform a "rubber engine/rubber aircraft" mission analysis to show the potential benefits for civil tilting rotor applications. The enabling technologies and developments needs of the most promising WSR concepts were identified. This report also indicates other potential applications for this technology.

## Establishment Of Propulsion Requirements

Three engine performance requirements are critical to the definition of the WSR turboshaft concept: 1) max cruise equivalent shaft power, 2) shaft power needed to hover on engine, and 3) the ratio of cruise to hover output shaft speed ($N_c/N_h$). NASA Ames and the four HSRC study aircraft companies were surveyed to determine the propulsion requirements of tilting rotor rotorcraft. The aircraft companies indicated that for high speed cruise (Mach ≈ 0.7), optimum $\eta_{prop}$ is probably achieved at 50% to 70% of hover rotor speed. They all felt, however, that the performance of a conventional turboshaft at 50% to 70% $N_c/N_h$ was unacceptably poor. Three of the four aircraft companies chose 80% $N_c/N_h$ as the best compromise between rotor and engine performance with a conventional turboshaft.

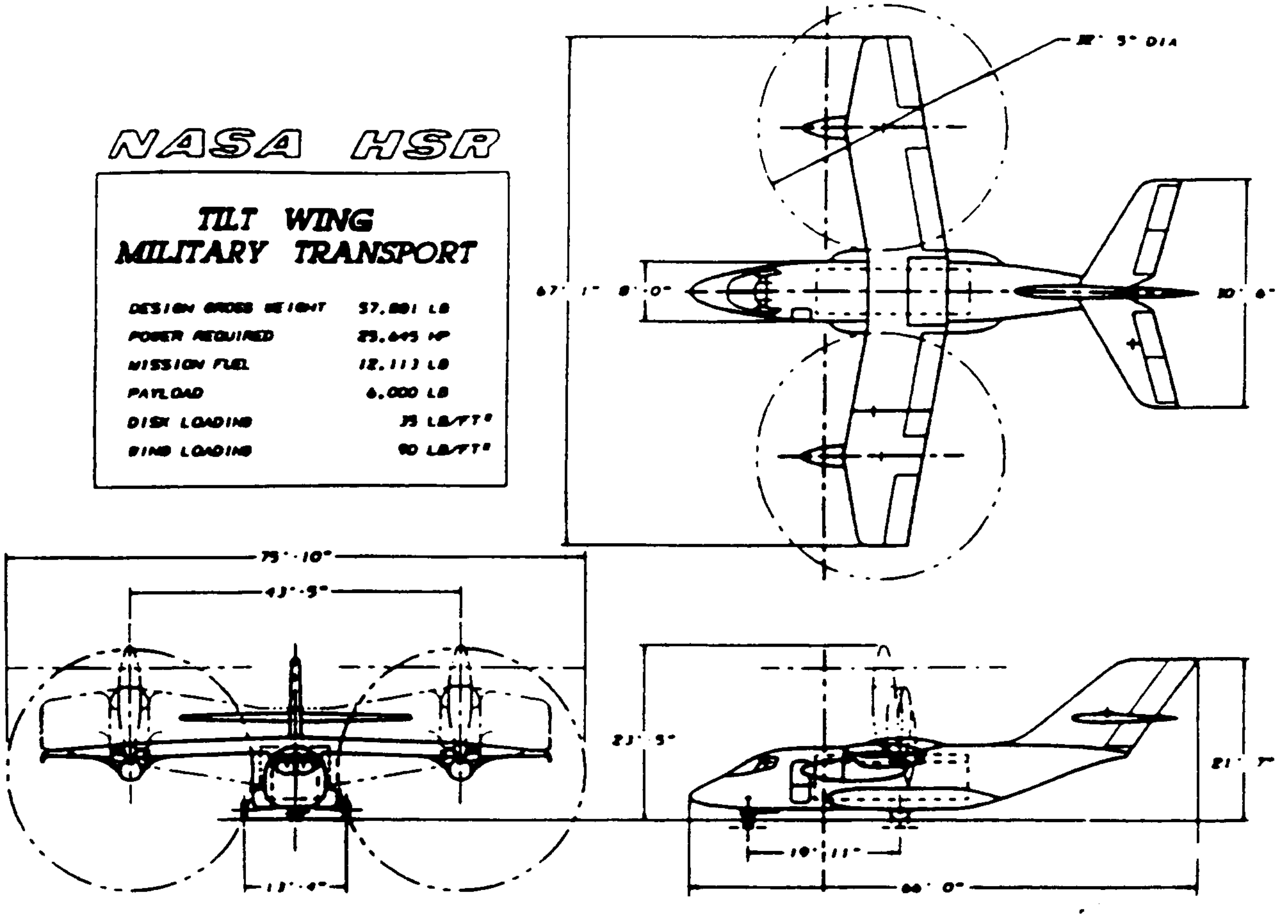
McDonnell Douglas selected a cruise rotor speed of 51% of the hover value for its tiltwing concept. MDHS claims a dramatic 22% improvement in proprotor performance by reducing cruise rotor speed from the typical 80% down to 51% of the hover value. NASA Ames has also shown a significant (~15%) improvement in cruise proprotor performance at 50% rotor speed. Both the MDHS and NASA rotorcraft concepts achieve this near 51% speed reduction by employing an undefined two speed transmission. The engines are run at full speed in cruise for peak efficiency, and no additional loss or weight is bookkept for the variable speed mechanism. Since this transmission technology does not currently exist, an efficient WSR turboshaft is necessary to take advantage of the high cruise $\eta_{prop}$ available at low rotor speeds.

On NASA Ames' recommendation, and with NASA Lewis' concurrence, the MDHS tiltwing performance requirements were chosen for the design and evaluation of the WSR turboshaft concepts. NASA selected this concept because it poses a significant challenge in terms of operating speed range. The benefits to propulsion system performance should be similar for tilt rotors and tiltwings. Figures 2 and 3 show the MDHS military transport tiltwing concept and mission. Table I gives the key engine performance requirements at critical operating conditions, while Table II indicates overall propulsion system (engine + transmission + rotor) thrust in cruise. The baseline propulsion system in this study was designed to cruise with a conventional turboshaft matched to a rotor optimized at 80% $N_c/N_h$.

TABLE I. CRITICAL ENGINE POWER REQUIREMENTS

McDonnell Douglas Helicopter Company Military Transport Tiltwing
Entire Mission At ISA + 15°C

| | Alt/Speed | Duration (Minutes) | (E)SHP (hp) (Per Engine) | Npt (Vs. Hover) |
|---|---|---|---|---|
| Takeoff, Hover OGE | SLS | 1 | 3054 | 100% |
| Takeoff, Hover OEI | SLS | 1/2 | 6108 | 100% |
| Max Cruise | 15K/450 Kt | <47 | 4135 | 51% |



NASA -Ames High Speed Rotorcraft Study

Figure 2. MDHC Military Transport Tiltwing.

Entire Mission At ISA + 15°C
6000 Lb Payload
6370 Lb Fixed Weight (Excluding Payload)

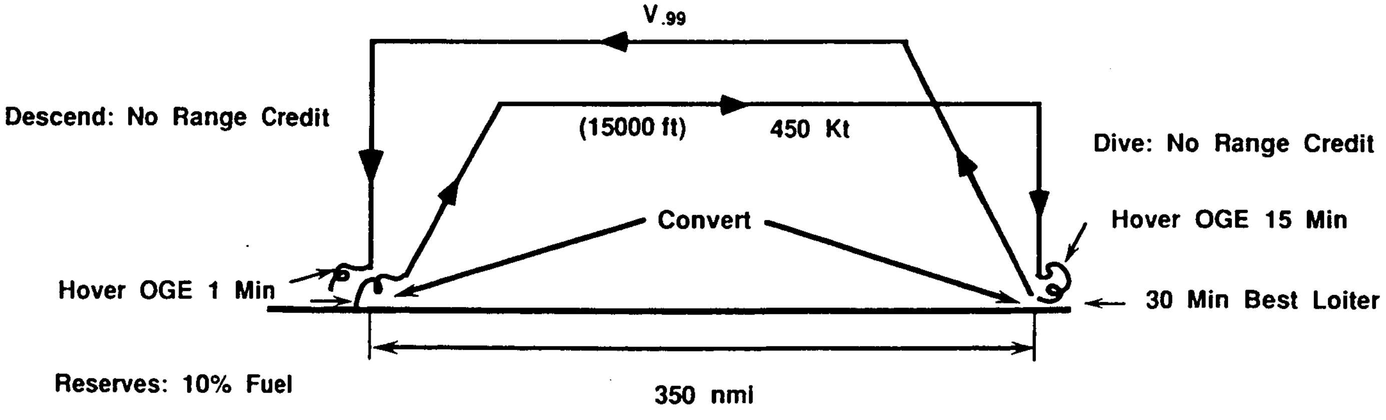


Figure 3. Military Transport Mission.

TABLE II. OVERALL PROPULSION SYSTEM PERFORMANCE REQUIREMENT.
(SYSTEM NET THRUST REQUIRED AT CRUISE)

MDHC Military Transport Tilt Wing
15K/450 Kt/ISA + 15°C Max Cruise

$ESHP_{Req}$ = 4135 HP Per Engine
$\eta$ Prop = 0.79 At 51% $V_{tip}$
$\eta_{GB}$ = 0.985
System FN $_{Req}$ (Prop & Jet) = 2330 Lb Per Engine

## Wide Speed Range Turboshaft Design Challenges

There are two major design challenges in achieving good performance from a turboshaft engine which cruises at 51% of the hover power turbine (PT) speed. The first design challenge is the large blade incidence angles at one or more operating conditions, resulting from operating the engine at approximately half power turbine speed ($N_{PT}$). Figure 4 shows a PT velocity diagram for a turbine designed with no blade incidence at 100% speed. When the PT is operated at half the rotational speed (U), the resulting blade incidence can be as much as 40° to 80°. This large swing in blade incidence causes poor performance at the off-design condition, and could result in massive flow separation and aeromechanics problems.

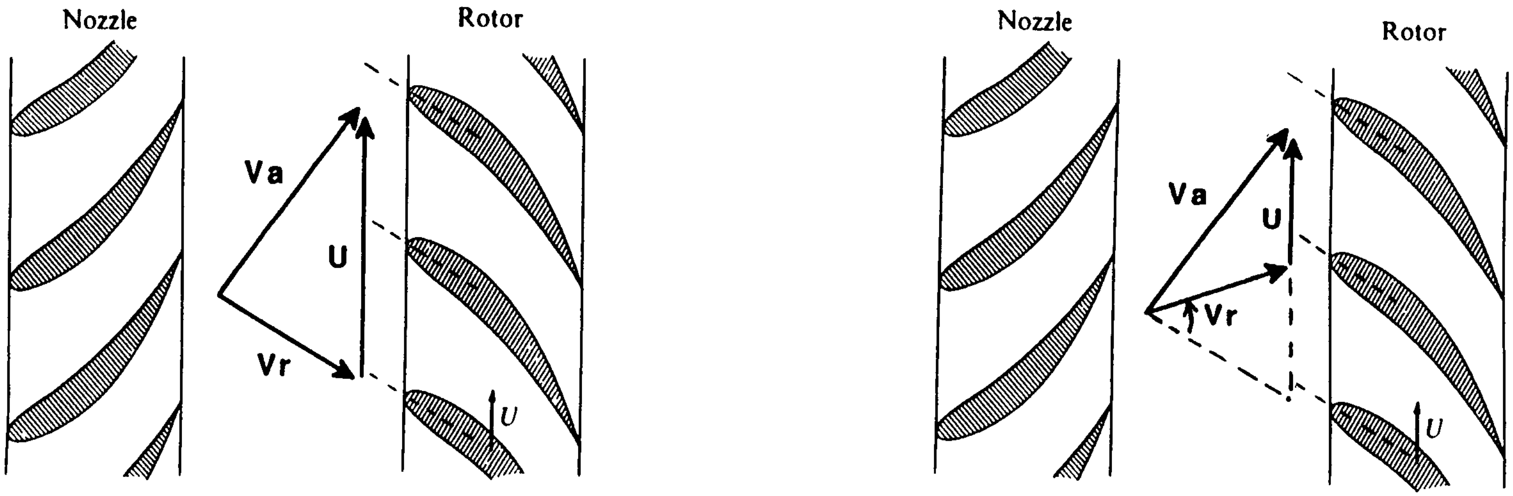
The second major design challenge is the large increase in PT loading at cruise due to the reduced $N_{PT}$. The loading parameter $\psi$ is defined by GEAE as:

$$\Psi = \frac{gJ\Delta h}{2Up^2} \propto \frac{1}{Npt^2} \sim \frac{\text{Turbine Stage Work}}{\text{Wheelspeed Kinetic Energy}}$$

where: $\Delta h$ = stage enthalpy drop
Up = blade pitchline rotational speed
g and J are constants
(Note: NASA defines $\psi$ as twice the GEAE value.)

Loading is inversely proportional to $N_{PT}^2$, and high loading per stage has an adverse impact on PT efficiency ($\eta_{PT}$). The loading at 51% $N_{PT}$ cruise is actually more than 3 times that of the full speed hover, OEI emergency power condition. Loading per stage could be reduced by adding turbine stages, but the swing in blade incidence increases 15° to 20° per added stage.

A number of power turbine concepts intended to address these design challenges were identified. A screening study was performed to select those concepts meriting a more detailed evaluation.



$100\%\ N_{PT}$ HOVER

$50\%\ N_{PT}$ CRUISE

- ZERO BLADE INCIDENCE DESIGN AT ONE CRITICAL OPERATING CONDITION RESULTS IN $40^0$ TO $80^0$ INCIDENCE AT ANOTHER.
    - RESULTS IN POOR PERFORMANCE AT THE OFF-DESIGN CONDITION.
    - POTENTIAL FOR MASSIVE FLOW SEPARATION OR AEROMECHANICS PROBLEMS.

Figure 4. WSR Power Turbine Blade Incidence.

## WSR Turboshaft Concept Screening Study

The speed range enhancing concepts identified here were developed in sufficient detail to evaluate their potential merits for this application. The unique speed range broadening features of these concepts are all contained within the power turbine module. These engine concepts are all GE38 cores integrated with the unique WSR PT concepts. Performance was evaluated versus the selected MDHS tiltwing propulsion requirements. Other considerations included cost, weight, risk, operability, reliability, and maintainability. The concepts examined in the screening study are as follows:

- Fixed Geometry PT, Incidence Tolerant Airfoils
  - 3 and 4 Stage Designs
- Variable Stator And OGV Geometry PT
- 4 Stage PT With Tandem Airfoil Blade Rows
- Variable Stator <u>And Rotor</u> Geometry PT
- Dual Flowpath Turbine
  - Alternate or Supplementary Configurations
  - Clutched or Directly Coupled
- Multi-Stage PT With Clutchable Stage(s)
- Single-To-Counter Rotating Convertible PT
- 3 Stage PT With System Optimized Cruise $N_{PT}$
  - Fixed Geometry, Incidence Tolerant Airfoils

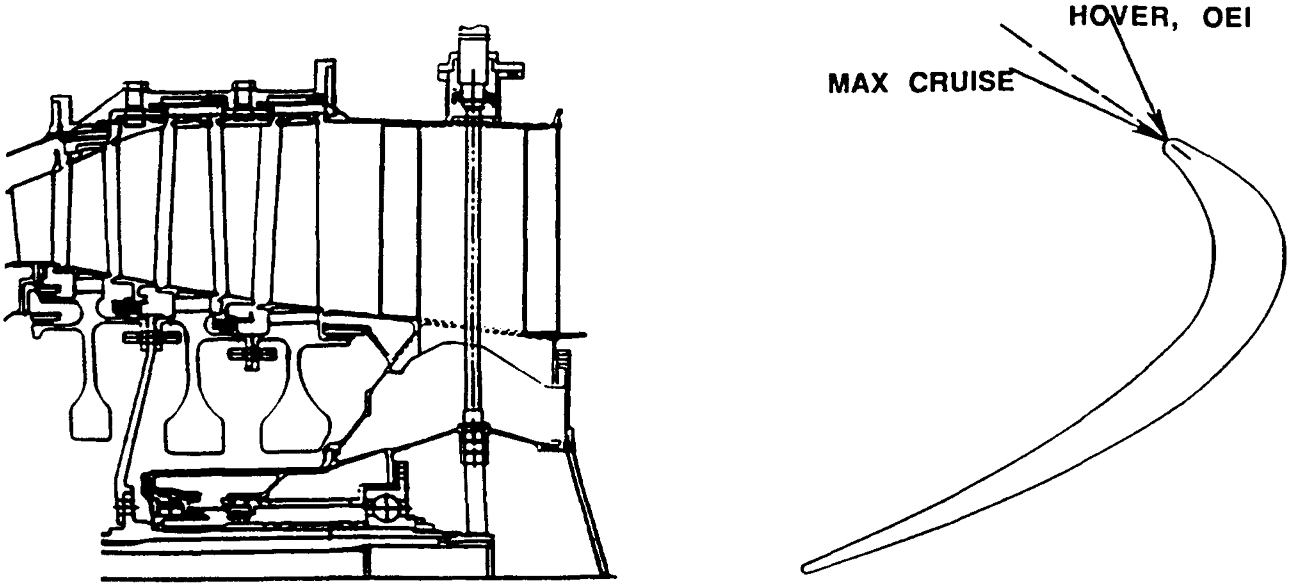
A brief discussion of each of these concepts follows.

### Fixed Geometry Power Turbine with Incidence Tolerant Airfoils

This 3 stage PT concept employs an incidence tolerant blade design. This airfoil design is intended to provide good operability and performance over the wide range of blade loading and incidence angles between the 51% $N_{PT}$ cruise and 100% $N_{PT}$ hover OEI conditions. (See Figure 5.) High blade incidence angles (+10° at cruise, -30° at hover, OEI) raised concerns about flow separation and performance. GE29 high blade incidence test data was used to help validate the performance predictions of the aero codes used in defining this design. In order to minimize risk, this WSR PT concept could be defined so that the blade incidence at all critical operating conditions is within test experience. PT efficiency at the 51% $N_{PT}$ cruise is approximately 7 points lower than a similarly optimized design at an 80% $N_{PT}$ cruise design point. (See Figure 6.) This is mostly due to the fact that loading more than doubles when reducing $N_{PT}$ from 80% down to 51%. A similar 4 stage PT design was also examined in an effort to reduce loading per stage, but the additional 20° swing in blade incidence between cruise and hover would undoubtedly result in flow separation. Overall propulsion system cruise efficiency of this concept is significantly higher than a conventional turboshaft and rotor optimized for 80% $N_{PT}$ cruise, due to the higher $\eta_{prop}$ available at the lower rotor speed.

### Variable Power Turbine Stator and OGV Geometry

A variation on the above turbine concept was developed which employed variable geometry in the stators and turbine outlet guide vanes (OGV's). (See Figure 7.) Unfortunately, variable stator geometry does not solve the blade incidence problem. It does, however, allow some tailoring of the engine cycle throughout the flight envelope. For these purposes it is sufficient to have only the first stage stator variable. An OGV design with a variable trailing edge is employed to maximize jet thrust at cruise, and to minimize exhaust losses at all operating conditions. The performance benefit of this concept is relatively small; a 1% improvement in cruise specific fuel consumption (SFC), and 2% more power at hover, OEI. These performance gains hardly offset the additional engine weight (+5%), cost, and complexity.



3 STAGE FIXED GEOMETRY PT LAYOUT

REPRESENTATIVE BLADE ROW CROSS SECTION DESIGN CRUISE $N_{PT}$ = 51%

Figure 5. 3 Stage Fixed Geometry PT With Incidence Tolerant Airfoils.

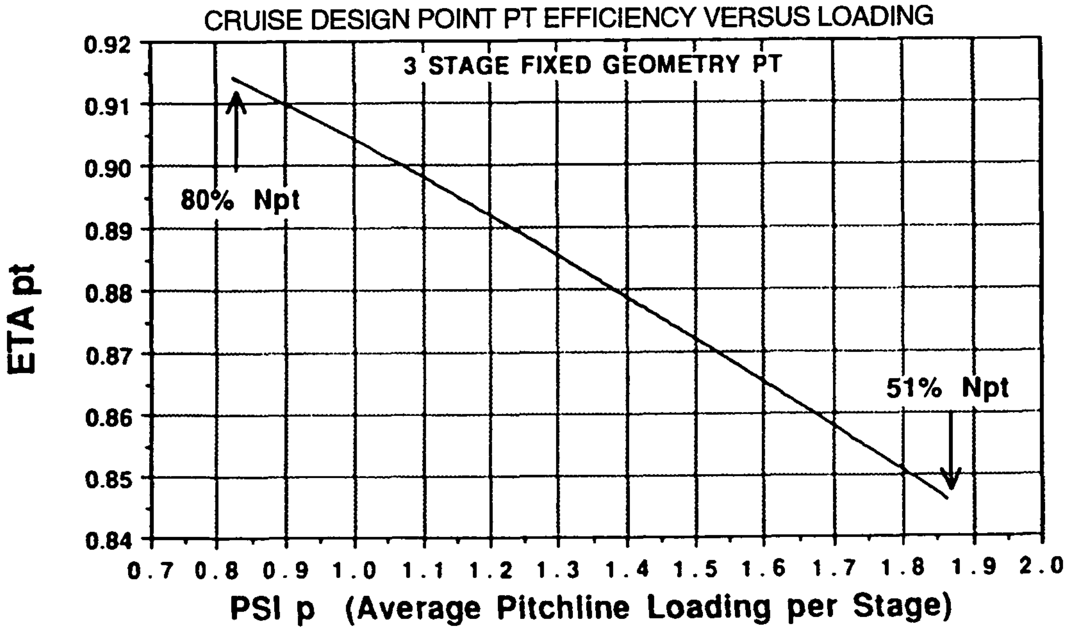


Figure 6. WSR Power Turbine Efficiency Versus Design Point Stage Loading.

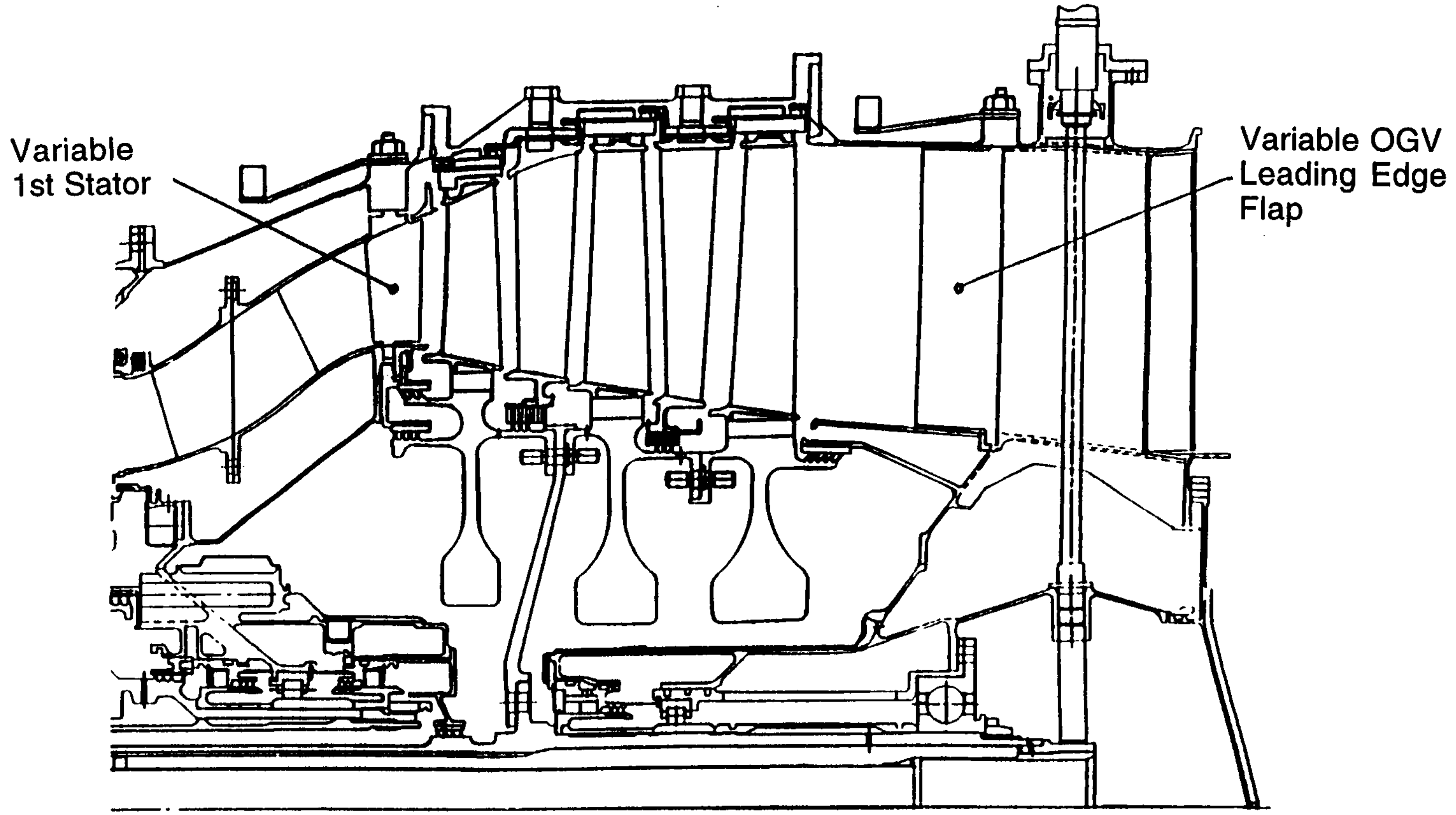
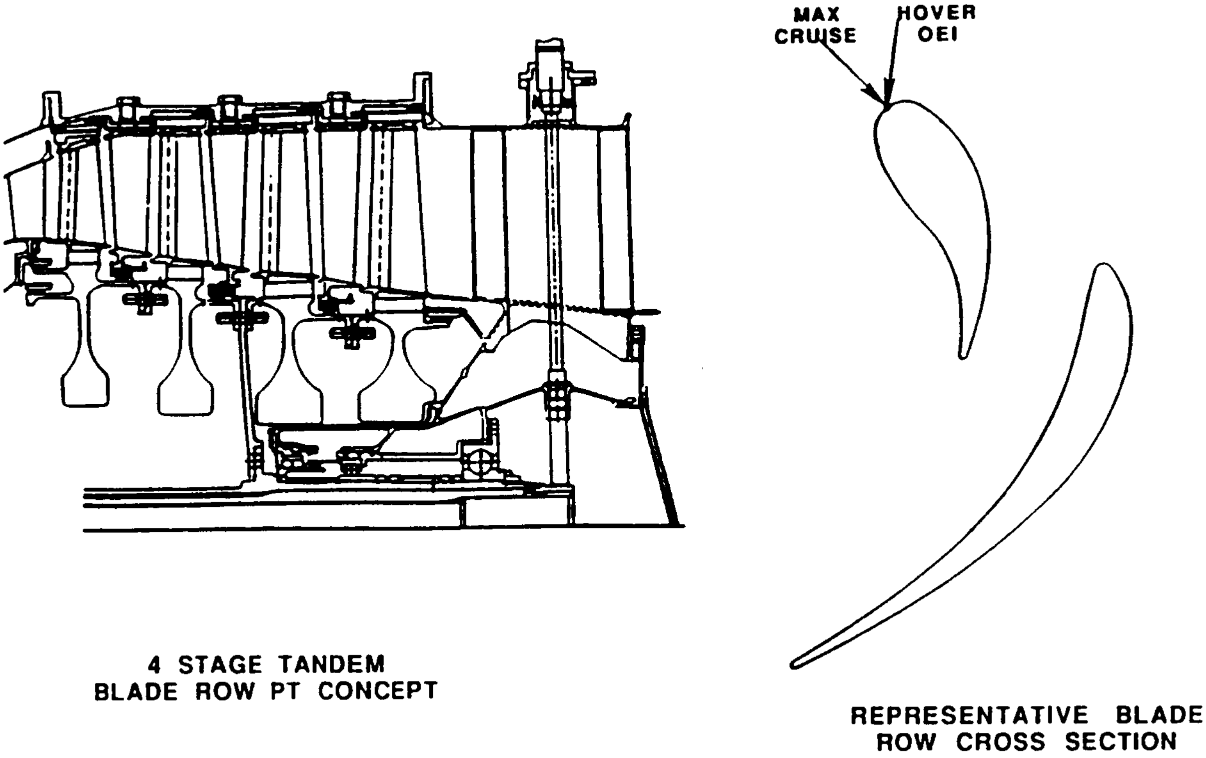


Figure 7. Variable Stator And OGV Geometry PT Concept.

## 4 Stage Power Turbine with Tandem Airfoil Blade Rows

The tandem blade row PT concept is intended to improve the PT efficiency at 51% $N_{PT}$ cruise by adding a 4th stage to reduce loading per stage. (See Figure 8.) The drawback of a 4 stage design is that it has a 15° to 20° larger range of blade incidence angles from cruise to hover than a 3 stage design. With a conventional single blade row design, these extremely high incidence angles would almost certainly result in massive flow separation one or more of the critical operating conditions.



4 STAGE TANDEM BLADE ROW PT CONCEPT

REPRESENTATIVE BLADE ROW CROSS SECTION

Figure 8. 4 Stage Tandem Blade Row PT Concept.

This novel WSR PT concept attempts to address this problem by employing two rows of turbine blades per stage to reduce the PT's sensitivity to incidence. The forward blade row would have a very incidence tolerant airfoil design. The aft row would have higher performance (and more incidence sensitive) airfoils, with leading edges interspersed between the aft portions of the forward airfoils. (See Figure 9.) The design intent is that the lightly loaded forward row would take most of the incidence losses, and help straighten and reattach the flow. Most of the work would be performed by the higher efficiency aft blade row. Assuming 60% of the incidence losses were borne by the forward row, and 70% of the work performed by the follower row, there is a potential 3% improvement in $\eta_{PT}$ at cruise with 1% better hover $\eta_{PT}$ than the 3 stage, incidence tolerant single blade row design. Most of the improvement in cruise $\eta_{PT}$ is due to the reduction in loading per stage due to the addition of the 4th stage. A 4 stage design would not be workable with a conventional single airfoil design. The performance improvement of the 4 stage tandem blade PT comes at the cost of higher risk, expense, weight, and complexity than the 3 stage single blade row design. The PT design shown is a fixed geometry design, and the comments regarding variable geometry in the 3 stage PT concept above apply here.

Representative Blade Row Cross Section From 4 Stage Tandem Blade WSR
Turboshaft Blade Incidence Indicated For Operating Conditions

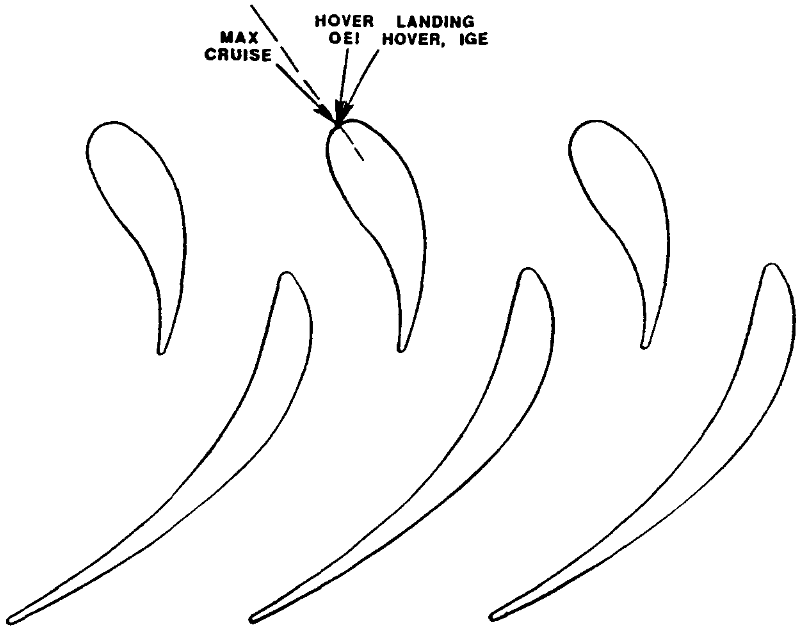


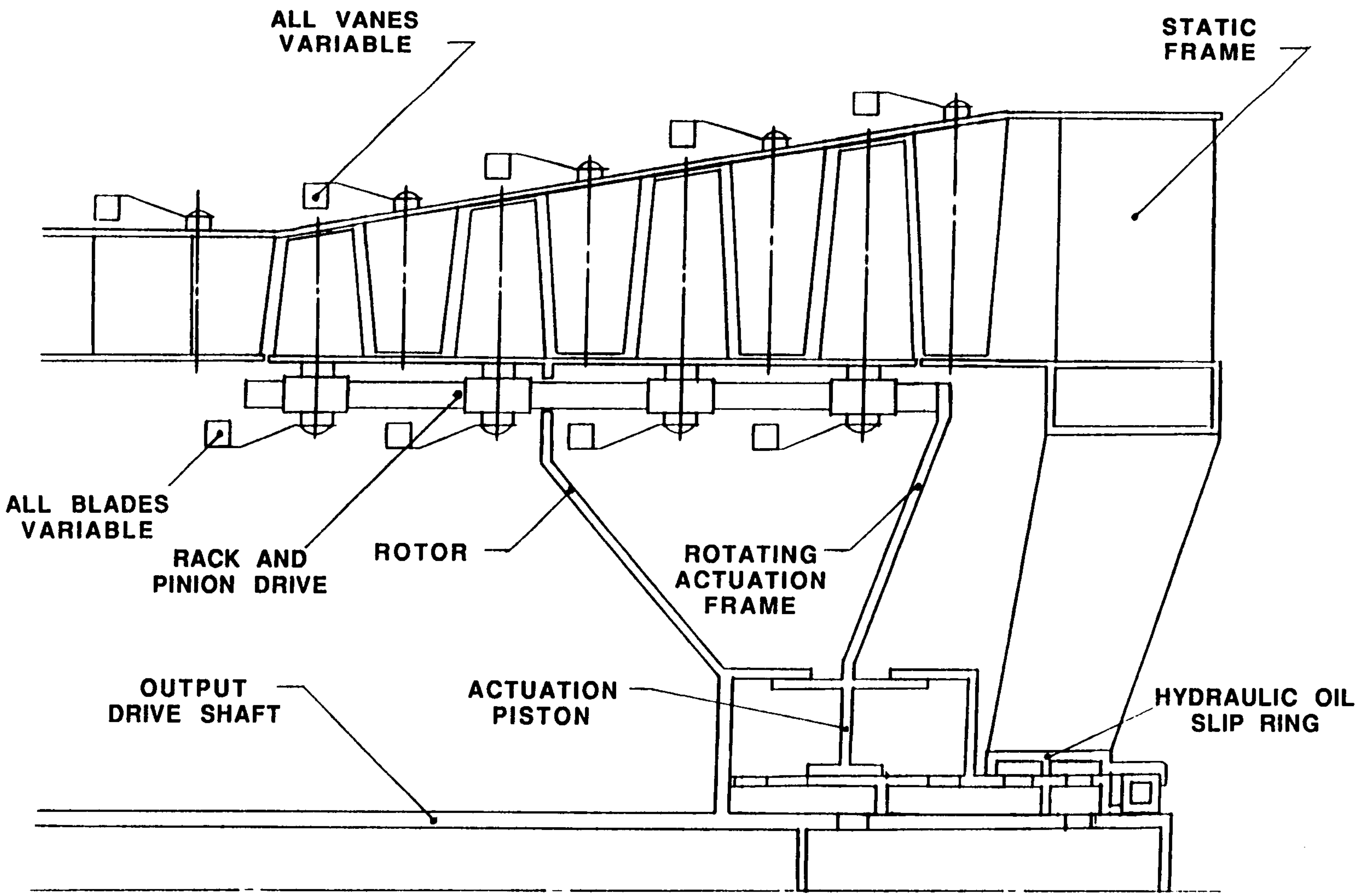
Figure 9. Tandem Airfoil Blade Row Concept.

### Variable Stator *and Rotor* Geometry Power Turbine

A power turbine design with variable rotor as well as stator geometry (Figure 10) in all stages could eliminate the blade incidence problem. This feature would not in itself reduce stage loading, but it would allow stages to be added for that purpose. At least some of the performance benefits would be lost to the inevitable leakage of a variable geometry design. Additionally, airfoil design would likely be somewhat compromised to allow for the variability feature. This concept would be extremely heavy, costly, and complex. Reliability is a big concern, and the failure mode of the variable geometry must default to the 100% $N_{PT}$ hover mode for an OEI landing. The feasibility of this design with current technology is at best questionable.

### Dual Turbine Flowpaths With Flow Diverter

There are many possible variations of this concept. The intent of this concept is to reduce stage loading in cruise. The basic premise is that flow would be directed through one turbine for the 100% $N_{PT}$ hover, then through the other turbine (or both turbines) for the low speed, high loading cruise condition. The turbines can be either supplementary (one turbine for 100% $N_{PT}$ hover, both turbines for 51% $N_{PT}$ cruise) or alternate designs (one turbine for hover, the other for cruise). (See Figure 11.) The turbines can either be parallel (two shafts geared together) or concentric (inner and outer flowpaths on the same turbine). (See Figure 12.) The basic problem is that unless the unloaded turbine is declutched, the windage power loss due to churning the "dead" air would be excessive (equivalent to 6% to 20% $\eta_{PT}$). Flow diverter leakage losses could be significant. Additionally this would be a complex, heavy, costly design due to the additional turbine flowpath and flow diverter.



VARIABLE STATOR AND ROTOR POWER TURBINE
CONCEPT SCHEMATIC

Figure 10. Variable Stator And Rotor Power Turbine. (Concept Schematic)

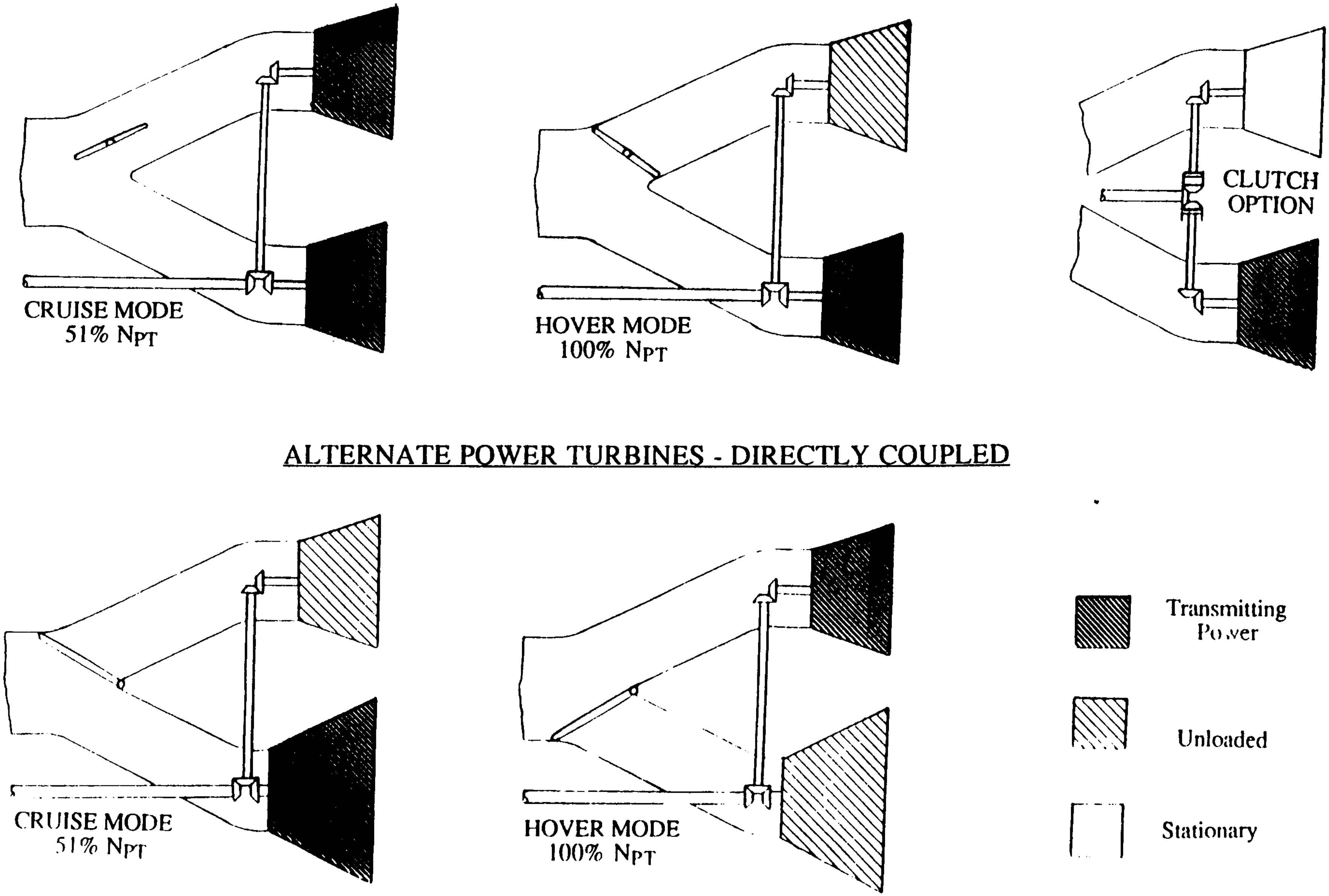


Figure 11. Supplementary Power Turbines - Directly Coupled.

# DUAL POWER TURBINE FLOWPATHS WITH FLOW DIVERTER

## CONCEPT SCHEMATIC
## SUPPLEMENTARY, CONCENTRIC POWER TURBINES

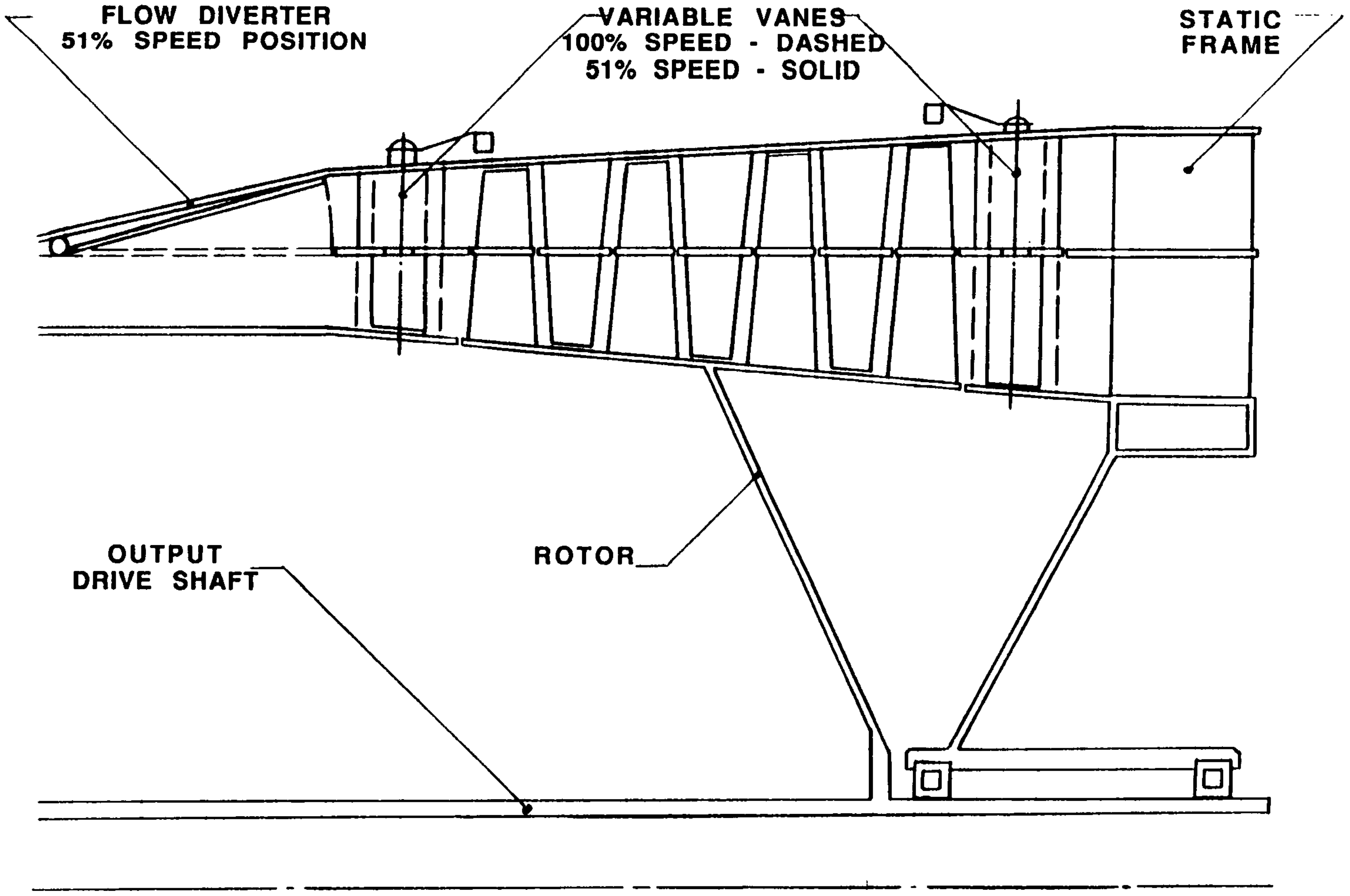


Figure 12. Dual Power Turbine Flowpaths With Flow Diverter.

## Multi-Stage Power Turbine With Clutchable Stage(s)

In 51% $N_{PT}$ cruise, this turbine would act as a conventional 4 or 5 stage design, with good cruise $\eta_{PT}$ due to reasonable loading per stage. (See Figure 13.) For the 100% $N_{PT}$ hover condition, one or more stages could be declutched and allowed to freewheel. (See Figure 14.) This would bring the hover loading and blade incidence angles closer to design (cruise) levels. This design has several drawbacks, including complexity, high losses during 100% $N_{PT}$ operation, and the mechanical feasibility of the clutch. If this type of clutch were feasible, one would also be able to design the two speed transmission proposed by MDHS and Ames, thereby eliminating the need for the WSR turboshaft concept.

## Single- to-Counter-rotating Convertible Power Turbine

Another unconventional PT concept considered is a turbine that could convert from a single-rotation turbine at full speed, to a counter-rotating turbine at 50% speed. There are several variations of this concept, but the most straightforward was a multistage counter-rotating turbine, with the two turbine sets geared to the same shaft via a differential. (See Figures 14 and 15.) The differential maintains a 100% relative speed difference between the two turbine sets. In cruise mode, the PT would function as a "conventional" geared counter-rotating turbine at 1/2 the hover output shaft speed. In hover, one of the two turbine sets would be stopped and locked, and the other would turn at 100% $N_{PT}$. Thus, in 100% $N_{PT}$ hover mode, the PT would act as a conventional single-rotation turbine with fixed stators. In this way, the blade incidence and loading swings between cruise and hover would be greatly reduced, because the difference in wheelspeed from blade row to blade row is held constant. This concept has several serious limitations. First, it functions efficiently only as a two speed device due to the clutch. Second, this is a very complex design, with a differential that would be a challenging mechanical design. Third, if the torque converter failed while in cruise mode, a vertical landing would be impossible at 50% $N_{PT}$. Once again, as in the previous concept, if such a braking device were feasible, a clutch could also be devised for a two speed transmission.

## Fixed Geometry Power Turbine with System Optimized Cruise $N_{PT}$

This PT concept offers an alternative way to meet the MDHC TW propulsion requirements (i.e., propulsion system net thrust and lift) with a lower development cost, lower risk, high performance design. The high level of $\eta_{prop}$ available at 51% $N_{PT}$ cruise was traded off against the improvement in $\eta_{PT}$ (and reduction in risk) afforded by designing for a higher cruise $N_{PT}$. A parametric study was performed to find the optimum cruise $N_{PT}$ for best overall propulsion system efficiency with a 3 stage, fixed geometry PT design. Figure 16 shows design point efficiency at cruise for the MDHC TW proprotor and the GEAE WSR 3 stage power turbine as a function of $N_{PT}$. The MDHC proprotor efficiency versus rotational speed curve shows that most of the gain in cruise $\eta_{prop}$ achieved by reducing $N_{PT}$ to 51% of the hover value is available by 62% $N_{PT}$. Combined efficiency ($\eta_{prop}$ times $\eta_{PT}$) versus percent $N_{PT}$ is also shown. $\eta_{prop}$ and $\eta_{PT}$ may be traded off against each other on an almost one-to-one basis in terms of overall propulsion system efficiency. The peak in this combined efficiency curve occurs at around 62% $N_{PT}$. An engine concept with a 3 stage, fixed geometry PT design was defined with a 62% cruise $N_{PT}$. The 30% reduction in cruise PT loading results in a 4.5% higher $\eta_{PT}$ than the 3 stage PT designed for 51% $N_{PT}$ cruise. The result is a net improvement in overall propulsion system cruise efficiency versus the 51% $N_{PT}$ 3 stage PT. While the 62% $N_{PT}$ cruise of this concept does not strictly meet the original engine goals, it does meet the *overall propulsion system requirements,* with good performance and a lower risk design.

Some of the studied concepts were found to not have sufficient merit for this application to warrant further study. The WSR PT concepts eliminated as a result of this screening study, and the reasons why, are listed in Table III.

# POWER TURBINE WITH CLUTCHABLE STAGE
## CONCEPT SCHEMATIC

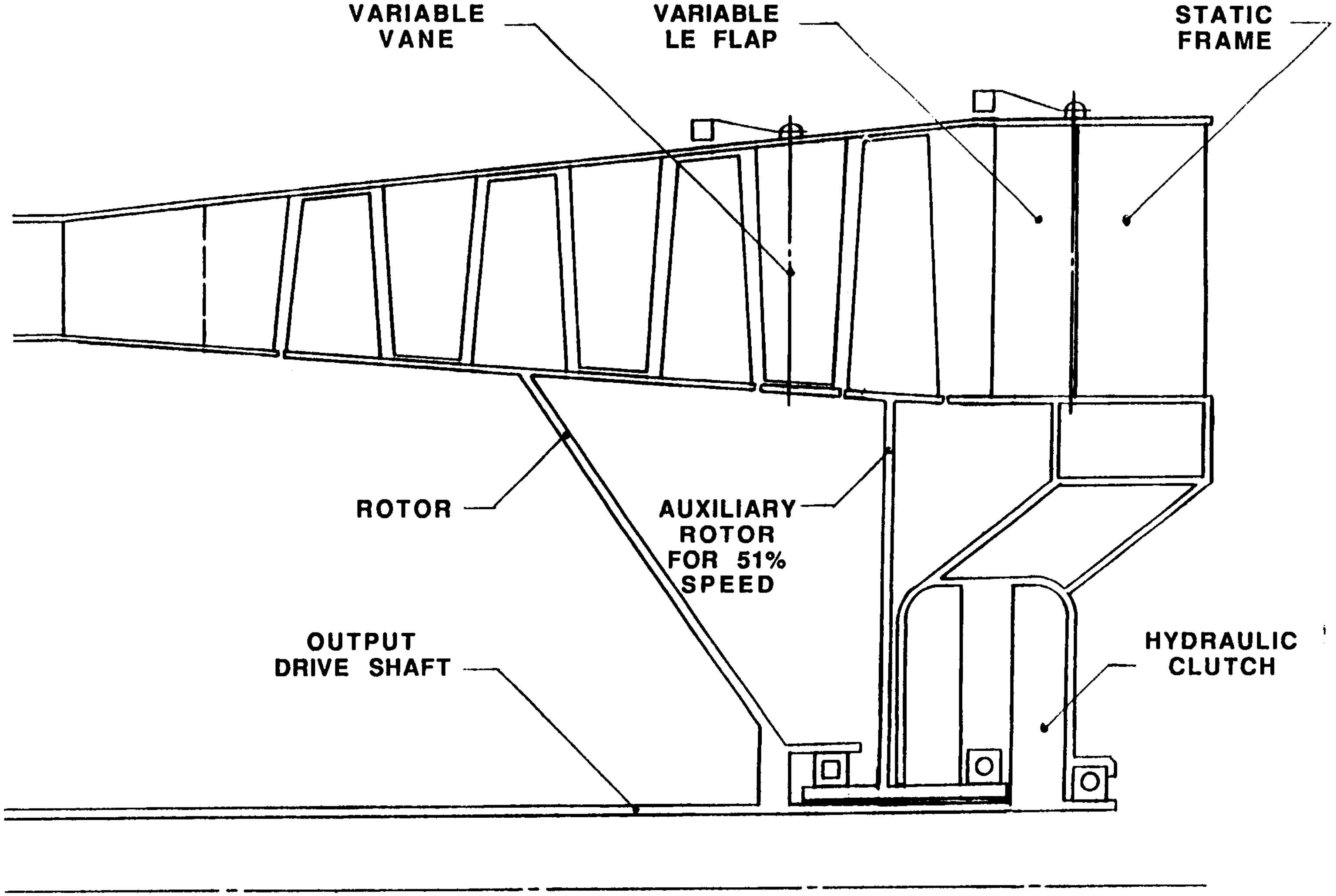


Figure 13. Power Turbine With Clutchable Stage.

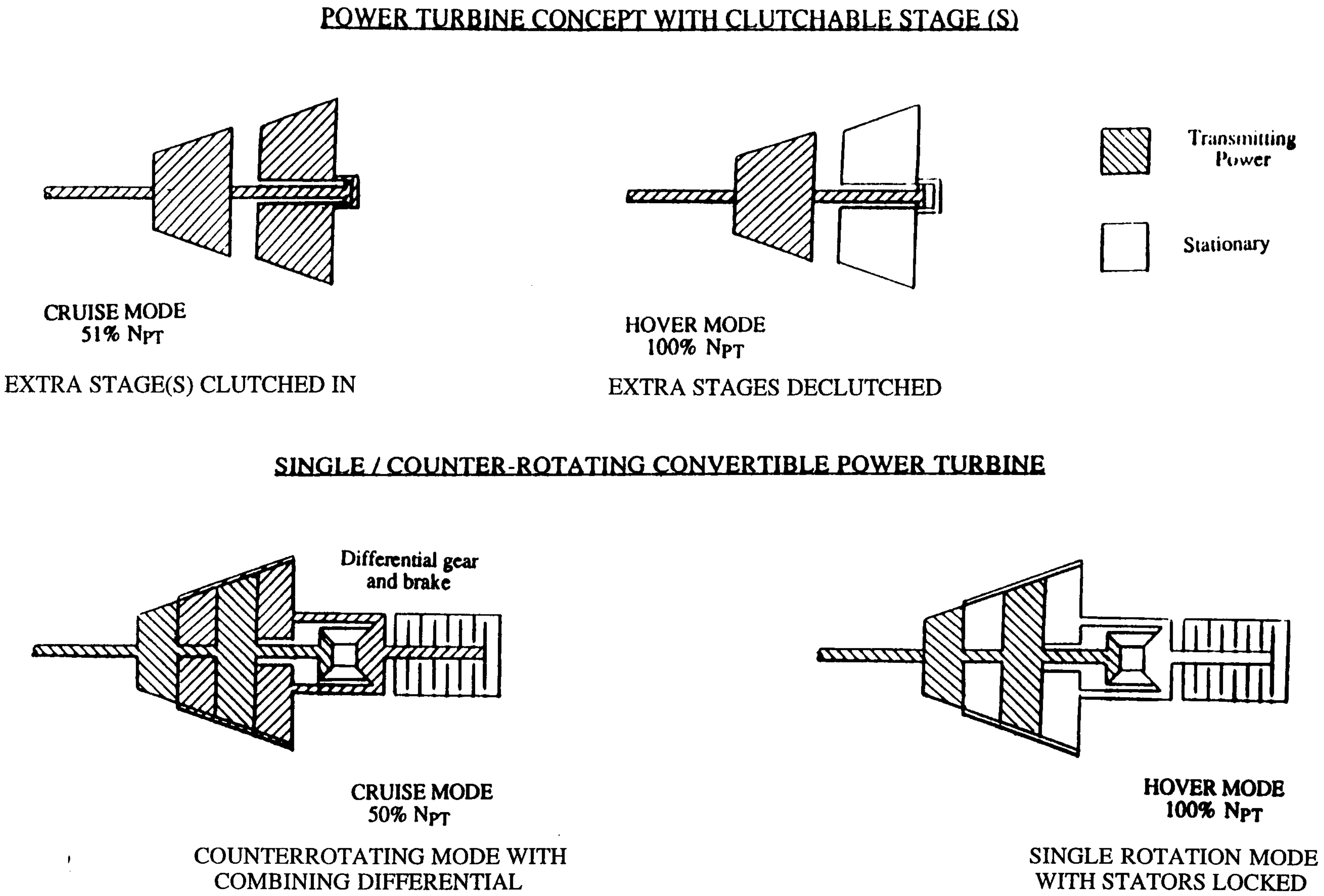
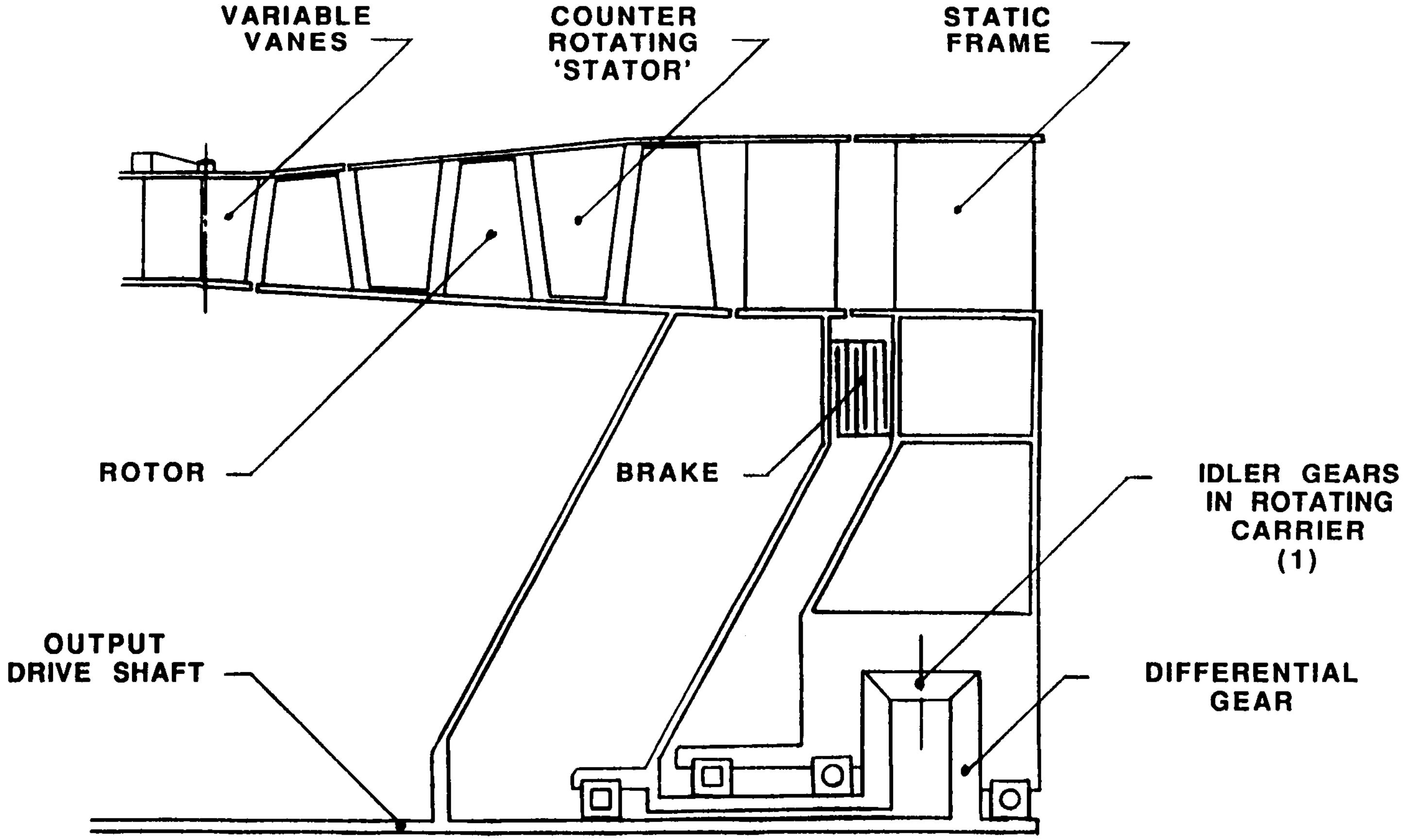


Figure 14. Clutched Power Turbine Concepts.

# SINGLE-TO-COUNTER-ROTATING CONVERTIBLE POWER TURBINE
## CONCEPT SCHEMATIC



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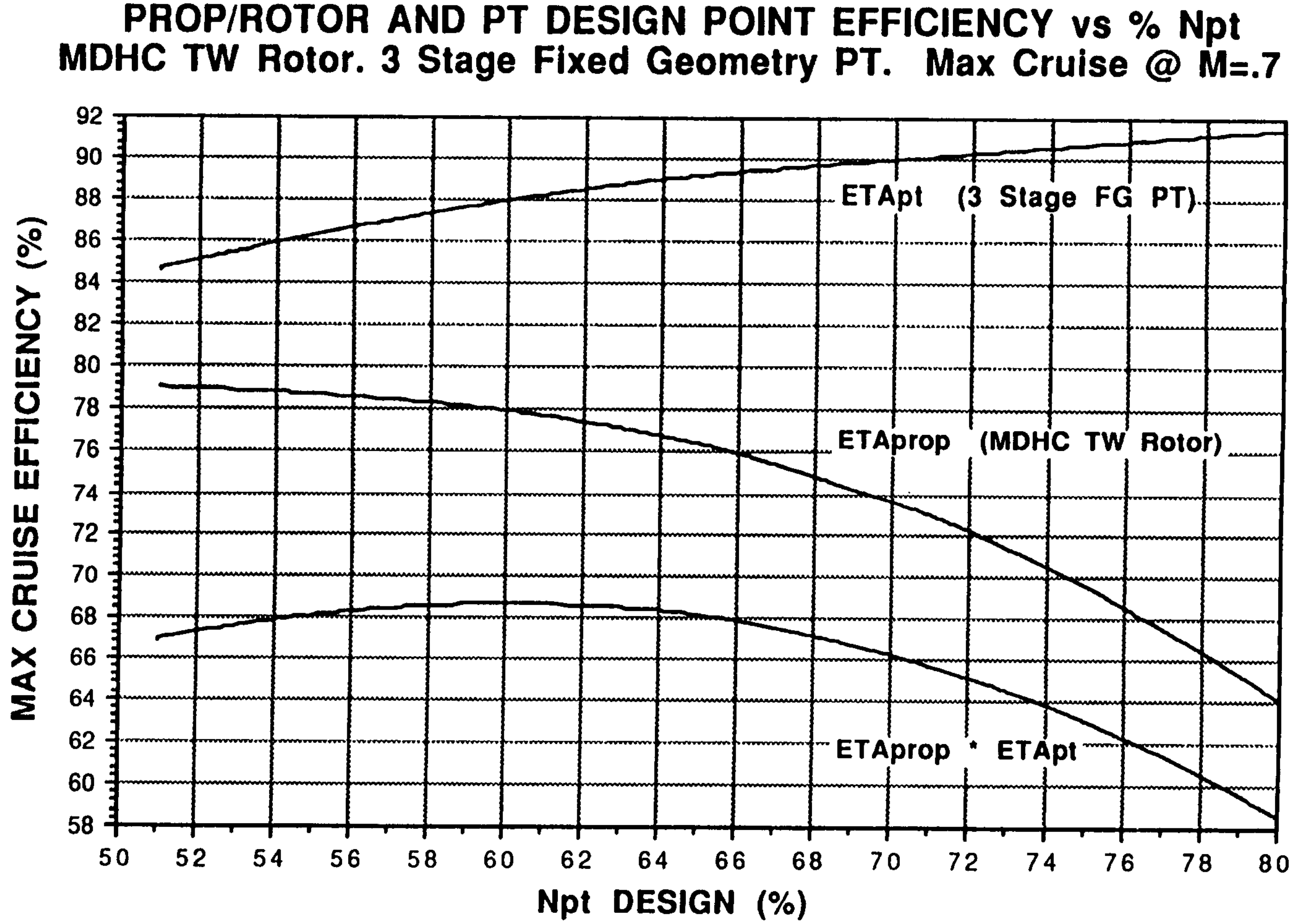
(1) PUTTING A BRAKE ON CARRIER RING IS AN ALTERNATE MEANS OF OBTAINING COUNTER-ROTATION.

Figure 15. Single-To-Counter-Rotating Convertible Power Turbine.

## FIXED GEOMETRY PT WITH SYSTEM OPTIMIZED CRUISE $N_{PT}$



- OPTIMUM CRUISE SYSTEM $N_{PT}$ HEAVILY DEPENDENT ON PROP CHARACTERISTICS, BUT GENERALLY > 51% $N_{PT}$ FOR INCIDENCE TOLERANT FIXED GEOMETRY PT.

Figure 16. Fixed Geometry PT With System Optimized Cruise $N_{PT}$.

TABLE III. WSR CONCEPTS NOT SELECTED FOR FURTHER DEFINITION.

- 4 Stage Single Blade Row Concept: Blade Incidence Swing Too High
- Variable Stator Geometry: No Payoff In This Application
- Variable Rotor Geometry: Too Complex, Heavy, High Risk
- Dual Turbine Flowpaths: Too Heavy, Losses Too High In 100% $N_{PT}$ Mode.
- All Clutched Concepts:
  - Torque Convertor As Yet Unproven At These Torque Density Levels (Risk)
    - Must Have Another Option Available If.TC Not Achieveable In Near Term
  - Primarily A Two Speed Engine. Unlocked Torque Convertor Has High Losses, Heat Rejection

## Preliminary Design Of Selected WSR Turboshaft Concepts

Three WSR PT concepts were chosen for preliminary design based on the results of the screening study: 1) 3 Stage Fixed Geometry PT with Incidence Tolerant Airfoils, 2) 4 Stage PT with Tandem Airfoil Blade Rows, and 3) 3 Stage PT with System Optimized Cruise $N_{PT}$. These power turbine concepts were developed into WSR turboshaft concepts by integrating them with growth GE38 (T407) engine cores. A conventional turboshaft with a 3 stage fixed geometry PT optimized for 80% $N_{PT}$ cruise was also defined. This engine was defined using the same design ground rules as the WSR concepts, and was used as the basis of comparison in evaluating the selected engine concepts. The engine designations of the selected concepts are supplied in Table IV.

TABLE IV. SELECTED WSR TURBOSHAFT CONCEPTS.

| | |
|---|---|
| • GE38 / T2A351 | 3 Stage PT<br>Incidence Tolerant Airfoils<br>51% $N_{PT}$ Cruise |
| • GE38 / T2A451 | 4 Stage PT<br>Tandem Blade Row Design<br>Incidence Tolerant Airfoils<br>51% $N_{PT}$ Cruise |
| • GE38 / T2A362 | 3 Stage PT<br>Incidence Tolerant Airfoils<br>62% $N_{PT}$ Cruise (System Optimized) |
| BASE ENGINE | |
| • GE38 / T2A380 | 3 Stage PT<br>80% $N_{PT}$ Cruise |

All the engine concepts were defined using current technology materials and design codes. No modifications were required to the GE38 core to accommodate the WSR PT's. The GE38 is designed to pass a power shaft through its core of sufficient diameter to handle the high torque resulting from reduced operating speeds. No critical speed problems are anticipated for either low or high $N_{PT}$ operation. The engine cycles were all matched at the max cruise flight condition. The core operating conditions at max cruise are identical for all concepts, so performance differences at cruise are entirely due to the differences in power turbines. While the engine concepts were defined in the nominal GE38 core size, they are scalable over a fairly wide range to meet the performance requirement of various applications. The design assumptions used for the preliminary design are given in Table V. Performance and installation data for all the concepts are given in Table VI.

## TABLE V. DESIGN ASSUMPTIONS

- GE38 Growth Cores, Scalable For Application
- Same Core Corrected Operating Conditions At Cruise For All Concepts
  - Corrected Speed = 98%, Corrected Airflow = 26.5 Lb/S, $T_{41}$ = 2410°F
  - Performance Differences Due To WSR Systems Only, Not Core Differences
- WSR Systems Compatible With GE38 Core. No Mods Required.
- Year 1992 Technology (Materials, Aero Codes) For WSR Components
  - Same Level Of Technology For All PT Designs (Incl. Base)
- All Power Turbines Have Shrouded Blades
- $A_AN^2$ Limit = $50 \times 10^9$ For All Power Turbine Designs
  ($A_AN^2$ = Exit Annulus Area x $N_{PT}^2$. Used As A Root Stress Indicator)

## TABLE VI. SELECTED ENGINE CONCEPT PERFORMANCE.

Nominal GE38 Core Size. Fixed Turbine Geometry
Sized At N2R = 98% At 15K/450/ISA+15°C Max Cruise

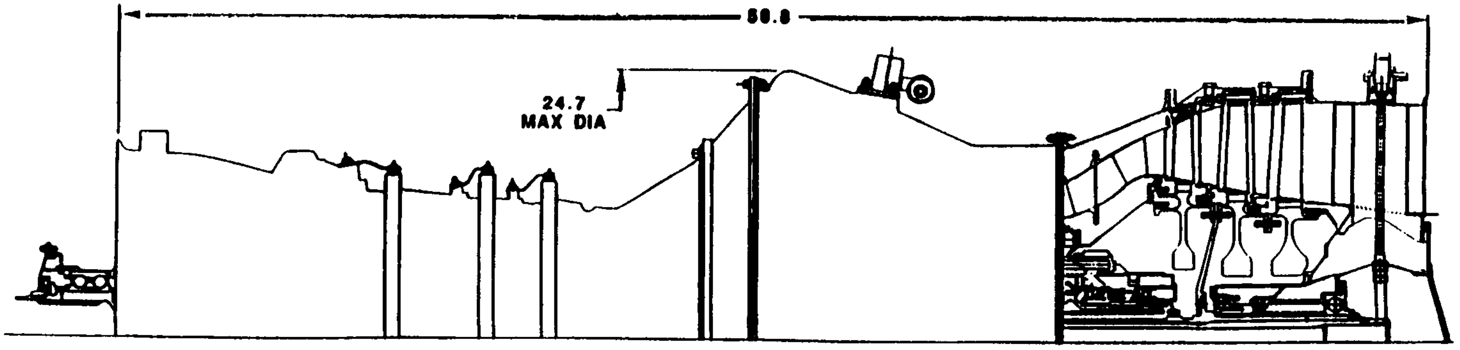
| ENGINE | | GE38/T2A380<br>(BASE) | T2A362 | | T2A351 | | T2A451 | |
|---|---|---|---|---|---|---|---|---|
| Cruise $N_{PT}$ | | 80% | 62% | | 51% | | 51% | |
| # Of PT Stages | | 3 | 3 | | 3 | | 4, Tandem Blades | |
| MAX CRUISE<br>15K/450 Kt/ISA + 15°C<br>T41 = 2410°F | ESHP | 4938 | 4732 | (-4.2%) | 4500 | (-8.9%) | 4677 | (-5.3%) |
| | ESFC | .325 | .34 | (+4.5%) | .357 | (+9.7%) | .344 | (+5.6%) |
| | $\Psi_{PPT}$ | .824 | 1.32 | (+60%) | 1.862 | (+126%) | 1.5 | (+82%) |
| | $\eta_{PT}$ | .914 | .884 | (-3.3%) | .846 | (-7.4%) | .877 | (-4.1%) |
| | $i_{RP}$ | +1° | +10° | | +10° | | +10° | |
| HOVER,<br>CONTINGENCY<br>SLS/ISA + 15°C<br>100% $N_{PT}$ | SHP | 7024 | 6903 | (-1.7%) | 6767 | (-3.7%) | 6786 | (-3.4%) |
| | $\Psi_{PPT}$ | .56 | .57 | | .56 | | .44 | (-21%) |
| | $\eta_{PT}$ | .919 | .907 | (-1.3%) | .888 | (-3.5%) | .90 | (-2.2%) |
| | $i_{RP}$ | -27° | -28° | | -30° | | -45° | |
| ENGINE WEIGHT (Lb) | | 1065 | 1078 | (+1.2%) | 1088 | (+2.2%) | 1170 | (+9.9%) |
| Max Diameter (In) | | 24.7 | 24.7 | | 24.7 | | 24.7 | |
| Overall Length (In) | | 58.8 | 58.8 | | 58.8 | | 62.5 | |

The GE38/T2A351 (Figure 17) was defined with a 3 stage, fixed geometry PT with incidence tolerant airfoil design, optimized for 51% $N_{PT}$ cruise. In a detailed design, GEAE's 3-D aero design codes would be used to optimize the leading edge shape for incidence tolerance, and minimize secondary flow effects. (See Figure 18.) Turbine performance at the two critical flight conditions can be predicted with a good degree of confidence, as blade incidence and turning angle were set within GEAE test experience. Figure 19 is an installation drawing of this concept.

# GE38/T2A351 ENGINE CONCEPT

## WIDE SPEED RANGE TURBOSHAFT

## 3 STAGE PT, 51% $N_P$ CRUISE



**POWER SHAFT**

- 100% RPM = 15000

**CORE**

- GE38 GROWTH CORE
- NOMINAL GE38 CORE SIZE
- NOMINAL CORE FLOW = 28 LB
- NOMINAL $P/P_{OV}$ = 22:1
- MAX POWER T41 = 2520°F
- SIZED @ 98% $N_{2R}$ @ CRUISE

**POWER TURBINE**

- 3 STAGES
- FIXED GEOMETRY DESIGN
- 100% $N_P$ HOVER
- 51% $N_P$ CRUISE
- MAX CRUISE $\eta_{PT}$ = 84.6%

WEIGHT = 1088 LB

Figure 17. GE38/T2A351 Engine Concept.

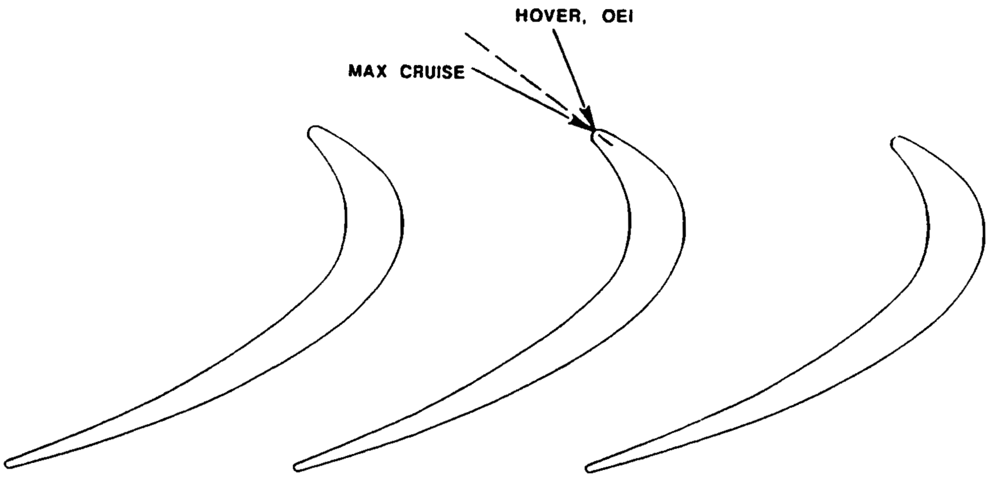


Figure 18. 3 Stage , Incidence Tolerant Airfoil PT Design Representative Blade Row Cross Section.

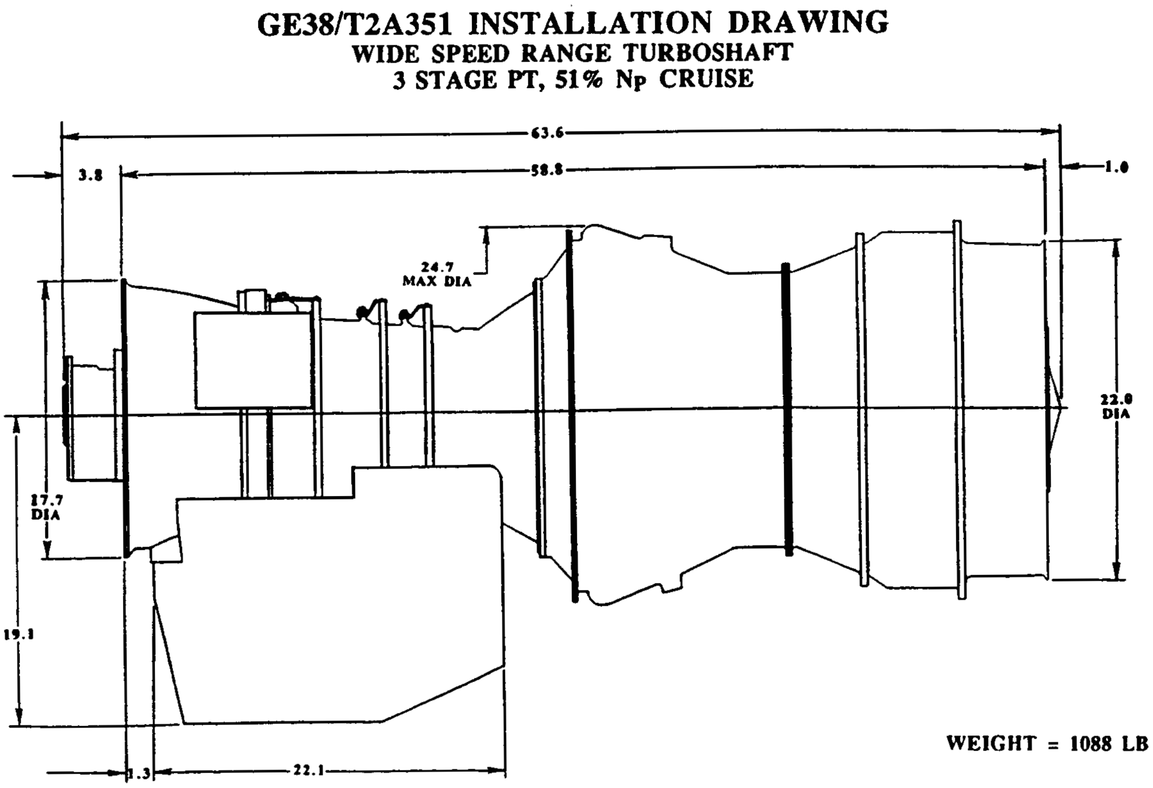


Figure 19. GE38/T2A351 Installation Drawing.

The GE38/T2A362 (Figure 20) has a similar 3 stage, incidence tolerant PT configuration, but was designed to cruise at 62% $N_{PT}$. Cruise $N_{PT}$ was optimized for overall propulsion system efficiency in a parametric study, using design point rotor performance characteristics supplied by MDHS. Cruise $\eta_{PT}$ is 4% better than the T2A351 because the higher $N_{PT}$ reduces turbine loading by 30%. This design represents an even lower risk than the T2A351, as more of the engine operating envelope is within the test database. Figure 21 is an installation drawing of the T2A362.

The GE38/T2A451 (Figure 22) has a 4 stage PT with a unique tandem blade row design (Figure 23). This is a fixed geometry, incidence tolerant design, optimized for 51% $N_{PT}$ cruise. The addition of a fourth stage reduces the turbine stage loading by 20%, yeilding more than 3% higher $\eta_{PT}$ than the T2A351. The added fourth stage also increases the swing in blade incidence between cruise and hover by an additional 15°. The tandem blade row design is intended to control the shift in flow field velocity distribution over this wide range of incidence angles. Engine weight is about 10% heavier than the baseline engine due to the additional PT stage and dual blade row design. Key design features are listed in Table VII. Figure 24 is an installation drawing of this concept.

TABLE VII. TANDEM BLADE CONCEPT: KEY DESIGN FEATURES.

- Tandem Blade Design Is Intended To Help Control Shift In Flow Field Velocity Distribution Over A Wide Range Of Incidence Angles

- Leading Blade Row Airfoil Leading Edge
  - Optimum Size
  - Large Wedge Angle
  - Optimum Inlet Metal Angle (For Particular Application)

- Leading And Following Blade Row Axial And Tangential Coupling Must Be Optimized To:
  1) Minimize Shifting Of Load Distribution Due To Incidence Swing
  2) Reguide And Reattach Separated Flow Into Follower Row
  3) Maintain Good Follower Mach No. Distribution

- GEAE Has The Analytical Tools To Execute A Tandem Blade Design

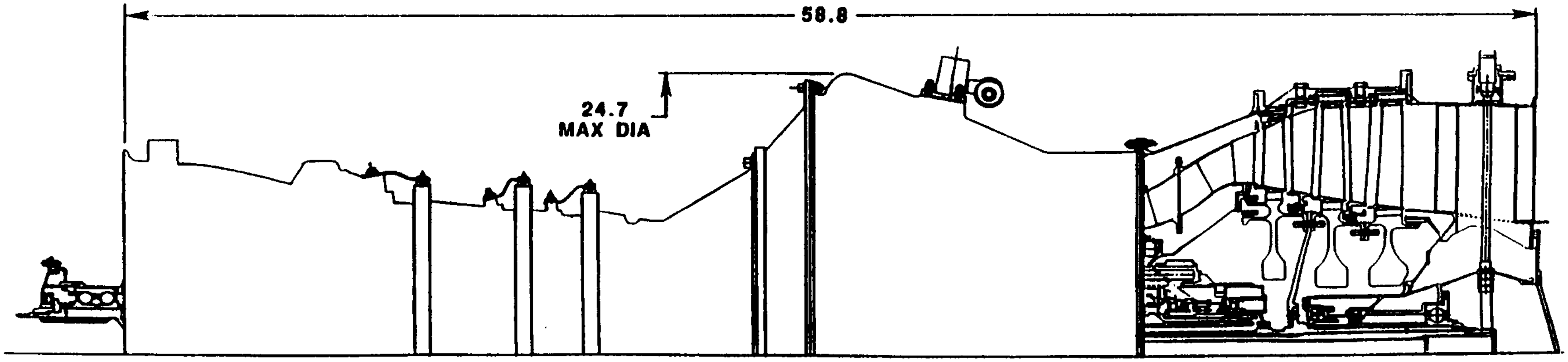
To GEAE's knowledge, a tandem airfoil configuration has never been used to enhance turbine performance at high blade incidence angles. High power operation at these high levels of blade incidence is not within GEAE test experience. This must be considered a higher risk concept, and the performance figures are an estimate of the potential of this design. GEAE possesses aero design and analysis codes that would allow definition and performance prediction of a tandem blade design. While a component test of a full aero design is needed to verify predicted performance, a simple cascade test could be used to validate the basic tandem blade row concept.

The baseline engine concept, the GE38/T2A380, has a 3 stage, fixed geometry PT designed to cruise at 80% $N_{PT}$. (See Figure 25.) This $N_{PT}$ is typical of a modern conventional turboshaft/turboprop in high speed cruise operation. The reduced loading due to the higher turbine speeds results in at least 3% higher $\eta_{PT}$ in cruise than any of the WSR PT concepts. Figure 26 is an installation drawing of the baseline engine concept.

# GE38/T2A362 ENGINE CONCEPT

## WIDE SPEED RANGE TURBOSHAFT

## 3 STAGE PT, 62% $N_P$ CRUISE



**POWER SHAFT**

- 100% RPM = 15000

**CORE**

- GE38 GROWTH CORE
- NOMINAL GE38 CORE SIZE
- NOMINAL CORE FLOW = 28 LB
- NOMINAL $P/P_{OV}$ = 22:1
- MAX POWER T41 = 2520°F
- SIZED @ 98% $N_{2R}$ @ CRUISE

**POWER TURBINE**

- 3 STAGES
- FIXED GEOMETRY DESIGN
- 100% $N_P$ HOVER
- 62% $N_P$ CRUISE
- MAX CRUISE $\eta_{PT}$ = 88.4%

WEIGHT = 1078 LB

Figure 20. GE38/T2A362 Engine Concept.

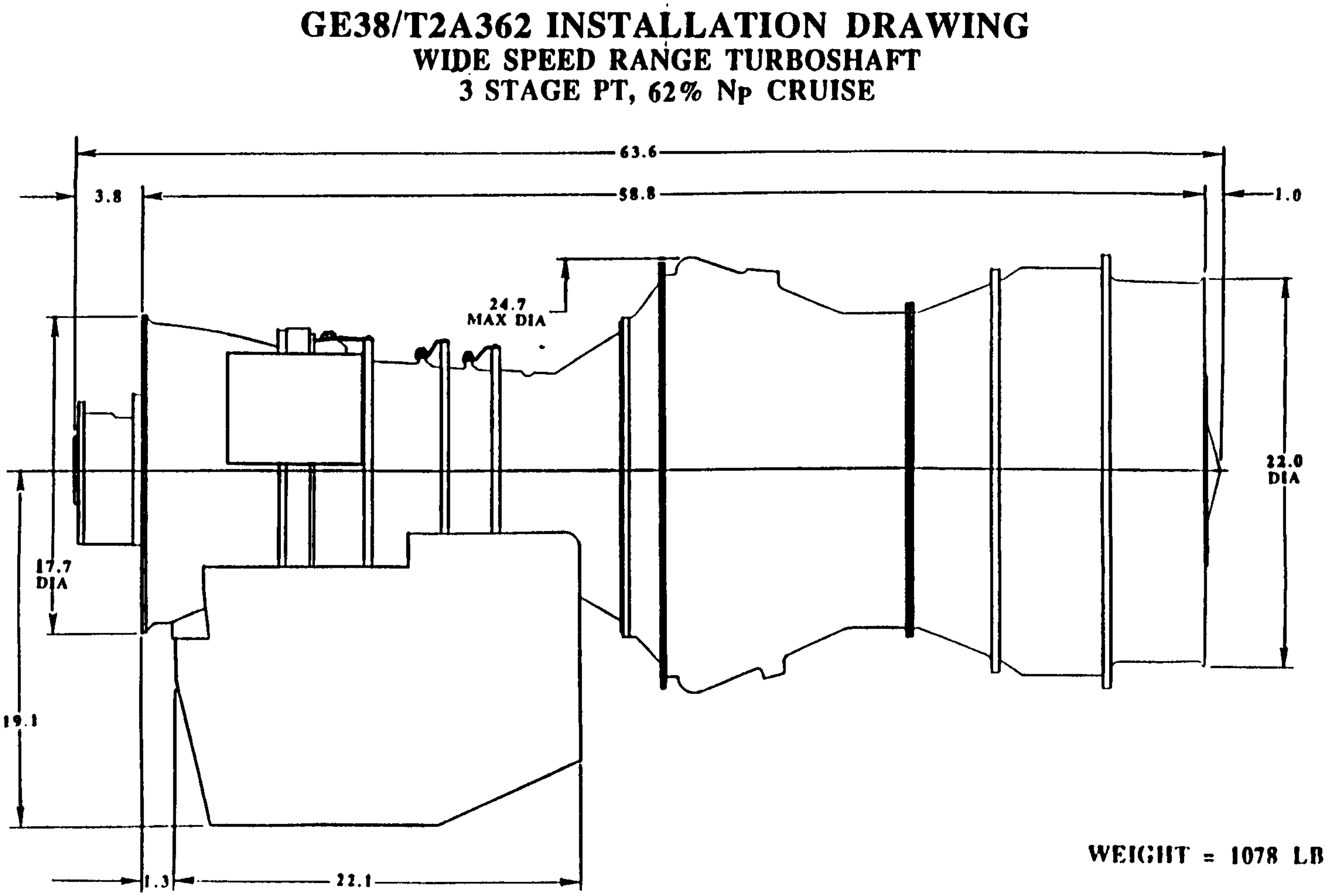
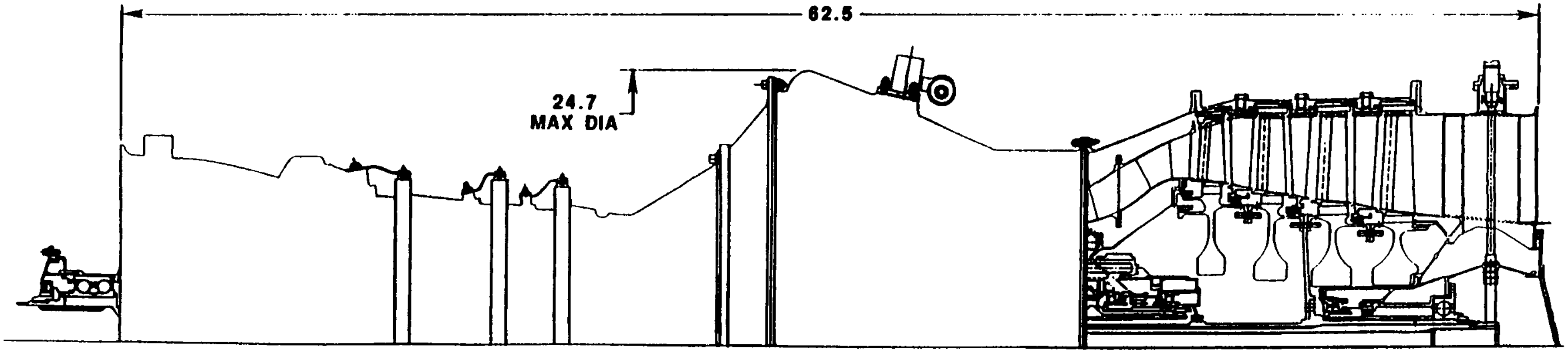


Figure 21. GE38/T2A362 Installation Drawing.

# GE38/T2A451 ENGINE CONCEPT

## WIDE SPEED RANGE TURBOSHAFT
## 4 STAGE, TANDEM AIRFOIL BLADE ROW PT
## 51% $N_P$ CRUISE



**POWER SHAFT**

- 100% RPM = 15000

**CORE**

- GE38 GROWTH CORE
- NOMINAL GE38 CORE SIZE
- NOMINAL CORE FLOW = 28 LB/S
- NOMINAL $P/P_{OV}$ = 22:1
- MAX POWER T41 = 2520°F
- SIZED @ 98% $N_{2R}$ @ CRUISE

**POWER TURBINE**

- 4 STAGES
- FIXED GEOMETRY DESIGN
- TANDEM AIRFOIL BLADE ROWS
- 100% $N_P$ HOVER
- 51% $N_P$ CRUISE
- MAX CRUISE $\eta_{PT}$ = 87.7%

WEIGHT = 1170 LB

Figure 22. GE38/T2A451 Engine Concept.

# TANDEM BLADE ROW PT CONCEPT
## DESIGN FEATURES

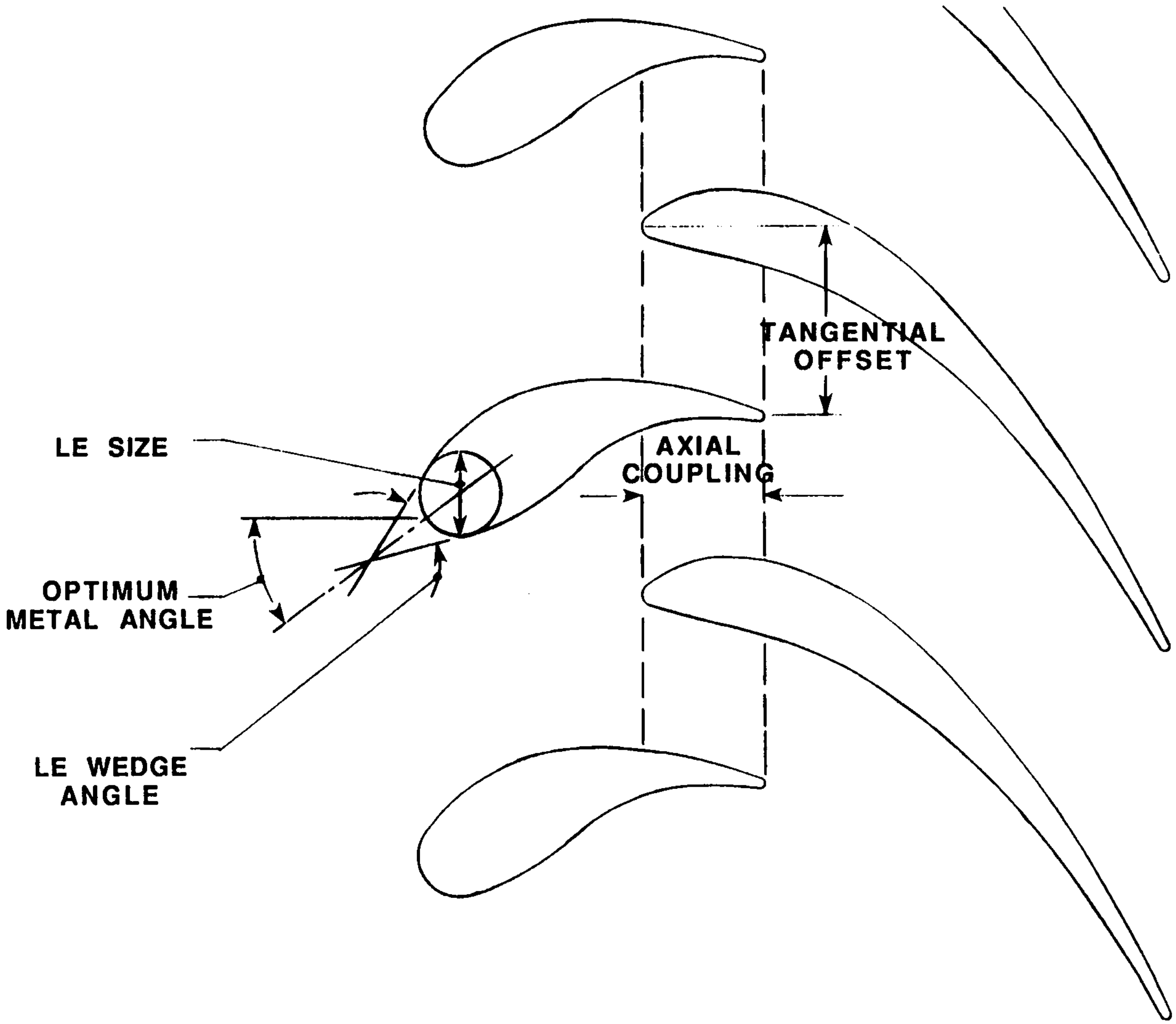
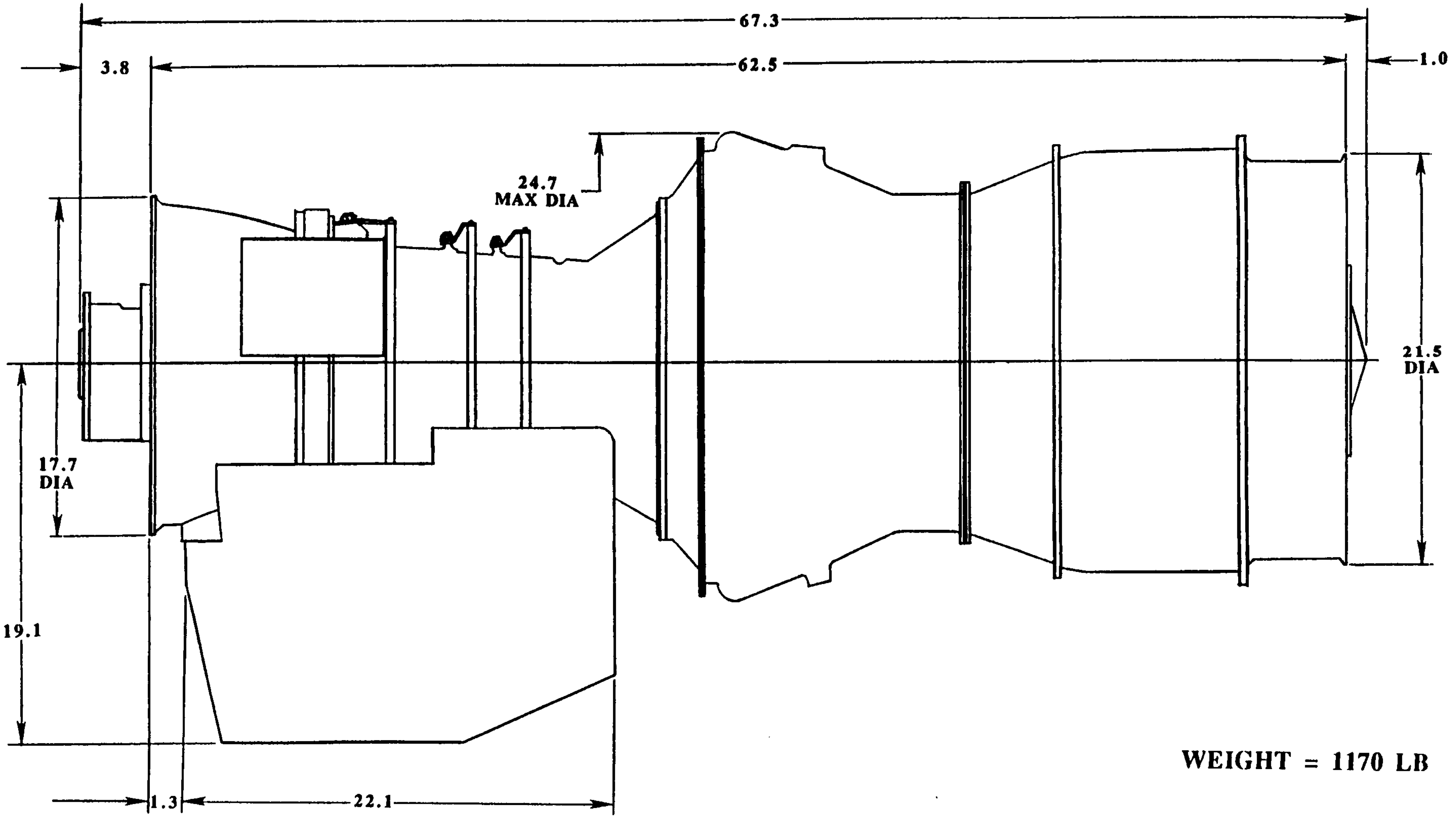


Figure 23. Tandem Blade Row PT Concept.

# GE38/T2A451 INSTALLATION DRAWING
## WIDE SPEED RANGE TURBOSHAFT
## 4 STAGE, TANDEM BLADE ROW PT, 51% $N_P$ CRUISE

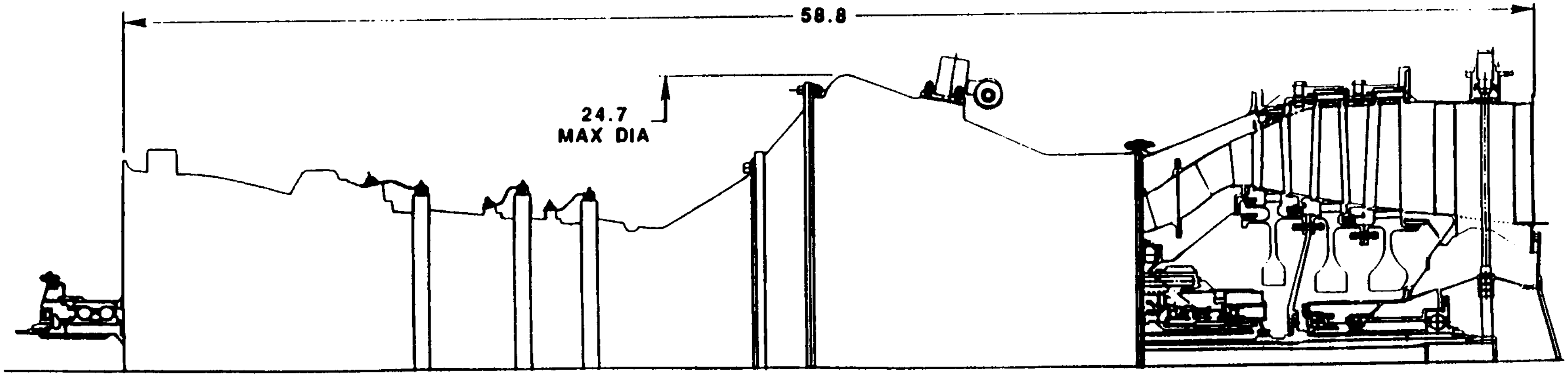


WEIGHT = 1170 LB

Figure 24. GE38/T2A451 Installation Drawing.

# GE38/T2A380 TURBOSHAFT ENGINE

## BASE TURBOSHAFT ENGINE
## 3 STAGE PT, 80% $N_P$ CRUISE



### POWER SHAFT

- 100% RPM = 15000

### CORE

- GE38 GROWTH CORE
- NOMINAL GE38 CORE SIZE
- NOMINAL CORE FLOW = 28 LB/S
- NOMINAL $P/P_{OV}$ = 22:1
- MAX POWER T41 = 2520°F
- SIZED @ 98% $N_{2R}$ @ CRUISE

### POWER TURBINE

- 3 STAGES
- FIXED GEOMETRY DESIGN
- 100% $N_P$ HOVER
- 80% $N_P$ CRUISE
- MAX CRUISE $\eta_{PT}$ = 91.4%

WEIGHT = 1065 LB

Figure 25. GE38/T2A380 Turboshaft Engine.

# GE38/T2A380 INSTALLATION DRAWING

## WIDE SPEED RANGE TURBOSHAFT
## 3 STAGE PT, 80% $N_P$ CRUISE

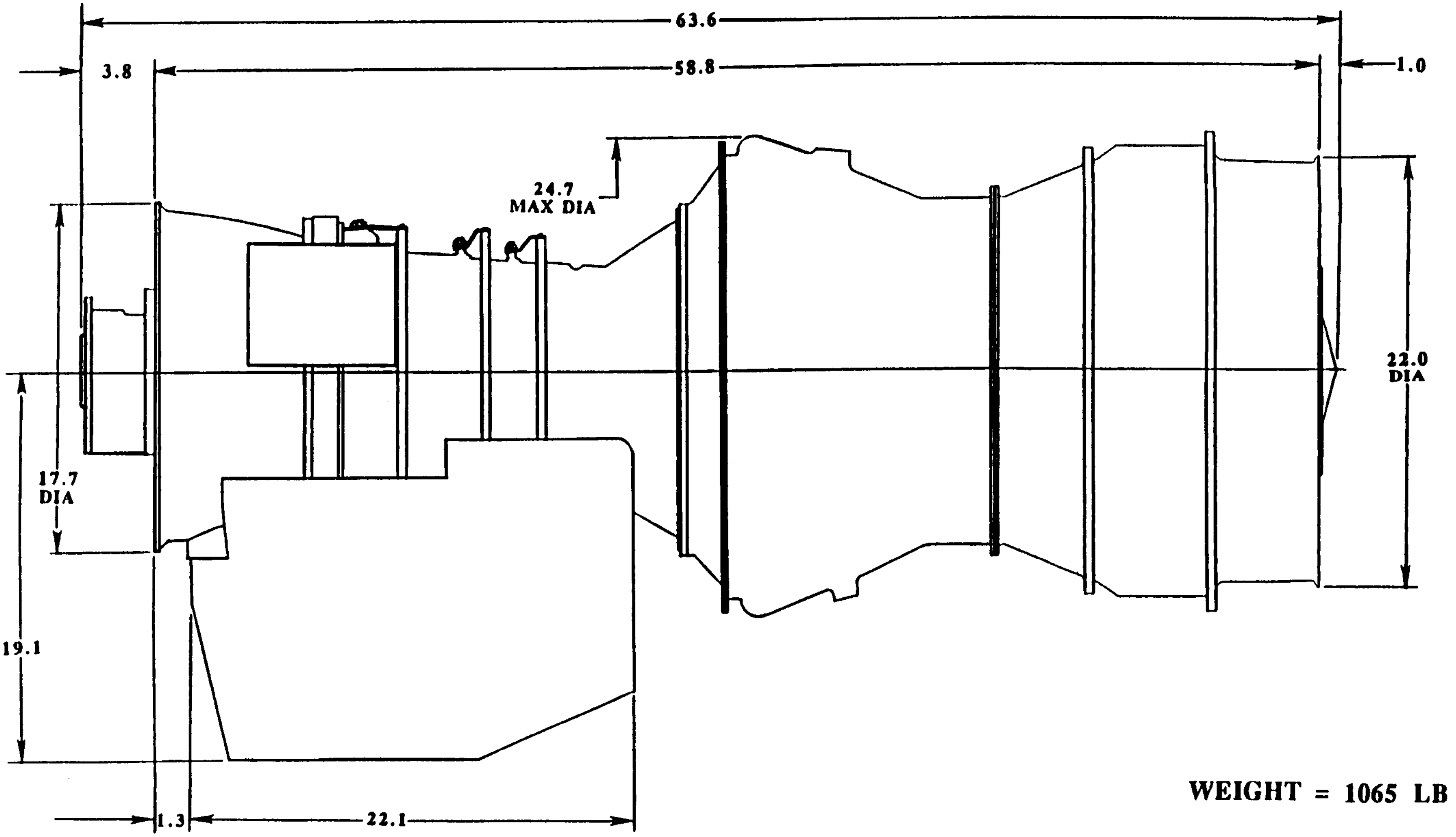


Figure 26. GE38/T2A380 Installation Drawing.

# RESULTS OF SELECTED CONCEPT EVALUATION

## MDHS Military Transport Propulsion System Comparison

The goal of the WSR turboshaft concept is to improve the overall propulsion system cruise efficiency of high speed tilting rotor rotorcraft. The performance of these concepts was evaluated against the baseline engine in the chosen MDHS military transport tiltwing application. The concepts were compared on the basis of overall propulsion system performance. The various engine concepts were scaled to meet the overall propulsion system (engine + proprotor) cruise net thrust requirement of the MDHS tiltwing transport. The results of this "fixed aircraft/rubber engine" comparison are shown in Table VIII. Figure 27 is a graphical representation of the overall propulsion system efficiency in cruise. Shown is the cruise thrust specific fuel consumption (TSFC) based on the combined thrust of the proprotor and engine exhaust nozzle.

The base turboshaft (GE38/T2A380) had to be scaled up 3% to meet the cruise system thrust system thrust requirement. In spite of the best engine performance in cruise, the poor proprotor efficiency at 80% $N_{PT}$ resulted in the largest engine. Cruise TSFC was significantly worse than any of the WSR turboshaft concepts. Scaling the base turboshaft to meet the 80% $N_{PT}$ max cruise requirement results in an engine with 21% more power capability than required for the 100% $N_{PT}$ OEI hover.

TABLE VIII. OVERALL PROPULSION SYSTEM PERFORMANCE COMPARISON.

MDHC Military Transport Tiltwing
Engines Scaled To Meet Fixed System Thrust Requirement Of
9320 Lb At Cruise

| ENGINE | | GE38/T2A380 (BASE) | T2A362 | | T2A351 | | T2A451 | |
|---|---|---|---|---|---|---|---|---|
| Cruise $N_{PT}$ | | 80% | 62% | | 51% | | 51% | |
| # Of PT Stages | | 3 | 3 | | 3 | | 4, Tandem Blades | |
| MAX CRUISE | Rotor ηprop | 64.5% | 77.4% | | 79% | | 79% | |
| 15K/450 Kt | | | | | | | | |
| ISA + 15°C | ESHP Required | 5087 | 4218 | (-17.1%) | 4135 | (-18.7%) | 4135 | (-18.7%) |
| | Core Scale Factor | 1.03 | .891 | (-13.5%) | .919 | (-10.8%) | .884 | (-14.2%) |
| | Cruise Fuel Burn (Lb/H) | 1655 | 1431 | ( " ) | 1476 | ( " ) | 1420 | ( " ) |
| | System Thrust SFC | .710 | .615 | ( " ) | .634 | ( " ) | .610 | ( " ) |
| HOVER, T/O | Hover Fuel Burn (Lb/H) | 1415 | 1408 | (-.5%) | 1423 | (+.5%) | 1400 | (-1%) |
| SLS/ISA + 15°C | | | | | | | | |
| 100% $N_{PT}$ | OEI ESHP Margin | 21% | 3% | | 4% | | 4% | |
| SCALED ENGINE WEIGHT (LB) | | 1097 | 960 | (-12.5%) | 1000 | (-8.8%) | 1034 | (-5.7%) |
| Scaled Engine Dia. (In) | | 25.1 | 23.3 | | 23.7 | | 23.2 | |
| Scaled Engine Length (In) | | 59.6 | 55.8 | | 56.6 | | 59.1 | |

The 3 stage incidence tolerant blade WSR concept designed to cruise at 51% $N_{PT}$ (GE38/T2A351) meets the cruise power requirements when scaled to 92% of its nominal core size. This results in an engine that is significantly lighter and more compact than the base turboshaft. The real payoff is the 10% improvement in cruise propulsion system efficiency compared to the base engine/rotor combination. This WSR engine concept has 3% power margin at the hover, OEI. In normal hover operation, this design has a fuel burn rate similar to the base engine.

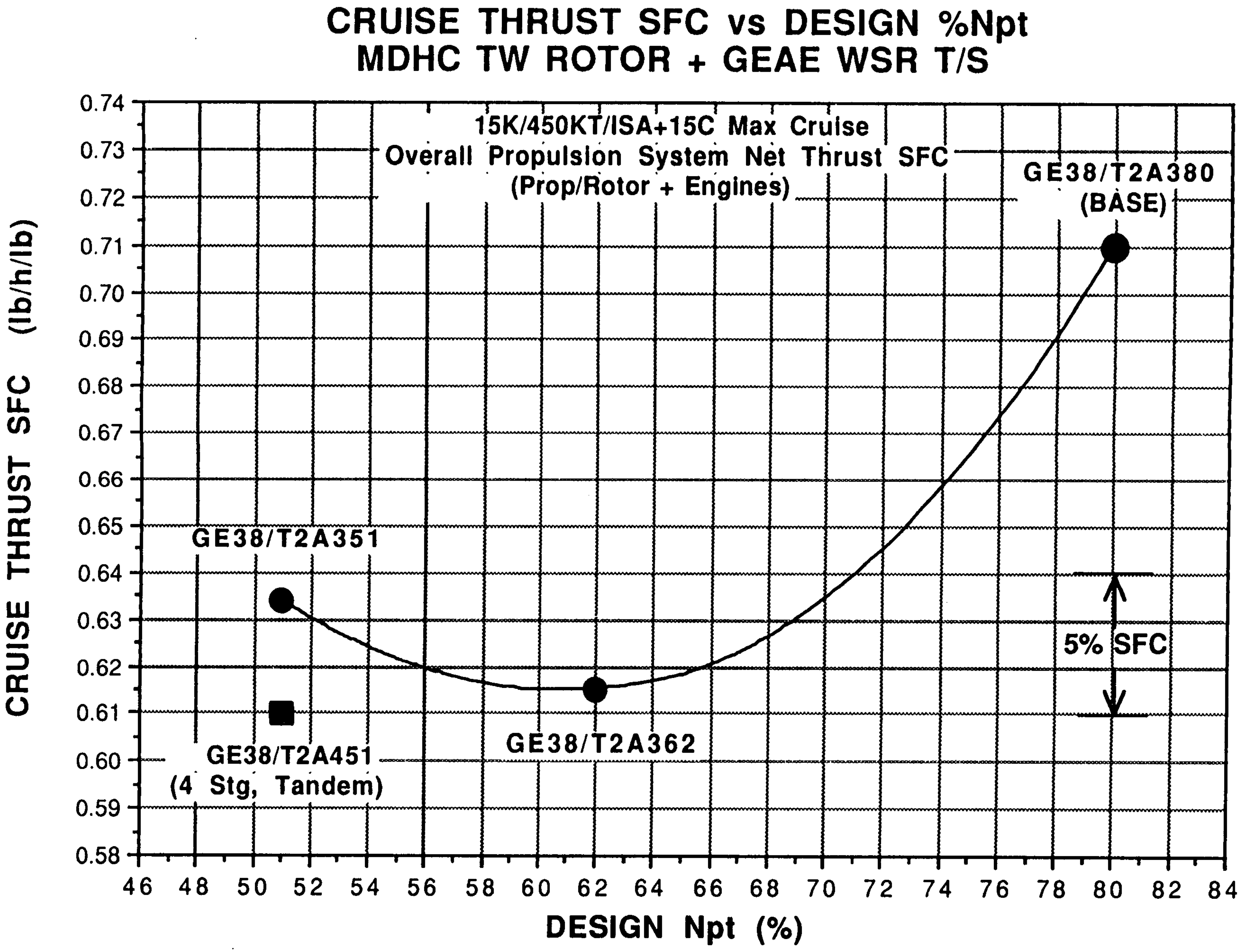


Figure 27. Cruise Thrust SFC Versus Design % Npt.

The GE38/T2A451 4 stage tandem blade engine concept shows a potential 14% improvement in cruise overall propulsion system efficiency compared to the base turboshaft. Even though the 4 stage tandem bladed PT is a heavy power turbine design, the engine is 5% lighter than the base turboshaft when scaled to meet the cruise propulsion requirements. When scaled to meet the cruise requirement, this concept meets the hover, OEI power requirement almost exactly. Fuel burn rate for normal takeoff is similar to the base turboshaft.

The GE38/T2A362 3 stage PT engine concept designed for 62% $N_{PT}$ cruise has 13% better cruise propulsion system efficiency than the base turboshaft. This engine concept has overall propulsion system thrust SFC within 1% of the 4 stage tandem design (see Figure 27), but is significantly lighter. Scaled to meet the cruise requirement, this engine is 12% lighter than the base engine. Hover SFC is similar to the base engine.

For this application, these WSR turboshaft concepts all offer significant improvements in cruise propulsion system efficiency and scaled engine weight compared to a conventional turboshaft.

## Civil Transport Mission Analysis of Selected Engine Concepts

Given the current emphasis on high speed rotorcraft for civil transport, GEAE decided to show the benefits of these engine concepts for civil applications. This evaluation was a first order "rubber engine/rubber aircraft" mission analysis. GEAE developed a civil transport based on the MDHS tiltwing. This was a 30 passenger aircraft with similar drag and rotor characteristics to the MDHS aircraft. The mission is a civil transport mission specified by NASA Ames for its HSRC studies. Study ground rules and mission profile are given in Table IX and Figure 28 respectively.

TABLE IX. GEAE CIVIL TRANSPORT TILTWING (MISSION/AIRCRAFT ANALYSIS).

- First Order, Rubber Aircraft/Rubber Engine Mission Analysis
- Civil Transport Tiltwing Based On MDHC Military Transport TW
  - 30 Pax, 4 Engine, 2 Rotor Transport
  - Same Disk Loading, Prop Characteristics As MDHC TW
  - Drag And Gross Weight Matched To MDHC TW At Cruise For Base Case

- NASA Ames HSRC Study Civil Transport Mission
  - Ames $V_{cruise}$, Range, Payload, Fixed Weight. Entire Mission At ISA +15°C
  - Civil Transport Mission Easier To Simulate => More Accurate Results

The three WSR turboshaft concepts showed significant benefits in reducing mission fuel burn and aircraft gross weight. The GE38/T2A351 reduced aircraft weight 9%, fuel burn 15%, and scaled engine weight 12% versus the baseline engine with its 80% $N_{PT}$ cruise. (See Table X.) The GE38/T2A451 4 stage tandem blade concept reduced fuel burn 17%, and scaled engine weight is 9% lighter than the baseline despite a heavier turbine design. The GE38/T2A362 with its system optimized PT gave the best results. Aircraft weight was reduced 12%, fuel burn reduced 18%, and scaled engine weight reduced 17% compared to an aircraft sized with the conventional turboshaft. While this analysis was performed using a tiltwing, the improved propulsion system cruise efficiency should similarly benefit a tiltrotor.

Civil Transport Mission

Entire Mission At ISA + 15°C
6000 lb Payload
5425 Lb Fixed Weight (Excluding Payload)

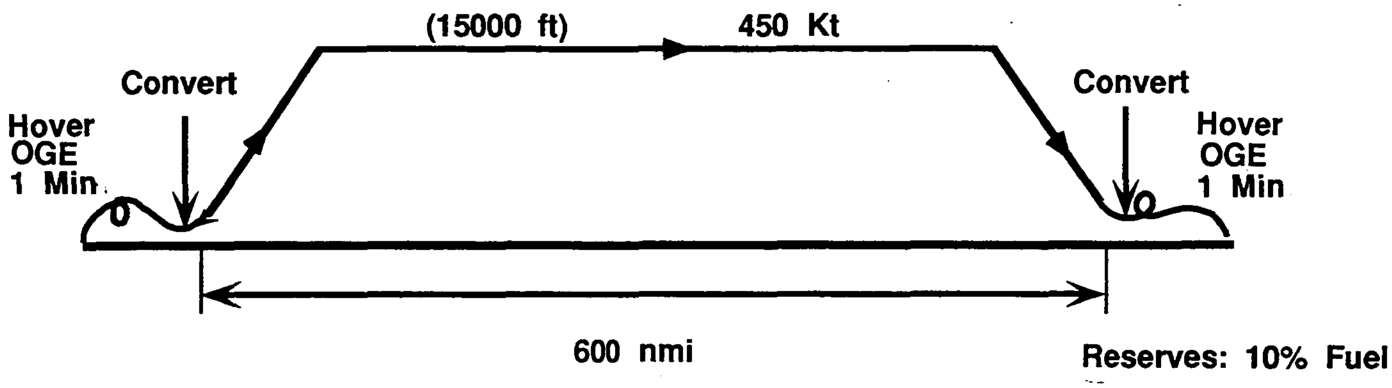


Figure 28. Civil Transport Mission.

TABLE X. MISSION ANALYSIS.

WSR Concepts In GEAE Civil Transport Tiltwing
(First Order, Rubber Engine/Rubber Aircraft Analysis)

| ENGINE | GE38/T2A380 (BASE) | T2A362 | | T2A351 | | T2A451 | |
|---|---|---|---|---|---|---|---|
| Cruise $N_{PT}$ | 80% | 62% | | 51% | | 51% | |
| # Of PT Stages | 3 | 3 | | 3 | | 4, Tandem | |
| AIRCRAFT | | | | | | | |
| Fixed Weight (Lb) | 5425 | 5425 | | 5425 | | 5425 | |
| Payload | 6000 | 6000 | | 6000 | | 6000 | |
| Scaled TOGW | 52534 | 46321 | (-11.8%) | 47751 | (-9.1%) | 47836 | (-8.9%) |
| Mission Fuel Burn | 8462 | 6936 | (-18%) | 7226 | (-14.6%) | 6989 | (-17.4%) |
| ENGINES | | | | | | | |
| Core Scale Factor | .989 | .811 | | .848 | | .817 | |
| Hover, OEI Margin | +23% | +22% | | +10% | | +6% | |
| Scaled Engine Weight | 1053 | 874 | (-17%) | 923 | (-12.3%) | 956 | (-9.2%) |

## Engine Shop Cost Comparison

GEAE also conducted a proprietary study to evaluate the production cost of these engine concepts versus a conventional turboshaft. The figure shown are shop costs and due not include engine development costs. The relative shop costs shown in Figure 11 are normalized by the cost of the baseline turboshaft engine. The 3 stage WSR engine concepts are both less than 1% more expensive to produce than the baseline engine. Part count and manufacturing difficulty are similar to the baseline engine. The added cost is mostly due to the additional material in these slightly heavier engines. The 4 stage tandem blade design has about 8% higher shop cost due to added weight and complexity of the tandem blade rows.

Relative engine costs were also assessed for the scaled engines in the civil transport mission analysis above. The WSR turboshaft concepts scaled to meet the mission requirements all had lower shop costs than the baseline engine. (See Table XI.)

TABLE XI. WSR TURBOSHAFT RELATIVE ENGINE SHOP COST.
(Does Not Include Development Costs)

| ENGINE | GE38/T2A380 (BASE) | T2A362 | | T2A351 | | T2A451 | |
|---|---|---|---|---|---|---|---|
| Cruise $N_{PT}$ | 80% | 62% | | 51% | | 51% | |
| # Of PT Stages | 3 | 3 | | 3 | | 4, Tandem | |
| RELATIVE COST | | | | | | | |
| Full Scale Cores | 1.0 | 1.005 | | 1.009 | | 1.076 | |
| Scaled For GEAE Tiltwing | 1.0 | .919 | (-8.1%) | .942 | (-5.8%) | .988 | (-1.2%) |

## Key WSR Turboshaft Technologies And Development Needs

The main critical technologies or areas of risk for these concepts center around the high blade incidence angles at 100% $N_{PT}$ operation. Both the 3 stage PT designs are within GEAE design and test experience at the two critical operating conditions. The 4 stage tandem blade row PT concept is unproven, and the performance predicted at hover, OEI may be difficult to achieve with the calculated 45° of blade incidence. In addition, blade incidence increases significantly at 100% $N_{PT}$ operation and lower power setting for all the WSR PT concepts. Blade incidence angles can become enormous at these lower power settings, especially for the 4 stage design. For the concepts designed for 51% $N_{PT}$ cruise, part power performance may be very poor at 100% $N_{PT}$ operation due to massive flow separation at these large incidence angles. Of even greater concern, these extreme blade incidence angles could pose serious aeromechanic problems, especially if the mission calls for extended low power 100% $N_{PT}$ operation.

The key technologies and development needs are listed in Table XII. For the tandem blade row concept, a full aero design and component test is needed to prove the validity of this concept, and to verify and calibrate the performance predictions of the aero codes. The performance at 100% $N_{PT}$ operation and lower power setting for all the selected concepts would similarly have to be verified. A cascade test is a relatively low cost way of validating the basic concepts to see if they merit further development.

TABLE XII. KEY TECHNOLOGIES/DEVELOPMENT NEEDS

Tandem Blade Row PT Concept
- Tandem Airfoil Performance At Cruise And Hover, OEI
  - Concept Not Yet Demonstrated For Incidence Control

All WSR Turboshaft Concepts
- Far Off Design Performance And Aeromechanics
  - Extremely High Blade Incidence At 100% $N_{PT}$/Low Power
  - Extended 100% $N_{PT}$/ Low Power Operation Is Aeromechanics Concern (Application Dependent)

HSRC With Max Cruise Velocity <400 Kt
- Hover OEI Power Capability
  - High Contingency Power Rating Required To Prevent Engine Being Sized By Hover OEI Requirement

Another key propulsion technology for HSRC turboshafts is contingency power capability for hover, OEI. The contingency power margin in this study was specified by NASA and is about 20% over a normal takeoff rating. With this definition of contingency power, all the engine concepts in this study had adequate power to hover on one engine in the given applications. This is a relatively high power rating, however, and will require technology development. It also must be remembered that the chosen application has a 450 kt cruise speed, and the propulsion system is sized for the high level of thrust required at high speed. Studies indicate that for HSRC with cruise speeds of 400 kt or less, the engines are generally sized by the power required to hover on one engine. A contingency power development program is needed to insure emergency hover capability will be available for civil applications.

## Other WSR Turbine Technology Applications

The incidence tolerant blade designs of these WSR PT concepts also have potential applications other than HSRC propulsion. GEAE has had several customers request turboprop engines designed to cruise efficiently at 75% of takeoff $N_{PT}$. The intended applications were commuter turboprops with cruise speeds of 300 kt or less. Customers have indicated that as turboprop cruise speeds rise, cruise $N_{PT}$ needs to be reduced even further. While reduced cruise $N_{PT}$ would benefit propeller efficiency, the main reason customers requested reduced cruise $N_{PT}$ is to reduce cabin noise for passenger comfort. As desired cruise $N_{PT}$ is reduced the propulsion requirements of future high speed civil turboprops could pose similar challenges in turbine blade loading and incidence swing as HSRC.

Incidence tolerant blade designs could also enhance the off-design performance of turboshafts in helicopter applications. Turboshafts in helicopters always operate at or near 100% $N_{PT}$, but run high blade incidence angles at key operating conditions. Helicopters need contingency power for hot day hover OEI, yet the key operating condition for fuel consumption is at approximately 40% of this power. This wide range in critical operating conditions can result in a large swing in blade incidence angles. An incidence tolerant PT design could help to improve performance over a larger portion of the turboshaft operating range in helicopter applications.

This technology could also be used in developing a “dual use” turboprop/turboshaft. There is a large disparity in the operating conditions at which SFC is important in a civil turboprop (high power, low $N_{PT}$) versus a military turboshaft (low power, high $N_{PT}$). Normally a common engine core is used for both civil turboprop and military turboshaft applications. For optimum performance in each application, a dedicated PT design would have to be defined for each of the diverse set of propulsion requirements. A single WSR PT design could be designed that would give good performance in both types of applications. This "dual use" unified turboprop/turboshaft PT design would not only provide commonalty, but would reduce effective engine development time and cost. Potential applications for this technology are summarized in Table XIII.

TABLE XIII. OTHER WSR TURBINE TECHNOLOGY APPLICATIONS.

- High Speed Cruise Noise Reduction, Efficiency (Turboprop)
  - Airframers Currently Request 75% $N_{PT}$ Cruise
- Better Off-Design Performance (Helicopter)
  - Helicopters Often Cruise At 40% To 50% Power At 100% $N_{PT}$
  - High Performance Over Wide Power Range
- Unified Turboprop/Turboshaft Power Turbine Design
  - Use Same PT Design For Both Applications
  - Savings In PT Development Time/Cost
  - Range In Requirements Is As Challenging As High Speed Rotorcraft
    - Turboprop Requires Good High Load/Low $N_{PT}$ Performance
    - Helicopter Requires Good Low Load/High $N_{PT}$ Performance

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**13. ABSTRACT** ***(Maximum 200 words)***

NASA-Lewis and NASA-Ames have sponsored a series of studies over the last few years to identify key high speed rotorcraft propulsion and airframe technologies. NASA concluded from these studies that for near term aircraft with cruise speeds up to 450 kt, tilting rotor rotorcraft concepts are the most economical and technologically viable. The propulsion issues critical to tilting rotor rotorcraft are: 1) high speed cruise propulsion system efficiency, and 2) adequate power to hover safely with one engine inoperative. High speed cruise propeller efficiency can be dramatically improved by reducing rotor speed, yet high rotor speed is critical for good hover performance. With a conventional turboshaft, this wide range of power turbine operating speeds would result in poor engine performance at one or more of these critical operating conditions. This study identifies several wide speed range turboshaft concepts, and analyzes their potential to improve performance at the diverse cruise and hover operating conditions. Many unique concepts were examined, and the selected concepts are simple, low cost, relatively low risk, and entirely contained within the power turbine. These power turbine concepts contain unique, incidence tolerant airfoil designs that allow the engine to cruise efficiently at 51% of the hover rotor speed. Overall propulsion system efficiency in cruise is improved as much as 14%, with similar improvements in engine weight and cost. The study is composed of a propulsion requirement survey, a concept screening study, a preliminary definition and evaluation of selected concepts, and identification of key technologies and development needs. In addition, a civil transport tilting rotor rotorcraft mission analysis was performed to show the benefit of these concepts versus a conventional turboshaft. Other potential applications for this technology are also discussed.

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