Investigation of Exoskeletal Engine Propulsion System Concept

Joseph M. Roche, Donald T. Palac, James E. Hunter, David E. Myers, and Christopher A. Snyder
Glenn Research Center, Cleveland, Ohio

Daniel N. Kosareo
ZIN Technologies, Inc., Brook Park, Ohio

David R. McCurdy and Kevin T. Dougherty
QSS Group, Inc., Cleveland, Ohio
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:


- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076
Investigation of Exoskeletal Engine Propulsion System Concept

Joseph M. Roche, Donald T. Palac, James E. Hunter, David E. Myers, and Christopher A. Snyder
Glenn Research Center, Cleveland, Ohio

Daniel N. Kosareo
ZIN Technologies, Inc., Brook Park, Ohio

David R. McCurdy and Kevin T. Dougherty
QSS Group, Inc., Cleveland, Ohio

National Aeronautics and Space Administration

Glenn Research Center

August 2005
Acknowledgments

The authors wish to acknowledge the assistance of those who aided in the preparation of this document. Christos C. Chamis, Christopher Dellacorte, and Andrew J. Provenza of NASA Glenn Research Center provided information on technologies and systems that constitute the exoskeletal engine concept. Louis M. Larosiliere provided information on turbomachinery aerodynamics and its application to the exoskeletal design. David Cherry, Eric Estill, Ken Willgoose, and Rob Beacock of General Electric Aircraft Engines mined the archives for data on a concept with some precedence for an exoskeletal design, the unducted fan. Ian Halliwell of Modern Technologies Corporation provided background and the results of previous exoskeletal engine preliminary design studies. Reza N. Zinolabedini provided NASTRAN eigenvalue buckling solutions for the stationery core structure under compressive thrust loading.

---

Trade names or manufacturers’ names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

This work was sponsored by the Low Emissions Alternative Power Project of the Vehicle Systems Program at the NASA Glenn Research Center.

---

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov
Investigation of Exoskeletal Engine Propulsion System Concept

Joseph M. Roche, Donald T. Palac, James E. Hunter, David E. Myers, and Christopher A. Snyder
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Daniel N. Kosareo
ZIN Technologies, Inc.
Brook Park, Ohio 44142

David R. McCurdy and Kevin T. Dougherty
QSS Group, Inc.
Cleveland, Ohio 44135

Summary

An innovative approach to aircraft gas turbine engine design that was disclosed in 1997 involves mounting compressor and turbine blades to an outer rotating shell. Designated the exoskeletal engine, the concept results in compression (especially preferable to tension for high-temperature ceramic materials, generally) as the dominant compressor and turbine blade force.

It was determined that the feasibility of an exoskeletal engine lay in the challenges of structural and mechanical design (as opposed to cycle or aerothermodynamic design), so the focus of this study was the development of a structural-mechanical definition of an exoskeletal concept, using the Rolls-Royce AE3007 regional airliner all-axial turbofan as a baseline. The effort was further limited to the definition of an exoskeletal high-pressure spool concept, where the major structural and thermal challenges are represented. A finite-element model of an exoskeletal engine high-pressure spool shell and bearing support structure was developed. Loads and deflections were calculated and were compared with material strengths at the temperatures expected for each portion of the shells. Magnetic and foil bearing system concepts were also defined. The mass of the high-pressure spool was calculated and compared with the mass of the comparable components of the AE3007 engine. It was found that the exoskeletal engine rotating components have the potential for significant weight savings over the rotating components of conventional engines. However, bearing technology development is required for this mass savings to emerge at an engine system level, since the mass of existing bearing systems would exceed rotating machinery mass savings. It is recommended that once bearing technology is sufficiently advanced, a “clean sheet” preliminary design of an exoskeletal system be accomplished. This design would take best advantage of exoskeletal engine features from the structural, mechanical, aerodynamic, thermal, and engine cycle perspectives. This will better quantify the potential for the exoskeletal concept to deliver benefits in mass, structural efficiency, and cycle design flexibility.

Introduction

To improve conventional turbine and compressor designs, it is hypothesized that ceramic materials would provide greater operating efficiency through higher operating temperatures and lighter engine weight. Some problems with ceramic materials are lower tensile strength and durability and damage tolerance when compared with refractory metals and nickel-based alloys, such as titanium, Hastelloy™ and Waspaloy™ that are currently used in conventional engines. Ceramics behave well in compressive loading situations where brittle fracture is minimized. A novel turbine design approach that relies on this characteristic of ceramic composites is the exoskeletal engine (Christos C. Chamis, August 9, 2002,
NASA Glenn Research Center, Cleveland, OH, personal communication), which was disclosed by Christos Chamis of NASA Glenn Research Center (GRC) in 1997. The exoskeletal concept exchanges the conventional internal rotating shaft with a stator and the stator with a rotating drum. Essentially, this concept turns a conventional gas turbine engine inside out. A cross-sectional diagram of an early conceptual exoskeletal engine configuration is shown in figure 1.

The exoskeletal engine does not in principle represent an engine cycle change, although cycle parameters could be affected somewhat in implementation. Rather, the exoskeletal concept deals primarily with engine structural and mechanical design. Some of the characteristic differences from conventional engine technology are as follows:

(1) Compressor and turbine blades are mounted to the inside of a drum rotor. Stators and combustors are mounted to a stationary hub. Blades are in compression instead of tension because of rotational inertia. Torque is transferred from turbines to compressors through the rotating drums.

(2) The drum rotor is supported by bearings between the outside of the rotor and an outer shell. In a multispool engine, the high-pressure drum rotor bearings may ride directly on the low-pressure spool drum rotor. In a partially exoskeletal engine, thrust and other forces are transferred through bearings between drum rotors and shells or hubs.

(3) For engines of sufficient size, a central core space (inside the stator rings) may be open (see fig. 2).

The motivations for considering an exoskeletal engine have included the opportunity to

(1) Reduce the part count and engine weight, achieve higher engine operating temperatures (or reduce/eliminate cooling), and increase component life through use of lightweight composite materials (particularly ceramic blades in compression and rotating wound shells under hoop stresses) in applications that are aligned with their strengths

(2) Reduce engine noise through management of the resulting inverted velocity profile (central flow velocity lower than surrounding flow velocity)

(3) Insert another engine cycle, such as a ramjet, into the open core space

---

Figure 1.—Exoskeletal engine concept projected view of exoskeletal engine composite fan rotor (from Christos C. Chamis, August 9, 2002, NASA Glenn Research Center, Cleveland, OH, personal communication).
Related Prior Efforts

**General Electric unducted fan.**—The General Electric unducted fan (UDF), developed as part of NASA’s advanced turboprop program in the 1980s, represents a successful, if not entirely similar, flight-proven predecessor to the exoskeletal engine concept as shown in figure 3. The UDF engine consisted of a standard high-pressure engine spool to which a low-pressure turbine (LPT) was added to directly drive a set of counterrotating highly swept propellers, also called unducted fan blades. The aft row of fan blades was driven by a conventional axial turbine, but the forward row of fan blades was driven by several rows of turbine blades mounted at their outer edge to a rotating drum. On the UDF, this drum was connected to and supported by a more conventional disk (ref. 1). Because the UDF low-pressure turbine drove a set of high-speed propellers (or a low-speed unducted fan), wheel speeds were low compared with turbofan engines. Centrifugal forces were not a factor in blade or drum design (David Cherry, Dec. 5, 2002, General Electric Aircraft Engines, Cincinnati, OH, private communication). In this respect, the UDF represents a significantly different set of design objectives and experience from those that would be relevant to an exoskeletal engine concept. However, the UDF does represent the successful implementation in flight of some elements of an exoskeletal engine architecture.

**Modern Technologies Corporation exoskeletal engine concept studies.**—NASA-sponsored studies of the exoskeletal engine concept were conducted by Modern Technologies Corporation between 1999 and 2001. These studies examined exoskeletal design concepts for 2000-, 5000-, and 25 000-lb thrust-class engines. Preliminary design concepts consisted of cycle definition and stage number and size...
definitions (no structural analyses were performed). The studies pointed out the critical need for exoskeletal engine preliminary design guidelines and structural constraints on preliminary design because of the departure from conventional engine design practices (ref. 2).

**Honeywell International, Inc., exoskeletal engine study.**—In early 2000, Honeywell International, Inc., developed an exoskeletal engine concept based on an existing engine (NASA Exoskeletal Engine Study Final Report, Honeywell International, Inc., May 23, 2000). Honeywell selected the AS900 engine (approx. 6500-lb thrust at sea level static conditions) as a basis for comparison. A single-spool concept was assembled but was rejected because of performance, operability, and engine-starting limitations as compared with a two-spool configuration. A two-spool engine concept was assembled. A layout of this concept was created, and an engine cycle simulation was assembled sufficient to calculate the performance of engine components. Hoop stresses in the drum rotors were calculated and were used to identify material options and weights. High-pressure spool (HPS) rotation speeds necessary to produce performance similar to the AS900 required bearings operating at approximately 9 million mm-rpm, beyond the state of the art for bearings. The performance of a lower speed high-pressure spool was calculated for a rotation speed within state-of-the-art bearing capabilities of 6 million mm-rpm. Engine weights were calculated for rolling-element and magnetic bearing options, and weights and performance were compared with the AS900 engine. Major conclusions of this effort were

1. An exoskeletal engine concept that delivers similar performance to an existing conventional engine is feasible but would have a radius approximately 30 percent smaller and would be approximately 50 percent longer.
2. Exoskeletal rotating machinery is lighter (in concept) than that for conventional engines.
3. Bearing system weight for an exoskeletal engine increases the total weight of the engine to 20 to 25 percent greater than that of a conventional engine.

It should be noted that the Honeywell AS900 engine has a centrifugal high-pressure compressor (HPC). Centrifugal compressors generally add weight and diameter but decrease the length of gas turbine engines. This creates some ambiguity about the directness of the comparison between the AS900 engine and a completely axial exoskeletal engine. However, the Honeywell study represented the first known assessment of the exoskeletal concept applied to an engine as a system. The findings of the Honeywell study indicated the importance of engine systems approach in any subsequent investigations, as well as the predominance of engine structures, materials, and bearings in the application of the exoskeletal concept.
Scope and Rationale

The present investigation focused on development and analysis of a gas turbine engine high-pressure spool of an exoskeletal engine concept. Goals of this investigation were to

1. Determine the weight of an exoskeletal engine HPS concept. The HPS, rather than an entire engine system, was selected for study because
   (a) The HPS typically represents the greatest challenges to structural, thermal, and bearing design in an engine, particularly for the exoskeletal concept characteristics of interest (e.g., high rotation speeds in compressor and turbine and high turbine temperatures). A preliminary calculation of hoop stresses in shells identified that small- to medium-size engine high-pressure spools, operating at comparable rotation speeds with existing engines, would challenge limits of existing structures and materials. A medium-class (approx. 10 000-lb thrust) engine high-pressure spool was chosen as the design example for this investigation.
   (b) The analysis of an HPS is manageable in a reasonable study period, yet is enough of an engine system in itself to provide system-level answers.
2. Perform requisite analysis to ensure that the concept is realistic yet aggressive. Analysis is needed to establish feasibility and traceability of weights of an exoskeletal HPS concept components. However, existing gas turbines benefit from 40 years of design refinement, so an aggressive approach gives the benefit of the doubt to an exoskeletal approach appropriate to making a comparison with an existing engine HPS.
3. Compare the weight of an exoskeletal HPS concept with a representative existing gas turbine engine HPS.
4. Identify technology challenges of the exoskeletal concept.

Several aspects of the exoskeletal engine were considered beyond the scope of this investigation. This investigation did not attempt to quantify the benefits of an exoskeletal engine for noise reduction or for compatibility with other engine cycles, such as a ramjet. It also did not include an optimization of an exoskeletal design, either structurally, aerodynamically, or thermodynamically, for a specific engine class or set of requirements. It is expected that these issues are more appropriately dealt with once an approach to exoskeletal engine structural and mechanical systems design and resolution of the inherent technology challenges have been accomplished.

Appendix A provides the output of the Weight Analysis Turbine Engine (WATE) computer program. The WATE code estimates the total engine weight by using the weights of the various components and/or subcomponents, based upon user inputs and conditions experienced. Appendix B presents the output of the NASA Engine Performance Program (NEPP), which develops a one-dimensional, steady-state thermodynamic cycle model and generates compressor and turbine maps. Appendix C presents the input data for an ANSYS structural analysis of the exoskeletal rotor when it is spinning at the over-speed condition of 16 400 rpm. This input file contains preprocessing, solution, and postprocessing commands to create the model, perform the analysis, and plot the results. Appendix D contains the input data for the Pro/Engineer® models of the compressor and turbine rotor blades. The input data for the exoskeletal compressor rotor blade shapes are based on the NACA 65A010 compressor airfoil shape.

Symbols

\[ AR \quad \text{blade aspect ratio} \]
\[ c \quad \text{chord} \]
\[ DN \quad \text{diameter-number of revolutions (for bearings), millions of mm-rpm} \]
\[ E \quad \text{modulus of elasticity, lb/in.}^2 \]
\(F\) force, lb \(_f\)
\(G\) shear modulus of elasticity, lb/in.\(^2\)
\(g\) gravitational constant
\(H\) blade height, in.
\(I\) area moment of inertia, in.\(^4\)
\(J\) polar moment of inertia
\(K\) matrix stiffness, lb/in.
\(k\) effective stiffness, lb/in.
\(L\) stage length, in.
\(M\) matrix mass, lb \(_m\)
\(m\) mass, lb \(_m\)
\(N\) rotational speed, rpm
\(\mathcal{N}_B\) number of blades
\(PR\) pressure ratio
\(r\) radius, in.
\(V\) shear force, lb \(_f\)
\(W\) weight, lb \(_m\)
\(W_B\) blade weight (also includes fir tree), lb \(_m\)
\(x\) axial location
\(\alpha\) coefficient of thermal expansion (CTE)
\(\gamma\) weight density, lb/in.\(^3\)
\(\delta\) radial deflection, in.
\(\theta\) angular deflection, rad
\(\theta\) stagger angle, deg
\(\mu\) Poisson’s ratio
\(\rho\) material density, lb\(_m/\)in.\(^3\)
\(\sigma\) stress, lb/in.\(^2\)
\(\phi\) camber line angle, deg
\(\omega\) rotational speed, rad/sec

Subscripts:
\(ACC\) accessories weight (also includes other weights that show up but are difficult to assign to one particular part)
\(a\) inner
\(B\) blade
\(b\) outer
\(c\) corrected
\(cu\) ultimate compressive allowable
\(cy\) ultimate compressive yield allowable
\(disk\) disk
\(e\) exit
\(H\) hub
\(i\) inlet
Assumptions, Key Challenges, and Approach

Assumptions

The first assumption was that the application of conventional aerothermodynamics design principles to an exoskeletal engine architecture was sufficient to identify the limiting structural and materials challenges. As mentioned above and in reference 2 (Halliwell), the design of exoskeletal engine blades and flow paths to deliver performance on a par with highly optimized conventional engines is likely to require significant study and development of design guidelines. For example, exoskeletal rotating blade tips are at a smaller radius than the blade root, which results in tip leakage at the engine hub increasing with rotational speed. Rotating blades supported at the outer radius and stators supported at their inner radius necessitate a structural design opposite that of conventional engines, affecting thickness, curvature, and blade dynamics. In an exoskeletal engine, the outer wall of the engine rotates with the blades, representing a large windage area (compared with a conventional shaft). The impacts on engine performance of these and other changes from conventional engine design are unknown. However, the exoskeletal engine concept proposes no intended deviations from the aerothermodynamic cycle design heritage of conventional engines. In lieu of design details, an earlier examination of the feasibility of the exoskeletal engine concept found it acceptable to transfer engine cycle parameters directly from a baseline conventional engine (Exoskeletal Technology Evaluation for Use in Aeropropulsion Applications. Presented to the Ultra-Efficient Engine Technology Program, Feb. 28, 2001). It was therefore assumed that any variations in engine aerothermodynamic cycle design are of small order compared with the issues of viability presented by structural-mechanical design and that an exoskeletal engine design can be assumed aerothermodynamically identical to a conventional engine for the purposes of this investigation.

The second assumption was that turbine engine subsystem and components currently in use can be applied to an exoskeletal engine at their existing performance levels. Typical gas turbine engine components, such as controls, actuators, and combustors, may pose significant engineering challenges in

\[
l_c \quad \text{maximum allowable compressive stress in fiber direction}
\]
\[
l_t \quad \text{maximum allowable tensile stress in fiber direction}
\]
\[
\text{max} \quad \text{maximum}
\]
\[
\text{min} \quad \text{minimum}
\]
\[
N \quad \text{nuts and bolts (also used to bolt disks together)}
\]
\[
n \quad \text{natural or local}
\]
\[
RD \quad \text{rotor drum}
\]
\[
r \quad \text{radial}
\]
\[
\text{row} \quad \text{row}
\]
\[
\text{stage} \quad \text{stage}
\]
\[
su \quad \text{ultimate shear allowable}
\]
\[
T \quad \text{tip}
\]
\[
t \quad \text{tangential}
\]
\[
tu \quad \text{ultimate tensile allowable}
\]
\[
ty \quad \text{tensile yield}
\]
\[
vm \quad \text{Von Mises}
\]
\[
\tau \quad \text{shear}
\]
\[
1 \quad \text{maximum principal stress, klb/in.}^2
\]
\[
2 \quad \text{minimum principal stress, klb/in.}^2
\]
their adaptation to an exoskeletal engine. For this investigation, however, the expectation was that no new technology would be required to apply these subsystems and components to an exoskeletal engine.

**Key Challenges**

**Development of structural and mechanical exoskeletal HPS concept.**—The central idea of an exoskeletal engine concept involves a change in the structural and mechanical design of the rotating machinery in a gas turbine engine. The concept is not proposed as a change to the engine cycle or aerodynamics, other than that necessary to accommodate changes to the structural and mechanical design. Thus, the system-level feasibility questions about the exoskeletal engine concept lie with the structural and mechanical architecture. The outer rotating shell of an exoskeletal system must withstand stresses due to the inertia of rotation, contain engine pressure loads, react to blade loads, and accommodate the engine nominal and contingency environments. It must also accommodate engine assembly and maintenance.

**Development of system-integrated bearing concept for exoskeletal HPS.**—The exoskeletal approach inherently involves large portions of an engine system rotating at larger radii than those in a conventional engine. The development of an appropriate bearing concept is a challenge that involves

1. Integration with the system structural concept to minimize bearing DN
2. Consideration of existing and emerging bearing technologies, including noncontact bearings
3. Consideration of both nominal and off-nominal engine conditions, including startup, maneuvering, and landing

**Approach**

A conceptual analysis was deemed sufficient to determine exoskeletal structural-mechanical viability and to compare the weight of a conventional engine with its exoskeletal counterpart. This approach included both identifying the key characteristics driving the viability and weight and selecting the pertinent engine subsystems for design and analysis. A representative conventional engine was selected and the exoskeletal analogue was created. This approach minimized the design and analysis effort while still providing the understanding of the engineering issues involved with the exoskeletal architecture. In detail, the process can be described as follows:

**Identification of suitable conventional gas turbine engine for comparison with exoskeletal concept.**—A valid comparison of an exoskeletal approach and the conventional approach required identification of an existing gas turbine engine with the following characteristics:

1. Representative of state-of-the-art gas turbine engine design, especially high-pressure spool rotation speeds and temperatures
2. Availability of design information, allowing modeling and adaptation of structures and mechanisms to an exoskeletal approach
3. Fully axial design (no centrifugal compressors or turbines)

**Design of exoskeletal analogue HPS concept.**—A conceptual design of an exoskeletal engine high-pressure spool was developed based on the NASA model of an existing engine. The conceptual design is described in the section Description of Exoskeletal System Concept. The approach to this design had neither a precedent nor design guidelines for exoskeletal components. Materials and structures concepts were defined consistent with the analogous environments from the conventional HPS example, consistent with an aggressive but realistic concept philosophy.

**Calculation of weight of exoskeletal analogue HPS concept.**—The weight of the exoskeletal HPS was calculated based on the design concept, as were the weights of shells and the stationary core. Blade weights were based on conventional engine blade weights but were modified for the exoskeletal
geometry. The weights of components, such as combustors, that were largely unaffected by the change to an exoskeletal design were adopted from existing engines.

**Verification of exoskeletal HPS concept structural integrity.**—Structural analyses were performed to verify the structural integrity of critical exoskeletal high-pressure spool components, such as drum rotors, bladed rings, and bearing supports. The intent was to show that the weight estimates were aggressive but reasonable. Finite-element models were not of sufficient detail to perform complete structural analyses considering the limited thermal analysis that was performed. The operating thermal environment was, however, considered in the selection of materials and in choosing an appropriate allowable stress range for applied mechanical loads. This approach was considered adequate for the purposes of this investigation. High-fidelity modeling and refinement of the environment to include all aerodynamic, inertial, and thermal loads to a greater degree of accuracy would be required prior to commitment to an exoskeletal engine development.

**Identification of technology challenges.**—This investigation attempted to discover not just whether an exoskeletal approach to gas turbine engine design is viable but also the critical characteristics upon which viability depends. Where new or improved technologies were important to the viability of the exoskeletal approach, they were identified. A preliminary assessment was made of the potential of new technologies to satisfy the requirements of the exoskeletal approach.

**Architecture Description**

Since the exoskeletal concept presents an aggressive departure from conventional turbine engines, it is imperative to look at the concept using a systems approach. A solid model of the concept was generated as the first step of the analysis and weight determination of the system. The method for developing reasonable weight comparisons consists of building component models for finite-element analyses (FEA) of the exoskeletal engine system. The intention is to look at all major components in the engine system with some consideration given to mounting and assembly procedures for all rotating parts. Hopefully, this approach will unveil any potentially significant benefits as well as any possible technical hurdles pursuant to a new direction in turbine engine technology. Finally, the comparison of engine weights as a product of the investigation will serve as the principal metric for an evaluation of exoskeletal versus conventional engine benefits.

**Description of Exoskeletal System Concept**

The exoskeletal engine architecture for this study is based on the Rolls-Royce (Allison) AE3007 engine. The design dimensions were scaled from a sketch of a longitudinal section through the AE3007 in Jane’s Aero-Engines (ref. 3). These scaled dimensions were input to NASA’s engine weight estimate computer code WATE (Weight Analysis Turbine Engine, refs. 4 and 5) to develop a government interpretation of an AE3007-like engine. Scaled dimensions and the output from the WATE code (appendix A) were used to generate a Pro/Engineer® (ref. 6) CAD model representation of the AE3007 exoskeletal engine.

The AE3007 engine shown in figure 4 is a two-shaft subsonic turbofan, and the shafts are concentric. The AE3007 engine has an axial-flow, high-pressure compressor, a combustion chamber, and a high-pressure turbine (HPT) all spinning on the outer shaft. The HPC has 14 stages, variable-inlet guide vanes, and variable-inlet stators in the first 5 rows. The overall pressure ratio of the HPC is 23. The combustion chamber is an annular design with 16 fuel nozzles. The HPT is a two-stage axial design with air-cooled blades. A three-stage, low-pressure turbine drives the inner shaft, which in turn drives a single-stage, wide-chord fan. The fan has a mass flow of 260 lb/sec and a bypass ratio of 5. The outer fan duct and jet pipe are composite designs.
Heritage of Rolls-Royce (Allison) AE3007-based NASA engine cycle model.—The NASA AE3007 cycle model was developed to support NASA’s goals assessment (ref. 7). Analytical models of various airframes and propulsion systems representative of the current state of the art were developed in sufficient detail to allow the inclusion of new technologies to assess the benefit of these technologies on system performance (size, cost, emissions, maintainability, etc.). To disseminate study assumptions and results, NASA developed models of these airframes and propulsion systems, based on publicly available information and good engineering judgment. Although the models developed may be similar in overall performance and capability to the actual airframes and propulsion systems in use, there could be significant differences between the NASA-developed models and the actual systems.

Development of AE3007 thermodynamic model.—As part of that activity, a model of a 50-passenger regional jet based on the EMB145 was developed, with its propulsion system based on the Rolls-Royce (Allison) AE3007. For its size and thrust class, the AE3007 is a moderately high-bypass, two-spool, mixed-flow turbofan. It uses only axial-flow components, reducing engine and core diameter. For this study, it was thought that its core diameter was within the state of the art for composite rotating materials. A one-dimensional, steady-state, thermodynamic cycle model was developed using the NASA Engine Performance Program (NEPP, ref. 8). A block model of the engine is shown in figure 5, indicating gas flow paths and mechanical connections. Table 1 shows gas conditions throughout the cycle at sea-level static conditions based on assumed component and overall engine performance (the actual NEPP output is listed in appendix B). Compressor and turbine maps were generated (refs. 9 and 10) based on component size and performance or were scaled from existing in-house maps with similar characteristics. The actual compressor and high-pressure turbine maps used are shown in figures 6 to 8. These maps are used for estimating the off-design performance of these components while the cycle model is “flown” over a range of Mach, altitude, and engine power conditions to generate performance data to be included in mission analyses. In addition, component maximum performance points are recorded (mass flow, temperature, pressure, torque, etc.) to be used to develop a flow-path weight model.
Figure 5.—NEPP model configuration for NASA AE3007.
TABLE 1.—NEPP AE3007 STATION PROPERTIES

<table>
<thead>
<tr>
<th>Station number</th>
<th>Mass flow, lbm/s</th>
<th>Pressure, psia</th>
<th>Temperature, °R</th>
<th>Fuel-to-air ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>257.4</td>
<td>14.7</td>
<td>545.7</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>257.4</td>
<td>14.5</td>
<td>545.7</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>257.4</td>
<td>24.0</td>
<td>641.9</td>
<td>0.0000</td>
</tr>
<tr>
<td>4</td>
<td>41.7</td>
<td>24.0</td>
<td>641.9</td>
<td>0.0000</td>
</tr>
<tr>
<td>5</td>
<td>41.7</td>
<td>23.7</td>
<td>641.9</td>
<td>0.0000</td>
</tr>
<tr>
<td>6</td>
<td>36.1</td>
<td>353.4</td>
<td>1465.0</td>
<td>0.0000</td>
</tr>
<tr>
<td>7</td>
<td>36.1</td>
<td>348.1</td>
<td>1465.0</td>
<td>0.0000</td>
</tr>
<tr>
<td>8</td>
<td>36.8</td>
<td>332.5</td>
<td>2792.1</td>
<td>0.0221</td>
</tr>
<tr>
<td>9</td>
<td>41.5</td>
<td>72.4</td>
<td>1942.6</td>
<td>0.0196</td>
</tr>
<tr>
<td>10</td>
<td>41.5</td>
<td>72.0</td>
<td>1942.6</td>
<td>0.0196</td>
</tr>
<tr>
<td>12</td>
<td>257.3</td>
<td>21.0</td>
<td>775.7</td>
<td>0.0031</td>
</tr>
<tr>
<td>13</td>
<td>257.2</td>
<td>20.9</td>
<td>775.7</td>
<td>0.0031</td>
</tr>
<tr>
<td>14</td>
<td>257.2</td>
<td>20.9</td>
<td>775.7</td>
<td>0.0031</td>
</tr>
<tr>
<td>15</td>
<td>41.5</td>
<td>18.1</td>
<td>1426.0</td>
<td>0.0196</td>
</tr>
<tr>
<td>16</td>
<td>41.5</td>
<td>18.0</td>
<td>1426.0</td>
<td>0.0196</td>
</tr>
<tr>
<td>20</td>
<td>215.8</td>
<td>23.6</td>
<td>641.9</td>
<td>0.0000</td>
</tr>
<tr>
<td>21</td>
<td>4.8</td>
<td>353.4</td>
<td>1465.0</td>
<td>0.0000</td>
</tr>
<tr>
<td>22</td>
<td>215.8</td>
<td>23.6</td>
<td>641.9</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Figure 6.—Compressor map for corrected flow as function of total pressure ratio.
Figure 7.—Turbine map for mass flow as function of pressure ratio.

Figure 8.—Turbine map for efficiency as function of pressure ratio.
Development of the AE3007 flow-path and weight model.---An engine flow-path and weight estimation model was developed using the WATE program (refs. 11 and 12) and was based on maximum conditions determined from NEPP. A graphical output detailing the WATE analysis of the engine flow path is shown in figure 9. The WATE code estimates the total weight of various components and subcomponents based on user inputs and conditions experienced. The weight of each component is developed from its subcomponent parts. For example, the compressor weight is determined on a stage-by-stage basis, based on the flow conditions and performance of each particular stage. Input parameters include blade hub-to-tip ratio, aspect ratio, disk type, and compressor end support (e.g., frame and bearing type). Different materials may also be chosen for the various parts (disk, rotor and stator blades, surrounding case, etc.). Such detail was required for previous study efforts to assess the effect of technologies that might be applicable to only one part, such as blades, disks, and so forth. This level of detail was also helpful to start the analysis of an exoskeletal version of the AE3007. However, the WATE analysis does not go into detailed blade design, the development of which will be discussed the following section. Since the exoskeletal analysis was limited to the high-pressure spool of the engine, more detailed gas flow conditions (from NEPP/WATE) and mechanical data (from WATE) were used for subsequent analyses. Tables 2 and 3 show these data.

<table>
<thead>
<tr>
<th>COMP#</th>
<th>Type</th>
<th>NSTAGE</th>
<th>WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare engine weight</td>
<td>1491</td>
<td>1</td>
<td>INLT 0</td>
</tr>
<tr>
<td>Accessories weight</td>
<td>141</td>
<td>2</td>
<td>FANH 1</td>
</tr>
<tr>
<td>Total engine weight</td>
<td>1632</td>
<td>3</td>
<td>SPLT 0</td>
</tr>
<tr>
<td>Inlet/nacelle weight</td>
<td>249</td>
<td>4</td>
<td>DUCT 0</td>
</tr>
<tr>
<td>Total engine pod weight</td>
<td>1882</td>
<td>5</td>
<td>HPC 14</td>
</tr>
<tr>
<td>Engine length</td>
<td>109.0</td>
<td>6</td>
<td>DUCT 0</td>
</tr>
<tr>
<td>Total engine pod length</td>
<td>128.2</td>
<td>7</td>
<td>PHUR 0</td>
</tr>
<tr>
<td>Engine maximum diameter</td>
<td>38.5</td>
<td>8</td>
<td>HPT 2</td>
</tr>
<tr>
<td>Nacelle maximum diameter</td>
<td>45.8</td>
<td>9</td>
<td>DUCT 0</td>
</tr>
<tr>
<td>Engine pod center of gravity location</td>
<td>33.4</td>
<td>10</td>
<td>LPT 3</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>14</td>
<td>DUCT 0</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>15</td>
<td>DUCT 0</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>11</td>
<td>FMIX 0</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>12</td>
<td>DUCT 0</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>13</td>
<td>NOZ 0</td>
</tr>
</tbody>
</table>

Figure 9.—WATE analysis of AE3007 flow path. (All dimensions are in inches and weight is in pounds.)
### TABLE 2.—NEPP/WATE AE3007 FLOW CONDITIONS THROUGH TURBOMACHINERY

<table>
<thead>
<tr>
<th>Component</th>
<th>Stage</th>
<th>Mass flow, lb/hr</th>
<th>Entrance temperature, °R</th>
<th>Entrance pressure, psia</th>
<th>Pressure ratio across stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC</td>
<td>1</td>
<td>41.68</td>
<td>638</td>
<td>23.3</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>699</td>
<td>31.2</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>759</td>
<td>40.7</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>820</td>
<td>52.0</td>
<td>1.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>880</td>
<td>65.3</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>940</td>
<td>80.7</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>999</td>
<td>98.6</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1058</td>
<td>119.0</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1117</td>
<td>142.2</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1175</td>
<td>168.4</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1233</td>
<td>197.7</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1290</td>
<td>230.5</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>1347</td>
<td>267.0</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1403</td>
<td>307.4</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exit</td>
<td>1465</td>
<td>351.9</td>
<td>-----</td>
<td></td>
</tr>
<tr>
<td>HPT</td>
<td>1</td>
<td>40.06</td>
<td>2693</td>
<td>329.2</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>42.62</td>
<td>2319</td>
<td>163.5</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>Exit</td>
<td>42.62</td>
<td>1944</td>
<td>72.1</td>
<td>-----</td>
</tr>
<tr>
<td>Component</td>
<td>Stage</td>
<td>Length, ( L_{\text{stage}} ) in.</td>
<td>Radius, ( r )_x, in.</td>
<td>Number, ( n_x )</td>
<td>Height, ( H_x )_B, in.</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>----------------------------------</td>
<td>---------------------</td>
<td>----------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>HPC (^a)</td>
<td>1</td>
<td>1.94</td>
<td>3.57</td>
<td>7.84</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.45</td>
<td>5.0</td>
<td>7.91</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.17</td>
<td>5.53</td>
<td>7.84</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.97</td>
<td>6.02</td>
<td>7.84</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.84</td>
<td>6.36</td>
<td>7.84</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.73</td>
<td>6.62</td>
<td>7.84</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.66</td>
<td>6.82</td>
<td>7.84</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.60</td>
<td>6.97</td>
<td>7.84</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.56</td>
<td>7.09</td>
<td>7.84</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.53</td>
<td>7.19</td>
<td>7.84</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.50</td>
<td>7.28</td>
<td>7.84</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.49</td>
<td>7.34</td>
<td>7.84</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.48</td>
<td>7.40</td>
<td>7.84</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.49</td>
<td>7.45</td>
<td>7.84</td>
<td>84</td>
</tr>
<tr>
<td>HPT</td>
<td>1</td>
<td>1.05</td>
<td>8.31</td>
<td>9.57</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>.67</td>
<td>8.31</td>
<td>9.51</td>
<td>63</td>
</tr>
</tbody>
</table>

\(^a\) HPC blades have a constant taper ratio of 0.833.
Exoskeletal Engine High-Pressure Spool

Figure 10 shows the conceptual design of the exoskeletal drum rotor assembly. Inverting the AE3007 design, the HPC and HPT rotor blades are mounted to the drum rotor and the stator rows are mounted to a stationary core. The stationary core outlines the rims of the original rotor disks on the AE3007 engine. Previous exoskeletal engine studies call for the complete elimination of the shafts and disks from the engine center (ref. 13), which would provide an open channel along the centerline (ref. 14). However, a stationary core with closed ends has been designed to support the stator blades. An AE3007-like exoskeletal design provides a convenient break at the LPT since it runs at a slower speed. Conceptually, the low-pressure spool would drive the fan via a separate drum rotor. The low-pressure spool drum rotor has been neglected in this study to focus on the exoskeletal high-pressure spool, which has greater physical demands.

A hypothetical exoskeletal engine assembly is depicted by the Pro/Engineer® model in figure 11, and the overall dimensions are shown in figure 12. To minimize the complexity of the study, three sections of the high-pressure spool (the HPC, combustion chamber, and HPT) were converted to an exoskeletal drum rotor design. The Pro/Engineer® model is intended for use in the conceptual design and analysis of an exoskeletal construction, and it is not a complete representation of the propulsion system.

Figure 11 shows the high-pressure spool as four sections. The HPC drum rotor assembly is broken down into two sections to permit material choice flexibility. Figure 13 shows the HPC drum rotor design in more detail. Graphite polyimide was investigated for the first seven stages where the temperature was below 600 °F. A titanium drum rotor is used for the last seven HPC stages where temperatures could rise to 950 °F. Hastelloy™ is used in the combustion chamber and HPT drum rotors because gas temperatures could approach 2500 °F.

A bearing system is located at each end of the high-pressure spool to support the rotating drum. As shown in figure 11, the bearings transfer the loads between the drum rotor and the struts and permit relatively free rotation with minimum friction.
Figure 11.—Pro/Engineer® model of AE3007–like exoskeletal engine. (All dimensions are in inches.)

Figure 12.—Overall dimensions for AE3007–like exoskeletal engine. (All dimensions are in inches.)

Inlet diameter  38.5
Overall diameter  43.5
Length  110.25

First high-pressure compressor drum rotor
Second high-pressure compressor drum rotor
Combustion chamber drum rotor
High-pressure turbine drum rotor

High-pressure spool rotating drum assembly
Struts
Bearing locations
An examination of figure 13 shows that the exoskeletal engine assembly and maintenance will be more difficult than that of the conventional engine. One question is how the rotor blades will be assembled to the drum rotor using acceptable methods of construction. One answer was to divide the rotor into integral bladed rings for each stage, as shown in figure 14. Similarly, the stator would also consist of integral bladed-ring components. Since composite materials have an immense potential use in the rotor blades supported in compression, the integral bladed ring is a natural step to blend function and assembly. Manufacturing an integral bladed ring will also be a challenge, but this approach should reduce weight. To build the exoskeletal engine, each stage is installed in the rotor drum in an assembly procedure that alternates between stator bladed rings and rotor bladed rings. Each ring would provide the necessary space for the adjacent stage, or one could design a separate spacer. Although assembly and maintenance time would be increased, this concept would eliminate a longitudinal split of the drum rotor and longitudinal mounting flanges that would create rotor instability.

As stated earlier, the WATE computer code was used to generate dimensions and weights of exoskeletal components. HPC and HPT blade dimensions were also output from the WATE code. Table 4 shows the dimensions used to generate Pro/Engineer® models of each rotor stage.

A generalized NACA wing design was used to create the HPC rotor blade with stagger angles at the root and tip as shown in figure 15. The design of the HPT rotor blades is similar, but a camber angle of 15° was used to define the HPT blade curvature as shown in figure 16.
TABLE 4.— BLADE DIMENSIONS FOR HPC AND HPT ROTOR STAGES

<table>
<thead>
<tr>
<th>Component</th>
<th>Stage</th>
<th>Radius, r, in.</th>
<th>Hub</th>
<th>Tip</th>
<th>Number of blades, nB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inlet, rN</td>
<td>Exit, rT</td>
<td>Chord length, in.</td>
<td>Blade width, in.</td>
</tr>
<tr>
<td>HPC</td>
<td>1</td>
<td>3.57</td>
<td>7.84</td>
<td>2.117</td>
<td>1.970</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.8</td>
<td>7.84</td>
<td>1.587</td>
<td>1.374</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.53</td>
<td>7.84</td>
<td>1.273</td>
<td>1.041</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.02</td>
<td>7.84</td>
<td>1.056</td>
<td>0.827</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.36</td>
<td>7.84</td>
<td>0.912</td>
<td>0.690</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6.62</td>
<td>7.84</td>
<td>0.802</td>
<td>0.590</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>6.82</td>
<td>7.84</td>
<td>0.718</td>
<td>0.516</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6.97</td>
<td>7.84</td>
<td>0.655</td>
<td>0.462</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>7.09</td>
<td>7.84</td>
<td>0.611</td>
<td>0.425</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.19</td>
<td>7.84</td>
<td>0.577</td>
<td>0.396</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>7.28</td>
<td>7.84</td>
<td>0.546</td>
<td>0.370</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>7.34</td>
<td>7.84</td>
<td>0.535</td>
<td>0.360</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>7.4</td>
<td>7.84</td>
<td>0.528</td>
<td>0.352</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>7.45</td>
<td>7.84</td>
<td>0.532</td>
<td>0.353</td>
</tr>
<tr>
<td>HPT</td>
<td>1</td>
<td>8.31</td>
<td>9.57</td>
<td>1.375</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.31</td>
<td>9.51</td>
<td>0.872</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Figure 14.—Integral bladed ring for high-pressure compressor drum rotor.
Structural Analysis and Assessment

Blade Investigation

Method of analysis.—Blade geometry was generated using the WATE code as summarized in the section Development of AE3007 flow-path and weight model. The blade height varied from 4.27 to 0.39 in. between HPC stages 1 to 14, respectively. This variation in height for HPC blades is illustrated in figure 17. Parameters such as thickness, taper ratio, and chord length were varied during the investigation iteration process as required to achieve a positive margin of safety. In some cases, the camber angle was adjusted to increase compression stresses while decreasing tension stresses in the blade. A ceramic matrix composite (CMC) blade will perform better in compression than in tension. The NACA airfoil 65A010 was used as a representative blade section for the HPC and is shown in figure 18.

Using this approach, the AE3007-like blade geometries were derived and modeled using Pro/Engineer® to formulate the starting point for a finite-element analysis of each stage in the HPC and HPT. One blade was modeled for each stage in an exoskeletal design (blade in compression). The aerodynamic loads were assumed to be the same for the exoskeletal configuration as those for the conventional engine. The NEPP software code provided pressure loads for each stage, which was combined with rotational inertia for a combined static load case solved using MSC/NASTRAN™ FEA software (ref. 15). The rotational speed of the engine is 16 400 rpm (overspeed condition). For each stage, the NEPP software code also provided temperature data, which was used to select appropriate materials for the finite-element analysis. Table 5 gives the entrance temperature range for stages 1 to 14 of the HPC.

Figure 15.—Rotor blade design for first high-pressure compressor stage of exoskeletal engine concept. (All dimensions are in inches.)

Figure 16.—Rotor blade design for first high-pressure turbine stage of exoskeletal engine concept. (All dimensions are in inches.)
TABLE 5.—ENTRANCE TEMPERATURES FOR HIGH-PRESSURE COMPRESSOR STAGES

<table>
<thead>
<tr>
<th>Stage</th>
<th>Temperature, °F</th>
<th>Stage</th>
<th>Temperature, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>178</td>
<td>8</td>
<td>598</td>
</tr>
<tr>
<td>2</td>
<td>239</td>
<td>9</td>
<td>657</td>
</tr>
<tr>
<td>3</td>
<td>299</td>
<td>10</td>
<td>715</td>
</tr>
<tr>
<td>4</td>
<td>360</td>
<td>11</td>
<td>773</td>
</tr>
<tr>
<td>5</td>
<td>420</td>
<td>12</td>
<td>830</td>
</tr>
<tr>
<td>6</td>
<td>480</td>
<td>13</td>
<td>887</td>
</tr>
<tr>
<td>7</td>
<td>539</td>
<td>14</td>
<td>943</td>
</tr>
</tbody>
</table>

High-pressure compressor analysis.—The first seven stages of the HPC utilize a lightweight polymer matrix composite (PMC) material. Graphite polyimide was selected as a suitable option having temperature-dependent properties up to 600 °F as shown in table 6. For stages 8 to 14, Titanium 6Al–4Valloy, hereinafter referred to as Titanium, was selected based on temperature capabilities up to 900 °F as shown in table 7. Other candidate materials used in the investigation of HPC blades include aluminum and WaspaloyTM with allowable stresses as shown in tables 8 and 9, respectively. These allowable material stresses were obtained from the Metallic Materials and Elements for Aerospace Vehicle Structures (ref. 16) and include the appropriate reductions for temperature. Similarly, the composite material properties (graphite polyimide) were derived from the HyperSizerTM (ref. 17) data base but with a 50-percent knockdown applied to account for life and durability effects. A summary of mechanical properties for materials in this investigation is presented in table 10.

TABLE 6.—MATERIAL ALLOWABLES USED FOR GRAPHITE POLYIMIDE

<table>
<thead>
<tr>
<th>Temperature, °F</th>
<th>Ultimate tensile force, ( F_{tu} ) klb/in.²</th>
<th>Ultimate compressive force, ( F_{cu} ) klb/in.²</th>
<th>Ultimate shear force, ( F_{su} ) klb/in.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>113</td>
<td>100</td>
<td>6.5</td>
</tr>
<tr>
<td>600</td>
<td>105</td>
<td>51</td>
<td>3.1</td>
</tr>
</tbody>
</table>
### TABLE 7.—MATERIAL ALLOWABLES USED FOR TITANIUM 6AL~4V

<table>
<thead>
<tr>
<th>Temperature, °F</th>
<th>Ultimate tensile force, ( F_{ut} ) klb/in.²</th>
<th>Ultimate compressive force, ( F_{cu} ) klb/in.²</th>
<th>Ultimate shear force, ( F_{su} ) klb/in.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>134</td>
<td>133</td>
<td>85</td>
</tr>
<tr>
<td>200</td>
<td>126</td>
<td>119</td>
<td>80</td>
</tr>
<tr>
<td>300</td>
<td>114</td>
<td>107</td>
<td>75</td>
</tr>
<tr>
<td>400</td>
<td>103</td>
<td>96</td>
<td>70</td>
</tr>
<tr>
<td>500</td>
<td>94</td>
<td>89</td>
<td>67</td>
</tr>
<tr>
<td>600</td>
<td>92</td>
<td>88</td>
<td>65</td>
</tr>
<tr>
<td>700</td>
<td>90</td>
<td>85</td>
<td>58</td>
</tr>
<tr>
<td>800</td>
<td>86</td>
<td>82</td>
<td>52</td>
</tr>
<tr>
<td>900</td>
<td>77</td>
<td>71</td>
<td>46</td>
</tr>
</tbody>
</table>

### TABLE 8.—MATERIAL ALLOWABLES USED FOR ALUMINUM

<table>
<thead>
<tr>
<th>Temperature, °F</th>
<th>Ultimate tensile force, ( F_{ut} ) klb/in.²</th>
<th>Ultimate compressive force, ( F_{cu} ) klb/in.²</th>
<th>Ultimate shear force, ( F_{su} ) klb/in.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>66</td>
<td>58</td>
<td>40</td>
</tr>
<tr>
<td>200</td>
<td>66</td>
<td>54</td>
<td>38</td>
</tr>
<tr>
<td>300</td>
<td>51</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td>400</td>
<td>30</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>550</td>
<td>25</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>600</td>
<td>25</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>650</td>
<td>24</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>700</td>
<td>24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 9.—MATERIAL ALLOWABLES USED FOR WASPALOY™

<table>
<thead>
<tr>
<th>Temperature, °F</th>
<th>Ultimate tensile force, ( F_{ut} ) klb/in.²</th>
<th>Ultimate compressive force, ( F_{cu} ) klb/in.²</th>
<th>Ultimate shear force, ( F_{su} ) klb/in.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>138</td>
<td>138</td>
<td>83</td>
</tr>
<tr>
<td>200</td>
<td>136</td>
<td>136</td>
<td>82</td>
</tr>
<tr>
<td>300</td>
<td>132</td>
<td>132</td>
<td>79</td>
</tr>
<tr>
<td>400</td>
<td>129</td>
<td>129</td>
<td>77</td>
</tr>
<tr>
<td>500</td>
<td>127</td>
<td>127</td>
<td>76</td>
</tr>
<tr>
<td>600</td>
<td>125</td>
<td>125</td>
<td>75</td>
</tr>
<tr>
<td>700</td>
<td>123</td>
<td>123</td>
<td>74</td>
</tr>
<tr>
<td>800</td>
<td>121</td>
<td>121</td>
<td>73</td>
</tr>
<tr>
<td>900</td>
<td>120</td>
<td>120</td>
<td>72</td>
</tr>
<tr>
<td>1000</td>
<td>118</td>
<td>118</td>
<td>71</td>
</tr>
<tr>
<td>1100</td>
<td>115</td>
<td>115</td>
<td>69</td>
</tr>
<tr>
<td>1200</td>
<td>112</td>
<td>112</td>
<td>67</td>
</tr>
<tr>
<td>1300</td>
<td>104</td>
<td>104</td>
<td>62</td>
</tr>
<tr>
<td>1400</td>
<td>90</td>
<td>90</td>
<td>54</td>
</tr>
<tr>
<td>1500</td>
<td>70</td>
<td>70</td>
<td>52</td>
</tr>
</tbody>
</table>

---

\( a \) Applied 20-percent knockdown factor to allowable strength at ½-hr exposure.

\( b \) Assumed 60-percent ultimate strength as shear allowable.
TABLE 10.—SUMMARY OF MECHANICAL PROPERTIES FOR BLADE ANALYSIS

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of elasticity, $E$, $\text{lb/} \text{in.}^2$</th>
<th>Material density, $\rho$, $\text{lb/} \text{in.}^3$</th>
<th>Coefficient of thermal expansion, $\alpha$, $1/\text{°F}$</th>
<th>Poisson’s ratio, $\mu$</th>
<th>Allowables</th>
<th>Ultimate tensile force, $F_{tu}$, $\text{klb/} \text{in.}^2$</th>
<th>Ultimate compressive force, $F_{cu}$, $\text{klb/} \text{in.}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>$2.4 \times 10^7$</td>
<td>0.056</td>
<td>$2 \times 10^{-5}$</td>
<td>0.33</td>
<td>See table 6</td>
<td>See table 6</td>
<td></td>
</tr>
<tr>
<td>polyimide</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>$1.48 \times 10^7$</td>
<td>0.160</td>
<td>$5.2 \times 10^{-6}$</td>
<td>0.3</td>
<td>See table 7</td>
<td>See table 7</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>$1 \times 10^7$</td>
<td>0.097</td>
<td>$1.3 \times 10^{-6}$</td>
<td>0.33</td>
<td>See table 8</td>
<td>See table 8</td>
<td></td>
</tr>
<tr>
<td>Waspaloy$^\text{TM}$</td>
<td>$30.6 \times 10^6$</td>
<td>0.298</td>
<td>$7.6$ to $7.9 \times 10^{-6}$</td>
<td>0.3</td>
<td>See table 9</td>
<td>See table 9</td>
<td></td>
</tr>
</tbody>
</table>

The solid model blade geometry for each stage of the HPC was imported in the MSC/PATRAN$^\text{TM}$ preprocessing software code (ref. 18) to create a finite-element model (FEM) for analysis. The initial blade models used a straight taper (ratio of tip chord to root chord is 1.0). Boundary conditions for conventional engine blades were fixed at the root or inside radius of the blade whereas the exoskeletal blade fixity is inverted as illustrated in figure 19.

Loads were applied to the exoskeletal blade FEM, including aerodynamic pressure acting on the blade combined with the rotating inertia. A static solution was then performed using MSC/NASTRAN$^\text{TM}$ for each stage of the HPC. The maximum radial displacement was 0.006 in. at the stage 1 blade tip. The maximum Von Mises stress in the first seven stages using graphite polyimide was 26.2 klb/in.$^2$ and occurred at the stage 5 blade root, resulting in a margin of safety of +0.95. The maximum buckling margin for the stage 1 PMC blades in compression is +2.24. It is interesting to note that both titanium and aluminum materials were investigated for the HPC stage 1 blades, and these selections fail in buckling for an exoskeletal design. Shear stress at the root of the stage 1 blade results in a negative margin of 0.60. Incorporating a taper in the blade design may reduce the negative margin, although a blade redesign such as this was not pursued in this investigation.

Stages 8 to 14 were investigated in a similar way, but the taper ratio of 1.0 was kept for each stage in this section of the HPC. Although Titanium 6Al$−$4V was the material of choice, a second material, Waspaloy$^\text{TM}$, was also investigated for these stages. The applied loads were combined aerodynamic pressure and rotational inertia for the static solutions using MSC/NASTRAN$^\text{TM}$. The peak stress and deflection results for this section of the HPC blade investigation are given in table 11 along with buckling margins of safety.

![Figure 19.—Boundary conditions for exoskeletal versus conventional engine.](image-url)
TABLE 11.—BLADE INVESTIGATION RESULTS FOR STAGES 1 TO 14

<table>
<thead>
<tr>
<th>Stage</th>
<th>Material</th>
<th>Maximum stress, $\sigma_{\text{max}}$, klb/in.²</th>
<th>Radial displacement, in.</th>
<th>Margin of safety, M.S. (buckling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Graphite polyimide</td>
<td>25,3</td>
<td>0.006</td>
<td>+2.24</td>
</tr>
<tr>
<td>5</td>
<td>Graphite polyimide</td>
<td>26.2</td>
<td>0.0009</td>
<td>+9.18</td>
</tr>
<tr>
<td>8</td>
<td>Ti6Al−4V</td>
<td>28.0</td>
<td>0.0008</td>
<td>+4.22</td>
</tr>
<tr>
<td>8</td>
<td>Waspaloy™</td>
<td>34.4</td>
<td>0.0005</td>
<td>+4.80</td>
</tr>
<tr>
<td>9</td>
<td>Ti6Al−4V</td>
<td>28.3</td>
<td>0.0006</td>
<td>+6.02</td>
</tr>
</tbody>
</table>

In summary, the lighter weight PMC works acceptably well in compression for the first seven stages of the HPC. Thus, graphite polyimide was used in tabulating the weights of the first seven stages of the compressor. Stages 8 to 14 of the HPC operate at temperatures above the practical range for PMC. Titanium was the selected material for blades in these stages and was used for weight calculation purposes.

**High-pressure turbine analysis**.—The HPT two-stage turbine is part of the high-pressure spool located aft of the combustion chamber and is subjected to higher temperatures than the HPC. Similar to the HPC, the blade geometry for the HPT was conceptually designed by first scaling the AE3007 drawing with output from the conventional design and WATE code for specific dimensions, as shown in table 4. Thermal analysis was then used to establish a thermal distribution across the blade as shown in figure 20. The intent of the investigation was to select a material that would not require cooling of the HPT blades and thereby achieve greater weight efficiency in an exoskeletal design. Based on the service temperature regime, a silicon-carbide-fiber matrix composite (SiC/SiC) was the preferred material for strength-to-weight properties. This CMC has the high-temperature capability and low-oxidation characteristics required for a combustion engine environment.

The assumed SiC/SiC properties used for this investigation are shown in table 12. The properties shown are estimated for a 1500 °F temperature under life-cycle service conditions. Although strength and durability in life-cycle applications are not readily available for SiC/SiC materials, the assumption was that these would be attainable values for current technology in CMC material systems.
TABLE 12.—PROJECTED CMC PROPERTIES AND ALLOWABLES
FOR EXOSKELETAL ENGINE ENVIRONMENT

<table>
<thead>
<tr>
<th>Modulus of elasticity, Gmodulus, Poisson’s</th>
<th>Coefficient of thermal expansion, α, 1/°F</th>
<th>Allowables</th>
</tr>
</thead>
<tbody>
<tr>
<td>E&lt;sub&gt;1,2&lt;/sub&gt;</td>
<td>E&lt;sub&gt;3&lt;/sub&gt;</td>
<td>G&lt;sub&gt;12&lt;/sub&gt;</td>
</tr>
<tr>
<td>30.4</td>
<td>21.3</td>
<td>11.4</td>
</tr>
</tbody>
</table>

At the start of the HPT investigation, the first-stage blades had a height of 1.26 in. and a root chord length of 1.146 in. The applied loads consisted of aerodynamic pressure (165.7 psi) combined with a 16 400-rpm inertial load. The blade model was rigidly supported at the root to simulate the integral blade ring held by the rotor drum for the inverted exoskeletal design. The second-stage HPT blades were 1.20 in. in height and had a root chord length of 0.727 in. Similarly, the inertial loading plus pressure (91.5 psi) were applied as a static load on the blade. A camber angle for the HPT blades was set at 15° and the taper ratio at 0.80. The analysis results for the first attempt of these HPT blade configurations show high negative margins for compression, tensile, and shear stresses in the exoskeletal design.

Two steps were taken to alleviate the high negative margins for stress:

1. The root chord length was increased in half-inch increments.
2. The blade thickness was increased by 25 percent over the derived AE3007 values.

These changes were effective in bringing the exoskeletal tensile and compressive stresses to a positive margin, but not until the chord length reached approximately 2.75 in. The practicality of this structural-driven parameter on engine performance is not part of the investigation. The results of this parametric study of varying the chord length are shown for the exoskeletal design in table 13. As in the case of the compressor, shear margins were negative and will require further design improvement. It was observed that the material allowable reductions at the service temperature were affecting the margins of safety. Based on the findings of this investigation, the elimination of cooling in the HPT will not be as readily achieved as it was originally believed. If cooling can be done in an exoskeletal design, the allowable stresses would increase, which helps to achieve positive margins of safety. The addition of cooling in the blades is complex and may bring weight penalties into the design.

TABLE 13.—EXOSKELETAL HIGH-PRESSURE TURBINE BLADE
MARGINS OF SAFETY FOR VARIED CHORD LENGTH

<table>
<thead>
<tr>
<th>Chord length, in.</th>
<th>Von Mises stress, σ&lt;sub&gt;vm&lt;/sub&gt;, klb/in.²</th>
<th>Maximum principal stress (M.S.), σ&lt;sub&gt;1&lt;/sub&gt;, klb/in.²</th>
<th>Minimum principal stress (M.S.), σ&lt;sub&gt;2&lt;/sub&gt;, klb/in.²</th>
<th>Shear stress, σ&lt;sub&gt;τ&lt;/sub&gt;, klb/in.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.146</td>
<td>167.0</td>
<td>62.7 (–0.75)</td>
<td>−182 (−0.88)</td>
<td>90.8 (−0.93)</td>
</tr>
<tr>
<td>1.719</td>
<td>37.5</td>
<td>33 (−0.53)</td>
<td>−44.4 (−0.49)</td>
<td>20.2 (−0.69)</td>
</tr>
<tr>
<td>2.0</td>
<td>29.1</td>
<td>29.2 (−0.47)</td>
<td>−36.1 (−0.38)</td>
<td>15.4 (−0.60)</td>
</tr>
<tr>
<td>2.5</td>
<td>19.9</td>
<td>20.8 (−0.25)</td>
<td>−24.6 (−0.09)</td>
<td>10.5 (−0.41)</td>
</tr>
<tr>
<td>3.0</td>
<td>15.9</td>
<td>12.4 (+0.25)</td>
<td>−19.7 (+0.14)</td>
<td>8.2 (+0.24)</td>
</tr>
</tbody>
</table>

*M.S., margin of safety.

Using the temperature distribution shown in figure 20, a thermal case was added to the FEA in an attempt to understand the full environmental effects on turbine blades. Difficulties were encountered, however, in the region of the blade root where rigid fixity was assumed. This fixity produced very high stress at the blade root for the static thermal solution. This result is very conservative since rigid fixity at the interface of the blade and integral blade ring (not modeled) is not entirely true. There will be some...
distortion of the ring due to expansion that may relieve the high stress at the root. When the root constraints are removed, the thermal stress is no longer an issue. The real answer lies somewhere in between and would require a fully modeled blade-ring component to gain an understanding of the thermally induced stresses. This component would require a higher fidelity thermal analysis and perhaps an engine cycle analysis, which was beyond the scope of this investigation. Thus, thermal loads were not included in the analysis and margin calculations for this investigation.

Some benefits were observed for CMC material in an exoskeletal arrangement for the HPT blades. There is insufficient data, however, to conclude that negative margins in the exoskeletal design can be eliminated. Increasing the chord length lowers bending stresses at the root but may not be feasible for aerodynamic and flow-rate considerations. Similar to the HPC blades, shear margins are negative in the CMC turbine blades, which would require a design fix. Unresolved negative margins may be an issue in the use of SiC/SiC blade material for the HPT stages. The addition of cooling would increase the allowable stresses while adding complexity to the design, and this would not necessarily remove the negative margins for CMC material. Nonetheless, the CMC material was used for the tabulation of weight. It remains to be proven that CMC blades can be used in a high-pressure turbine stage meeting all strength and durability requirements. The purpose of this investigation, as stated before, was to take an aggressive approach for the potential exoskeletal engine design.

**Drum Rotor Investigation**

This section summarizes the stress analysis and sizing of the drum rotor in the exoskeletal engine design concept. This work is part of an overall effort to determine a feasible size and weight for the exoskeletal drum rotor. The objective of this stress analysis is to determine the adequacy of the drum rotor concept when it rotates at 16,400 rpm, the engine overspeed condition.

This stress analysis is performed using the ANSYS® finite-element analysis software (ref. 19). A longitudinal section through the drum can be modeled as a two-dimensional axisymmetric model as shown in figure 21. The final stress state for this section as a body of revolution is then determined using ANSYS for analyzing an axisymmetric solid. In a rotating body, the two components of displacement (radial and axial) in any plane section of the body along its axis of symmetry completely define its state of stress. Thus, the use of an axisymmetric model greatly reduces the modeling and analysis time compared with that of an equivalent three-dimensional model.

The exoskeletal drum rotor is modeled on a 360° basis as shown in figure 13. Since ANSYS requires the model to be defined in the plane \( Z = 0.0 \), the global Cartesian \( Y \)-axis is assumed to be the axis of symmetry. Furthermore, the model is developed only in the +\( X \)-quadrants, which defines the radial direction.

To minimize the complexity of the study, this analysis focuses only on three sections of the high-pressure spool of the exoskeletal rotor. The geometry is scaled from the AE3007 drawing, and the dimensions are shown in figure 22. The drum rotor is separated into four sections to permit material choice flexibility. The material choices are shown in figure 23.

![Figure 21.—Axisymmetric model of exoskeletal drum rotor.](image-url)
Figure 24 shows the boundary conditions and loads applied to the exoskeletal drum rotor model. Since the rotor blades are discontinuous about the axis, an equivalent centrifugal force for each row of blades is applied to the inner radius of the disks. The weight of each rotor blade is obtained from the Pro/Engineer® model of the exoskeletal rotor. The total centrifugal force is calculated as a lumped mass at the disk inner radius spinning at 16 400 rpm:

$$F = m r_a \omega^2 = \frac{W_{\text{row}}}{g} r_a \left[ \frac{2 \pi (N)}{60} \right]^2$$

(1)

where $F$ is the total centrifugal force, $m$ is lumped mass, $r_a$ is the disk inner radius, $\omega$ is the rotational speed (radians per second), $W_{\text{row}}$ is the total weight of all of the blades in that row, $g$ is the gravitational constant, and $N$ is the rotational speed (revolutions per minute). These centrifugal forces are applied to the FEM on a 360° basis, which evenly distributes the blade load on each disk.

Boundary conditions are applied to the drum rotor model at the bearing locations. There are two radial bearings (one at each end), and one thrust bearing at the inlet to the high-pressure spool. Referring to figure 24, an axial constraint is applied at the thrust bearing location. This axial constraint prevents free body motion along the spin axis.

The radial bearings are neither infinitely compliant nor rigid. Without accurate stiffness values, the actual bearing stiffness falls between no constraint and a rigid constraint. To bound the problem, two model cases are defined in the initial investigation: (1) rigid constraints are applied at the two radial bearing locations (as shown in fig. 24) and (2) no radial constraints are applied at the ends of the drum rotor model (as shown in fig. 25).
Case 1.—Figure 25 shows a radial displacement contour plot for the exoskeletal drum rotor with radial constraints. The displacement plot shows zero radial growth at the rotor ends and a maximum radial displacement of 0.092 in. at the peak of the combustion section shell. The radial stress contours for case 1 are shown in figure 26. The magnitude of the peak radial stresses indicates that the model is likely to be overconstrained at the aft radial bearing location.

The tangential stress contours for case 1 are shown in figure 27. The maximum tangential stress value of 314 720 psi at the end of the combustor section may be too great because the drum rotor is overconstrained. If the drum rotor is not free to grow in the radial direction at the ends, the heavy combustor section increases the stress near the joint flange at the high-pressure turbine.

The minimum and maximum axial stresses shown in figure 28 also indicate that the model is overconstrained at the aft radial bearing location.

Case 2.—Figure 29 shows the radial displacement contour plot for the drum rotor without radial constraints. The displacement plot shows radial growth at the rotor ends and a maximum radial displacement of 0.092 in. at the peak of the combustion section shell. The maximum radial displacement in case 2 is similar to case 1. However, each end of the drum rotor assembly is free to grow in the radial direction.
Figure 26.—Radial stresses for drum rotor with radial constraints. Speed, 16 400 rpm.

Figure 27.—Tangential stresses for drum rotor with radial constraints. Speed, 16 400 rpm.
The radial stresses for case 2 are shown in figure 30. The radial stresses in case 2 are lower because the drum rotor is free to grow in the radial direction at the ends.

The tangential stress contours for case 2 are shown in figure 31. Now, the maximum tangential stress has dropped to a value of 263 610 psi. The maximum tangential stress in the combustor section near the joint flange is lower because the drum rotor is free to grow in the radial direction at the ends.

The minimum and maximum axial stresses, as shown in figure 32, also occur in the combustor section near the joint flange with the HPT. These axial stresses appear to be bending stresses because the heavy combustor section hinges at that joint flange.
As a check to the validity of peak stresses observed in the drum rotor, a simplified hand calculation of a rotating disk as shown in figure 33 was used to determine the stresses due to rotation. Additional forces operate on the disks because the rotor blades are also pushing out on the inner radius of the disks, which cause additional stresses at that interface. There are no additional forces on the combustion section, which makes it easier to compare the finite-element results with fundamental theory.

Figure 30.—Radial stresses for drum rotor without radial constraints. Speed, 16 400 rpm.

Figure 31.—Tangential stresses for drum rotor without radial constraints. Speed, 16 400 rpm.
In a spinning disk, the inertia forces create tangential and radial stresses due to the tangential elongation of the disk. In other words, both the circumference and the radius of the disk grow due to the centrifugal forces acting on material within the spinning disk.

From Shigley (ref. 20), the maximum radial stress for the simplified rotating disk occurs at the radius location $r = (r_a + r_b)/2$:

$$\sigma_{r,\text{max}} = \frac{3 + \mu}{8} \frac{\gamma \omega^2}{g} \left( r_b - r_a \right)^2$$

$$= \frac{3 + 0.33}{8} \frac{0.298}{386.4} \left[ \frac{16400(2\pi)}{60} \right]^2 (10.375 - 9.75)^2$$

$$= 370 \text{ psi}$$

Figure 32.—Axial stresses for drum rotor without radial constraints. Speed, 16 400 rpm.

Figure 33.—Simple rotating disk. Material, Hastelloy™; weight density, $\gamma$, 0.298 lb/in.$^3$; Poisson’s ratio, $\mu$, 0.33; engine rotational speed, $N$, 16 400 rpm.
where $\sigma_{r,\text{max}}$ is maximum radial stress, $\mu$ is Poisson's ratio, $\gamma$ is weight density, $\omega$ is rotational speed, $g$ is the gravitational constant, and $r_b$ and $r_a$ are the outer and inner disk radii, respectively.

Referring to figures 26 and 30, this stress value certainly falls within the stress contours shown in each plot. This radial stress calculation cannot validate either case 1 or case 2.

From Shigley (ref. 20), the maximum tangential stress $\sigma_{t,\text{max}}$ occurs at the inner boundary of the disk where $r = r_a$. For the combustion section this value is calculated as follows:

$$\sigma_{t,\text{max}} = \frac{3 + \mu}{4} \frac{\gamma \omega^2}{g} \left( \frac{r^2}{r^2} + \frac{1 - \mu}{3 + \mu} \frac{r^2_a}{r^2} \right)$$

$$= \frac{3 + 0.33}{4} \frac{0.298}{386.4} \left[ \frac{16 400(2\pi)}{60} \right]^2 \left( \frac{10.375^2 + 1 - 0.33}{3 + 0.33} \right) \left( \frac{9.75^2}{3 + 0.33} \right)$$

$$= 240 057 \text{ psi}$$

This stress calculation is in close agreement with the finite-element results for the exoskeletal drum rotor without radial constraints at the bearings.

Encouraged by these calculations, another study is performed using the model from case 2 (no rigid constraints at the radial bearing locations). Although the stresses were significantly reduced, the maximum tangential stress in the exoskeletal drum rotor exceeds the ultimate strength of the material, Hastelloy X™, selected for the shell over the combustion section. An adequate design is needed before the weight of the exoskeletal rotor concept is tallied.

**Trade study.**—The normal procedure for performing a finite-element analysis involves (1) defining the model, its boundary conditions, and loads, (2) obtaining a solution, and (3) interpreting the results. If the results indicate a design change is necessary, the whole process must be repeated. The model definition alone may be time consuming. The ANSYS Parametric Design Language (APDL, ref. 21) gives the user the ability to automate this process with user-defined variables (parameters) and programming input. The exoskeletal drum rotor model was generated using design parameters that could be easily changed. The ANSYS input data file for the exoskeletal drum rotor is found in appendix C.

The exoskeletal drum rotor model is generated using design parameters to vary the thickness of the drum rotors and rotor disks (i.e., bladed rings). A trade study is performed with this model to track the impact on rotor stresses as these thicknesses are varied. The objective of this study is to find a design in which the stresses are below the material limits while minimizing the rotor weight. A range of plausible drum rotor and bladed-ring thicknesses are used in this study to minimize stresses and weight.

Figure 34 shows the result of this trade study in a carpet plot. Unfortunately, this study shows that no combination of drum rotor and bladed-ring (disks) thicknesses can overcome the inertia forces in this design concept. Referring to the stress equations for a rotating disk, the maximum tangential stress (eq. (3)) is proportional to the square of the radius. The stress in the exoskeletal rotor increases rapidly as the rotor diameter and thicknesses increase. By moving the rotating body out to a larger diameter, the exoskeletal rotor concept increases the mass moment of inertia and weight beyond the capability of current materials. The maximum tangential stress is also proportional to the square of the rotational speed. Reducing the engine speed would significantly reduce stresses in the rotor. Furthermore, since the maximum tangential stress is directly proportional to weight density, the use of high-strength-to-weight composite materials would help to reduce stresses. However, these composite materials may not be suitable for high-temperature combustion environments where the strength is needed.

The weight estimates in this study will use a bladed-ring (disk) thickness of 0.375 in. and a drum rotor thickness of 0.125 in. The resulting weights generated in tables 14 to 16 are considered a lower bound for the structural weight of a drum rotor assembly in this size class.
TABLE 14.—HIGH-PRESSURE COMPRESSOR DRUM ROTOR WEIGHT ESTIMATE

(a) Blade ring assembly

<table>
<thead>
<tr>
<th>Rotor stage</th>
<th>Mass, lb-sec²/in.</th>
<th>Single airfoil weight, lb</th>
<th>Number of blades</th>
<th>Total blade airfoil weight, lb</th>
<th>Total blade-ring assembly weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.841 × 10⁻³</td>
<td>3.8025</td>
<td>5.83 × 10⁻²</td>
<td>21</td>
<td>1.223</td>
</tr>
<tr>
<td>2</td>
<td>6.031 × 10⁻³</td>
<td>2.3302</td>
<td>2.38 × 10⁻²</td>
<td>28</td>
<td>.667</td>
</tr>
<tr>
<td>3</td>
<td>6.469 × 10⁻³</td>
<td>2.4997</td>
<td>1.18 × 10⁻²</td>
<td>35</td>
<td>.412</td>
</tr>
<tr>
<td>4</td>
<td>5.592 × 10⁻³</td>
<td>2.1608</td>
<td>6.41 × 10⁻³</td>
<td>42</td>
<td>.269</td>
</tr>
<tr>
<td>5</td>
<td>4.962 × 10⁻³</td>
<td>1.9172</td>
<td>3.90 × 10⁻³</td>
<td>49</td>
<td>.191</td>
</tr>
<tr>
<td>6</td>
<td>4.879 × 10⁻³</td>
<td>1.8854</td>
<td>2.49 × 10⁻³</td>
<td>56</td>
<td>.139</td>
</tr>
<tr>
<td>7</td>
<td>3.975 × 10⁻³</td>
<td>1.5358</td>
<td>1.67 × 10⁻³</td>
<td>62</td>
<td>.103</td>
</tr>
<tr>
<td>8</td>
<td>9.242 × 10⁻³</td>
<td>3.5710</td>
<td>3.38 × 10⁻³</td>
<td>68</td>
<td>.230</td>
</tr>
<tr>
<td>9</td>
<td>1.089 × 10⁻²</td>
<td>4.2065</td>
<td>2.54 × 10⁻³</td>
<td>74</td>
<td>.188</td>
</tr>
<tr>
<td>10</td>
<td>1.010 × 10⁻²</td>
<td>3.9039</td>
<td>1.96 × 10⁻³</td>
<td>78</td>
<td>.153</td>
</tr>
<tr>
<td>11</td>
<td>9.633 × 10⁻³</td>
<td>3.7223</td>
<td>1.51 × 10⁻³</td>
<td>82</td>
<td>.124</td>
</tr>
<tr>
<td>12</td>
<td>1.049 × 10⁻²</td>
<td>4.0552</td>
<td>1.30 × 10⁻³</td>
<td>84</td>
<td>.109</td>
</tr>
<tr>
<td>13</td>
<td>8.459 × 10⁻³</td>
<td>3.2684</td>
<td>1.11 × 10⁻³</td>
<td>85</td>
<td>.095</td>
</tr>
<tr>
<td>14</td>
<td>9.242 × 10⁻³</td>
<td>3.5710</td>
<td>1.00 × 10⁻³</td>
<td>84</td>
<td>.084</td>
</tr>
</tbody>
</table>

(b) Drum rotor

<table>
<thead>
<tr>
<th>Stage</th>
<th>Mass, lb-sec²/in.</th>
<th>Number</th>
<th>Mass, lb-sec²/in.</th>
<th>Weight, lb</th>
<th>Drum rotor weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.247 × 10⁻²</td>
<td>1</td>
<td>1.298 × 10⁻²</td>
<td>8.6840</td>
<td>5.0168</td>
</tr>
<tr>
<td>2</td>
<td>4.441 × 10⁻³</td>
<td></td>
<td></td>
<td>17.1589</td>
<td>13.70</td>
</tr>
</tbody>
</table>

Total drum rotor weight, lb 77.28

---

Figure 34.—Trade study for exoskeletal rotor design.
TABLE 15.—COMBUSTOR DRUM ROTOR WEIGHT ESTIMATE

<table>
<thead>
<tr>
<th>Stage</th>
<th>Combustor drum rotor Mass, lb-sec²/in.</th>
<th>Weight, lb</th>
<th>Number</th>
<th>Flange Mass, lb-sec²/in.</th>
<th>Weight, lb</th>
<th>Total drum rotor weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.112x10⁻¹</td>
<td>42.9719</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>42.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total combustor drum rotor weight, lb</td>
</tr>
</tbody>
</table>

TABLE 16.—HIGH-PRESSURE TURBINE DRUM ROTOR WEIGHT ESTIMATE

(a) Blade ring assembly

<table>
<thead>
<tr>
<th>Rotor stage</th>
<th>Ring Mass, lb-sec²/in.</th>
<th>Weight, lb</th>
<th>Single airfoil weight, lb</th>
<th>Number of blades N</th>
<th>Total blade airfoil weight, lb</th>
<th>Total blade-ring assembly weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.332x10⁻³</td>
<td>1.6737</td>
<td>------</td>
<td>------</td>
<td>2.5</td>
<td>4.17</td>
</tr>
<tr>
<td>2</td>
<td>1.123x10⁻²</td>
<td>4.3394</td>
<td>------</td>
<td>------</td>
<td>1.5</td>
<td>5.84</td>
</tr>
</tbody>
</table>

(b) Drum rotor

<table>
<thead>
<tr>
<th>Drum rotor</th>
<th>Flange Mass, lb-sec²/in.</th>
<th>Weight, lb</th>
<th>Number</th>
<th>Mass, lb-sec²/in.</th>
<th>Weight, lb</th>
<th>Drum rotor weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.498x10⁻²</td>
<td>17.3812</td>
<td>------</td>
<td>---</td>
<td>---</td>
<td>17.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total drum rotor weight, lb</td>
</tr>
</tbody>
</table>

**Rotor Dynamics Assessment**

This section covers a preliminary lateral vibration analysis of a flexible beam designed to simulate the exoskeletal rotor design. The purpose of the analysis is to determine if this structure has natural vibration modes within the operating speed range of the AE3007 turbine engine.

In this analysis, the drum assembly is mounted to two flexible bearings, which in turn are rigidly fixed. Dynamic coupling with other systems in the engine through the bearings is neglected. Since bearings play a vital role in the dynamic behavior of a rotor, one must select the appropriate bearing stiffness to ensure against potentially destructive vibrations. Thus, another purpose of this analysis is to evaluate the bearing stiffness for the exoskeletal drum rotor design.

A computer code, CRTSPD (ref. 22), has been developed especially for determining the critical speeds and mode shapes of shaft systems. This program uses a lumped-parameter rotor representation to determine all critical speeds of the exoskeletal drum rotor design. A critical speed is defined as the condition where the rotating speed of the rotor coincides with the natural frequency (ref. 23).

Prudent design practice should prevent any coincidence of critical speeds and the rated speed. As a result, the following criterion has been adopted. For a single-span rotor, the critical speeds must be outside a range of 15 percent below to 25 percent above the running speed to provide an adequate margin of safety. The high-pressure compressor and turbine in the AE3007 engine have an operating speed of 14 600 rpm, and a maximum overspeed condition of 16 400 rpm. Therefore, based on these running speeds, any critical speed must be below 12 410 rpm and above 20 500 rpm.
Lumped-parameter vibration model.—Rotating motion requires a distinctive rotor structural-dynamic model and an eigenvalue analysis. Eigenvalue analysis refers to the mathematical calculation of undamped natural frequencies (critical speeds) and mode shapes. The distribution of the mass and stiffness along the rotor and the bearing support stiffness determine the mode shapes (ref. 23).

Structural-dynamic models for flexible rotors are derived by using Timoshenko’s beam models for bending and shear deflection (ref. 24), transverse and rotary inertia, and gyroscopic effects. The lumped-parameter vibration model is traditionally used to account for the distributed elastic and inertial properties of a rotor. The rotor is modeled as a collection of several rigid bodies connected by massless elastic beam elements. Assuming the rotor is axisymmetric, the general equation of motion for a lumped-parameter model, shown in figure 35, is defined by the following set of transfer matrix equations (ref. 2):

\[
\begin{bmatrix}
\delta_n' \\
\theta_n' \\
V_n' \\
M_n'
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
(m_n\omega^2 - K_n) & 0 & 1 & 0 \\
0 & (I_n - J_n)\omega^2 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\delta_n \\
\theta_n \\
V_n \\
M_n
\end{bmatrix}
\]

\[
\begin{bmatrix}
\delta_{n+1}' \\
\theta_{n+1}' \\
V_{n+1}' \\
M_{n+1}'
\end{bmatrix} =
\begin{bmatrix}
1 & L_n & L_n^3/6EI_n & L_n^2/2EI_n \\
0 & 1 & L_n^2/2EI_n & L_n/NI_n \\
0 & 0 & 1 & 0 \\
0 & 0 & L_n & 1
\end{bmatrix}
\begin{bmatrix}
\delta_n' \\
\theta_n' \\
V_n' \\
M_n'
\end{bmatrix}
\]

Where \(\delta\) is radial deflection (inches), \(\theta\) is angular deflection (radians), \(V\) is shear force (pounds), \(M\) is bending moment (pounds-inches), \(K\) is matrix stiffness (pounds per inches), \(I\) is area moment of inertia (inches\(^4\)), \(J\) is polar moment of inertia (inches\(^4\)), \(L\) is shaft section length (inches), \(E\) is modulus of elasticity (pounds per square inch), and \(\omega\) is shaft speed (radians per second).

Historically, two approaches have been developed to derive and solve the governing matrix equations for a lumped-parameter flexible rotor model (ref. 25). M.A. Prohl (ref. 26) and N.O. Myklestad (ref. 27) independently developed the transfer-matrix formulation method, which is now known as the Myklestad-Prohl method. Myklestad and Prohl both developed a tabular method to find the modes and frequencies of structures, such as airplane wings and turbine blades. C. Biezeno and R. Grammel developed (1959) the general mass-stiffness-matrix approach (ref. 25). Both these methods have been used to develop computer programs that define flexible-rotor matrix models from rigid-body equations and to perform the eigenvalue analysis.
Calculations of rotor critical speeds and the corresponding amplitudes of vibration require the use of a computer program such as CRTSPD. To analyze the complex geometry of the exoskeletal design, the rotor was divided into a suitable number of sections defining a series of interconnected uniform beams. Figure 36 shows a schematic of the CRTSPD model, which can contain up to 30 sections. The computer input data for each section consist of an external weight, section length, shaft outer and inner diameters, transverse moment of inertia, and rotational (polar) moment of inertia.

The generic representation of the exoskeletal rotor is a single-span, two-bearing system. In this system, the rotor, bladed disks, and bearings are assumed to be axisymmetric. In addition, all materials are assumed to be quasi-isotropic.

The computer program CRTSPD allows the user to (1) model the disk as an integral part of the shaft or (2) model only the shaft and add the disk mass properties externally. The advantage to modeling the disks as integral members of the shaft is that the program automatically calculates the cross-sectional properties. The disadvantage is that the section stiffness may be more than twice that of the shaft under the disk. However, when the disk mass properties are put separately, one loses the additional stiffness that the disks add to the shaft. In the exoskeletal case, only the drum rotor is modeled with the disk mass properties applied externally. Since critical speeds (or natural frequencies) in a flexible system are proportional to stiffness (i.e., \( \omega_n = (k/m)^{1/2} \)), this approach is more conservative. The exoskeletal rotor should be considerably stiffer than the original AE3007 because of its larger diameter. For this investigation, it is assumed that the exoskeletal rotor will behave as a rigid body on two soft bearings. If any critical speeds occur in the range of 12 410 to 20 500 rpm, the model must be modified to include the disk.
Table 17 shows the CRTSPD input data file for the exoskeletal rotor, and table 18 shows the bearing stiffness for each bearing used in this analysis. A bearing stiffness of 20 000 lb/in. is selected for this rotor (Andrew J. Provenza, March 19, 2003, NASA Glenn Research Center, Cleveland, OH, personal communication), which is a typical stiffness value for magnetic bearings.

### Table 17—CRTSPD LUMPED-PARAMETER MODEL FOR EXOSKELETAL ROTOR

<table>
<thead>
<tr>
<th>STATION</th>
<th>WEIGHT</th>
<th>LENGTH</th>
<th>SHAFT DIAMETER</th>
<th>POLAR MOM.</th>
<th>TRANS. MOM.</th>
<th>Ex10^6</th>
<th>DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LB</td>
<td>IN.</td>
<td>OUTSIDE</td>
<td>INSIDE</td>
<td>LB-IN.**2</td>
<td>LB-IN.**2</td>
<td>LB/IN.*3</td>
</tr>
<tr>
<td>1</td>
<td>34.792</td>
<td>2.920</td>
<td>16.680</td>
<td>16.430</td>
<td>0.133E+05</td>
<td>5637.</td>
<td>0.056</td>
</tr>
<tr>
<td>2</td>
<td>5.987</td>
<td>2.340</td>
<td>16.680</td>
<td>16.430</td>
<td>0.129E+04</td>
<td>643.1</td>
<td>0.056</td>
</tr>
<tr>
<td>3</td>
<td>3.870</td>
<td>2.440</td>
<td>16.680</td>
<td>16.430</td>
<td>0.128E+04</td>
<td>640.0</td>
<td>0.056</td>
</tr>
<tr>
<td>4</td>
<td>3.726</td>
<td>2.040</td>
<td>16.680</td>
<td>16.430</td>
<td>0.128E+04</td>
<td>638.0</td>
<td>0.056</td>
</tr>
<tr>
<td>5</td>
<td>3.153</td>
<td>1.930</td>
<td>16.680</td>
<td>16.430</td>
<td>0.127E+04</td>
<td>634.8</td>
<td>0.056</td>
</tr>
<tr>
<td>6</td>
<td>2.793</td>
<td>1.820</td>
<td>16.680</td>
<td>16.430</td>
<td>0.127E+04</td>
<td>633.3</td>
<td>0.056</td>
</tr>
<tr>
<td>7</td>
<td>3.090</td>
<td>1.420</td>
<td>16.680</td>
<td>16.430</td>
<td>0.129E+04</td>
<td>646.6</td>
<td>0.160</td>
</tr>
<tr>
<td>8</td>
<td>3.060</td>
<td>1.310</td>
<td>16.680</td>
<td>16.430</td>
<td>0.132E+04</td>
<td>658.6</td>
<td>0.160</td>
</tr>
<tr>
<td>9</td>
<td>9.514</td>
<td>1.370</td>
<td>16.680</td>
<td>16.430</td>
<td>0.132E+04</td>
<td>657.7</td>
<td>0.160</td>
</tr>
<tr>
<td>10</td>
<td>5.758</td>
<td>1.260</td>
<td>16.680</td>
<td>16.430</td>
<td>0.131E+04</td>
<td>656.8</td>
<td>0.160</td>
</tr>
<tr>
<td>11</td>
<td>5.365</td>
<td>1.250</td>
<td>16.680</td>
<td>16.430</td>
<td>0.131E+04</td>
<td>654.7</td>
<td>0.160</td>
</tr>
<tr>
<td>12</td>
<td>5.171</td>
<td>1.290</td>
<td>16.680</td>
<td>16.430</td>
<td>0.131E+04</td>
<td>655.2</td>
<td>0.160</td>
</tr>
<tr>
<td>13</td>
<td>5.445</td>
<td>1.180</td>
<td>16.680</td>
<td>16.430</td>
<td>0.131E+04</td>
<td>653.9</td>
<td>0.160</td>
</tr>
<tr>
<td>14</td>
<td>4.587</td>
<td>1.180</td>
<td>16.680</td>
<td>16.430</td>
<td>0.130E+04</td>
<td>652.0</td>
<td>0.160</td>
</tr>
<tr>
<td>15</td>
<td>4.757</td>
<td>0.930</td>
<td>16.680</td>
<td>16.430</td>
<td>0.129E+04</td>
<td>647.5</td>
<td>0.160</td>
</tr>
<tr>
<td>16</td>
<td>5.454</td>
<td>0.880</td>
<td>16.680</td>
<td>16.430</td>
<td>0.125E+04</td>
<td>626.4</td>
<td>0.160</td>
</tr>
<tr>
<td>17</td>
<td>3.144</td>
<td>1.000</td>
<td>17.000</td>
<td>16.750</td>
<td>70.1</td>
<td>35.11</td>
<td>0.297</td>
</tr>
<tr>
<td>18</td>
<td>3.063</td>
<td>2.000</td>
<td>17.950</td>
<td>17.700</td>
<td>235.</td>
<td>118.4</td>
<td>0.297</td>
</tr>
<tr>
<td>19</td>
<td>4.306</td>
<td>2.000</td>
<td>19.220</td>
<td>19.970</td>
<td>368.</td>
<td>185.5</td>
<td>0.297</td>
</tr>
<tr>
<td>20</td>
<td>4.261</td>
<td>1.720</td>
<td>20.400</td>
<td>20.150</td>
<td>412.</td>
<td>207.3</td>
<td>0.297</td>
</tr>
<tr>
<td>21</td>
<td>3.266</td>
<td>1.000</td>
<td>21.260</td>
<td>21.010</td>
<td>347.</td>
<td>173.9</td>
<td>0.297</td>
</tr>
<tr>
<td>22</td>
<td>1.233</td>
<td>0.000</td>
<td>21.580</td>
<td>21.340</td>
<td>138.</td>
<td>68.92</td>
<td>0.297</td>
</tr>
<tr>
<td>23</td>
<td>2.477</td>
<td>2.000</td>
<td>21.360</td>
<td>21.110</td>
<td>279.</td>
<td>140.4</td>
<td>0.297</td>
</tr>
<tr>
<td>24</td>
<td>4.903</td>
<td>2.000</td>
<td>20.930</td>
<td>20.680</td>
<td>542.</td>
<td>272.5</td>
<td>0.297</td>
</tr>
<tr>
<td>25</td>
<td>5.553</td>
<td>2.640</td>
<td>20.430</td>
<td>20.180</td>
<td>585.</td>
<td>295.0</td>
<td>0.297</td>
</tr>
<tr>
<td>26</td>
<td>7.936</td>
<td>0.000</td>
<td>20.140</td>
<td>19.900</td>
<td>322.</td>
<td>162.9</td>
<td>0.297</td>
</tr>
<tr>
<td>27</td>
<td>5.912</td>
<td>0.950</td>
<td>20.020</td>
<td>19.770</td>
<td>0.226E+04</td>
<td>1129.</td>
<td>0.297</td>
</tr>
<tr>
<td>28</td>
<td>6.954</td>
<td>1.450</td>
<td>20.020</td>
<td>19.770</td>
<td>0.243E+04</td>
<td>1213.</td>
<td>0.297</td>
</tr>
<tr>
<td>29</td>
<td>9.042</td>
<td>1.310</td>
<td>20.020</td>
<td>19.770</td>
<td>0.247E+04</td>
<td>1234.</td>
<td>0.297</td>
</tr>
<tr>
<td>30</td>
<td>28.350</td>
<td>0.000</td>
<td>20.020</td>
<td>19.770</td>
<td>0.720E+04</td>
<td>3598.</td>
<td>0.297</td>
</tr>
</tbody>
</table>

---

196.920 42.750 48308.500
TABLE 18.—CRTSPD BEARING STIFFNESSES

BEARING STATIONS 1 30

SPEED DEPENDENT BEARING CHARACTERISTICS

<table>
<thead>
<tr>
<th>BEARING NUMBER</th>
<th>BEARING LOCATION</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>20000.0</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>28.50</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>20000.0</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>28.50</td>
<td>0.0000E+00</td>
</tr>
</tbody>
</table>

Results of eigenvalue analysis.—The modes of vibration (critical speeds) of the rotor system may be divided into two categories: (1) modes where the rotor behaves essentially as a rigid body and (2) flexural modes where the rotor whirls with a characteristic deflection curve.

Figure 37 shows the two rigid-body modes for the exoskeletal rotor. In the first critical speed at 2467 rpm, the bearing support points at each end of the rotor move in phase with one another. The locus of the rotor’s whirling motion traces a cylindrical path.

At the second rigid-body mode, at a critical speed of 5776 rpm, the bearing support points move out of phase with one another. As seen in figure 37, there is a node point near or at the midspan where the deflection crosses the spin axis. The locus of the rotor’s whirling motion traces two cones, point to point.

Figure 38 shows the third mode of the exoskeletal rotor, which occurs at 261 570 rpm. The third critical speed is the first flexural mode of the exoskeletal rotor, and it is due to the bearing flexibility. Using differential equations, F.C. Linn and M.A. Prohl (ref. 28) showed that the rigid-body critical speeds both approach zero as the bearing flexibility approaches infinity, as shown in figure 39. In this case, the third critical speed at 261 570 rpm is the first “free-free” mode of the rotor system because there is no apparent restraint at either support point (ref. 29).
**Rotor dynamics summary.**—Assuming the bearing stiffness for this rotor design is 20,000 lb/in. for the entire speed range, the first and second undamped critical speeds or rigid-body modes occur at 2467 and 5776 rpm, respectively. These speeds are well below the operating speed of 14,600 rpm for the exoskeletal rotor design concept. Usually, the rotor flexural modes require more design consideration because the rotor and stator can vibrate out of phase with one another, which may cause rubbing of seals or internal damage. However, the third critical speed (or first flexural mode) occurs at 261,570 rpm, and this speed is well above the 16,400 rpm overspeed condition. Further study is recommended to analyze the response to imbalance, bearing location, bearing damping, and damping in the supporting structure. In this preliminary analysis, the limits placed on the critical speeds ensure satisfactory operation at the design speeds of the exoskeletal engine.

**Stationary Core Investigation**

**Description.**—The stationary core at the center of the exoskeletal engine forms the inner flow-path surface of the inlet, compressor, combustion chamber, turbine, and nozzle exit, whereas the drum rotor forms the outer flow-path surface. Additionally, the core functions as a backup structure for the stator guide vanes. The guide vanes are nonrotating, fixed-position blades integrally machined as a bladed-ring assembly. There is one guide vane ring assembly for each stage of the compressor and turbine. The ring assembly slides onto the stationary core with interlocking spacers between each stage row to accommodate the respective rotating stages of the drum.

The stationary core consists of four distinct sections along its length with each section made from a different material. The use of multiple materials gave the lightest weight design possible while providing adequate structural strength and thermal management. The first section enveloped the inlet and first seven stages of the compressor and was made of graphite polyimide to handle operating temperatures up to 600 °F. Titanium was used for the second section, which included the final seven stages of the compressor and just up to the combustion chamber. Combined pressure and temperature were the design drivers for the material selection in the combustion chamber. For this section, Hastelloy X™ was chosen for its high-strength and extreme-temperature properties. A CMC of SiC/SiC was selected for the last section, which consisted of the turbine and exit region assumed to be operating at 2200 °F or higher. This CMC does not have a particularly favorable strength-to-weight ratio but was selected to eliminate the
need for cooling and thereby realize a net weight savings. Specific details of attaching the various shells to one another were not addressed in this study, but additional weight to account for attachments was added to the weight summary prediction.

**Analysis.**—A finite-element shell model of the core structure was developed with appropriate material properties assigned at each section of the core. The model was constrained axially at the forward thrust ring station near the inlet. A second constraint was added at the aft ring location of the core to allow for lateral support of the structure and thermal growth along the axis. The applied boundary conditions provided an effective relief of any thermal expansion in the core structure. The primary load comes from the combustion pressure and resulting thrust of the engine. The load path for this pressure is in the compression of the core shell, and the thrust is transferred through attachment vanes between the stationary core and the nacelle at the thrust ring location. The net thrust causes an overall compression load in the core structure that could result in buckling of the shell.

Strength and linear buckling loads were determined for the stationary core. Adjustments to shell thickness were made to ensure positive margins of safety for strength and stability. A hand calculation was performed using the line loads to compute shell buckling. Results of this preliminary assessment yielded a thickness requirement of 0.05 in. for the graphite polyimide, 0.09 in. for the titanium, 0.12 in. for the Hastelloy™, and 0.12 in. for the SiC/SiC. These thicknesses were used in determining weight estimates for the stationary core assembly and guide vanes; the subtotal is 100.5 lb as listed in table 19. Figure 40 shows the stationary core Von Mises stress results for the core segments. Figure 41 illustrates the deformed shape of the first buckling mode. As shown, the critical section of the core has a 17-percent margin of safety against buckling for the shell thickness provided.

**TABLE 19.—EXOSKELETAL CONCEPT STATIONARY CORE**

[Ring thickness, 0.10 in.]

(a) Weight summary

<table>
<thead>
<tr>
<th>Rotor stage</th>
<th>Single airfoil weight, lb</th>
<th>Number of blades, (n_b)</th>
<th>Total blade weight, lb</th>
<th>Radius, (r), in.</th>
<th>Weight density, (\gamma), lb/in.(^3)</th>
<th>Axial location, (x_0), in.</th>
<th>(x_1), in.</th>
<th>Ring weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0583</td>
<td>21</td>
<td>1.22</td>
<td>3.57</td>
<td>0.056</td>
<td>2.25</td>
<td>3.59</td>
<td>0.17</td>
</tr>
<tr>
<td>2</td>
<td>0.0238</td>
<td>28</td>
<td>0.67</td>
<td>4.80</td>
<td>0.056</td>
<td>4.72</td>
<td>5.79</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>0.0118</td>
<td>35</td>
<td>0.41</td>
<td>5.53</td>
<td>0.056</td>
<td>7.24</td>
<td>8.15</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>0.0064</td>
<td>42</td>
<td>0.27</td>
<td>6.02</td>
<td>0.056</td>
<td>9.28</td>
<td>10.19</td>
<td>0.19</td>
</tr>
<tr>
<td>5</td>
<td>0.0039</td>
<td>49</td>
<td>0.19</td>
<td>6.36</td>
<td>0.056</td>
<td>11.31</td>
<td>12.01</td>
<td>0.16</td>
</tr>
<tr>
<td>6</td>
<td>0.0025</td>
<td>56</td>
<td>0.14</td>
<td>6.62</td>
<td>0.056</td>
<td>13.19</td>
<td>13.78</td>
<td>0.14</td>
</tr>
<tr>
<td>7</td>
<td>0.0017</td>
<td>62</td>
<td>0.10</td>
<td>6.82</td>
<td>0.056</td>
<td>14.59</td>
<td>15.23</td>
<td>0.15</td>
</tr>
<tr>
<td>8</td>
<td>0.0034</td>
<td>68</td>
<td>0.23</td>
<td>6.97</td>
<td>0.160</td>
<td>16.02</td>
<td>16.41</td>
<td>0.27</td>
</tr>
<tr>
<td>9</td>
<td>0.0025</td>
<td>74</td>
<td>0.19</td>
<td>7.09</td>
<td>0.160</td>
<td>17.37</td>
<td>17.80</td>
<td>0.31</td>
</tr>
<tr>
<td>10</td>
<td>0.0020</td>
<td>78</td>
<td>0.15</td>
<td>7.19</td>
<td>0.160</td>
<td>18.60</td>
<td>19.09</td>
<td>0.35</td>
</tr>
<tr>
<td>11</td>
<td>0.0015</td>
<td>82</td>
<td>0.12</td>
<td>7.28</td>
<td>0.160</td>
<td>19.86</td>
<td>20.32</td>
<td>0.34</td>
</tr>
<tr>
<td>12</td>
<td>0.0013</td>
<td>84</td>
<td>0.11</td>
<td>7.34</td>
<td>0.160</td>
<td>21.10</td>
<td>21.66</td>
<td>0.41</td>
</tr>
<tr>
<td>13</td>
<td>0.0011</td>
<td>85</td>
<td>0.09</td>
<td>7.40</td>
<td>0.160</td>
<td>22.38</td>
<td>22.74</td>
<td>0.27</td>
</tr>
<tr>
<td>14</td>
<td>0.0010</td>
<td>84</td>
<td>0.08</td>
<td>7.45</td>
<td>0.160</td>
<td>23.55</td>
<td>23.92</td>
<td>0.28</td>
</tr>
<tr>
<td>HPT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0080</td>
<td>40</td>
<td>0.32</td>
<td>8.31</td>
<td>0.076</td>
<td>39.04</td>
<td>39.95</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>0.0037</td>
<td>63</td>
<td>0.23</td>
<td>8.31</td>
<td>0.076</td>
<td>41.40</td>
<td>42.25</td>
<td>0.34</td>
</tr>
</tbody>
</table>

(b) Weight totals

<table>
<thead>
<tr>
<th>Blade airfoil, lb</th>
<th>Ring, lb</th>
<th>Blade and rings, lb</th>
<th>Stator shell, lb</th>
<th>Attachments, lb</th>
<th>Total weight of blade and rings, stator shell, and attachments, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.54</td>
<td>4.09</td>
<td>8.6</td>
<td>88.9</td>
<td>3.0</td>
<td>100.5</td>
</tr>
</tbody>
</table>
The exoskeletal engine concept requires large-diameter radial bearings on the outside diameter of the rotating drum located at both ends of the spool (as shown in fig. 42). A thrust bearing is located near the outside diameter at the inlet side of the compressor spool. The large diameter coupled with the high rotational speed poses significant challenges for bearing technology. State-of-the-art bearings for conventional engines with lubricating systems can operate at very high revolutions per minute and not exceed state-of-the-art rotational speed, which is approximately $4 \text{ M } DN$ (ref. 30). For the case of the exoskeletal high-pressure spool, the bearings operate at $7 \text{ M } DN$, well beyond the state of the art. Recent work of Sullivan at the NASA Glenn Research Center has shown thermal problems with carbon-carbon (C-C) bearings for the exoskeletal application (ref. 31). There are no known lubricated systems that can handle this magnitude of velocity; consequently, noncontact bearing systems are needed to accommodate the demands of the exoskeletal high-pressure spool heat loads. Among the candidates for investigation would be (1) foil bearings and (2) magnetic bearings.

**Foil bearings.**—The foil bearings shown in figure 43 are noncontacting and ride on a thin film of air, which is generated hydrodynamically (ref. 32) by the rotational speed. Lightweight foils are used to suspend and center the shaft. The current state-of-the-art size for this type bearing is about 4 in. in diameter (ref. 31). Typical foil bearing applications use a single foil rolled around the shaft as seen in the figure.

Competing foil bearing design technology employs a bumped foil to suspend the shaft (fig. 44). For the large-diameter application on the exoskeletal engine architecture, a hybrid system is envisioned as one in which the bumped foil provides stiffness and multiple foils are used to keep the large-diameter shaft centered (as shown in fig. 45). The complexity of the design and the significant increase in diameter
both lead to a significant and long-duration technical effort. Some of the drawbacks for the foil system include the high startup torque, the need for set-down/lift-off mechanical bearings and associated positioning hardware to accommodate anticipated duty cycle requirements. Unfortunately, no current bearing system can handle the heat generated by this system; consequently, an alternative system must be considered. For the purpose of this study, high-pressure air generated with an auxiliary power unit (APU) was selected to provide stiffness. With the help of a fast-acting control system, the bearing could be stiffened to handle extreme loads experienced in flight. The use of localized stiffening creates a viable backup bearing option, without relying on high-temperature material technology that may not be available in the near future. The weight estimation for this type of bearing system in the exoskeletal concept for this investigation was extrapolated since no data exist at the large diameter required. A concern about bearing stability is addressed by extending the width of the bearing to 4 in.
Magnetic bearings.—In the case of a magnetic bearing system, there are some advances in this area of research and development (R&D). Most of this R&D, however, has been focused on small-diameter shafts that may be completely encased by a magnetic bearing housing. For the large-diameter shaft in this study, it was considered that a passive rotor may be applicable with a minimum of four electric magnetic poles at 90° apart, as shown in figure 46. The stiffness of the large-diameter system and radial growth after spinup are among the technical challenges to overcome. For example, an exoskeletal concept as studied would have a calculated radial growth of 0.040 in. at the bearing on the turbine end of the spool. Radial growth of this magnitude would result in stability problems; consequently, a magnet pole positioning system would be required to maintain the appropriate clearances for the operation of the magnetic bearing system. This positioning system would require high-speed sensing and positioning. The passive magnetic laminate and its mounting hardware will require high structural integrity to resist the extremely high inertial forces. This would most likely drive an increase in the weights; however, this is not considered for the present study in the total weight compilation. Although not inconsequential, the weight resulting from the magnetic bearing power consumption was not considered in this study.

Similar to the foil bearings, a backup bearing system is needed for off-nominal loading events. These events would include gust and hard-landing loads as well as loss-of-blade imbalance loads. The approximate sizing of the backup bearing system was done using a 5-g loading and a three-blade imbalance force of 76 000 lb. For this study, we assumed that this backup system would add 75 lb for the short-duration, off-nominal events considered. The above weight of 75 lb is only a place holder and should be considered as a low-fidelity number. This backup system would prevent excessive excursion from a centered position if temperatures were tolerable. Unfortunately, the high heat load prevents a system of this nature from functioning properly and without advances in lubrication and materials, would most certainly result in catastrophic bearing failure.

Bearing weights.—The support structure for the bearing system (discussed in the next section) requires nominally a 47-lb total structure weight for the rings and struts at the forward and aft bearing support locations. The computed weights for a magnetic and foil bearing system as applicable in an exoskeletal design are tabulated in table 20. These weights will be considered as minimum weights since the historical data needed for sizing large-diameter, noncontact bearings in a flight propulsion system are not available.
TABLE 20.—EXOSKELETAL ENGINE BEARING WEIGHT SUMMARY
[All weights are in pounds.]

<table>
<thead>
<tr>
<th>Bearing concept alternatives</th>
<th>Magnetic bearing system</th>
<th>Foil bearing system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing support structure</td>
<td>46.6</td>
<td>46.6</td>
</tr>
<tr>
<td>E-coils</td>
<td>96.8</td>
<td>Auxiliary power unit</td>
</tr>
<tr>
<td>Positioning motors</td>
<td>95</td>
<td>Compressor</td>
</tr>
<tr>
<td>Electrical controllers</td>
<td>30</td>
<td>Manifolding</td>
</tr>
<tr>
<td>Permanent magnets</td>
<td>54.3</td>
<td></td>
</tr>
<tr>
<td>Backup bearing</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>397.7</td>
<td>Total weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>196.6</td>
</tr>
</tbody>
</table>

Summary.—The increase in diameter for a rotating drum versus the conventional shaft bearings creates bearing speeds well beyond the current operational capabilities for state-of-the-art lubricated bearing systems. This has prompted the consideration of other bearing schemes, such as a foil or magnetic systems. Both systems appear to meet the requirements of the exoskeletal application although neither technology is currently ready for operation at this size. Current developments in the foil bearing technologies indicate it may take 20 years to achieve foil bearings for this diameter. The magnetic bearings appear to be too heavy for this application and would also face a lengthy technology development program if selected. Regardless of these drawbacks, both bearing types were considered in the final comparison with the existing AE3007 high-pressure-spool weight comparison.

Bearing Housing Study

Description.—The bearing housing structure shown in figure 47 and modeled in figure 48 provides support for the exoskeletal rotor bearings located at each end of the rotor assembly. The fore and aft housings were designed as a ring structure attached to the engine nacelle frame through eight support vanes. The bearing rings and support vanes are made of 0.5-in.-thick titanium for strength and stiffness.
Analysis.—Stress and stability analyses were performed to size the bearing housing structure and to estimate its weight. The design load condition assumes that three side-by-side compressor blades have been detached, which results in an imbalance load of 7600 lb at 16 400 rpm. A maximum 8000-lb engine thrust load and the 7600-lb imbalance load were applied simultaneously to the bearing housing FEM, and a static analysis solution was executed in MSC/NASTRAN. Results of the static analysis show a peak Von Mises stress of 34 klb/in.² in the vanes and a maximum deformation of 0.0612 in. This stress result is well below the titanium compressive yield strength of 110 klb/in.² Using the same model, a linear buckling analysis was also performed to check the stability of the bearing ring support struts. The results are shown in figure 49. In summary, the bearing support configuration would sustain the applied service loads with sufficient margin. The corresponding structural weight was calculated to be 46.6 lb for both the fore and aft bearing housings.

Findings, Observations, and Enabling Technology Identification

Findings

(1) The exoskeletal high-pressure spool with a foil bearing system provides no weight advantage over a conventional design. The exoskeletal high-pressure spool with a magnetic bearing system weighs significantly more than the conventional design. This weight takes into account the expected weight savings that could be realized if a conventional engine were to make use of ceramic materials and switch to integral bladed disks. In addition, the exoskeletal weights assume that the negative margins in the drum rotor and blades could be overcome without additional weight impact. A summary of these weights is given in table 21. These findings reveal that the conceptual exoskeletal rotor and stator can be lighter than their conventional counterparts, subject to the assumptions and conditions of this study. However, the integrated exoskeletal high-pressure spool system is as heavy as or is heavier than its conventional counterpart primarily because of the bearing system mass.
### TABLE 21.—WEIGHT COMPARISON

[All weights are in pounds.]

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Exoskeletal with magnetic bearings</th>
<th>Exoskeletal with foil bearings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td></td>
<td>Rotor drum</td>
<td></td>
</tr>
<tr>
<td>HPC</td>
<td>187.3</td>
<td>142.6</td>
<td></td>
</tr>
<tr>
<td>HPT</td>
<td>79.7</td>
<td>Rotor drum</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>267.0</td>
<td>142.6</td>
<td></td>
</tr>
<tr>
<td>Stator</td>
<td></td>
<td>Stator</td>
<td></td>
</tr>
<tr>
<td>HPC</td>
<td>111.1</td>
<td>100.5</td>
<td></td>
</tr>
<tr>
<td>HPT</td>
<td>54.1</td>
<td>Stator</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>165.2</td>
<td>100.5</td>
<td></td>
</tr>
<tr>
<td>Bearings</td>
<td></td>
<td>Bearing system</td>
<td></td>
</tr>
<tr>
<td>Shaft</td>
<td></td>
<td>Housings</td>
<td></td>
</tr>
<tr>
<td>Bearings</td>
<td></td>
<td>E-coils</td>
<td>96.8</td>
</tr>
<tr>
<td>Total</td>
<td>59.6</td>
<td>Position motors</td>
<td>95.0</td>
</tr>
<tr>
<td>Weight savings</td>
<td></td>
<td>Bearing system</td>
<td></td>
</tr>
<tr>
<td>Material change</td>
<td>−38.7</td>
<td>Housings</td>
<td>46.6</td>
</tr>
<tr>
<td>Bladed disk design</td>
<td>−10.0</td>
<td>Auxiliary power unit</td>
<td>84.0</td>
</tr>
<tr>
<td>Total</td>
<td>−48.6</td>
<td>Position motors</td>
<td>42.0</td>
</tr>
<tr>
<td>Total system weight</td>
<td>443.2</td>
<td>Total system weight</td>
<td>640.9</td>
</tr>
</tbody>
</table>

(2) A requirement for turbine blade cooling is indicated in the exoskeletal design of an AE3007-like high-pressure spool examined in this study. Differential temperatures at the blade-to-ring interface could introduce excessive blade stresses. Blade cooling is a conventional approach to avoiding such thermal-induced stresses, but the development of cooling strategies for ceramic blades (which today are used to avoid cooling) is beyond the scope of this study and is a significant technology challenge.

(3) Shell material choices are limited by high temperatures and the need for light weight (low rotational inertia). The rotating drum operational environment is very demanding such that stiff, strong, low-density materials are required to sustain the high inertial forces and, at the same time, high thermal loads in the vicinity of the combustor and turbine require materials that can survive in an elevated temperature environment. Unfortunately, the thermal-resistant materials are very dense, and the strong lightweight materials are not temperature resistant. Within the scope of this investigation, no solution was identified using currently available materials, which is an indication that high-temperature, lightweight shell structures appear to be a critical design and technology challenge should an exoskeletal engine development be undertaken.

(4) Compressor blade analysis revealed that the taller metallic compressor blades, if used, in the exoskeletal high-pressure spool would have been buckling critical. Negative margins were also obtained in shear for compressor blades. These findings are a basis for considering composite materials for taller blade rows in exoskeletal compressors.

**Observations**

(1) An inherent characteristic of the exoskeletal design approach is keeping rotational inertia low, which is opposed to providing a large central flow area for potential noise reduction or alternative cycle integration. The exoskeletal approach places blades and their supporting structure at the outer diameter of the system. Throttle response, maneuvering loads, and containment are among many factors that drive
rotating machinery masses down at larger diameters and/or reduce rotational speeds. Since reductions in rotational speed directly impact engine performance, exoskeletal engines are driven toward lower diameters (which restricts the core space available for noise reduction or other cycle implementation).

(2) The increased rotary inertia of an exoskeletal design will require higher power for starting and have a slower response to changes in throttle setting.

(3) The fabrication of a woven preform of exoskeletal bladed rings would be difficult because of the complexity of the yarn paths and the large ring diameters. The densification of complex structures with tight surface tolerances has not been demonstrated. CMC’s are also difficult to densify without obstructing cooling passages. Machining the passages after densification would weaken the structure by cutting fibers. Inserting refractory metal rods in the cooling passages during densification could only be done if the passages were straight.

Enabling Technology Identification

(1) Large-diameter bearing capability for high-speed bearings, noncontact or contact types: Even under the best of assumptions, rotor and stator weight savings are offset by the weight of a noncontact bearing system such as foil bearings. The use of magnetic bearings may be less of a technology leap, but they increase the system weight beyond that of conventional engine systems.

(2) Manufacturing capability for a bladed-ring component: The capability of manufacturing CMC ring blades as an integrated component with precise geometry and uniform mechanical properties needs to be developed. Durability under life-cycle and environmental conditions (especially critical thermal conditions as noted in the Findings section) needs to be demonstrated before composite materials could be considered in a gas turbine engine.

Conclusions

1. The spool weight (neglecting bearings) of an exoskeletal engine may be equal to or less than the weight of the spool of a conventional engine. It was found that mounting blades inside a shell, rather than on a shaft, can result in rotating structure weights as low as or potentially lower than blades on shaft-mounted disks. This conclusion is based on an aggressive preliminary assessment of a potential exoskeletal design approach.

2. An advancement in bearing technology is required before a more precise assessment of exoskeletal engine feasibility can be undertaken. Current bearing technologies are inadequate for the high rotational speeds at large diameters required in exoskeletal systems. The present maturity of enabling bearing technologies is insufficient to provide a precise assessment of the system implications of their integration in an exoskeletal engine.

Recommendations

1. The next logical step in an examination of exoskeletal engine feasibility is to consider a “clean sheet” design approach to a specific exoskeletal design goal. The design of an exoskeletal system to its best advantage (especially involving changes to the engine cycle) was not attempted during this investigation. A clean sheet exoskeletal design, free of constraints driven by comparability to an existing engine, may discover alternatives that improve the weight and performance or lessen the technology challenges of the exoskeletal approach. Other applications of the exoskeletal concept have been suggested and may serve as compelling design goals. Noise reduction has been proposed through an inversion of the velocity profile at the convergence of “free flow” central core flow with the exhausts of
the spools. The open central core has also been proposed for the integration of a ramjet or other cycle. An extension of the exoskeletal approach appears in the concept of vaneless counterrotating gas turbines. A clean sheet exoskeletal implementation for a specific design goal that examines competitive weight characteristics is a logical next step in the assessment of exoskeletal viability.

2. Exoskeletal implementation has been shown to be reliant on advancements in bearing technology. Therefore, a critical path to exoskeletal engine consideration is through bearing technology advancement. It is recommended that consideration of exoskeletal requirements be added to goals for high-diameter-rotation-speed aerospace bearing technology programs.
Appendix A

Weight Analysis Turbine Engine (WATE) Output for AE3007

NEPP-WATE-98, March 1998

50 PAX ENGINE - Current Technology Baseline (revised for 'ND NMODE=1,DRAW=T, LONG=F, DOUTH=T, NCODE=-1, AMAC=F, NCASE=1, BOAT=F, ICEC=0,
TABLES=T, INPUT=T, LOAD=F, INST=0, MAPLOT=F, MAXNIT=100, ITERM=1, IW=1, &END
&D MODE=1, CALB=1, CBFL=0.020, ERB=0.80, ICBCMP=5,
KONFIG(1,1)=1,1,0,2,0, SPEC(1,1)=260.0, 0.0, 0, 0.00, 8600.1,1 ,0 ,0 ,0.44,27.,
KONFIG(1,2)=4,2,0,3,0, SPEC(1,2)=1.60, 0, 1, 3401, 1, 3402, 1, 3403, 1, 0,
0, 0.8750, 1.62, 0.9000,
KONFIG(1,3)=7,3,0,4,20, SPEC(1,3)=5.3, 0.00, 0.015,
KONFIG(1,4)=2,4,0,5,0, SPEC(1,4)=0.10,
KONFIG(1,5)=4,5,0,6,21, SPEC(1,5)=1.25, 0.115, 1, 3707, 1, 3708, 1, 3709, 1, 0,
0.8600, 15.0, 0.950,
KONFIG(1,6)=2,6,0,7,0, SPEC(1,6)=0.15, 8*0,
KONFIG(1,7)=2,7,0,8,0, SPEC(1,7)=0.45, 0.0., 0., 2760., 0.995, 18400, 5*0.6,
KONFIG(1,8)=5,8,21,9,0, SPEC(1,8)=3.45, 0.977, 1, 3801, 1, 3802, 1, 1,
0.6850, 1., 9100, 7000., 1, 1122, 2.,
KONFIG(1,9)=2,9,0,10,0, SPEC(1,9)=0.005, 6*0., 0.55,
KONFIG(1,10)=5,10,0,15,0, SPEC(1,10)=2.10, 0., 1, 3803, 1, 3804, 1, 1,
1.00, 1., 920, 5000.0, 1, 8888, 4,
KONFIG(1,14)=2,20,0,22,0, SPEC(1,14)=0,
KONFIG(1,15)=2,15,0,16,0, SPEC(1,15)=0.01,
KONFIG(1,11)=8,16,22,12,0, SPEC(1,11)=0, 0.3, .95, 1,
KONFIG(1,12)=2,12,0,13,0, SPEC(1,12)=.0005, 8*0.,
KONFIG(1,13)=9,13,0,14,0, SPEC(1,13)=0.0, 7004, 0., 0., 7003, 0., 0., 0.3, 0.5, 11

KONFIG(1,21)=11,5,8,23,0, SPEC(1,21)=18000., 8*1,
KONFIG(1,22)=11,2,10,0,0, SPEC(1,22)=7000., 0.435, 0.435, 6*1,
KONFIG(1,23)=10,0,0,0,0, SPEC(1,23)=100.0,

Design Point CNTLs... IF NEEDED

KONFIG(1,31)=12, SPCNTL(1,31)=1,1, 'STAP', 1, 15, 35.5, 0,
KONFIG(1,32)=12, SPCNTL(1,32)=1,5, 'DOUT', 5, 15, 0.0,
KONFIG(1,33)=12, SPCNTL(1,33)=13,2, 'STAP', 2, 6, 345.7, 0,
KONFIG(1,34)=12, SPCNTL(1,34)=4,7, 'PERF', 4, 0, 7580., 1,
KONFIG(1,35)=12, SPCNTL(1,35)=4,7, 'PERF', 4, 0, 1955., 0,

Off-Design CNTLs
KONFIG(1,41)=12, SPCNTL(1,41)=1,1, 'STAP', 8, 13, 0, 0, 0, 0,
KONFIG(1,42)=12, SPCNTL(1,42)=1,2, 'STAP', 8, 2, 0, 0, 0,
KONFIG(1,43)=12, SPCNTL(1,43)=1,5, 'DOUT', 8, 5, 0, 0, 0,
KONFIG(1,44)=12, SPCNTL(1,44)=1,6, 'STAP', 8, 8, 0, 0, 0,
KONFIG(1,45)=12, SPCNTL(1,45)=1,10, 'STAP', 8, 10, 0, 0, 0,
KONFIG(1,46)=12, SPCNTL(1,46)=2,11, 'DOUT', 8, 11, 0, 0, 0,
KONFIG(1,50)=12, SPCNTL(1,50)=1,21, 'DOUT', 8, 21, 0, 0, 0,
KONFIG(1,51)=12, SPCNTL(1,51)=1,22, 'DOUT', 8, 22, 0, 0, 0,

Part Power and Operational Controls
KONFIG(1,55)=16, SPCNTL(1,55)=1,57, 'DOUT', 4, 2, 1.1, 0, 1, -1, 0, 1, 9,
KONFIG(1,56)=16, SPCNTL(1,56)=0,58, 'DOUT', 4, 2, 1.1, 0, 1, -1, 0, 1, 9,
KONFIG(1,57)=12, SPCNTL(1,57)=1,3, 'DOUT', 5, 2, 23, 0, 0, 0, 0,
KONFIG(1,58)=12, SPCNTL(1,58)=1,3, 'STAP', 6, 22, 0.70, 0, 0, 0,

control for marching via temp.
KONFIG(1,60)=12, SPCNTL(1,60)=4,7, 'PERF', 4, 0, 7580, 0, 0,
JFLOW = (FLOCAL EXECUTION ORDER)

1  2  3  4  5  6  7  8  9  10  15  14  11
12 13 0  0  0  0  0

1   < INLT 1>
2   < COMP 2>
3   < SPLIT 3>   < SPLIT 3>
4   < DUCT 4>   < DUCT 14>
5   < COMP 5>   < MIXR 11>
21  < COMP 5>
6   < TURB 8>
7   < DUCT 6>
8   < BRNR 7>   < TURB 10>
9   < DUCT 9>   < TURB 8>
10  < DUCT 10>  < TURB 8>
11  < MIXR 11>  < DUCT 15>
12  < DUCT 12>  < MIXR 11>
13  < NOZZ 13>  < DUCT 12>
14

SHAFT (21) IS CONNECTED TO ( 5) AND ( 8) AND (23) AND
SHAFT (22) IS CONNECTED TO ( 2) AND (10) AND
1

0 THE FOLLOWING REPRESENTS THE CONFIGURATION FOR MODE= 1
50 PAX ENGINE - Current Technology Baseline (revised for ' CONFIGURATION DATA 22 STATIONS 60 COMPONENTS

<table>
<thead>
<tr>
<th>COMPONENT NUMBER</th>
<th>NKIND</th>
<th>COMPONENT TYPE</th>
<th>UPSTREAM STATIONS</th>
<th>DOWNSTREAM STATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>INLT</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>COMP</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>SPLIT</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>DUCT</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>COMP</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>DUCT</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>BRNR</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>TURB</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>DUCT</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>TURB</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>8</td>
<td>MIXR</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>DUCT</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>9</td>
<td>NOZZ</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>DUCT</td>
<td>20</td>
<td>22</td>
</tr>
</tbody>
</table>
VARIABLE CONTROL INFORMATION

ACTIVE:
CNTL 34: vary des. exit T or f/a of BRNR 7 so that net jet thrust = 0.75800D+04

INACTIVE:
CNTL 31: vary weight-flow rate of 1 so that weight-flow rate at station 5 = 0.35500D+02
CNTL 32: vary "R" value of 5 so that % surge margin of 5 = 0.15000D+02
CNTL 33: vary design PR of 2 so that total pressure at station 6 = 0.34570D+03
CNTL 35: vary des. exit T or f/a of BRNR 7 so that net jet thrust = 0.19550D+04
CNTL 41: vary weight-flow rate of 1 so that flow-rate error at station 13 = 0.00000D+00
CNTL 42: vary "R" value of 2 so that flow-rate error at station 2 = 0.00000D+00
CNTL 43: vary "R" value of 5 so that flow-rate error at station 5 = 0.00000D+00
CNTL 44: vary PR used to read map of 8 so that flow-rate error at station 8 = 0.00000D+00
CNTL 45: vary PR used to read map of 10 so that flow-rate error at station 10 = 0.00000D+00
CNTL 46: vary inlet area JM2 flow of 11 so that static press. error of 11 = 0.00000D+00
CNTL 50: vary RPM or speed ratio of 21 so that (HP)net/(HP)total of 21 = 0.00000D+00
CNTL 51: vary RPM or speed ratio of 22 so that (HP)net/(HP)total of 22 = 0.00000D+00
CNTL 57: vary bypass flow ratio of 3 so that % surge margin of 2 = 0.23000D+02
CNTL 58: vary bypass flow ratio of 3 so that Mach number at station 22 = 0.70000D+00
CNTL 60: vary des. exit T or f/a of BRNR 7 so that net jet thrust = 0.75800D+04

CONDITIONAL CONTROL INFORMATION

ACTIVE:
VCNT 55: watch "R" value for maps of 2; trigger value is 0.11000D+01 which turns on/off switch of CNTL 57 to 0.10000D+01
VCNT 56: watch "R" value for maps of 2; trigger value is 0.11000D+01 which turns on/off switch of CNTL 58 to 0.00000D+00

INACTIVE:
None!!!
INPUT - Warning: the maximum component number used, 60, does not equal the number of components configured in any one mode, 36!

<table>
<thead>
<tr>
<th>UPDATED INPUT DATA TO REFLECT CALCULATED INPUT COMPONENT NO. TYPE</th>
<th>SPEC 1</th>
<th>SPEC 2</th>
<th>SPEC 3</th>
<th>SPEC 4</th>
<th>SPEC 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEC 6</td>
<td>SPEC 7</td>
<td>SPEC 8</td>
<td>SPEC 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1    INLT</td>
<td>260.00000000</td>
<td>0.0000000000</td>
<td>14.69600000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>2    COMP</td>
<td>1.6000000000</td>
<td>0.0000000000</td>
<td>3298.567025</td>
<td>1.561712846</td>
<td></td>
</tr>
<tr>
<td>3    SPLT</td>
<td>5.3000000000</td>
<td>0.0000000000</td>
<td>0.0150000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>4    DUCT</td>
<td>0.0100000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>5    COMP</td>
<td>1.2500000000</td>
<td>0.1150000000</td>
<td>17088.15477</td>
<td>3707.000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>6    DUCT</td>
<td>0.0150000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>7    BRNR</td>
<td>0.0450000000</td>
<td>0.0000000000</td>
<td>2792.143036</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>8    TURB</td>
<td>3.4500000000</td>
<td>0.9770000000</td>
<td>1.108284344</td>
<td>3801.000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>9    DUCT</td>
<td>0.0050000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>10   TURB</td>
<td>2.1000000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>11   NOZZ</td>
<td>327.6979091</td>
<td>508.8929531</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>12   DUCT</td>
<td>0.0100000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>13   NOZZ</td>
<td>696.0257350</td>
<td>7003.000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>14   DUCT</td>
<td>0.0100000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>15   DUCT</td>
<td>0.0100000000</td>
<td>0.0000000000</td>
<td>0.0000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>21   SHFT</td>
<td>18000.00000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>22   SHFT</td>
<td>7000.000000</td>
<td>0.435000000</td>
<td>0.435000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>23   LOAD</td>
<td>-100.000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
</tbody>
</table>

MODE   1 NOW BEING USED
0CASE IDENTIFICATION     50 PAX ENGINE - Current Technology Baseline (revised for '}

STATION PROPERTY OUTPUT DATA

<table>
<thead>
<tr>
<th>MACH</th>
<th>STATIC FLOW</th>
<th>INTERFACE CORRECTED TOTAL FUEL/AIR CORRECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FLOW</td>
</tr>
<tr>
<td></td>
<td>STATN</td>
<td>PRESSURE TEMPERATURE RATIO FLOW</td>
</tr>
<tr>
<td></td>
<td>NNEP-ARP?</td>
<td>STATP1 STATP2 STATP3 STATP4 STATP5</td>
</tr>
<tr>
<td></td>
<td>STATP6</td>
<td>STATP7 STATP8</td>
</tr>
<tr>
<td>1-1</td>
<td>257.4356705</td>
<td>14.69600000 545.6700000 0.000000000 264.0504947</td>
</tr>
<tr>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>COMPONENT NO.</td>
<td>DATOUT1</td>
<td>DATOUT2</td>
</tr>
<tr>
<td>---------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>2-2</td>
<td>257.4388394</td>
<td>14.5490400</td>
</tr>
<tr>
<td>3-3</td>
<td>257.4388394</td>
<td>23.97330869</td>
</tr>
<tr>
<td>4-4</td>
<td>41.68325273</td>
<td>23.97330869</td>
</tr>
<tr>
<td>5-5</td>
<td>41.67950672</td>
<td>23.73357560</td>
</tr>
<tr>
<td>6-6</td>
<td>36.05277331</td>
<td>353.4369834</td>
</tr>
<tr>
<td>7-7</td>
<td>36.05277331</td>
<td>348.1354286</td>
</tr>
<tr>
<td>8-8</td>
<td>36.84889128</td>
<td>332.4693343</td>
</tr>
<tr>
<td>9-9</td>
<td>41.53179226</td>
<td>72.39087045</td>
</tr>
<tr>
<td>10-10</td>
<td>41.53188612</td>
<td>72.02891609</td>
</tr>
<tr>
<td>12-12</td>
<td>257.2874728</td>
<td>21.04741771</td>
</tr>
<tr>
<td>13-13</td>
<td>257.2470341</td>
<td>20.91060949</td>
</tr>
<tr>
<td>14-14</td>
<td>257.2470341</td>
<td>20.91060949</td>
</tr>
<tr>
<td>15-15</td>
<td>41.53188612</td>
<td>18.14278133</td>
</tr>
<tr>
<td>16-16</td>
<td>41.53188612</td>
<td>17.96135352</td>
</tr>
<tr>
<td>17-17</td>
<td>215.7555866</td>
<td>23.61370906</td>
</tr>
<tr>
<td>18-18</td>
<td>215.7555866</td>
<td>23.61370906</td>
</tr>
</tbody>
</table>

**COMPONENT OUTPUT DATA**

<table>
<thead>
<tr>
<th>COMPONENT NO.</th>
<th>DATOUT1</th>
<th>DATOUT2</th>
<th>DATOUT3</th>
<th>DATOUT4</th>
<th>DATOUT5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach</td>
<td>Ram drag</td>
<td>V-fps</td>
<td>V-knots</td>
<td>T2/T1</td>
<td>P2/P1</td>
</tr>
<tr>
<td>1 INLT</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>1.000000000</td>
<td>1.000000000</td>
<td></td>
</tr>
<tr>
<td>2 COMP</td>
<td>0.990000000</td>
<td>1.052056221</td>
<td>0.000000000</td>
<td>R-map</td>
<td>% Margin</td>
</tr>
<tr>
<td>3 SPLIT</td>
<td>0.876798381</td>
<td>1.647758800</td>
<td>Tot W main</td>
<td>React. W</td>
<td></td>
</tr>
<tr>
<td>4 DUCT</td>
<td>0.867798381</td>
<td>257.4388394</td>
<td>0.000000000</td>
<td>A-sq. in.</td>
<td></td>
</tr>
<tr>
<td>5 COMP</td>
<td>0.908306189</td>
<td>0.015000000</td>
<td>0.000000000</td>
<td>Eta)poly.</td>
<td>(Ea)adia.</td>
</tr>
<tr>
<td>6 DUCT</td>
<td>0.867798381</td>
<td>149.3820019</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>7 SPLIT</td>
<td>0.908306189</td>
<td>157.5684700</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>8 DUCT</td>
<td>0.908306189</td>
<td>175.5684700</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>9 SPLIT</td>
<td>0.908306189</td>
<td>28.42719819</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
</tbody>
</table>

**COMPONENT OUTPUT DATA**

<table>
<thead>
<tr>
<th>COMPONENT NO.</th>
<th>DATOUT1</th>
<th>DATOUT2</th>
<th>DATOUT3</th>
<th>DATOUT4</th>
<th>DATOUT5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach</td>
<td>Ram drag</td>
<td>V-fps</td>
<td>V-knots</td>
<td>T2/T1</td>
<td>P2/P1</td>
</tr>
<tr>
<td>1 INLT</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>1.000000000</td>
<td>1.000000000</td>
<td></td>
</tr>
<tr>
<td>2 COMP</td>
<td>0.990000000</td>
<td>1.052056221</td>
<td>0.000000000</td>
<td>R-map</td>
<td>% Margin</td>
</tr>
<tr>
<td>3 SPLIT</td>
<td>0.876798381</td>
<td>1.647758800</td>
<td>Tot W main</td>
<td>React. W</td>
<td></td>
</tr>
<tr>
<td>4 DUCT</td>
<td>0.867798381</td>
<td>257.4388394</td>
<td>0.000000000</td>
<td>A-sq. in.</td>
<td></td>
</tr>
<tr>
<td>5 COMP</td>
<td>0.908306189</td>
<td>0.015000000</td>
<td>0.000000000</td>
<td>Eta)poly.</td>
<td>(Ea)adia.</td>
</tr>
<tr>
<td>6 DUCT</td>
<td>0.867798381</td>
<td>149.3820019</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>7 SPLIT</td>
<td>0.908306189</td>
<td>157.5684700</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>8 DUCT</td>
<td>0.908306189</td>
<td>175.5684700</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>9 SPLIT</td>
<td>0.908306189</td>
<td>28.42719819</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
</tbody>
</table>

**COMPONENT OUTPUT DATA**

<table>
<thead>
<tr>
<th>COMPONENT NO.</th>
<th>DATOUT1</th>
<th>DATOUT2</th>
<th>DATOUT3</th>
<th>DATOUT4</th>
<th>DATOUT5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach</td>
<td>Ram drag</td>
<td>V-fps</td>
<td>V-knots</td>
<td>T2/T1</td>
<td>P2/P1</td>
</tr>
<tr>
<td>1 INLT</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>1.000000000</td>
<td>1.000000000</td>
<td></td>
</tr>
<tr>
<td>2 COMP</td>
<td>0.990000000</td>
<td>1.052056221</td>
<td>0.000000000</td>
<td>R-map</td>
<td>% Margin</td>
</tr>
<tr>
<td>3 SPLIT</td>
<td>0.876798381</td>
<td>1.647758800</td>
<td>Tot W main</td>
<td>React. W</td>
<td></td>
</tr>
<tr>
<td>4 DUCT</td>
<td>0.867798381</td>
<td>257.4388394</td>
<td>0.000000000</td>
<td>A-sq. in.</td>
<td></td>
</tr>
<tr>
<td>5 COMP</td>
<td>0.908306189</td>
<td>0.015000000</td>
<td>0.000000000</td>
<td>Eta)poly.</td>
<td>(Ea)adia.</td>
</tr>
<tr>
<td>6 DUCT</td>
<td>0.867798381</td>
<td>149.3820019</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>7 SPLIT</td>
<td>0.908306189</td>
<td>157.5684700</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>8 DUCT</td>
<td>0.908306189</td>
<td>175.5684700</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>9 SPLIT</td>
<td>0.908306189</td>
<td>28.42719819</td>
<td>(PR)comp.</td>
<td>Mach in</td>
<td>T exit</td>
</tr>
<tr>
<td>Stage</td>
<td>Mach in</td>
<td>T&lt;sub&gt;exit&lt;/sub&gt;</td>
<td>Fuel/Wa</td>
<td>(dP/P)&lt;sub&gt;mom.&lt;/sub&gt;</td>
<td>(dP/P)</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>----------------</td>
<td>---------</td>
<td>---------------------</td>
<td>--------</td>
</tr>
<tr>
<td>DUCT</td>
<td>0.000000000</td>
<td>0.015000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>1465.037705</td>
</tr>
<tr>
<td>BNR</td>
<td>0.000000000</td>
<td>0.045000000</td>
<td>0.000000000</td>
<td>0.002209047</td>
<td>0.000000000</td>
</tr>
<tr>
<td>TURB</td>
<td>12223.74322</td>
<td>18006.80836</td>
<td>1.000000000</td>
<td>3.460363063</td>
<td>0.89445188</td>
</tr>
<tr>
<td>DUCT</td>
<td>0.000000000</td>
<td>0.005000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>1942.626873</td>
</tr>
<tr>
<td>TURB</td>
<td>8428.951686</td>
<td>3073.102608</td>
<td>1.000000000</td>
<td>2.162877116</td>
<td>0.907538139</td>
</tr>
<tr>
<td>NOZZ</td>
<td>360.1563202</td>
<td>476.4345421</td>
<td>0.950000000</td>
<td>0.500000000</td>
<td>507.9996455</td>
</tr>
<tr>
<td>DUCT</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>641.9425052</td>
</tr>
<tr>
<td>NOZZ</td>
<td>7467.934584</td>
<td>942.6401219</td>
<td>1.422877619</td>
<td>0.996935621</td>
<td>0.997373314</td>
</tr>
<tr>
<td>DUCT</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td>0.000000000</td>
</tr>
<tr>
<td>SHFT</td>
<td>0.010503844</td>
<td>18006.80836</td>
<td>18006.80836</td>
<td>1.393533823</td>
<td></td>
</tr>
<tr>
<td>LOAD</td>
<td>-100.000000</td>
<td>18006.80836</td>
<td>0.000000000</td>
<td>0.000000000</td>
<td></td>
</tr>
</tbody>
</table>

**CONTROL INFORMATION**

- ACTIVE CNTLs: 46, 45, 44, 43, 58, 42, 41, 50, 51
- ACTIVE VNTLs: 55, 56

- MACH = 0.0000
- ALTITUDE = 0.0
- RECOVERY = 0.9900

- 4 ITERATIONS 14 PASSES

**AIRFLOW (LB/SEC):** 257.44
**GROSS THRUST:** 7467.93
**FUEL FLOW (LB/HR):** 2867.11
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>NET THRUST</td>
<td>7467.93</td>
<td></td>
</tr>
<tr>
<td>NET THRUST/AIRFLOW</td>
<td>29.0089</td>
<td></td>
</tr>
<tr>
<td>INLET RAM/ADDED DRAG</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>BOATTAIL DRAG</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>INSTALLED THRUST</td>
<td>7467.93</td>
<td></td>
</tr>
<tr>
<td>SPILLAGE + LIP DRAG</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>TOTAL NACELLE DRAG</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>RIT (T41)</td>
<td>2693.7</td>
<td></td>
</tr>
<tr>
<td>CORR AIRFLOW (LB/SEC)</td>
<td>266.7</td>
<td></td>
</tr>
<tr>
<td>FNIN1</td>
<td>7467.93</td>
<td></td>
</tr>
<tr>
<td>SFCIN1</td>
<td>0.3839</td>
<td></td>
</tr>
<tr>
<td>FNIN2</td>
<td>7467.93</td>
<td></td>
</tr>
<tr>
<td>SFCIN2</td>
<td>0.3839</td>
<td></td>
</tr>
<tr>
<td>EI (G NOX/KG FUEL)</td>
<td>28.555</td>
<td></td>
</tr>
<tr>
<td>MASS AVG. VJET</td>
<td>942.64</td>
<td></td>
</tr>
<tr>
<td>PROPULSIVE EFFICIENCY</td>
<td>0.00000000</td>
<td></td>
</tr>
</tbody>
</table>

0 CUSTOMER BLEED WAS EXTRACTED FROM COMPRESSOR 5

TOTAL TEMPERATURE = 1306.6705  TOTAL PRESSURE = 236.2536  WEIGHT FLOW = 0.8336  ENERGY RATIO = 0.8000
Appendix B

NASA Engine Performance Program (NEPP) Output

&D IWT=2, &END
OMODE  1 NOW BEING USED
&W
  IPLT = T,
  ISII = F,
  ISIO = F,
  PLOT = T,
  SKIPIT = F,
ILENG =   1,   2,   3,   4,   5,   6,   7,   8,   9,  10,
        11,  12,13,
ACCS   =   0.0950,
DISKWC =     1. ,
DISKWI =     1. ,
DISKWT =     1. ,
IWMEC(1,  1) =     1,     12,      1,      10,     -12,
                   1,      0,       0,       0,      1,
                   0,
IWMEC(1,  2) =     48,      3,      0,       1,       1,
                   0,      0,     -2,       0,       1,
                   0,      0,       0,       0,       0,
IWMEC(1,  3) =     7,      0,
IWMEC(1,  4) =     47,      3,      0,       1,     14,
                   -3,      0,       0,     12,       0,
                   2,      0,       0,       0,       0,
IWMEC(1,  6) =     2,      2,      0,
IWMEC(1,  7) =     21,      1,      1,
IWMEC(1,  8) =     51,      3,      0,       0,       2,
                   0,      5,       0,       0,       5,
                   0,      0,       1,       0,       1,
IWMEC(1,  9) =     2,      2,      0,
IWMEC(1, 10) =     52,      3,      0,       0,       3,
                   1,     -6,       0,       0,       2,
                   0,      0,       0,       0,       1,
IWMEC(1, 11) =     82,      0,
IWMEC(1, 12) =     2,      1,      0,
IWMEC(1, 13) =     9,      1,      2,       0,       1,
                   1,      5,       0,       0,       0,
IWMEC(1, 14) =     2,      3,      0,     -4,
IWMEC(1, 15) =     2,      1,
IWMEC(1, 21) =    11,      2,      8,       0,       0,
                   0,      5,       2,
IWMEC(1, 22) =    11,      1,     10,       0,       0,
                   0,      2,       3,
FRVAL(1,  1) =    0.11,      1. ,     0.1,     1.0,       0,
                0.10,     0.1,       0,       0,       0,
                0.1,      0,       1,       2,       2,
                0,      0,       0,
FRVAL(1,  2) =    0.12,     1.0,     0.1,     1.4,       6,
                0.12,     0.2,       0,       0,       0,
                1,      0,     -5,       0,       0,
                1,     100.,     0.9,
FRVAL(1,  3) = 0.12, 1.0, 0.1, 0.8, 0,
               0.12, 0.2, 0, 0, 0,
               0.00, 1, -2, 2, 3,
               0, 0, 0,
FRVAL(1,  4) = 0.12, 1.0, 0.1, 1.8, 3,
               0.12, 0.1, 0, 0, 0,
               5, 0, 0, 0, 0,
               0, 0, 0,
FRVAL(1,  6) = 0.12, 1.0, 0.1, 1.2, 6,
               0.12, 0.2, 0, 0, 0,
               0.50, 0, 0, 5, 5,
               0, 0, 0,
DESVAL(1,  1) = .80, 1000., 0., 0., 0,
               1, 1, 1, 0, 0,
               0.4, 0, 1650., 70., 0,
               0.1, 0.1, 0.09, 0, 0,
DESVAL(1,  2) = .550, .407, 0, 0, 1.8,
               1, 0, 0.39, 0, 0,
               0, 0, 0, 0, 0,
               24, 0, 1.1, 0.024, 0.10,
               2.8, 2.8, 1.4, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 0, 0, 0,
               50, 0, 0, 0.135, 5.9,
               1, 1, 2.5, 2.5, 0,
               0, 1, 0, 0, 0,
               0, 0, 0, 0, 0,
               1, 0.6, 1.5, 1.1, 0.05,
               0, 0, 0, 0, 0,
DESVAL(83,2) = 1360.,
DESVAL(1,  3) =
DESVAL(1,  4) = .500, 0, 0, 0, 0,
               5.0, -1, 0, 0,
DESVAL(1,  5) = 0.34, 0.31, 0, 0, 1.4,
               1, 1.0, 0.455, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 0.84, 0.162, 0.08,
               2.2, 0.8, 0.833, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 0.75, 0.163, 0.18,
               1.0, 1.0, 3.1, 1.2, 0,
               0, 5, 0, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 0, 0, 0,
               36, 0, 0, 2.5, 0,
               0, 0, 0, 0, 0,
               0, 0, 0, 0, 0,
               0, 0, 1000., 0, 9,
DESVAL(1,  6) = 0.3, 0, 0, 0, 0,
               4, -1, 0, 0, 0,
DESVAL(1,  7) = 50, 0.013, 0, 0,
               0, 0,
DESVAL(16,7) = 0.29, 0.29,
DESVAL(1,  8) = .100, .300, 0.34, 0, 0,
               1, 1, 0, 0, 0,
               0, 0, 0, 0, 0,
               0, .281, 0.71, 0.70, 0.2,
               1.2, 1.8, 1,
DESVAL(36, 8) = 0, 0.28, 0.92, 0.38, 0.17,
DESVAL(76, 8) = 0.28, 0.32, 100000,
DESVAL(1, 9) = 0.3, 0, 0, 0, 0,
0.8, -1, 0, 0,
DESVAL(1, 10) = 0.165, 0.319, 0.280, 0, 0,
1.3, 1, 0, 0, 0,
0, 0, 0, 0, 0,
0, 0.286, 1.22, 0.20, 0.2,
2.8, 3.7, 1,
DESVAL(36, 10) = 0, 0.28, 1.11, 0.057, 0.12,
DESVAL(76, 10) = 0.28, 0.32, 100000,
DESVAL(1, 11) = 0.64, 12, 1.0, 0, 0,
0, 0, 0, 0, 0,
0, 0, 0, 0, 0,
0, 0, 0, 0, 0,
0.156, 0.1,
DESVAL(1, 12) = 0.41, 0, 0, 0, 0,
0.25, -1, 0, 0,
DESVAL(1, 13) = 0.19, 1000., 0, 0.5, 8.3,
0, 0, 0, 0, 0,
1, 0, 0.8, 0, 0,
0.281, 0.1, 1., 1., 0,
DESVAL(26, 13) = 0, 0.1, 1, 1, 1,
DESVAL(1, 14) = 0.45, 0, 0, 0, 0,
0, -1, 0,
DESVAL(7, 21) = 80000, 0.6, 5, 8, 0,
0, 0, 0, 0, 0.30,
DESVAL(21, 21) = 0.186, 3, 21, 0.5,
DESVAL(26, 21) = 0.186, -4, 60, 0.5,
DESVAL(7, 22) = 80000, 0.6, 2, 10, 0,
0, 0, 0, 0, 0.30,
DESVAL(21, 22) = 0.186, 1, 5, 0.5,
DESVAL(26, 22) = 0.186, 2, 6.5, 0.5,
DESVAL(31, 22) = 0.186, -5, 70, 0.5,
&END

WEIGHT INPUT IS IN ENGLISH UNITS
WEIGHT OUTPUT IS IN ENGLISH UNITS

INPUT - Warning: the maximum component number used, 22, does not equal the number of components configured in any one mode, 17!

**************
*            *
*          FANH 2 *
*            *
**************2

MAX CONDITIONS OCCUR AT

***************************************************************************
 ALT   MN   VALUE
 PTOT  0.  0.000  14.5 LB/SQIN
 TTOT  0.  0.000  545.7 DEG R
 CWIN 35000.  0.700  316.3 LB/SEC
***************************************************************************

DUCT
 M NO  VEL  T TOT  P TOT  P STAT  AREA  GAM
 0.550  612.  546.  2095.  1706.  6.8408  1.4001

UTIPMAX STRESS  DEN  W/AREA  TR  H/T
 1519.9  71855.2  0.160  2.127  1.400  0.390
### COMPRESSOR 2 MECHANICAL DESIGN

**LOADING**

<table>
<thead>
<tr>
<th>N STG</th>
<th>DIAM</th>
<th>U TIP C</th>
<th>RPM</th>
<th>C RPM</th>
<th>MAX RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.031</td>
<td>1.00</td>
<td>38.46</td>
<td>1360.0</td>
<td>8312.4</td>
<td>8104.1</td>
</tr>
</tbody>
</table>

**STAGE 1**

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.</td>
<td>52.</td>
<td>36.</td>
<td>6.</td>
<td>0.</td>
<td>43.</td>
<td>40.</td>
<td>9.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CL</th>
<th>CL2</th>
<th>RHOD</th>
<th>RHOB</th>
<th>RHOS</th>
<th>RHOC</th>
<th>RHOFCR</th>
<th>AR</th>
<th>ARS</th>
<th>NS</th>
<th>DFCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>14.9</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.050</td>
<td>2.80</td>
<td>2.50</td>
<td>50</td>
<td>1.10</td>
</tr>
</tbody>
</table>

**STAGE I**

<table>
<thead>
<tr>
<th>CL</th>
<th>CL2</th>
<th>RHOD</th>
<th>RHOB</th>
<th>RHOS</th>
<th>RHOC</th>
<th>RHOFCR</th>
<th>AR</th>
<th>ARS</th>
<th>NS</th>
<th>DFCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>14.9</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.050</td>
<td>2.80</td>
<td>2.50</td>
<td>50</td>
<td>1.10</td>
</tr>
</tbody>
</table>

**COMPRESSOR COMPONENT WEIGHT SUMMARY**

<table>
<thead>
<tr>
<th>WTDSK</th>
<th>WTBLD</th>
<th>WTDRM</th>
<th>WTST/IGV</th>
<th>WTSF</th>
<th>WTCAS</th>
<th>WTNAB</th>
<th>WTCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.1</td>
<td>51.5</td>
<td>9.0</td>
<td>35.6</td>
<td>6.1</td>
<td>43.3</td>
<td>0.0</td>
<td>40.5</td>
</tr>
</tbody>
</table>

**FRAME COMPONENTS INFORMATION**

<table>
<thead>
<tr>
<th>FRAME WT</th>
<th>LENGTH</th>
<th>GAP</th>
<th>#FRAMES</th>
<th>ARF</th>
<th>RHOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.57</td>
<td>5.0</td>
<td>0.0</td>
<td>6</td>
<td>1.40</td>
<td>0.120</td>
</tr>
</tbody>
</table>

**CASE WT**

<table>
<thead>
<tr>
<th>HUB WT</th>
<th>UP SUPP</th>
<th>LW SUPP</th>
<th>RHOS</th>
<th>THSUP</th>
<th>WTTOWER</th>
<th>TS DIAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.22</td>
<td>0.00</td>
<td>0.00</td>
<td>0.120</td>
<td>0.20</td>
<td>19.89</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**FRAME WT** = 56.17

**N STG**

<table>
<thead>
<tr>
<th>WEIGHT</th>
<th>LENGTH</th>
<th>CENGRA</th>
<th>INERTIA</th>
<th>LENGTH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>294.37</td>
<td>5.92</td>
<td>15.9</td>
<td>6724.1</td>
<td>19.94</td>
</tr>
</tbody>
</table>

**DUCT**

<table>
<thead>
<tr>
<th>M NO</th>
<th>VEL</th>
<th>T TOT</th>
<th>P TOT</th>
<th>P STAT</th>
<th>AREA</th>
<th>GAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.407</td>
<td>495.</td>
<td>638.</td>
<td>3394.</td>
<td>3029.</td>
<td>5.7070</td>
<td>1.3981</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PR</th>
<th>AD</th>
<th>EF</th>
<th>PO</th>
<th>TO</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6200</td>
<td>0.8750</td>
<td>3394.0</td>
<td>637.7</td>
<td>8132.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HI</th>
<th>HO</th>
<th>WI</th>
<th>CWI</th>
</tr>
</thead>
<tbody>
<tr>
<td>130.43</td>
<td>152.54</td>
<td>260.00</td>
<td>269.37</td>
</tr>
</tbody>
</table>

*********************** TOTAL COMP WEIGHT IS 294.366

*******

* *
* DUCT 4 *
* *
***********2

**MAX CONDITIONS OCCUR AT**

<table>
<thead>
<tr>
<th>ALT</th>
<th>MN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTOT</td>
<td>0.</td>
</tr>
<tr>
<td>TTOT</td>
<td>0.</td>
</tr>
</tbody>
</table>

**FRAME COMPONENTS INFORMATION**

<table>
<thead>
<tr>
<th>FRAME WT</th>
<th>LENGTH</th>
<th>GAP</th>
<th>#FRAMES</th>
<th>ARF</th>
<th>RHOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.40</td>
<td>1.7</td>
<td>0.2</td>
<td>45</td>
<td>1.00</td>
<td>0.110</td>
</tr>
</tbody>
</table>
CASE WT  HUB WT  UP SUPP  LW SUPP  RHOS  THSUP  WTTOWER  TS DIAM
1.30  1.12  10.77  6.85  0.100  0.10  0.00  1.00

FRAME WT  =  22.43

DUCT ,  4
RH=  10.51  RT=  12.20  LENG=  8.46
AREA=  0.838  RHO=.168
WTC(OUTER)  WTC(INNER)  WTT(REV)  WT(TOTAL)  TMIN
5.4467  4.6912  0.0000  32.5692  0.0500

*************
*           *
*  HPC   5  *
*           *
*************2

MAX CONDITIONS OCCUR AT
****************************************
ALT      MN    VALUE
PTOT    0.     0.000      23.7 LB/SQIN
TTOT    0.     0.000     641.9 DEG R
CWIN  35000.     0.700      31.4 LB/SEC
****************************************

DUCT
M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
0.340   416.   638.    3360.    3102.     1.0638   1.3981

UTIPMAX STRESS     DEN  W/AREA   TR     H/T
1121.4 50562.4   0.300   1.211   0.833   0.455

COMRESSOR  5 MECHANICAL DESIGN

LOADING   N STG   DIAM  U TIP C    RPM   C RPM   MAX RPM
0.974  14.00  15.68  1000.0 16202.9 14613.0 16387.3

FRAME COMPONENTS INFORMATION

FRAME WT    LENGTH     GAP    #FRAMES   ARF    RHOF
13.17      5.3      0.0       9      0.80    0.120
CASE WT   HUB WT  UP SUPP   LW SUPP   RHOS  THSUP   WTTOWER   TS DIAM
6.32     2.87    13.36     3.97   0.120   0.20    0.00       1.00

FRAME WT  =  39.70

STAGE    1
VARIABLE INLET GUIDE VANE PRESENT
WIGV  RHOIGV  ARIGV  NBIGV
8.   0.160    2.50     36

WD   WB   WS   WSSF   WN   WC   WFCR   WTDRUM
6.     4.3    2.   2.     8.     0.   1.
CL   CL2  RHOD  RHOB  RHOS  RHOC  RHOFCR  AR   ARS   NS   DFCR
4.5   4.5   0.160   0.160   0.160   0.160   0.000  2.20  3.10  26  3.00
PR   DEL H   MACH   AREA   R HUB   R TIP   NB   UTIPMAX   STR    WEIGHT   TIN   TMAX
STAGE I
| Stage | WD | WB | WS | WSSF | WN | WC | WFCR | WTDRUM | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |
|-------|----|----|----|-------|----|----|------|--------|----|----|------|------|------|------|----------|----|----|---|-----|----|-----|---|-----|----|-------|----|-----|
| 1.3363 | 14.7 | 0.340 | 1.064 | 3.57 | 7.84 | 21 | 1121.4 | 26967. | 33. | 638. | 642. | 107. |
| STAGE 2 | 2 7. | 2. | 1. | 1. | 6. | 0. | 1. | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |
| 1.3043 | 14.7 | 0.338 | 0.838 | 4.80 | 7.84 | 28 | 1121.4 | 21341. | 20. | 699. | 701. | 127. |
| STAGE 3 | 3 6. | 1. | 1. | 1. | 5. | 0. | 1. | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |
| 1.2779 | 14.7 | 0.336 | 0.674 | 5.53 | 7.84 | 35 | 1121.4 | 17202. | 17. | 759. | 760. | 137. |
| STAGE 4 | 4 6. | 1. | 1. | 1. | 1. | 4. | 0. | 1. | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |
| 1.2558 | 14.7 | 0.334 | 0.552 | 6.02 | 7.84 | 42 | 1121.4 | 14095. | 15. | 820. | 818. | 142. |
| STAGE 5 | 5 6. | 1. | 1. | 1. | 1. | 3. | 0. | 1. | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |
| 1.2372 | 14.7 | 0.331 | 0.458 | 6.36 | 7.84 | 49 | 1121.4 | 11716. | 13. | 880. | 877. | 146. |
| STAGE 6 | 6 6. | 0. | 0. | 1. | 1. | 3. | 0. | 1. | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |
| 1.2210 | 14.7 | 0.329 | 0.386 | 6.62 | 7.84 | 56 | 1121.4 | 9859. | 11. | 940. | 936. | 146. |
| STAGE 7 | 7 6. | 0. | 0. | 1. | 1. | 3. | 0. | 1. | CL | CL2 | RHOD | RHOB | RHOS | RHOC | RHOFCR | AR | ARS | NS | DFCR | PR | DEL | H | MACH | AREA | R | HUB | R | TIP | NB | UTIPMAX | STR | WEIGHT | TIN | TMAX |

NASA/TM—2005-213369 64
### STAGE 8

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>0</td>
<td>0</td>
<td>0.</td>
<td>0</td>
<td>1.</td>
<td>2.</td>
<td>0.</td>
</tr>
</tbody>
</table>

**CL** CL2 RHOD RHOB RHOS RHOC RHOFCR AR ARS NS DFCR

| 1.4 | 1.4 | 0.160 | 0.160 | 0.160 | 0.160 | 0.000 | 1.45 | 2.08 | 88 | 3.00 |

**PR** DEL H MACH AREA R HUB R TIP NB UTIPMAX STR WEIGHT TIN TMAX

### STAGE 9

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>0</td>
<td>0</td>
<td>0.</td>
<td>0</td>
<td>1.</td>
<td>2.</td>
<td>0.</td>
</tr>
</tbody>
</table>

**CL** CL2 RHOD RHOB RHOS RHOC RHOFCR AR ARS NS DFCR

| 1.3 | 1.3 | 0.160 | 0.160 | 0.160 | 0.160 | 0.000 | 1.34 | 1.93 | 95 | 3.00 |

**PR** DEL H MACH AREA R HUB R TIP NB UTIPMAX STR WEIGHT TIN TMAX

### STAGE 10

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>0</td>
<td>0</td>
<td>0.</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**CL** CL2 RHOD RHOB RHOS RHOC RHOFCR AR ARS NS DFCR

| 1.2 | 1.2 | 0.300 | 0.300 | 0.160 | 0.300 | 0.000 | 1.23 | 1.78 | 101 | 3.00 |

**PR** DEL H MACH AREA R HUB R TIP NB UTIPMAX STR WEIGHT TIN TMAX

### STAGE 11

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>0</td>
<td>0</td>
<td>0.</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**CL** CL2 RHOD RHOB RHOS RHOC RHOFCR AR ARS NS DFCR

| 1.2 | 1.2 | 0.300 | 0.300 | 0.160 | 0.300 | 0.000 | 1.12 | 1.64 | 106 | 3.00 |

**PR** DEL H MACH AREA R HUB R TIP NB UTIPMAX STR WEIGHT TIN TMAX

### STAGE 12

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>0</td>
<td>0</td>
<td>0.</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**CL** CL2 RHOD RHOB RHOS RHOC RHOFCR AR ARS NS DFCR

| 1.1 | 1.1 | 0.300 | 0.300 | 0.160 | 0.300 | 0.000 | 1.02 | 1.49 | 110 | 3.00 |

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****

**STAGE HUB TIP RATIO IS 0.94 DES LIMIT IS 0.94**

**HUB TIP RATIO IS TOO HIGH REDUCE HUB TIP RATIO INPUT**

**PR** DEL H MACH AREA R HUB R TIP NB UTIPMAX STR WEIGHT TIN TMAX

### STAGE 13

<table>
<thead>
<tr>
<th>WD</th>
<th>WB</th>
<th>WS</th>
<th>WSSF</th>
<th>WN</th>
<th>WC</th>
<th>WFCR</th>
<th>WTDRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>0</td>
<td>0</td>
<td>0.</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**CL** CL2 RHOD RHOB RHOS RHOC RHOFCR AR ARS NS DFCR

| 1.0 | 1.0 | 0.300 | 0.300 | 0.160 | 0.300 | 0.000 | 1.00 | 1.49 | 110 | 3.00 |
1.1  1.1  0.300  0.300  0.160  0.300  0.000  0.91  1.35  112  3.00

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
STAGE HUBTIP RATIO IS 0.94  DES LIMIT IS 0.94
** HUB TIP RATIO IS TOO HIGH REDUCE HUB TIP RATIO INPUT **
PR  DEL  H  MACH  AREA  R  HUB  R  TIP  NB  UTIPMAX  STR  WEIGHT  TIN  TMAX
STAGE I
1.1512  14.7  0.314  0.147  7.40  7.84  85  1121.4  7044.  17.  1347.  1347. 315.

STAGE 14
WD  WB  WS  WSSF  WN  WC  WFCR  WTDRUM
11.  0.  0.  0.  0.  4.  0.  1.
CL  CL2  RHOD  RHOB  RHOS  RHOC  RHOFCR  AR  ARS  NS  DFCR
1.1  1.1  0.300  0.300  0.160  0.300  0.000  0.80  1.20  112  3.00

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
STAGE HUBTIP RATIO IS 0.95  DES LIMIT IS 0.94
** HUB TIP RATIO IS TOO HIGH REDUCE HUB TIP RATIO INPUT **

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
STAGE BLADE HEIGHT IS 0.39  DES LIMIT IS 0.40
** STAGE BLADE HEIGHT IS TOO SMALL CHANGE DES OPR OR REDUCE H/T INPUT **
PR  DEL  H  MACH  AREA  R  HUB  R  TIP  NB  UTIPMAX  STR  WEIGHT  TIN  TMAX
STAGE I
1.1448  14.7  0.312  0.131  7.45  7.84  84 1121.4  6292.  17.  1403.  1406. 323.

COMPRESSOR COMPONENT WEIGHT SUMMARY
WTDSK  WTLBD  WTDRM  WTST/IGV  WTFSF  WTAS  WTNAB  WTCR
109.2  10.4  10.9  17.5  9.4  55.7  9.5  0.0

N STG  WEIGHT  LENGTH  CENGRA  INERTIA  LENGTH2
14  262.49  33.90  14.8  2797.8  33.90

DUCT
M NO  VEL  T  TOT  P  TOT  P  STAT  AREA  GAM
0.310  566.  1460.  50401.  47255.  0.1182  1.3526

PR  AD  EF  PO  TO  HP
15.0000  0.8600  50400.9  1459.6  12028.
HI  HO  WI  CWI
152.54  358.53  41.27  28.82

*********************** TOTAL COMP WEIGHT IS  262.489

****************************************
**
** DUCT 6 **
**
***********************2

MAX CONDITIONS OCCUR AT
***********************
ALT  MN
PTOT  0.  0.000
TTOT  0.  0.000

DUCT,  6
RH= 7.53 RT= 7.83 LEN=  1.21
AREA= 0.102 RHO=.286
WTC(OUTER)  WTC(INNER)  WTT(REV)  WT(TOTAL)  TMIN
 1.0137    0.9744    0.0000    1.9881    0.0593

*************
*           *
* PBUR 7  *
*           *
*************

MAX CONDITIONS OCCUR AT

<table>
<thead>
<tr>
<th>ALT</th>
<th>MN</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTOT</td>
<td>0.000</td>
<td>348.1 LB/SQIN</td>
</tr>
<tr>
<td>TTOT</td>
<td>0.000</td>
<td>1465.0 DEG R</td>
</tr>
<tr>
<td>CWIN</td>
<td>0.000</td>
<td>2.6 LB/SEC</td>
</tr>
</tbody>
</table>

*************

Burner Number 7

<table>
<thead>
<tr>
<th>RIN</th>
<th>ROUT</th>
<th>LENGTH</th>
<th>MACH</th>
<th>WSPEC</th>
<th>TMIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.772</td>
<td>9.197</td>
<td>7.800</td>
<td>0.027</td>
<td>2.282</td>
<td>0.080</td>
</tr>
</tbody>
</table>

CAS WT  INC WT  LIN WT  NOZ WT  FRAME  WTOT
10.5    6.6    16.2    4.1    76.8    129.8

HPC Structural Case: Weight  Length  Density
15.6    12.1    0.160

*************

MAX CONDITIONS OCCUR AT

<table>
<thead>
<tr>
<th>ALT</th>
<th>MN</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTOT</td>
<td>0.000</td>
<td>332.5 LB/SQIN</td>
</tr>
<tr>
<td>TTOT</td>
<td>0.000</td>
<td>2792.1 DEG R</td>
</tr>
<tr>
<td>CWOUT</td>
<td>39000.</td>
<td>16.4 LB/SEC</td>
</tr>
</tbody>
</table>

*************

Duct

<table>
<thead>
<tr>
<th>M</th>
<th>NO</th>
<th>VEL</th>
<th>T TOT</th>
<th>P TOT</th>
<th>P STAT</th>
<th>AREA</th>
<th>GAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>245.</td>
<td>2693.</td>
<td>47411.</td>
<td>47105.</td>
<td>0.4940</td>
<td>1.2957</td>
<td></td>
</tr>
</tbody>
</table>

Max Tip Max Stress  Den  W/Area  TR  H/T
1353.5 23726.3 0.281 0.356 1.000 0.868

Turbine 8 Mechanical Design

<table>
<thead>
<tr>
<th>H/T</th>
<th>N STG LOADING</th>
<th>AREA</th>
<th>GE LOADING</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.868</td>
<td>2.000</td>
<td>0.340</td>
<td>0.494</td>
</tr>
</tbody>
</table>

UT Tip Tip Radius  Hub Del H  RPM  Max RPM  Torq
1353.5 9.6 8.3 215.3 16202.9 16202.9 46992.

Stage 1

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.1</td>
<td>11.9</td>
<td>0.0</td>
<td>2.5</td>
<td>4.7</td>
<td>2.4</td>
<td>10.7</td>
<td>1.20</td>
<td>1.20</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>0.281</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WSSFX  WTRS  WTSRHD  WDRUMX  WTRSHD  WTDSD  WTACC
2.7 1.1 2.3 6.2 0.0 0.0 11.7
<table>
<thead>
<tr>
<th>PR</th>
<th>DEL H</th>
<th>MACH</th>
<th>AREA</th>
<th>R HUB</th>
<th>R TIP</th>
<th>NB</th>
<th>MAXUTIP</th>
<th>STR</th>
<th>WEIGHT</th>
<th>LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAGE I</td>
<td>2.0133</td>
<td>107.6</td>
<td>0.100</td>
<td>0.494</td>
<td>8.31</td>
<td>9.57</td>
<td>40</td>
<td>1353.5</td>
<td>23726.</td>
<td>90.24</td>
</tr>
<tr>
<td>STAGE 2</td>
<td>2.2697</td>
<td>107.6</td>
<td>0.200</td>
<td>0.469</td>
<td>8.31</td>
<td>9.51</td>
<td>63</td>
<td>1345.1</td>
<td>22537.</td>
<td>57.99</td>
</tr>
</tbody>
</table>

### TURBINE COMPONENT SUMMARY

<table>
<thead>
<tr>
<th>WTDSK</th>
<th>WTISD</th>
<th>WTID</th>
<th>WTDSB</th>
<th>WTBLD</th>
<th>WTRSH</th>
<th>WTDRM</th>
<th>WTRBS</th>
<th>WTST</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.4</td>
<td>19.7</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
<td>0.0</td>
<td>10.1</td>
<td>1.9</td>
<td>7.5</td>
</tr>
<tr>
<td>3.8</td>
<td>4.3</td>
<td>17.5</td>
<td>3.9</td>
<td>19.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FRAME WT = 44.91**

### DUCT

<table>
<thead>
<tr>
<th>M NO</th>
<th>VEL</th>
<th>T TOT</th>
<th>P TOT</th>
<th>P STAT</th>
<th>AREA</th>
<th>GAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.300</td>
<td>624.0</td>
<td>1944.0</td>
<td>10355.0</td>
<td>9764.0</td>
<td>0.6897</td>
<td>1.3166</td>
</tr>
</tbody>
</table>

**AN**^2 = 26.1 (BILLIONS IN2-RPM2)**

### MAX CONDITIONS OCCUR AT

#### ALT  MN

<table>
<thead>
<tr>
<th>PTOT</th>
<th>0.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTOT</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**DUCT 9**

#### RH= 8.25  RT= 10.00  LENG= 1.39

| AREA= 0.694 | RHO=.286 |
| WTC (OUTER) | WTC (INNER) | WTT (REV) | WT (TOTAL) | TMIN |
**MAX CONDITIONS OCCUR AT**

<table>
<thead>
<tr>
<th>ALT</th>
<th>MN</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTOT</td>
<td>0.000</td>
<td>72.0 LB/SQIN</td>
</tr>
<tr>
<td>TTOT</td>
<td>0.000</td>
<td>1943.6 DEG R</td>
</tr>
<tr>
<td>CWOUT</td>
<td>35000.0</td>
<td>63.6 LB/SEC</td>
</tr>
</tbody>
</table>

**DUCT**

<table>
<thead>
<tr>
<th>M NO</th>
<th>VEL</th>
<th>T TOT</th>
<th>P TOT</th>
<th>P STAT</th>
<th>AREA</th>
<th>GAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.165</td>
<td>345.</td>
<td>1944.</td>
<td>10306.</td>
<td>10124.</td>
<td>1.2154</td>
<td>1.3166</td>
</tr>
</tbody>
</table>

**STAGE 1**

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOB</td>
<td>RHOD</td>
<td>RHOS</td>
<td>RHOC</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.2</td>
<td>7.1</td>
<td>0.0</td>
<td>11.2</td>
<td>14.4</td>
<td>2.1</td>
<td>11.2</td>
<td>2.80</td>
<td>2.80</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>0.286</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STAGE 2**

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOB</td>
<td>RHOD</td>
<td>RHOS</td>
<td>RHOC</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.4</td>
<td>6.8</td>
<td>0.0</td>
<td>11.6</td>
<td>15.1</td>
<td>2.0</td>
<td>10.7</td>
<td>3.25</td>
<td>3.25</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>0.286</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STAGE 3**

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOB</td>
<td>RHOD</td>
<td>RHOS</td>
<td>RHOC</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>7.0</td>
<td>0.0</td>
<td>15.0</td>
<td>19.2</td>
<td>2.1</td>
<td>11.6</td>
<td>3.70</td>
<td>3.70</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>0.286</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TURBINE 10 MECHANICAL DESIGN**

<table>
<thead>
<tr>
<th>H/T</th>
<th>N STG LOADING</th>
<th>AREA</th>
<th>GE LOADING</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.742</td>
<td>3.000</td>
<td>0.280</td>
<td>1.215</td>
</tr>
</tbody>
</table>

**UTIPMAX STRESS**

<table>
<thead>
<tr>
<th>DEN</th>
<th>W/AREA</th>
<th>TR</th>
<th>H/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>808.2</td>
<td>15638.4</td>
<td>0.286</td>
<td>0.821</td>
</tr>
</tbody>
</table>

**STAGE I**

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOB</td>
<td>RHOD</td>
<td>RHOS</td>
<td>RHOC</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.2</td>
<td>7.1</td>
<td>0.0</td>
<td>11.2</td>
<td>14.4</td>
<td>2.1</td>
<td>11.2</td>
<td>2.80</td>
<td>2.80</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>0.286</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PR</th>
<th>DEL H</th>
<th>MACH</th>
<th>AREA</th>
<th>R HUB</th>
<th>R TIP</th>
<th>NB</th>
<th>MAXUTIP</th>
<th>STR</th>
<th>WEIGHT</th>
<th>LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>808.2</td>
<td>11.1</td>
<td>8.3</td>
<td>139.8</td>
<td>8312.4</td>
<td>8312.4</td>
<td>61667.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STAGE I**

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOB</td>
<td>RHOD</td>
<td>RHOS</td>
<td>RHOC</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.4</td>
<td>6.8</td>
<td>0.0</td>
<td>11.6</td>
<td>15.1</td>
<td>2.0</td>
<td>10.7</td>
<td>3.25</td>
<td>3.25</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>0.286</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PR</th>
<th>DEL H</th>
<th>MACH</th>
<th>AREA</th>
<th>R HUB</th>
<th>R TIP</th>
<th>NB</th>
<th>MAXUTIP</th>
<th>STR</th>
<th>WEIGHT</th>
<th>LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>808.2</td>
<td>11.1</td>
<td>8.3</td>
<td>139.8</td>
<td>8312.4</td>
<td>8312.4</td>
<td>61667.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WDISK</th>
<th>WISD</th>
<th>WID</th>
<th>WBLADE</th>
<th>WVANE</th>
<th>WNB</th>
<th>WCASE</th>
<th>AR</th>
<th>ARS</th>
<th>TLBLADE</th>
<th>TLVANE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHOB</td>
<td>RHOD</td>
<td>RHOS</td>
<td>RHOC</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.0</td>
<td>7.0</td>
<td>0.0</td>
<td>15.0</td>
<td>19.2</td>
<td>2.1</td>
<td>11.6</td>
<td>3.70</td>
<td>3.70</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>0.286</td>
<td>0.320</td>
<td>0.280</td>
<td>0.280</td>
<td>83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
STAGE I

<table>
<thead>
<tr>
<th>PR</th>
<th>DEL H</th>
<th>MACH</th>
<th>AREA</th>
<th>R HUB</th>
<th>R TIP</th>
<th>NB</th>
<th>MAXUTIP</th>
<th>STR</th>
<th>WEIGHT</th>
<th>LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6348</td>
<td>46.6</td>
<td>0.268</td>
<td>1.621</td>
<td>8.27</td>
<td>11.95</td>
<td>92</td>
<td>866.6</td>
<td>20858.</td>
<td>86.89</td>
<td>2.23</td>
</tr>
</tbody>
</table>

TURBINE COMPONENT SUMMARY

<table>
<thead>
<tr>
<th>WTDSK</th>
<th>WTISD</th>
<th>WTID</th>
<th>WTDSB</th>
<th>WTBLD</th>
<th>WTRSH</th>
<th>WTRBS</th>
<th>WTST</th>
</tr>
</thead>
<tbody>
<tr>
<td>59.6</td>
<td>20.9</td>
<td>0.0</td>
<td>0.0</td>
<td>37.9</td>
<td>0.0</td>
<td>16.1</td>
<td>3.9</td>
</tr>
<tr>
<td>6.5</td>
<td>9.0</td>
<td>33.6</td>
<td>6.2</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FRAME COMPONENTS INFORMATION

<table>
<thead>
<tr>
<th>FRAME WT</th>
<th>LENGTH</th>
<th>GAP</th>
<th>#FRAMES</th>
<th>ARF</th>
<th>RHOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.93</td>
<td>3.8</td>
<td>1.9</td>
<td>6</td>
<td>1.20</td>
<td>0.120</td>
</tr>
</tbody>
</table>

CASE WT = 26.49

N STG LENGTH WEIGHT CENGRA INERTIA

3 12.92 268.87 5.7 4766.

DUCT

<table>
<thead>
<tr>
<th>M NO</th>
<th>VEL</th>
<th>T TOT</th>
<th>P TOT</th>
<th>P STAT</th>
<th>AREA</th>
<th>GAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.319</td>
<td>576.6</td>
<td>1441.</td>
<td>2705.</td>
<td>2528.</td>
<td>2.1345</td>
<td>1.3401</td>
</tr>
</tbody>
</table>

***** AN**2 = 21.2 (BILLIONS IN^2-RPM^2) *****

<table>
<thead>
<tr>
<th>PR</th>
<th>TR</th>
<th>AD EF</th>
<th>PO</th>
<th>TO</th>
<th>TO.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8103</td>
<td>1.3491</td>
<td>0.9200</td>
<td>2704.9</td>
<td>1440.6</td>
<td>1440.6</td>
</tr>
</tbody>
</table>

H IN | H OUT | AREA | FLOW | HP |
| 499.95 | 360.17 | 5.93 | 41.13 | 8133. |

*********************** TOTAL TURB WEIGHT IS 268.869

***************

* *
* FMIX 11 *
* *
***************

MAX CONDITIONS OCCUR AT

******* ALT MN **********

<table>
<thead>
<tr>
<th>ALT</th>
<th>MN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTOT</td>
<td>0.000</td>
</tr>
<tr>
<td>TTOT</td>
<td>0.000</td>
</tr>
</tbody>
</table>

*********************** LENGTH= 14.77 WEIGHT = 46.81

***************

* *
* DUCT 12 *
* *
***************
MAX CONDITIONS OCCUR AT
********************
ALT         MN
PTOT       0.  0.000
TTOT       0.  0.000
********************

*************
*   *    
* NOZ 13 *
*   *    
************2

MAX CONDITIONS OCCUR AT
********************
ALT         MN
PTOT       0.  0.000
TTOT       0.  0.000
********************

NOZZLE 13
TOTAL NOZZLE COMPONENT WEIGHT = 67.49

NOZZ WEIGHT= 53.73 TOT LENGTH= 18.155 TR WT= 1.50
THROAT AREA= 689.66 EXIT AREA= 689.66
MIXER EJECTOR LENGTH = 0.00 TRANS DUCT LENGTH = 0.00

NOZZLE WEIGHT BREAKDOWN
OUTER WALL = 53.73 PLUG = 12.26 NOZZ DENS = .2810
INNER WALL = 0.00 MIXER-EJECTOR = 0.00 PLUG DENS = .2810
CONV INNER WALLS = 0.00 NOZ AC LIN = 0.00 CASE DENS = .2810
DIV INNER WALLS = 0.00 PLG AC LIN = 0.00 M/E DENS = .2810
2-D SIDEWALLS = 0.00 AC SPLIT PLATE = 0.00 ACOU DENS = .0900
VAR AREA C & A = 0.00
VAR AREA MISC = 0.00
2-D TRANS DUCT= 0.00

*************
*   *    
* DUCT 14 *
*   *    
************2

MAX CONDITIONS OCCUR AT
********************
ALT         MN
PTOT       0.  0.000
TTOT       0.  0.000
********************

FRAME COMPONENTS INFORMATION

<table>
<thead>
<tr>
<th>FRAME WT</th>
<th>LENGTH</th>
<th>GAP</th>
<th>#FRAMES</th>
<th>ARF</th>
<th>RHOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.20</td>
<td>3.7</td>
<td>18.3</td>
<td>3</td>
<td>1.80</td>
<td>0.120</td>
</tr>
<tr>
<td>CASE WT</td>
<td>HUB WT</td>
<td>UP SUPP</td>
<td>LW SUPP</td>
<td>RHO S</td>
<td>THSUP</td>
</tr>
<tr>
<td>5.29</td>
<td>3.46</td>
<td>0.00</td>
<td>11.60</td>
<td>0.120</td>
<td>0.10</td>
</tr>
</tbody>
</table>

FRAME WT = 23.55

DUCT, 14
RH=  12.52  RT=  19.12  LENG=  56.10
AREA=  4.557  RHO=.168

WTC(OUTER)  WTC(INNER)  WTT(REV)  WT(TOTAL)  TMIN
56.6164     37.0721      0.0000    117.2388      0.0500

*******
*         *
* DUCT 15 *
*         *
*******2

MAX CONDITIONS OCCUR AT
************
ALT  MN
PTOT  0.  0.000
TTOT  0.  0.000
************

*******
*         *
* SHAF 21 *
*         *
*******2

MAX TORQUE CONDITION
**********************
TORQUE
0.7
**********************

SHAFT  21
DO  DI  LENG  DN  WT
2.24  2.07  13.41  0.92  6.6

BEARING  #  3  4
BEARING WT 3.8  4.8
TOTAL SHAFT WEIGHT =  15.22

TOTAL INERTIA OF THIS SPOOL IS  5022.

*******
*         *
* SHAF 22 *
*         *
*******2

MAX TORQUE CONDITION
**********************
TORQUE
2.7
**********************

SHAFT  22
DO  DI  LENG  DN  WT
1.67  1.00  64.31  0.35  49.1

BEARING  #  1  2  5
BEARING WT 3.2  3.2  4.0
TOTAL SHAFT WEIGHT =  59.56
TOTAL INERTIA OF THIS SPOOL IS 11490.

*************
*     *       * INLT 1 *
*     *
*************2

MAX CONDITIONS OCCUR AT
***************
ALT   MN
PTOT  0.  0.000
TTOT  0.  0.000
***************
INLET 1

MDA SUBSONIC LOW DRAG INLET

INLET WEIGHT
WTINLT = 0.00  DUCTWT = 0.00
BDRWT  = 0.00  TDRWT  = 0.00
ENG MT  = 58.55  FIRE WL= 0.00
FAN DIA= 38.46  LDUCT = 0.00  LDUCTS = 0.00

INLET LENGTH = 19.23

NACELLE WEIGHT
NAC WT   = 191.18
INL CWL WT = 49.10  INLET LEN = 18.93
FAN CWL WT = 4.27  FAN BLD LEN = 2.96
FAN EXH CWL WT = 126.02  FAN EXH LEN = 106.00
CORE CWL WT = 0.00  CORE CWL LEN= 0.00  CWL AVG DIAM = 14.82
ANTI-ICE WT  = 3.98
ACOUSTIC WT = 0.00
BULKHEAD WT  = 7.81

TOTAL INLET/NACELLE WEIGHT = 249.74

*************
*     *
*  ACCS WT *       *
*     *
*************2

ACCS WT= 141.722

1

<table>
<thead>
<tr>
<th>NSTAGE</th>
<th>COMP NO</th>
<th>WT</th>
<th>COMP LEN</th>
<th>ACCU LEN</th>
<th>UPSTREAM RADIUS RI</th>
<th>RO</th>
<th>RI RO</th>
<th>RI RO</th>
<th>RI RO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>250.</td>
<td>19.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>294.</td>
<td>5.9</td>
<td>6.0</td>
<td>7.5</td>
<td>0</td>
<td>0.0</td>
<td>10.4</td>
<td>19.2</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.</td>
<td>10.4</td>
<td>19.2</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td>10.4</td>
<td>12.2</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>33.</td>
<td>8.5</td>
<td>14.0</td>
<td>10.5</td>
<td>12.2</td>
<td>0.0</td>
<td>10.5</td>
<td>12.2</td>
</tr>
<tr>
<td>COMP</td>
<td>NAME</td>
<td>TOT WT</td>
<td>ROTOR</td>
<td>STATOR</td>
<td>FRAME</td>
<td>LT</td>
<td>LTM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>--------</td>
<td>-------</td>
<td>--------</td>
<td>-------</td>
<td>----</td>
<td>----</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>FANH</td>
<td>294.4</td>
<td>112.6</td>
<td>125.6</td>
<td>56.2</td>
<td>19.9</td>
<td>14.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>HPC</td>
<td>262.5</td>
<td>140.1</td>
<td>82.6</td>
<td>39.7</td>
<td>33.9</td>
<td>28.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>HPT</td>
<td>193.1</td>
<td>94.2</td>
<td>54.1</td>
<td>44.9</td>
<td>4.4</td>
<td>4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>LPT</td>
<td>268.9</td>
<td>140.7</td>
<td>101.7</td>
<td>26.5</td>
<td>12.9</td>
<td>7.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BARE ENGINE WEIGHT = 1491
ACCESSORIES WEIGHT = 141
TOTAL ENGINE WEIGHT = 1633
INLET/NACELLE WEIGHT = 249
TOTAL ENGINE POD WEIGHT = 1883

ENGINE LENGTH = 109.0
TOTAL ENGINE POD LENGTH = 128.2
ENGINE MAX DIAMETER = 38.5
NACELLE MAX DIAMETER = 45.8
ENGINE POD C.G. LOCATION = 33.4
Appendix C

ANSYS Axisymmetric Model Input File for Exoskeletal Rotor

This appendix contains the input data for an ANSYS structural analysis of the exoskeletal rotor when it is spinning at the overspeed condition of 16 400 rpm. The centrifugal force from each row of blades is represented by discrete force applied to the rotor. This model was used to generate the analysis results discussed in the section Drum Rotor Investigation. The ANSYS computer program is a large-scale multipurpose finite-element program that may be used for solving several classes of engineering analyses. The program contains many special features, one of which allows the two-dimensional modeling of a solid of revolution or an axisymmetric body. The use of axisymmetry reduces the size of the model by simplifying the generation of the geometry, structural loads, and boundary conditions.

This input file contains preprocessing, solution, and postprocessing commands to create the model, perform the analysis, and plot the results. The general preprocessor (PREP7) section contains solid modeling and mesh generation commands and is also used to define all other analysis data (geometric properties (real constants), material properties, etc.). Parameters are used in the geometry definition to provide more flexibility for the analyst to change the design. Loads and constraints are defined in the solution section (SOLUTION) where the analysis is also executed. The analysis results are reviewed using the postprocessor (POST1), in which plots are created to display distorted geometries, stress contours, and margins of safety contours. All plots of the geometry, mesh, and results are stored in a graphics file (file.grph), which may be viewed with the ANSYS Display utility. Another analyst may re-create the model by inputting this listing in either an ANSYS interactive session or a batch job.

The following ANSYS FEA input listing was generated by Daniel N. Kosareo.

/BATCH

! ANSYS RELEASE= 7.0 UP20021010 01/08/03Daniel N. Kosareo

/SHOW,file,grph

! DEFINE PARAMETERS

!*ASK,DTHK,BLADE MOUNTING RING THICKNESS,0.375

!*ASK,RTHK,ROTOR THICKNESS,0.125

!*ASK,FHGT,FLANGE HEIGHT,0.5

! PREPROCESSING MODULE

/PREP7
/TITLE,Exoskeletal AE3007 Engine, Rotor Design, 16400 RPM
/WIN,1,-1,1,-.88,1
/VIEW,1,,1
/VUP,1,X

! DEFINE ELEMENT TYPES (Plane Axisymmetric Elements)
ET, 1, PLANE82,,1
*REPEAT, 21, 1
!
! MATERIAL PROPERTIES FOR GRAPHITE-POLYIMIDE COMPOSITE Gr/P
!
MP, EX, 1, 24.0E+06
MP, NUXY, 1, 0.33
MP, DENS, 1, (0.056/386.4)
MP, ALPX, 1, 20E-06
!
! MATERIAL PROPERTIES FOR TITANIUM Ti-6Al-4V
!
MP, EX, 2, 16.0E+06
MP, NUXY, 2, 0.31
MP, DENS, 2, (0.160/386.4)
MP, ALPX, 2, 4.9E-06
!
! MATERIAL PROPERTIES FOR HASTALLOY X
!
MP, EX, 3, 29.8E+06
MP, NUXY, 3, 0.32
MP, DENS, 3, (0.297/386.4)
MP, ALPX, 3, 7.5E-06
!
! MATERIAL PROPERTIES FOR SILICON-CARBIDE SiC/SiC
!
MP, EX, 4, 10.9E+06
MP, NUXY, 4, 0.07
MP, DENS, 4, (0.08/386.4)
MP, ALPX, 4, 1.7E-06
!
! SOLID AXISYMMETRIC MODEL
!
K, 1, 7.84, 0.00
K, 2, 7.84, 2.25          ! Stage 1
K, 4, 7.84, 3.59
KFILL, 2, 4
K, 5, 7.84, 4.72          ! Stage 2
K, 7, 7.84, 5.79
KFILL, 5, 7
K, 8, 7.84, 7.24          ! Stage 3
K, 10, 7.84, 8.15
KFILL, 8, 10
K, 11, 7.84, 9.276        ! Stage 4
K, 13, 7.84, 10.19
KFILL, 11, 13
K, 14, 7.84, 11.314       ! Stage 5
K, 16, 7.84, 12.01
KFILL, 14, 16
K,17,7.84,13.19 ! Stage 6
K,19,7.84,13.78
KFILL,17,19
K,20,7.84,14.585 ! Stage 7
K,22,7.84,15.23
KFILL,20,22
K,23,7.84,16.02 ! Stage 8
K,25,7.84,16.41
KFILL,23,25
K,26,7.84,17.37 ! Stage 9
K,28,7.84,17.80
KFILL,26,28
K,29,7.84,18.60 ! Stage 10
K,31,7.84,19.09
KFILL,29,31
K,32,7.84,19.86 ! Stage 11
K,34,7.84,20.32
KFILL,32,34
K,35,7.84,21.1 ! Stage 12
K,37,7.84,21.66
KFILL,35,37
K,38,7.84,22.38 ! Stage 13
K,40,7.84,22.74
KFILL,38,40
K,41,7.84,23.55 ! Stage 14
K,43,7.84,23.92
KFILL,41,43
K,44,7.84,24.68
K,45,7.84+0.5*(10.29–7.84)/(32.4–24.68),24.68+0.5
K,46,7.84+(32.4–24.68–0.5)*(10.29–7.84)/(32.4–24.68),32.4–0.5
K,47,10.29,32.4
K,48,10.29+0.5*(9.57–10.29)/(39.04–32.4),32.4+0.5
K,49,10.29+(39.04–32.4–0.5)*(9.57–10.29)/(39.04–32.4),39.04–0.5
K,50,9.57,39.04 ! HPT Stage 1
K,52,9.57,39.95
KFILL,50,52
K,53,9.51,41.4 ! HPT Stage 2
K,55,9.51,42.25
KFILL,53,55
K,56,9.51,42.25+0.5
L,1,2
*REPEAT,55,1,1
K,57,7.84+DTHK,0.00
K,58,7.84+DTHK,3.59
K,59,7.84+DTHK,5.79
K,60,7.84+DTHK,8.15
K,61,7.84+DTHK,10.19
K,62,7.84+DTHK,12.01
K,63,7.84+DTHK,13.78
K,64,7.84+DTHK,15.23
<table>
<thead>
<tr>
<th>K</th>
<th>Value</th>
<th>DTHK</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>7.84+DTHK, 16.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>66</td>
<td>7.84+DTHK, 17.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>7.84+DTHK, 19.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>7.84+DTHK, 20.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>7.84+DTHK, 21.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>7.84+DTHK, 22.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>7.84+DTHK, 23.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>9.57+DTHK, 39.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>9.57+DTHK, 39.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>9.51+DTHK, 42.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>9.51+DTHK, 42.25+0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **L, 57, 58**: *REPEAT, 24, 1, 1
- **L, 57**: *REPEAT, 15, 3, 1
- **L, 44, 72**: *REPEAT, 7, 1, 1
- **L, 52, 79**: L, 55, 80
- **L, 56, 81**
- **KGEN, 2, 57, 63, 1, RTHK, , ,**
- **K, 89, KX(64) + RTHK, 15.23−0.5**
- **K, 90, KX(64) + RTHK, 15.23**
- **K, 91, KX(64) + RTHK, 15.23+0.5**
- **KGEN, 2, 65, 71, 1, RTHK, , ,**
- **K, 99, KX(71) + RTHK, 24.68−0.5**
- **KGEN, 2, 72, 78, 1, RTHK, , ,**
- **K, 107, KX(78) + RTHK, 39.04+0.5**
- **KGEN, 2, 79, 81, 1, RTHK, , ,**
- **L, 82, 83**: *REPEAT, 28, 1, 1
- **L, 57, 82**: *REPEAT, 7, 1, 1
- **L, 64, 90**: L, 65, 92
- **L, 72, 100**: *REPEAT, 7, 1, 1
- **L, 79, 108**: L, 80, 109
- **L, 81, 110**
- **KGEN, 2, 89, 91, 1, FHGT, , ,**
- **KGEN, 2, 99, 101, 1, FHGT, , ,**
- **KMODIF, 114, KX(116)**
- **KMODIF, 115, KX(116)**
- **KGEN, 2, 105, 107, 1, FHGT, , ,**
- **KMODIF, 118, KX(117)**
- **KMODIF, 119, KX(117)**
- **L, 111, 112**
L, 112, 113
L, 89, 111
*REPEAT, 3, 1, 1
L, 114, 115
L, 115, 116
L, 99, 114
*REPEAT, 3, 1, 1
L, 117, 118
L, 118, 119
L, 105, 117
*REPEAT, 3, 1, 1
/PNUM, KP, 1
KPLO
LPLO
/PNUM, KP, 0
/NUM, -1
/DEVICE, VECT, ON
LPLO
/NUM, 1
/DEVICE, VECT, OFF
/DEVICE, RAST, ON
LPLO
/COM
KSEL, S, KP, , 1, 4, 1
KSEL, A, KP, , 57, 58
LSLK, S, 1
AL, ALL ! Area 1
KSEL, S, KP, , 4, 7, 1
KSEL, A, KP, , 58, 59
LSLK, S, 1
AL, ALL ! Area 2
KSEL, S, KP, , 7, 10, 1
KSEL, A, KP, , 59, 60
LSLK, S, 1
AL, ALL ! Area 3
KSEL, S, KP, , 10, 13, 1
KSEL, A, KP, , 60, 61
LSLK, S, 1
AL, ALL ! Area 4
KSEL, S, KP, , 13, 16, 1
KSEL, A, KP, , 61, 62
LSLK, S, 1
AL, ALL ! Area 5
KSEL, S, KP, , 16, 19, 1
KSEL, A, KP, , 62, 63
LSLK, S, 1
AL, ALL ! Area 6
KSEL, S, KP, , 19, 22, 1
KSEL, A, KP, , 63, 64
LSLK, S, 1
AL, ALL                    ! Area 7
KSEL, S, KP,, 22, 25, 1
KSEL, A, KP,, 64, 65
LSLK, S, 1
AL, ALL                    ! Area 8
KSEL, S, KP,, 25, 28, 1
KSEL, A, KP,, 65, 66
LSLK, S, 1
AL, ALL                    ! Area 9
KSEL, S, KP,, 28, 31, 1
KSEL, A, KP,, 66, 67
LSLK, S, 1
AL, ALL                    ! Area 10
KSEL, S, KP,, 31, 34, 1
KSEL, A, KP,, 67, 68
LSLK, S, 1
AL, ALL                    ! Area 11
KSEL, S, KP,, 34, 37, 1
KSEL, A, KP,, 68, 69
LSLK, S, 1
AL, ALL                    ! Area 12
KSEL, S, KP,, 37, 40, 1
KSEL, A, KP,, 69, 70
LSLK, S, 1
AL, ALL                    ! Area 13
KSEL, S, KP,, 40, 43, 1
KSEL, A, KP,, 70, 71
LSLK, S, 1
AL, ALL                    ! Area 14
ALLSEL
A, 43, 44, 72, 71          ! Area 15
*REPEAT, 7, 1, 1, 1, 1     ! Areas 16-21
KSEL, S, KP,, 50, 52, 1
KSEL, A, KP,, 78, 79
LSLK, S, 1
AL, ALL                    ! Area 22
KSEL, S, KP,, 52, 55, 1
KSEL, A, KP,, 79, 80, 1
LSLK, S, 1
AL, ALL                    ! Area 23
ALLSEL
A, 55, 56, 81, 80          ! Area 24
A, 57, 58, 83, 82          ! Area 25
*REPEAT, 6, 1, 1, 1, 1     ! Areas 26-30
KSEL, S, KP,, 88, 90, 1
KSEL, A, KP,, 63, 64
LSLK, S, 1
AL, ALL                    ! Area 31
KSEL, S, KP,, 90, 92, 1
KSEL, A, KP,, 64, 65
LSLK,S,1
AL,ALL                      ! Area 32
ALLSEL
A,65,66,93,92                ! Area 33
*REPEAT,6,1,1,1,1          ! Areas 34-38
KSEL,S,KP,,98,100,1
KSEL,A,KP,,71,72
LSLK,S,1
AL,ALL                      ! Area 39
ALLSEL
A,72,73,101,100             ! AREA 40
*REPEAT,6,1,1,1,1        ! Areas 41-45
KSEL,S,KP,,106,108
KSEL,A,KP,,78,79
LSLK,S,1
AL,ALL                      ! AREA 46
ALLSEL
A,79,80,109,108             ! AREA 47
A,80,81,110,109             ! AREA 48
A,89,90,112,111             ! Area 49
A,90,91,113,112             ! Area 50
A,99,100,115,114            ! Area 51
A,100,101,116,115           ! Area 52
A,105,106,118,117           ! Area 53
A,106,107,119,118           ! Area 54
ADEL,16,21,1,1
ASEL,S,AREA,,25,30,1
AADD,ALL                      ! AREA 16
ASEL,S,AREA,,31,49,18
AADD,ALL                      ! AREA 17
ASEL,S,AREA,,32,39,1
ASEL,A,AREA,,50,51,1
ASEL,A,AREA,,15,15,1
AADD,ALL                      ! AREA 18
ASEL,S,AREA,,40,45,1
ASEL,A,AREA,,52,53,1
AADD,ALL                      ! AREA 15
ASEL,S,AREA,,46,48,1
ASEL,A,AREA,,54,54,1
ASEL,A,AREA,,24,24,1
AADD,ALL                      ! AREA 19
ALLSEL
NUMCMP,AREA
/PNUM,AREA,1
APLO
/PNUM,AREA,0
/PNUM,KP,1
APLO
/PNUM,KP,0
/PNUM,AREA,1
APLO
APLO, 1, 14, 1
APLO, 15, 19, 1
APLO, 20, 21, 1
/PNUM, AREA, 0
*DO, ANUM, 1, 7, 1
ASEL, S, AREA, , ANUM, ANUM, 1
AATT, 1, 1, ANUM
*ENDDO
*DO, ANUM, 8, 14, 1
ASEL, S, AREA, , ANUM, ANUM, 1
AATT, 2, 1, ANUM
*ENDDO
ASEL, S, AREA, , 15
AATT, 3, 1, 15
ASEL, S, AREA, , 16
AATT, 1, 1, 16
ASEL, S, AREA, , 17
AATT, 2, 1, 17
ASEL, s, AREA, , 18
AATT, 2, 1, 18
ASEL, S, AREA, , 19
AATT, 3, 1, 19
ASEL, S, AREA, , 20
AATT, 4, 1, 20
ASEL, S, AREA, , 21
AATT, 4, 1, 21
ALLSEL
/pnum, mat, 1
aplo
/pnum, mat, 1
!
! AUTOMATED FINITE ELEMENT MESHING
!
esize, RTHK/2
MSHAPE, 0, 2D
MSHKEY, 2
amesh, all
/pnum, type, 1
eplo
/pnum, type, 0
KSEL, S, KP, , 1, 57, 56
KSEL, A, KP, , 82, 82, 1
LSLK, S, 1
NSLL, S, 1
CP, 1, UY, ALL
KSEL, S, KP, , 56, 81, 81-56
KSEL, A, KP, , 110, 110, 1
LSLK, S, 1
NSLL, S, 1
CP, 2, UY, ALL
ALLSEL
FINI
!
! SOLUTION MODULE
!
/SOLU
ANTYPE, STATIC, NEW
OUTRES, ALL, ALL
TIME, 1.0
!
! ROTATIONAL SPEED
!
ROTPD=2*PI*16400/60
OMEGA, 0, ROTPD, 0, 0
!
! DISPLACEMENT CONSTRAINTS
!
DK, 1, UY, 0
! DK, 82, UX, 0
! DK, 110, UX, 0
!
! CENTRIFUGAL FORCES DUE TO WEIGHT OF BLADES AT EACH ROW
!
FK, 3, FX, 21*0.05825*7.84*ROTPD*ROTPD/386.4
FK, 6, FX, 28*0.02382*7.84*ROTPD*ROTPD/386.4
FK, 9, FX, 35*0.01176*7.84*ROTPD*ROTPD/386.4
FK, 12, FX, 42*0.0064084*7.84*ROTPD*ROTPD/386.4
FK, 15, FX, 49*0.0038977*7.84*ROTPD*ROTPD/386.4
FK, 18, FX, 56*0.0024879*7.84*ROTPD*ROTPD/386.4
FK, 21, FX, 62*0.0016691*7.84*ROTPD*ROTPD/386.4
FK, 24, FX, 68*0.0033844*7.84*ROTPD*ROTPD/386.4
FK, 27, FX, 74*0.0025427*7.84*ROTPD*ROTPD/386.4
FK, 30, FX, 78*0.0019597*7.84*ROTPD*ROTPD/386.4
FK, 33, FX, 82*0.0015143*7.84*ROTPD*ROTPD/386.4
FK, 36, FX, 84*0.0013144*7.84*ROTPD*ROTPD/386.4
FK, 39, FX, 85*0.0011129*7.84*ROTPD*ROTPD/386.4
FK, 42, FX, 84*0.0010030*7.84*ROTPD*ROTPD/386.4
/PBC, ALL, , 1
APLO
/PBC, ALL, , 0
SBCTRA
/PBC, ALL, , 1
EPLO
/PBC, ALL, , 0
LSWRITE, 1
LSSOLVE, 1
FINI
!
! POSTPROCESSING
/POST1
SET, 1, 1
/DSCALE, 1, 1.0
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of Radial Displacements (in)
PLNS, U, X
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of Radial Stresses (Sx)
PLNS, S, X
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of Axial Stresses (Sy)
PLNS, S, Y
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of Tangential (Hoop) Stresses (Sz)
PLNS, S, Z
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of 1st Principal Stress (S1)
PLNS, S, 1
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of 2nd Principal Stress (S2)
PLNS, S, 2
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of 3rd Principal Stress (S3)
PLNS, S, 3
/ANNOT, DELE
/ANNOT, ON
/TSPEC, 15, .9, 2, 0.
/TLABEL, -.9,.94, Contour Plot of Max. Equivalent Stress (Seqv)
PLNS, S, EQV
/ANNOT, DELE
FINI
/EXIT
Appendix D
Blade Profiles for Exoskeletal Rotor

This appendix contains the input data for the Pro/Engineer® models of the compressor and turbine rotor blades. The exoskeletal compressor rotor blade shapes are based on the NACA 65A010 compressor airfoil shape. The NACA 65A010 profile is a symmetric shape specifically developed for compressor applications. This profile is shown in figure 50 and is listed in table 22. This airfoil has a 10-percent-thickness-to-chord ratio.

<table>
<thead>
<tr>
<th>Length-to-chord ratio, x/c, percent</th>
<th>Thickness-to-chord ratio, y/c, percent</th>
<th>Length-to-chord ratio, x/c, percent</th>
<th>Thickness-to-chord ratio, y/c, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>40</td>
<td>4.995</td>
</tr>
<tr>
<td>.5</td>
<td>.765</td>
<td>45</td>
<td>4.983</td>
</tr>
<tr>
<td>.75</td>
<td>.928</td>
<td>50</td>
<td>4.863</td>
</tr>
<tr>
<td>1.25</td>
<td>1.183</td>
<td>55</td>
<td>4.632</td>
</tr>
<tr>
<td>2.5</td>
<td>1.623</td>
<td>65</td>
<td>4.304</td>
</tr>
<tr>
<td>5</td>
<td>2.182</td>
<td>65</td>
<td>3.809</td>
</tr>
<tr>
<td>7.5</td>
<td>2.65</td>
<td>70</td>
<td>3.432</td>
</tr>
<tr>
<td>10</td>
<td>3.04</td>
<td>75</td>
<td>2.912</td>
</tr>
<tr>
<td>15</td>
<td>3.658</td>
<td>80</td>
<td>2.352</td>
</tr>
<tr>
<td>20</td>
<td>4.127</td>
<td>85</td>
<td>1.771</td>
</tr>
<tr>
<td>25</td>
<td>4.483</td>
<td>90</td>
<td>1.188</td>
</tr>
<tr>
<td>30</td>
<td>4.742</td>
<td>95</td>
<td>.604</td>
</tr>
<tr>
<td>35</td>
<td>4.912</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

A stagger angle θ is used for the base and the tip of the compressor blades, which gives the blade a twist along its length. The stagger angle is applied at the centroid of the airfoil, as shown in figure 51. In the high-pressure turbine, the airfoil camber line is curved, and the symmetric shape of the NACA 65A010 profile is distributed about the camber line. The curved camber line changes the fluid flow to the desired direction. In the case of the exoskeletal design, the curved camber line is a circular arc as shown in figure 52. The stagger angle θ of the curved airfoil is the average of the camber line inlet angle φi and exit angle φe. From basic trigonometry, the radius r of the camber line is given by the following equation:

![Figure 50.—NACA 65A010 blade shape.](image1)

![Figure 51.—Airfoil stagger angle for compressor blades.](image2)
\[ r = \frac{c \sin \theta}{\cos \phi_c - \cos \phi_i} \]  \hspace{1cm} (D1)

where \( c \) is the chord.

In the Pro/Engineer® model, each point of the NACA 65A010 profile has a local radius \( r_n \) and a local camber line angle \( \phi_n \), which are defined by the following set of equations:

\[ \Delta \phi_n = 2 \theta \left( \frac{x}{c} \right) \]  \hspace{1cm} (D2a)

\[ r_n = r + c \left( \frac{y}{c} \right) \]  \hspace{1cm} (D2b)

\[ \phi_n = 90 + \phi_i - \Delta \phi_n \]  \hspace{1cm} (D2c)

The coordinates for each point on the profile are given by the following transformations:

\[ x_n' = r_n \cos \phi_n + \frac{c}{2} \]  \hspace{1cm} (D3)

\[ y_n' = r_n \sin \phi_n - \frac{c}{\tan \theta} \]  \hspace{1cm} (D4)
References

An innovative approach to gas turbine design involves mounting compressor and turbine blades to an outer rotating shell. Designated the exoskeletal engine, compression (preferable to tension for high-temperature ceramic materials, generally) becomes the dominant blade force. Exoskeletal engine feasibility lies in the structural and mechanical design (as opposed to cycle or aerothermodynamic design), so this study focused on the development and assessment of a structural-mechanical exoskeletal concept using the Rolls-Royce AE3007 regional airliner all-axial turbofan as a baseline. The effort was further limited to the definition of an exoskeletal high-pressure spool concept, where the major structural and thermal challenges are represented. The mass of the high-pressure spool was calculated and compared with the mass of AE3007 engine components. It was found that the exoskeletal engine rotating components can be significantly lighter than the rotating components of a conventional engine. However, bearing technology development is required, since the mass of existing bearing systems would exceed rotating machinery mass savings. It is recommended that once bearing technology is sufficiently advanced, a “clean sheet” preliminary design of an exoskeletal system be accomplished to better quantify the potential for the exoskeletal concept to deliver benefits in mass, structural efficiency, and cycle design flexibility.