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Task 6 - Advanced Turbine Systems Program Conceptual Design and Product Development

Topical Report
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For
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1.0 ABSTRACT

The Allison Engine Company has completed the Task 6 Conceptual Design and Analysis of Phase II of the Advanced Turbine System (ATS) contract. At the heart of Allison's system is an advanced simple cycle gas turbine engine. This engine will incorporate components that ensure the program goals are met. Allison plans to commercialize the ATS demonstrator and market a family of engines incorporating this technology. This family of engines, ranging from 4.9 MW to 12 MW, will be suitable for use in all industrial engine applications, including electric power generation, mechanical drive, and marine propulsion. In the field of electric power generation, the engines will be used for base load, standby, cogeneration, and distributed generation applications.

Allison's ATS addresses the four program goals in the following manner:

- Efficiency - The turbine selected for the ATS uses Allison's latest single-crystal alloys incorporating the most efficient component cooling technology that Allison has developed. These features allow the turbine to operate at a rotor inlet temperature (RIT) of 1427°C (2600°F). The compression system for this engine, which has an overall pressure ratio of approximately 28:1, is based on technology previously demonstrated at Allison. The engine that uses these components will demonstrate a thermal efficiency that is more than 15% better than the best in class today.

- Environment - The combustion system selected for this engine incorporates a catalytically stabilized, lean premix system with ceramic components requiring no significant wall cooling. This system will achieve acceptance in severe nonattainment areas, producing less than 8 ppm on oxides of nitrogen, and 20 ppm carbon monoxide (CO) and unburned hydrocarbons (UHC).

- Cost of Power - The bus bar cost of energy for the Allison ATS engine is more than 10% better than the present state of the art for systems meeting ATS environmental requirements. This improvement is the result of the high efficiency and the low emissions inherent in Allison's engine and its system design.

- Reliability, Availability, and Maintainability - The Allison ATS will be designed to have high reliability and low maintenance costs. Critical components will be designed using Allison's latest life analysis methods. Component and material tests will be conducted to verify these analyses. The engines will be modular by design to allow field maintenance and service in the minimum time possible. The ATS system will meet or exceed the RAM of current engines.

- Fuel Flexibility - The Allison ATS will be adaptable to operate on coal and biomass fuels after conversion.

The systems produced and marketed by Allison will have a positive impact on several areas of interest to the U.S. Government. From an environmental aspect, the Allison family of ATS engines will significantly reduce the amount of nitrogen oxide (NOx) released to the atmosphere when compared to conventional gas turbine engines of like power. A second area of interest to the Government is employment of the U.S. work force. Based on future sales forecasts, the presence of the ATS product line will result in a significant increase in jobs in the gas turbine industry alone. Additional jobs will be created in the various support industries. These products will be superior to any gas turbine systems in the world and will achieve worldwide acceptance. The resulting increase in foreign sales revenue will have a positive impact on the U.S. balance of trade.

2.0 EXECUTIVE SUMMARY

Allison Engine Company has completed the Task 6 System Definition and Analysis activity as required in Morgantown Energy Technology Center (METC) contract DE-AC21-93MC29257. This report presents the results of the Gas Fired Advanced Turbine System (GFATS) conceptual design activity. This activity resulted in the definition of a system that meets the requirements for high efficiency and low emissions while being cost effective, reliable, and maintainable at the same time. This system will be ready to be marketed in the year 2000. Allison has selected technologies for this system that best meet these low emissions, high efficiency requirements. Allison is committed to design, develop, and demonstrate the ATS as a full-scale unit by the year 2000.

The critical technologies incorporated in the Allison ATS engine include the following:

- lean premixed catalytically enhanced combustion
- high temperature ceramic combustor components and transition duct
- 1427°C (2600°F) high pressure (HP) turbine rotor inlet temperature (RIT)
- single-crystal Castcool®* airfoils for HP turbine first stage

The ATS gas turbine, shown in Figure 5.1-1, is a nominal 12 MW (16,086 hp) simple cycle engine that will use existing HP compressor aerodynamics with a two-stage LP compressor driven by the power turbine. The overall compression ratio is approximately 28:1. To meet the low emission requirements of the ATS an ultra low emission, lean premixed, catalytic enhanced combustion system is used. The two-stage HP turbine is an industrial version of an advanced aircraft turbine that is designed to operate at turbine RITs in excess of 1427°C (2600°F). A prototype of this turbine was tested in 1994. Since the ATS engine is one member of a family of advanced industrial gas turbines, component commonality between engines is an important aspect of the conceptual design optimization process. The thermal efficiency of the ATS engine is approximately 42%, more than a 15% improvement over the state of the art industrial gas turbine engines. Preliminary cost studies have indicated that this system will achieve a cost of energy savings that is greater than 10% compared with today's systems. Maintainability and reliability have also been considered in this conceptual design with particular emphasis on modularity of the gas turbine engine.

In conclusion, the Allison ATS will meet and exceed all of the DOE's requirements for this system.

* Castcool is a registered trademark of Allison Engine Company.

3.0 INTRODUCTION

The objective of Task 6 is to develop a conceptual design for the GFATS that the contractor selected in Task 3 and could demonstrate, at full scale, in the 1998-to-2000 time frame. This report provides detail on all aspects of the ATS design including both critical and noncritical components of the engine and the GFATS itself as a full system.

The requirements placed on the ATS by the contract SOW are the following:

- 15% improvement in thermal efficiency over Allison 1991 state of the art
- firing temperatures equal to or greater than 1427°C (2600°F)
- environmentally superior
  - -NOx less than 8 ppmvd at 15% O2
  - -20 ppmvd for CO and UHC
- reliability, availability, and maintainability (RAM) levels comparable with today's systems
- fuel flexibility
- cost of electricity 10% less than 1991 systems at bus bar

This report presents material covering both the component designs and material systems selected for all ATS engine hardware. Another section of this report deals with the entire system and includes complete conceptual designs for a turnkey generator plant and a generator set. This section provides plan and elevation drawings of the GFATS showing preliminary arrangement of all equipment. All the ATS program requirements were considered during conceptual design of the system.

Allison has now completed this task, including internal management reviews of the selected conceptual design. This topical report satisfies the Task 6 reporting requirement.

4.0 BACKGROUND

Allison has been a participant in the DOE's ATS program since its inception. Phase I of the program followed a series of discussions between the DOE, members of the gas turbine industry, and end users to determine the direction to be taken with future utility size turbine system. During Phase I of ATS, Allison conducted feasibility studies of various gas turbine systems that would achieve the objectives of the program. The configuration selected was a 140 MW combined cycle system with a bottoming cycle. Allison planned to team with a utility size turbine manufacturer and incorporate its advanced industrial/aircraft hot section technology in a utility engine. It was determined that the incorporation of advanced hot section technology was a necessity to meet the performance requirements of the program. Much of the effort in Phase I concentrated on evaluating cooling technology and materials, including ceramics, for the turbine airfoils for potential application to utility size engine hardware.

In Phase II the Allison program focused on an industrial engine version of the ATS. The objective of Task 3 of Phase II was to conduct trade studies of various cycles and engine configurations leading to the selection of an engine that the contractor could design, build, and demonstrate at full scale in the 1998 to 2000 timeframe. Preliminary studies were conducted on more than 30 engine/cycle configurations built around seven different core engines. This list was shortened to six engines on the basis of estimated system cost, complexity, and ability to create a family of engines. A family of ATS engines covering a wide range of powers with maximum hardware commonality is required to financially justify the ATS as a product. More in-depth cycle analyses were conducted, and engine costs were determined with design to cost techniques in use at Allison. A review of the resulting performance and cost data lead to the selection of Allison's candidate ATS engine. This engine, referred to in this report as ATS-5, is an advanced simple cycle machine incorporating the latest hot section and combustion technology that has been developed at Allison. The resulting engine, its enclosure, and the balance of the plant comprise a system that meets or exceeds the contractual requirements of ATS.

5.0 DISCUSSION

5.1 ATS FAMILY

5.1.1 ATS-1 Through -5

Based on Allison's market studies and future product plans it will be necessary for the engine used in the ATS to be part of a family of engines incorporating several levels of turbine and combustion technology. These engines will cover a wide range of powers while maximizing component commonality. ATS-5 is the most aggressive of these engines and is Allison's candidate GFATS engine. This is the engine that is the subject of this topical report. The following describes, in general terms, the configuration of this engine as well as the other four simple cycle engines in the ATS family:

- ATS-5: The HP compressor of the ATS-5 engine is derived from the Allison AE 2100 aircraft engine's compressor. It uses the same flow path, but the wheel, shaft, and case materials are changed to lower cost iron- and nickel-based alloys since titanium's weight advantage is not needed for industrial engines. A new two-stage low pressure (LP) compressor is used in conjunction with the HP compressor to raise the overall pressure ratio. The combustion system for this engine is a lean premix, ultra low emission, catalytic unit. The HP turbine is common to that used in the AE 301X advanced aircraft engine currently under development at Allison. This turbine will operate at a RIT of 1427°C (2600°F). A new four-stage power turbine specifically designed for use in an industrial engine is used in this engine. This engine will develop 12 MW (16,086 hp).
- ATS-4: This engine is modified to limit the HP turbine RIT to 1316°C (2400°F) instead of the 1427°C (2600°F) RIT of the ATS-5 engine. At this temperature ATS-4 will provide significantly increased hot section life compared to ATS-5 for those operators who do not require the full power capability of the ATS-5 engine. The power of this engine is 9.4 MW (12,636 hp).
- ATS-3: This 7.4 MW (9881 hp) engine differs from ATS-5 by virtue of having a three-stage power turbine, and there is no LP compressor. The only major new component needed for this engine is an inlet housing that will mount directly to the HP compressor case in place of the LP compressor.
- ATS-2: The same relationship and benefits exist between ATS-2 and ATS-3 as exist between ATS-4 and ATS-5. Operating at an RIT of 1316°C (2400°F), this engine produces 5.7 MW (7694 hp).
- ATS-1: This engine develops 4.9 MW (6572 hp) and is similar to ATS-2 and ATS-3 but incorporates the AE 3007 HP turbine. This aircraft engine is entering production at Allison at the present time. In the ATS-1 application the RIT is 1093°C (2000°F).

5.1.2 ATS-6

ATS-6 is the model designation that Allison assigned to an intercooled and recuperated (ICR) member of the ATS family of engines. Preliminary performance analysis and configuration definition studies were conducted, and it was found that this engine would require an entirely different LP compressor than any other engine in the family. The HP compressor would also be new, incorporating an axial section in front of the intercooler and a centrifugal section behind it. To maximize turbine commonality to other ATS engines it would be necessary to steam inject the turbine in two locations, one in front of the HP turbine and the other in front of the power turbine. This engine would have a thermal efficiency in excess of 50% and would produce 12.9 MW (17,383 hp). However, the economics of this engine with its expensive support systems and at projected fuel prices are not attractive at this time. It also does not meet the ATS program objective regarding cost of electricity at the terminals.

5.2 DETAIL DESCRIPTION OF THE ATS-5 ENGINE

The Allison GFATS engine, identified in this report as ATS-5, is an advanced technology simple cycle engine. This engine incorporates the latest hot section materials and cooling technology that is being developed at Allison for advanced military and commercial aircraft engines. The ultra low emissions combustion system is the other area where advanced technology is required to meet ATS program objectives. The lean premixed catalytic combustion system incorporated in this engine is based on technology Allison is developing in other DOE and industry funded programs. Other areas of this engine are based on current state-of-the-art components both in production and under development at Allison.

The following subsections of this Topical Report discusses in detail all aspects of the ATS-5 engine design and performance.

5.2.1 Performance

The ATS engine is an advanced technology simple cycle engine that is based on Allison's latest production aircraft engine family. The engine incorporates high temperature turbine technology that Allison is developing for future high performance military and commercial engines. The two-stage gas generator turbine drives the high pressure compressor and incorporates the most advanced materials and cooling technology that Allison has developed. The high pressure compressor is a 14-stage axial flow machine incorporating existing AE 2100 engine aerodynamics and flow-path hardware. Materials are changed to lower cost industrial engine materials. A two-stage low pressure compressor boosts the flow and pressure to the inlet of the high pressure compressor and incorporates variable geometry to limit the minimum surge margin (10%) during part power and/or off standard day operation. When variable geometry is insufficient to limit the minimum surge margin, an overboard bleed valve between the compressors will be opened. A four-stage power turbine drives the low pressure compressor as well as the skid mounted gearbox and generator. The combustion system is a single can, hot wall, silo type (off line), combustor with ceramic components. A fuel staging system introduces fuel to the lean premix chambers that, in turn, feed the combustor. This system will allow the engine to meet the emission requirements of severe nonattainment areas throughout the engine's operating range. Designed for operation on natural gas fuels, the combustion system will be adaptable to future biomass and coal-derived fuels. A 32-bit microprocessor based digital control system incorporating all the engine monitoring and control functions will be used.

5.2.2 Compressors

The ATS compression system consists of a two-stage LP compressor and a 14-stage HP compressor operating in series.

5.2.2.1 LP Compressor

The LP compressor is aerodynamically and mechanically derived from (1) the LP compressor used in the 578-DX propfan engine and (2) the 501-KB7 boost compressor. The 578-DX had a three-stage LP compressor operating at 10,290 rpm, whereas, the 501-KB7 is a single-stage compressor operating at 14,540 rpm. Both designs employ advanced 2-D aerodynamics and basic 3-D aerodynamics. The 578-DX was mechanically a very simple design using bolted wheels and spacers in a straddle mounted rotor (see Figure 5.2.2-1). While this was a heavy design for a flight engine, it provided a very low risk mechanical design. The ATS LP compressor is a close derivative of the 578-DX mechanical design.

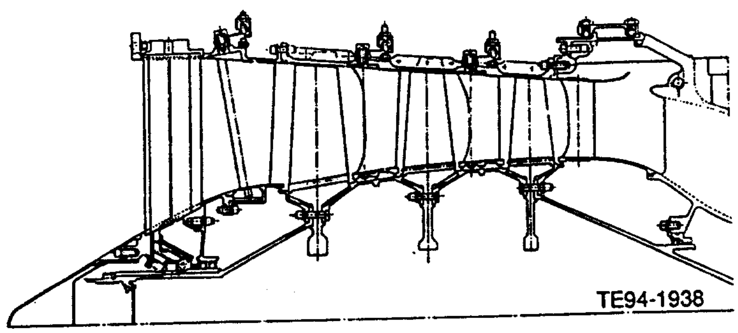

Figure 5.2.2-1. 578-DX LP compressor.

5.2.2.1.1 *Aerodynamics*

Preliminary aerodynamic design of the ATS LP compressor is based on 2-D flow theory. In Phase III, 3-D Navier Stokes equations will be used to refine this 2-D design.

The stage pressure ratio (1.320) is indicative of the conservatism of this design. A high technology compressor could achieve the overall LP pressure rise in one stage instead of two.

As can be seen the efficiency is relatively flat over the entire operating range. This should yield good off design performance as well as good performance at the design point. Although the operating line is not shown on the map, current estimates indicate this compressor should have approximately 20% surge margin.

5.2.2.1.2 *Mechanical Design*

As can be seen in Figure 5.2.2-1, the ATS LP compressor configuration closely resembles the 578-DX LP compressor. By patterning the mechanical design after the 578-DX the compressor mechanical development should be minimized. The primary difference in mechanical design of the ATS-5 from the 578-DX is the inlet housing.

The ATS engine radial inlet housing is aerodynamically scaled from the 571 radial inlet. Detailed aerodynamic analysis of the flow path has not yet been performed. This analysis is scheduled to be completed early in Phase III. The radial inlet housing uses a six strut configuration. These struts provide the support for the front sump housing as well as oil passages to the front sump. Also, the primary load path to the front engine mount is through these struts. The front engine mount is located on the front face of the radial inlet. The inlet housing is C355 aluminum material. An aluminum housing is less expensive than a steel housing due to castability and machining characteristics. The inlet plenum interface is designed in such a way that the plenum does not have to be removed to install or remove the engine. The engine simply 'plugs' into the plenum.

The LP compressor rotor uses a simple straddle mount design with the rotor supported by bearings in the inlet housing and the intermediate support. This configuration greatly reduces rotor dynamic development. The supercritical power turbine shaft is not significantly affected by the LP rotor in this arrangement. If the rotor were not straddle mounted, the mass of the LP rotor would be much more critical to the LP rotor dynamics. This rotor configuration also allows for an extremely rugged mechanical design. The blades are trapped by the spacers eliminating the need for complicated blade retention features. The wheels and the spacers are simply bolted together using retained bolts. This eliminates much of the highly specialized tooling generally associated with compressor rotor assembly. The material for the compressor wheels and spacers is Custom 450 steel. This material provides high yield and fatigue strength and is corrosion resistant. Therefore, no anti-corrosion coating is required. The blades in the 578-DX LP compressor were titanium to reduce weight and attachment stresses. Preliminary stress analysis indicates that titanium blades will not be required to achieve an acceptable attachment stress. Therefore, the ATS LP compressor blades are 17-4PH steel to minimize cost. This material is also corrosion resistant and will require no anti-corrosion coating.

The LP compressor case consists of two 180 deg segments. This configuration is extremely common, both at Allison and other gas turbine manufacturers. The blade tracks will employ a currently available abradable coating (Metco 313 aluminum-graphite), which provides excellent abradability and good erosion characteristics. The case is ductile iron material. This material will provide adequate containment capability while still providing good strength characteristics. However, this material is not corrosion resistant. Therefore, the case will be coated with a two-part aluminum coating such as Alseal 598. This should provide good corrosion protection in hostile environments for at least 30,000 hr.

The LP compressor uses variable geometry on the inlet guide vane and the first-stage vane to maximize off design performance and to aid in starting. The LP compressor variable geometry system is also required to maintain constant output speed, while varying engine output power. The variable vanes are patterned after the AE 2100 variable vanes. By using this configuration much of the actuation hardware for the compressor variable geometry (CVG) system can be common to the HP compressor actuation system. Also, the inner band design from the AE 2100 is used in the LP compressor. This patented inner band design uses two 180 deg segments that snap into place on the vane stems. The second-stage vane is a 360 deg ring that is trapped between the compressor case and the intermediate support. Currently no decision has been made as to whether this vane will be a fabricated assembly or a one piece casting. The 501-KB7 boost vane, which is very similar in design, is a fabricated assembly. However, a recent design study indicates that a one-piece Inco 718 casting could be a lower cost alternative.

5.2.2.2 HP Compressor

5.2.2.2.1 Aerodynamics

The ATS HP compressor is an aerodynamic copy of the AE 2100 turboprop engine. By using the AE 2100 aerodynamic design for the HP compressor, the ATS program can incorporate the latest aerodynamic technology with no development expense or risk.

The AE 2100 compressor employs 3-D aerodynamics to provide advanced performance characteristics, and has been fully developed on the compressor rig. By using the AE 2100 blades and vanes the risk associated with using a compressor of this technology level has been eliminated. The ATS turbine flow capacity is sized to ensure that adequate surge margin is maintained in the HP compressor.

5.2.2.2.2 Mechanical Design

The mechanical design, while based on the AE 2100, is significantly more rugged in construction. No stress analysis of the HP wheels has been performed to date. However, by increasing the mass of the wheel webs the last continuous fiber stress will be significantly reduced. Thus, the ATS wheels operate at much lower stress levels than the AE 2100. The compressor tiebolt, common to most Allison high pressure compressor designs, and the compressor shafts have been combined into a single-shaft arrangement. This creates an extremely stiff rotor design to minimize the dynamic effect of the overhung gasifier turbine. This was found to be a concern in the AE 2100 design, and a great deal of effort was required to optimize the rotor dynamic design. By increasing the stiffness of the ATS rotor, the rotor dynamic analysis in Phase III should be much simpler, even with a heavier HP turbine rotor.

The HP case is constructed from a casting patterned after the AE 2100 design. The abradable blade track coating bonded to the I.D. of this case is the highest risk technology in the compression system. The high compressor discharge temperature precludes the use of any of the abradable coatings currently used in Allison production engines. Thus, the advanced technology coating, Amdry XPT268, currently being evaluated in the AE 3007, will be required. However, even this coating may be marginal. If this coating does not perform as expected, the ATS engine will use a more conventional high temperature blade track system, such as feltmetal. While this technology is proven it is more expensive and does not have the performance characteristics of the Amdry XPT268 coating.

As stated previously, the vanes are common to the AE 2100 engine. This also allows for the same CVG actuation design as the AE 2100. The aerodynamic design currently indicates that the AE 2100 vane schedule will work on the ATS. Therefore, the entire actuation system from the AE 2100 can be used, as is. This system uses a 3-D four bar linkage system to rotate the vanes per the prescribed start schedule. This schedule is defined by the engine inlet temperature and the HP rotor speed. The engine control is preprogrammed with this schedule. An electronic signal is sent from the control to an engine supplied servo valve, which in turn modulates hydraulic pressure to the actuation cylinders. A linear variable differential transducer (LVDT) built into the hydraulic cylinder will provide feedback information to the control. The hydraulic actuation cylinder rotates a torque tube that has drive arms welded to it for each stage of variable geometry. These drive arms are connected via a drive link to the variable vane synchronizing rings. The synchronizing rings then rotate the variable vanes through drive arms.

The intermediate support connects the LP and HP compressor mechanically and aerodynamically. The aerodynamic swan neck is nearly identical to the swan neck connecting the AE 3007 HP compressor to the fan. Thus, there is little risk in predicting the aerodynamic characteristics of the duct. Also, the aerodynamic affect on the HP compressor is minimal and is well documented on the AE 3007. The inter-compressor start bleed is incorporated into the outer wall of the intermediate support. A full annulus is used on the flow path to minimize any distortion effects on the HP compressor. This transitions into a single large bleed port. Thus, a single butterfly type bleed valve can be used to regulate the bleed flow. This type of valve is not only inexpensive, but also has very low leakage rates. Since, the ATS engine does not have an accessory gearbox, the starter pad is located directly on the intermediate support. The starter shaft passes through the top vertical strut and engages the HP rotor with a bevel gear. The starter will be a skid provided item. Hydraulic, electric, and air turbine starters will all be offered as options.

5.2.2.3 Diffuser

The ATS engine incorporates a dump type diffuser that reduces the velocity and increases the static pressure of the compressor discharge air prior to its entering the combustion chamber. In addition to converting the kinetic energy in the air to pressure energy, the diffuser performs several other important functions in the engine. The inner wall of the diffuser forms the inner flow path of the combustion section, and it supports the center sump, the transition duct, and the stationary member of the HP turbine front air seal. The shape of the diffusing section will be optimized for minimum pressure loss. Both analyses, using computational fluid dynamics methods, and scale model testing will be used to accomplish this task.

5.2.3 Combustion System

Allison has defined the configuration for the ATS combustion system and has been developing key technology elements for its successful implementation. The ATS combustion system is an off-line silo configuration. This single cylindrical combustor is positioned with its axis perpendicular to the engine centerline and is mounted on top of the engine between the diffuser and the turbine inlet annulus. The upper portion of the combustion liner will be an effusion-cooled metallic piece. The lower portion of the liner is fabricated from a silicon carbide material. A catalytic element will be located in the combustor between the upper and lower portions of the combustion liner. The combustion system will operate under ultra-lean stoichiometry to minimize NOx formation. The following section of this report summarizes the operating characteristics of this system. For a more thorough description of this system refer to the Topical Report for Task 8 of this contract.

5.2.3.1 Combustor Design

The ATS combustion system has been designed to prevent formation of harmful pollutants. This is accomplished by creating a combustion system that consists of several distinct fuel injection and combustion zones to provide a system that is capable of emissions prevention over the full range of engine operating conditions. The combustion system features a catalytic element that limits gas temperature and NOx production.

A portion of the fuel-air mixture enters the pilot/preburner zone, which is necessary to start the gas turbine and bring it up to full speed. Once the catalyst is activated, the pilot is used to preheat a portion of the fuel/air mixture such that the overall fuel/air mixture temperature is sufficient for catalytic combustion.

The second zone is the catalyst fuel injector/premixer zone where the remaining fuel and air combine with the preheated mixture prior to entering the catalyst. The design of these modules is such that this mixture quickly achieves uniform preheat temperature and velocity by the catalyst stage.

At the catalytic stage, premixed fuel and air enter the catalyst and undergo partial combustion. The post catalyst homogeneous combustion stage is designed with the required residence time to complete the burnout of the remaining fuel and subsequent CO.

The target emissions goals warrant a need to maintain the entire combustor volume at a uniform temperature because temperature nonuniformities and quenching in the near wall regions lead to high levels of CO and UHC. This indicates a need to minimize or eliminate entirely the quenching effects due to wall cooling. Consequently, Allison will design a ceramic hot wall combustor. The preliminary design has established the combustor size to be such that a single-piece ceramic structure is favored for minimizing air leakages and emissions contamination. However, structural issues associated with such an integrated single combustor unit will have to be evaluated. The advantages associated with the use of multiple ceramic rings will also be assessed.

The fuel/air mixture to achieve the required combustor exit temperature is fed to the catalyst. If the inlet temperature is sufficiently high, the catalyst promotes a reaction rate sufficient to induce a temperature rise in the catalyst substrate as well as the gaseous mixture. This substrate temperature rise, however, is limited to a relatively low value by the specific (proprietary) catalyst composition. Additional stages may be required to achieve the required catalyst outlet temperatures; however, this was not necessary for the ATS operating conditions. This partially combusted fuel air mixture then enters a post catalyst zone where it spontaneously combusts to complete the reaction and yield the necessary outlet temperature. As a result, the thermally sensitive catalyst substrate does not reach the maximum obtained temperatures. This allows for the use of a metal substrate, which combined with limited temperature gradients, will improve the durability of the catalytically enhanced combustion system.

5.2.3.2 Balance of Combustion System Design

5.2.3.2.1 Combustion System Cases

The combustion system outer cases form the portion of the main carcass of the engine between the compressor outlet diffuser and the turbine case. In addition to enclosing and supporting the combustion liner and the catalytic element of the combustion system, this structure provides support for the combustor to turbine transition duct.

The main portion of this structure will be comprised of three Inconel castings: a 180 deg lower half, and two 90 deg upper quadrants enclosing the combustor to turbine transition duct. This construction is required in order to facilitate assembly of the engine. The outer casing for the actual combustor components is a cylindrical Inconel piece that bolts to the top of the quadrant cases. A mounting flange is provided on this case for a compressor surge dump valve. A cast Inconel dome bolted to the top of the outer casing completes the combustion case system. The dome provides mounting ports for the lean premix modules, and it also provides support for the fuel manifolds.

5.2.3.2.2 Transition Duct

The transition duct (Figures 5.2.3-1 and 5.2.3-2) is a thin-walled structure that forms the flow path from the exit of the combustion chamber through a 90 deg turn to the inlet of the HP turbine. Unique challenges are associated with this component because of the temperature it must withstand. In order to minimize NOx formation, it is desired that this duct operate with little or no cooling air, which further complicates the material selection process.

Allison has been working with DuPont/Lanxide during Phase II of the ATS contract to develop a transition duct fabricated from SiC/SiC ceramic composite material. A report on the work done by DuPont/Lanxide is included at the end of this report. In addition to the ceramic composite material Allison has evaluated the possibility of using a thermal barrier coated (TBC) HA188 or HA230 metallic duct as an alternate design. This metal duct will need to be effusion cooled or made of Lamilloy®* cooled in order to survive its operating environment.

5.2.4 Gas Generator Turbine

The selected engine configuration uses a two-stage gas generator turbine from a classified demonstrator program. Because the original design was intended to operate at a higher temperature and speed, this selection minimizes development cost and risk. The turbine flow size is close to the ATS requirements, and aerodynamic adaptation is feasible. To further minimize expense, the gas generator turbine will also be used in a growth version of the AE 3007 turbofan engine. The following subsections detail the efforts expended in selecting the configuration and adapting to the ATS.

5.2.4.1 Aerodynamics

Trade studies were performed to determine a suitable model on which to base the ATS power generation system. The models examined incorporated derivatives of a number of engine component combinations, including the AMAC compressor, an advanced subsonic turbine, the Model 572 compressor and gas generator turbine, the T406 compressor, the AE 301X gas generator turbine, and new power turbine designs. The selected configuration uses the AE 2100 compressor coupled with the AE 301X gas generator turbine and a new power turbine.

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* Lamilloy is a registered trademark of Allison Engine Company.

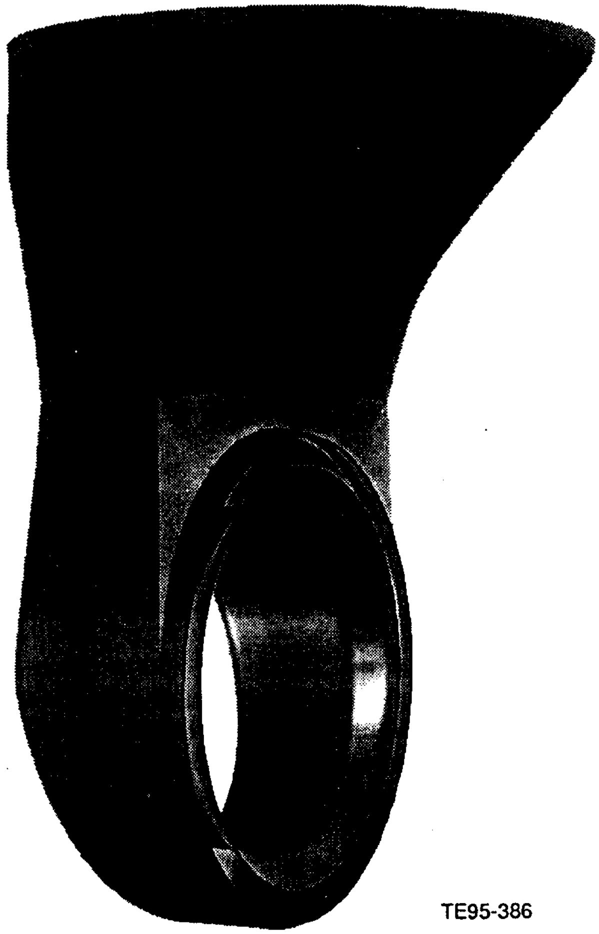

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Figure 5.2.3-1. Thin-walled transition duct (side view).

Aerodynamic design parameters have been established from performance cycle studies. The selected engine, designated the ATS-5, has an overall pressure ratio of 28.3, a firing temperature of 1427°C (2600°F), and an output power of 12 MW (16,086 shp) at design point conditions. The Allison Advanced Subsonic Turbine, as adapted to the AE 301X, is incorporated as the gas generator turbine. This turbine has two air cooled axial flow stages, and features the first commercial usage of Castcool technology in the first-stage vane and blade.

The gas generator design philosophy emphasizes commonality with existing engine hardware.

As mentioned previously, the Allison Advanced Subsonic Turbine adaptation to the AE 301X engine is the selected configuration for the ATS gas generator turbine. This core can handle the 1427°C (2600°F) requirement, and its two stages are able to produce the corrected flow and work required. Cooling air requirements are minimized by the incorporation of Castcool technology. Low flow coefficient aerodynamics reduce over-tip leakage. Low solidity blading reduces cost and increases performance. For the ATS application the second-stage blade is reset open 2 deg. The efficiency goal is 88.2%.

Cooling flows used to model the gas generator turbine were derived from the AE 301X core cooling flow breakdown by scaling to the ATS-5 cycle flow and temperature.

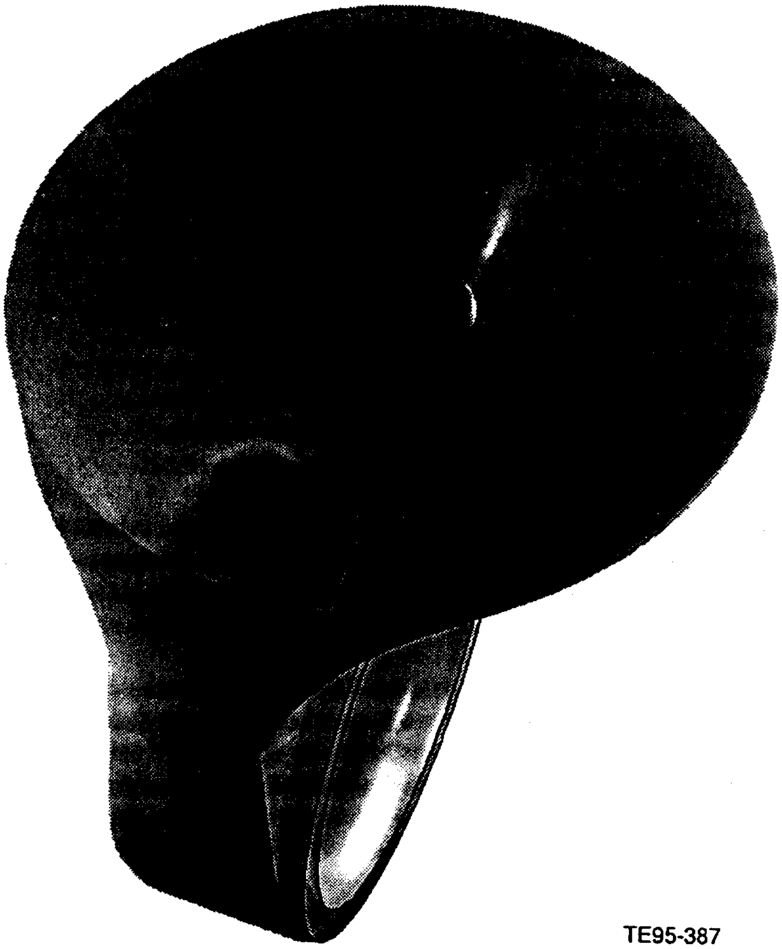

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Figure 5.2.3-2. Thin-walled transition duct (top view).

The gas generator turbine flow path is the same as for the AE 301X.

A controlled vortex velocity diagram was generated specifically for the ATS-5 performance cycle. Scaled cooling flows, loss characteristics, and AE 301X geometry were used as input. Tip clearances were estimated as 0.001 inch per inch of tip diameter. Overall expansion ratio and shaft output power were matched. Both rotors are unshrouded. The second-stage blade throat distribution reflects a reset of 1.9 deg open, which was necessary to control second-stage reaction. Inlet and exit temperature were assumed constant since the circumferentially averaged exit conditions from the combustor's transition were calculated as constant with radius.

Turbine airfoil section contours were developed along conical surfaces defined by the design program (ATCVORTX) streamlines. Each airfoil was designed interactively on the Allison turbine design system. Airfoil sections were analyzed with an Allison-developed 2-D inviscid blade-to-blade flow analysis (ATDELYPR). The sections were modified until aerodynamically acceptable surface velocities were achieved and mechanical design criteria satisfied.

Turbine maps were created for the ATS-5 gas generator turbine in order to predict off-design and transient performance.

Turbine performance maps were generated for ATS-1 through -4 to aid in predicting transient and off-design performance. However, detailed blading designs and analyses for ATS-1 through -4 have not been completed.

5.2.4.2 Mechanical Design

As stated previously, the mechanical design configuration of the gas generator turbine comes from a classified program which produced the Allison Advanced Subsonic Turbine. The primary unique feature is the incorporation of Allison's advanced cooling technology. This technology permits operation at gas temperatures well beyond the melting point of the materials used. The technology originated as Lamilloy, which is a quasitranspiration cooling scheme using multiple porous walls featuring arrays of pedestals and pins. Cooling effectiveness levels are significantly higher than the most advanced film cooling technology. The improved effectiveness can be used to reduce the required cooling air, or improve airfoil life at a given temperature.

At ATS cycle conditions, turbine airfoils using Lamilloy cooling on the airfoil suction and pressure surfaces use less airflow for cooling than comparable advanced film-cooled airfoils. Performance studies on the ATS engine have shown that to achieve the high thermal efficiency needed, while maintaining low component risk, this cooling air economy is essential.

Lamilloy airfoils were originally developed as a multipiece fabrication, employing cover sheets bonded to a spar. Recently, Allison has developed a process known as Castcool. This process enables the casting of small holes and finely detailed, intricate, passages in an integral single-crystal casting. The technology permits the casting of advanced cooling schemes such as Lamilloy into one piece airfoils. Bonding processes are eliminated, and the airfoil costs are reduced to the level of advanced fabricated film-cooled airfoils.

The ATS turbine incorporates the Castcool technology as the prime choice in both the first-stage vane and blade. Because the prototype AE 301X design was originally conceived for higher temperature operation, effort has been applied to identify areas where less costly cooling geometry may be applied. The investigation and optimization of cooling geometry is summarized in the Task 8 Topical Report.

During ATS Phase II, design efforts were also directed toward adapting the remainder of the gas generator turbine to the ATS engine.

The basic arrangement of a two-stage axial flow turbine is retained. The wheels are cantilever mounted from integral shafting that is splined and clamped to an extension shaft from the compressor. A rotating spacer or interstage seal is clamped between the two turbine wheels. The first-stage vane is simply supported by an inner vane support panel and an outer vane case. The second-stage vane and interstage seal stator are cantilever mounted from the same outer vane case. This general arrangement essentially duplicates that employed in the AE 2100 engine, which has passed flight qualification tests and is currently in production.

Cost and complexity have been re-assessed, and some modifications selected on a cost versus benefit basis. For ATS, the rotating panel on the upstream side of the first-stage wheel has been redesigned to integrate a coverplate and seal into one piece. This change reduces the difficulty of machining the forward wheel face.

Labyrinth seals and honeycomb stators are incorporated on the forward seal panel to replace higher cost brush seals. Performance differences are small at this location and insufficient to justify the added cost of brush seals.

The original design was configured to withstand both higher temperatures and higher operating speeds. A preliminary design assessment showed the 1-2 spacer does not need a web to withstand ATS conditions. It may, therefore, be fabricated from a ring forging instead of a pancake forging, saving considerable material.

The preliminary design assessment also showed the wheels could possibly be made of a lower cost wheel alloy. However, this is contingent on lower wheel cavity temperatures which may not prevail at the desired purge flows. A detailed assessment and additional test data are needed before this change can be made.

The primary design approach is to retain the high temperature gas generator turbine technology originally developed. Adaptation to the ATS did lead to a study of alternatives. Two stages of ceramic turbine vanes were configured to replace the first- and second-stage cooled vanes. The advantage is a reduction in cooling air.

The second-stage blade is internally cooled by a more conventional, less costly, method. Multipass convection cooling with trailing edge discharge is employed. The material requirements at ATS conditions have been reanalyzed. This analysis indicates that a stress rupture life goal may be met without employing a single-crystal material.

5.2.4.2.1 *Coatings*

Coating investigations have been conducted to assess airfoil material oxidation/corrosion life at anticipated ATS conditions. Dynamic oxidation testing at 1038°C (1900°F) for 5000 hr revealed that the high cost NiCoCrAlY overlay coating is superior to a diffused platinum-aluminide coating. The platinum-aluminide coating is, in turn, superior to a standard diffused aluminide coating. Bare materials were significantly inferior to coated materials.

The ATS configuration will employ the lower cost platinum aluminide coating. Allison has developed an electrophoretic method of applying the platinum aluminide coating prior to diffusion heat treatment. The low cost Allison Electrophoretic Process (AEP) will therefore be used. The AEP application technique is amenable to Castcool.

5.2.4.2.2 *Case and Vane Mounting*

The gas generator turbine case and vane arrangement will be retained from the AE 301X design. Brush seal mounting of ceramic blade tracks will simplify the design by eliminating hangers to support cooled metal blade track segments.

5.2.4.2.2.1 First-Stage Turbine Vane

5.2.4.2.2.1.1 *Castcool Primary Design.* The primary design configuration selected is essentially identical to that adopted for the AE 301X. The high cost of this technology has led to an effort to identify zones on the part where less costly geometry may be used without compromising integrity. Heat transfer effectiveness testing has been conducted to optimize the configuration. A detailed summary of this effort may be found in the Task 8 Topical Report.

5.2.4.2.2.1.2 *Ceramic Backup Design.* An alternate configuration is a ceramic vane, which may reduce the required burner outlet temperature by eliminating some cooling flow. However, this alternate would provide less tolerance for impact damage from debris, hard carbon, etc. The first-stage vanes are lightly stressed as they are simply supported by a surrounding metal structure, making the ceramic vane option more likely in this location than downstream.

Detailed analysis of the ceramic vane design has not been conducted. Preliminary discussions with ceramic vendors have revealed limitations of shape capability, as well as an absence of data above 1370°C (2500°F). With the current state of the art, the ceramic vane needs to be cooled for operation at ATS conditions. Although preliminary heat transfer analysis indicates a simple convection cooling scheme with trailing edge discharge would be adequate, discussions with suppliers has not shown feasibility. The coring and machining required are beyond the current level of experience.

Until higher temperature material capability is demonstrated, or manufacturing capability is developed for cooling, a ceramic vane design is considered a potential backup.

5.2.4.2.2.2 Second-Stage Turbine Vane

5.2.4.2.2.2.1 Air-cooled Primary Design. The primary design selected is identical to that designed for the AE 301X. The construction is a doublet vane casting internally cored for an impingement tube. Cooling air discharge is on the pressure surface immediately forward of the trailing edge. The vanes are supported from the turbine vane case, and carry a small panel load from the 1-2 interstage seal. Due to the cantilever construction, the bending stresses in operation dictate a higher creep strength nickel-based material.

5.2.4.2.2.2.2 Ceramic Backup Design. The lower temperature level at this location permits the use of a number of ceramic materials, such as sintered silicon nitride, produced by several suppliers. The primary drawback is the complexity of construction required to accommodate the ceramic material. The ceramic second-stage vane arrangement has been pursued as a configuration study, and no detailed analyses have been performed.

5.2.5 Power Turbine

5.2.5.1 Power Turbine Aerodynamics

The ATS power turbine is a new design. Aerodynamic requirements could not be satisfied using existing hardware.

The airfoil counts used to generate the flow path are tentatively established. Blade attachment considerations or dynamic response to vane passage may change these values.

Controlled vortex velocity diagrams were generated for the new four-stage power turbine. The Allison ATCVORTX program was run using loss buckets and exit angles patterned after the successful AE 3007 power turbine. The shrouded rotor tip clearances were estimated as 0.001 x tip diameter. Turbine inlet conditions were taken from the gas generator turbine exit. Overall expansion ratio and shaft output power of the ATS-5 performance cycle were matched.

Turbine airfoil section contours were developed in the same manner as the gas generator turbine using the Allison turbine design system. Additional design iterations were explored to examine the effect of different blade materials and their required blade section areas. None of the blades are cooled, thus, the blades may be more aggressively tapered to lower stress, permit the use of lower cost materials, or reduce attachment stresses.

A great deal of effort went into this optimization of blade area (and mass). Shortening the third- and fourth-stage blade meridional chords at the tip reduced the shroud width and lowered shroud weight and centrifugal loading. This effectively reduced the cross-sectional areas required to meet the stress and life goals in the following paragraphs.

Using conservative assumptions, a minimum life requirement was imposed on each blade.

5.2.5.2 Power Turbine Mechanical Design

The power turbine design for the ATS engine family will have new airfoils that are not aero-derivative. The general arrangement, however, will be very similar to the successful AE 2100 and AE 3007 engines. Departures from these design arrangements are largely to reduce cost at the expense of weight, given that weight is not a significant constraint for industrial engines.

5.2.5.2.1 Power Turbine Rotor

Design layout studies have produced a rotor configuration similar to the AE 3007 engine. Major components of the ATS power turbine rotor include a forward shaft, wheels with separate insertable blades, high diameter interstage spacers, and an aft stub shaft. All of the major components will be individually balanced to minimize unbalance moments and assure stability of the shafting. Blade weight variability is assessed, and blade position used to balance the wheels. The assembly will also be balanced in two planes.

The ATS power turbine rotor construction is intended to be rugged and readily assembled. Low diameter bolted flanges using self-retaining bolts will ease assembly and assure piloting consistency. No cross-key joints or curvic couplings are used because they are expensive to produce, prone to wear, and costly to refurbish.

5.2.5.2.1.1 Power Turbine Blades

An extensive evaluation of the ATS blading was undertaken to assure that all blades may remain uncooled while minimizing the attachment loads. Mechanical properties for a number of representative cast blade materials were used in calculations to determine the minimum blade area progression to satisfy life requirements.

The minimum blade area progression determined with each material also defines the lowest attainable attachment load. Aerodynamic evaluation is necessary to assure that the aerodynamic requirements are also met. In some cases, an excessive hub area requirement will not be aerodynamically acceptable and eliminate a material from consideration.

The assumed temperature levels greatly determine the blade area requirements. A worst-case radial temperature profile was assumed that is representative of current engines. If the low emissions combustor being designed for the ATS produces a flat profile as expected, the blade design will be conservative, and have some margin for uprating. The mean temperature assumed in the analysis was taken from interstage aerodynamic data.

Blade failures within the expected engine life are **not** acceptable in the industrial engine market. The life goal was therefore established prior to stress rupture failure. Statistically this analysis produces one blade failure in 741 engines (-3σ set).

Blade shapes are still considered preliminary pending full aerodynamic refinement. A dynamic analysis using the Allison design system was performed on the preliminary shapes to determine if there are any responsive modes that require attention, i.e., changes in mass, stiffness, or vane count. This analysis shows no responsive modes coincident with known sources of excitation in the engine operating range. These sources include up to three engine orders (multiples of rotating speed), plus upstream and downstream vane passage frequencies. A feasible design solution is therefore believed to exist with these blade definitions.

As a final audit of the preliminary blade design, a lifing program, BS01, maintained by the Allison Stress Analysis group was exercised. More optimistic temperature assumptions were used. A relatively flat radial temperature profile was assumed, taken from combustor rig testing of an experimental combustor. The results of this analysis show ample design margin in the current blade area distributions.

5.2.5.2.1.2 Power Turbine Wheels and Blade Attachments

Power turbine wheel shapes were defined using an Allison wheel sizing program known as BD75. Input includes blade and attachment loads, bore and rim diameters, rotational speed, material properties (thermal expansion, elastic modulus), and design allowables for tangential, radial, and equivalent stress in the rim, web, and bore. The design allowables reflect cyclic life goals, wheel integrity, and burst constraints.

Since the engine will employ electronic controls similar to the AE 2100 flight engine, similar rotor speed limits for integrity and burst were used. These limits were established from an analysis of the maximum speed attained in the unlikely event of a sudden loss of load. In the case of a flight engine, a 10% design margin is added to meet certification requirements. Rotor integrity is set at 115% of maximum steady-state speed, and burst is set at 139%.

Forging costs for representative wheel materials were surveyed. Based on this survey, the selected material offers a good combination of corrosion resistance, strength, and machinability. The higher cost materials offer only weight reduction, which is not a primary consideration.

Blade and attachment loads were estimated from the above blade design study. The resulting wheel shapes were evaluated and appear similar. A substantial manufacturing cost savings is possible if the wheel shapes are identical. Only one set of manufacturing tooling and gaging needs to be procured, and setups are common. A common forging may also be procured. For reasons of economy, the wheel shapes were therefore made identical.

The blade attachments have also been investigated. Because of the high cost of developing a new attachment form and associated tooling, existing engines were surveyed. Additional analysis will be undertaken to determine if the reduced blade count in the ATS and a wider wheel lug can provide the needed capacity increase.

Since the interstage spacers' free ring stresses are well below the LCF allowable, they are configured as webless rings, slightly thickened beneath the seals for stability. The spacers are designed to be common to minimize procurement cost.

5.2.5.2.2 Power Turbine Case and Vanes

The power turbine case and vane arrangement essentially duplicates that employed in the AE 2100 and AE 3007 engines. Case thickness is governed by blade containment analysis. Because weight is not a consideration, the case will be made from the least cost form of material, cast or wrought. A new, low-expansion alloy is preferred for minimizing blade tip clearance. Strength, cost, machinability, and corrosion resistance are also attractive.

The ATS power turbine vanes will be cast as integral rings, which has been found to be lower in manufacturing cost than individual segments. The inner vane bands are typically slit by a wire EDM process to break up the hoop continuity and minimize thermal stresses. This technique has been successfully employed in the AE 2100 engine.

Vanes will be coated with a diffused aluminide coating applied using the Allison electrophoretic process (AEP).

5.2.5.2.3 *Rear Turbine Bearing Support (RTBS)*

The RTBS is the rear structural element of the engine, providing support for the power turbine radial bearing and its sump. Airfoil-shaped tangential struts connect the cylindrical inner sump support to the conical inner flow-path ring and the conical outer case wall. The diffusing flow path through the RTBS forms the entrance section of the exhaust diffuser which is attached to the rear outer flange of this part. The RTBS is a one-piece casting. A combination of cast and machined passages transmit oil to and from the sump.

5.2.6 Cooling Circuit Description

The turbine cooling circuit in the ATS engine is patterned after the AE 301X, which is very similar to the AE 2100 currently in production. The first four airfoils are cooled, except in the case of the alternate ceramic vane construction. The gas generator flow path is jacketed by compressor discharge air. The small amount of leakage flow purges these cavities and cools the endwalls or cases. Leakage into the flow path serves to purge the wheel cavities.

In the power turbine a novel approach is being pursued. The third-stage vane is hollow and serves to transmit lower pressure ninth-stage bleed air into the power turbine wheel cavities. A smaller penalty for leakage is paid because of the use of lower pressure air, with less compressor work wasted.

This configuration has been modeled and a preliminary analysis of ATS engine secondary flows has been performed. This analysis assesses cooling and leakage flows throughout the engine based on estimates of flow areas or clearances, and passage geometry. For the ATS engine the seal clearances were conservatively assessed based on actual experience in the T406 and AE 2100 engine programs. This first pass shows areas where further development or refinement are required.

5.2.7 Shafting

5.2.7.1 HP Shafting

The HP shafting design of the ATS engine is nearly identical to the successful AE 2100 engine shafting. The one exception is that the ATS shafting has both bearings running on the same shaft rather than on separate shafts that are bolted together. This will ensure that both bearings are concentric, which will help control HP system vibration. A two-bearing arrangement was selected with the thrust bearing located between the compressor and turbine. In this way, the turbine is overhung, which removes the need for an additional sump and bearing between the HP and LP turbines. This arrangement has worked well on the AE 2100 engines. The dynamic characteristics (critical speeds and response to unbalance), as well as the torque capacity of this HP shafting, will be similar to the AE 2100 and were not studied at this stage of design. These will be studied during the detailed design phase when the squeeze film dampers are defined.

5.2.7.2 LP Shafting

After the aerodynamics were optimized for high efficiency and commonality to the AE 2100, the LP shafting was designed.

The rotordynamics of the LP shafting was analyzed. After several iterations, the rotordynamics analysis defined an acceptable shaft configuration.

Mode shapes of all of these resonances were identified.

In addition to determining the critical frequencies of the LP rotor system, a logdec analysis was performed to determine whether or not the modes below operating speed could be adequately controlled. The optimum damping coefficients were determined and plots of response to unbalance were run with the optimized damping coefficients. As part of Phase III, the shaft will be rig tested to verify all analytical predictions and to empirically optimize the damping and stiffness of the bearing supports.

5.2.8 Bearings and Thrust Load

Anti-friction type bearings were selected for the ATS engine primarily because of the limited space available for the front HP compressor bearing, and secondarily because of Allison's extensive experience using anti-friction bearings.

5.2.8.1 Rotor Thrust Optimization and Seal Selection

In order to calculate bearing life, the HP and LP rotor thrust loads needed to be determined. A secondary flow model adapted from the AE 301X was used to accomplish this. Thrust balance seals were incorporated and sized to ensure that no thrust load crossovers occur on either rotor in the engine. A face seal was added aft of the last LP turbine wheel to form a balance cavity.

5.2.8.2 LP Rotor Bearings

The ATS engine will use only three bearings with the rotor thrust bearing being located in the intermediate sump between the LP compressor and the LP turbine. This thrust bearing was analyzed to determine its fatigue life. Resizing the rear thrust balance seal reduced the expected thrust load and allowed a split inner ring ball bearing to be used.

The front and rear LP roller bearings are designed to be the same part number. The analysis of these bearings will be done during the detail design phase.

5.2.8.3 HP Rotor Bearings

For the HP system, a bearing arrangement similar to the AE 2100 and T406 engines was selected; namely, a two bearing system in which the thrust bearing is located in front of the overhung turbine. This configuration eliminates the complexity of an additional sump between the HP turbine and LP turbine. Once again, the thrust bearing was analyzed to determine its fatigue life.

5.2.9 Engine Sumps

The ATS-5 engine has four sumps, each of which will be discussed in detail in this section of this report. Efforts have been made to simplify these sumps as compared to those in other aero-derivative industrial engines. These sumps were also modularized as much as possible to facilitate assembly and pressure testing. Wherever possible parts will be commonized within and between sumps.

5.2.9.1 Front Sump

The front sump contains the LP compressor/output shaft radial bearing. Pressure oil is fed through a cored/machined hole in another strut to an O-ring sealed annular gallery around the outer diameter of the sump housing. A series of machined passages in the sump housing and a separate nozzle feed the oil to the required locations for bearing lubrication and seal runner cooling. Two identical carbon face seal assemblies will be used at the front and rear of this sump. In the unlikely event of a seal or bearing failure, the front sump module can be removed, repaired, and reinstalled with no other engine disassembly.

5.2.9.2 Intermediate Sump

The intermediate sump is located in the main support structure between the LP and HP compressors. This sump contains the LP compressor rotor thrust bearing, the HP compressor front radial bearing, and the starter geartrain. This sump is comprised of two housings and the intermediate support. The forward housing, which bolts into the front of the intermediate support, contains the LP rotor thrust bearing, the forward sump seal, and the starter driven bevel gearset. By placing the bearings for both gears in the forward housing these gears can be set prior to installation of this component in the intermediate support. The aft housing, which bolts into the rear of the intermediate support, contains the front HP compressor radial bearing and the rear sump seal. Carbon face type seals are used in both locations in this sump. The stationary components of both seals are identical, but each seal requires a unique runner.

Lubricating oil is supplied to this sump through a passage in an intermediate support strut to an annular gallery around the forward housing. A series of cross-drilled passages in the housing feeds a nozzle that lubricates the LP rotor thrust bearing and cools the front seal runner. One of these passages also transfers oil to the aft housing. Passages in this housing direct oil to the starter geartrain bearings and spline, the HP compressor front bearing, and the rear seal runner. Oil is scavenged through the bottom strut in the intermediate support. Pressure testing of this sump can be accomplished after the forward and aft modules are assembled in the intermediate support.

5.2.9.3 Center Sump

The primary purpose of this sump is to support the HP rotor thrust bearing. As with the other sumps in the engine, this sump is sealed by two carbon face seals. The stationary portions of these seals are identical and are common to those used in the front and rear sumps. However, unique runners are required for each seal.

Lubricating oil is supplied to this sump by a tube passing through a strut in the diffuser and attached to the front of the center sump housing. Oil is scavenged through a similar tube through the strut at the bottom of the diffuser. By virtue of its one-piece housing and inner sleeve, this sump, like the front sump, can be assembled and pressure tested as a module.

5.2.9.4 Rear Sump

The rear sump houses the rear LP turbine radial bearing. The carbon face seal at the front of this sump is identical to those used in the front sump. The rear of this sump is sealed by the rear sump cover.

As in the other sumps in the engine, lubricating oil is delivered to the sump through the supporting structure, in this case the RTBS. A separate tube is used to transfer the oil from the rear inner face of the RTBS to the rear of the sump housing. Cross-drilled holes and a separate nozzle feed the oil to the required locations to lubricate the bearing and cool the seal runner. The scavenging of this sump is accomplished in a similar manner through the bottom strut in the RTBS.

5.2.10 Engine Mounts

5.2.10.1 Front Engine Mount

The front engine mount is located on the front face of the radial inlet. This primary engine mount uses a bolt circle and pilot diameter to mount the engine directly to the reduction gearbox or to a mount ring. This design will simplify installation and alignment of the engine in the skid, as compared to a conventional trunnion-style mounting system. The front engine mount reacts all axial and lateral loads. Part of the vertical load is reacted at the front mount; however, most of the vertical load is reacted at the rear mount since it is nearly in line with the engine center of gravity.

5.2.10.2 Rear Engine Mount

The rear engine mount system uses two side mount pads, one on either side of the outer combustion case at the engine horizontal centerline. Links with ball joints connect the engine to the skid bedplate.

5.2.11 Controls System

For the ATS Program, Allison has drawn on its extensive experience with gas turbine engine control system technology. Allison will utilize the technology base developed for industrial full authority digital electronic controls (FADEC) like those used with the 501-K family of industrial engines. These sophisticated tools, coupled with applicable test and field experience, will assist Allison in achieving the highest level of performance on the ATS.

The conceptual design study has established that the main component of this system will be a 32-bit microprocessor-based digital control. The digital control can be easily adapted for use on all engine system applications for all types of fuel systems and combustor configurations. Complex control algorithms and sequencing logic, as is required for staged low emission combustor control, can be readily incorporated in the digital control. The use of a digital control allows field adjustments, algorithm, and logic changes to be made within software, thus minimizing potential engine downtime. By using an approach that is based on extensive software and hardware testing in addition to Allison's digital control experience with a variety of engines, the best possible engine control system will be provided. The candidate control provided by Allison will have the following features:

- high degree of reliability, maintainability, and supportability
- not easily affected by noise, temperature, or electromagnetic interference
- configurable with universal high level programming language
- hardware data protection, which will eliminate the possibility of accidental software and/or data corruption
- convenient adjustment of engine schedules to accommodate fuel with a wide range of lower heating values
- all safety-related functions and environmental considerations required for the protection of the engine and other equipment
- engine and control system diagnostic capabilities
- user-friendly operator interface to communicate engine parameters and engine alarm/shutdown status without interrupting engine operation
- ability to monitor vital engine sensors and other components
- the ability to monitor engine parameters, check engine and control fault history, and make control adjustments remotely via a modem connection
- control system protection through use of a "watchdog" timer
- simple adjustability of control parameters, such as governor gains and engine setpoints, without interrupting engine operation
- fault log storage area in nonvolatile memory to allow for investigations of shutdowns and engine history
- data logging capability to record transient data

These features will ensure consistent engine performance, provide maximum equipment compatibility and availability, and minimize downtime for control adjustments or fault investigation, if required.

5.3. ATS SYSTEM

This section of the Task 6 Topical Report covers the enclosure and driven equipment for the ATS engine as well as the balance of plant equipment.

5.3.1 Skid

The baseplate for the gas turbine, gearbox, and generator is fabricated from I-beam structural steel. The baseplate will be free of any system natural frequencies within the operating speed ranges of the rotating equipment.

All external welds are continuous seam welds. The baseplate is stress relieved after welding. The mounting surfaces for the engine, gearbox, and generator are machined flat and parallel during a single set-up machining operation to provide accurate machinery alignment.

The lifting points are located approximately equidistant from the center of gravity.

5.3.1.1 Enclosure

The enclosure (Figure 5.3-1) is an all-bolted assembly, which includes standard corners, posts, sills, roof and wall sections, and doors. Exterior surfaces are galvanized steel and painted. Doors and wall sections are filled with fiberglass, fire-retardant insulation, and will include corrosion-resistant, perforated metal inside covering. Access doors include stainless steel hinges and a key lock latch.

The enclosure insulation provides sound attenuation. In addition, the engine air inlet and exhaust ducts will be externally lagged by the contractor. The resultant noise guarantee is 90 dBA near field at one meter from the genset enclosure, and 60 dBA far field (122 meters).

The engine air inlet system includes a self-cleaning canister air filter, an inlet silencer with stainless steel internals, ductwork, expansion joint, and a stainless steel air inlet plenum. Differential pressure gages measure the pressure drop across the filter, and the indicator is located inside the enclosure.

The engine exhaust system includes a stainless steel diffuser and transition assembly, which directs the exhaust from a horizontal input to a vertical outlet. A bellows-type expansion joint connects the exhaust transition to an expansion joint. The engine tailpipe connects to the diffuser by a slip joint, to allow for engine expansion.

Cooling and ventilating air for the generator and engine is drawn through a self-cleaning air filter by two roof-mounted ventilation fans. The air is drawn into both ends of the generator by shaft-mounted fans. After cooling the generator windings, the air exits through the bottom of the generator and is then ducted to the engine compartment. It exits to the outside via a roof-mounted silencer and discharge hood.

5.3.1.2 Starter

The starter will be mounted vertically on the top of the engine driving through an overrunning clutch. The customer's control room would house a variable frequency inverter, which converts a constant-frequency electrical input to a variable power, variable frequency output. The inverter includes input line filters. The starting motor is cooled by forced air flow.

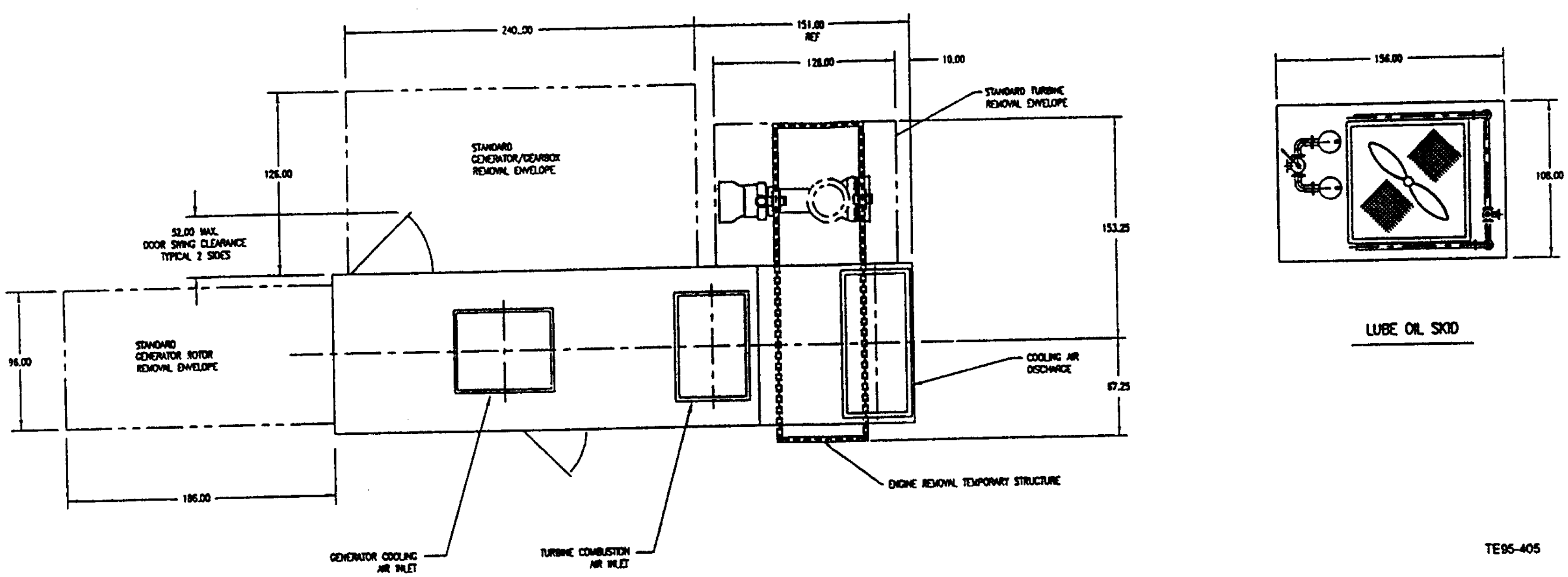

Figure 5.3-1. Plan view of the gas generator enclosure showing removal clearances.

5.3.1.3 Generator and Gearbox

The electric generator will be an Ideal Electric type "SAB" 4-pole synchronous machine, which will meet or exceed NEMA standard MG-1, part 22. The generator includes brushless exciter and permanent magnet alternator. The generator features an integral pole laminated rotor, developed by Ideal. The field poles and spider are punched as one piece, providing a very durable and reliable system. The rotor is supported by sleeve bearings at both ends, which are force feed lubricated. The rotor is balanced per NEMA standards, and is capable of 125% overspeed for 1 minute without damage. The bearings and the stator include temperature detectors.

The generator will be capable of operating at rated kVA and temperature rise at an altitude of 3300 ft, and can withstand a short circuit current of 300% for 10 sec.

The speed reduction gearbox will be a lightweight, compact, high efficiency star epicyclic machine. The gear rating is per AGMA 421.06 SF 1.1, and is rated for an input power of 19,679 shp (14,680 kW) at 10,836 rpm, with an output speed of 1800 rpm. The efficiency is 98.5 % at rated conditions.

The gearbox will be directly mounted onto the generator end frame. The gear includes a rotating annulus coupling, which directly connects to the generator shaft end. A separate low speed coupling is eliminated.

The gearbox is of the double helical star (fixed carrier) type. A central sunwheel meshes with the planetary wheels, which in turn mesh with two annuli with opposite handed helices. The annulus assembly is connected to the coupling flange by a double element toothed ring. The combination of the flexibly coupled sun wheel and the limited radial flexibility of the annuli assure equal loading at all meshes.

The gearbox requires 435 L/min (115 gpm) of synthetic lube oil at 207 kPaG (30 psig) delivery pressure.

5.3.1.4 Electrical System

The powerplant electrical design is based on a stand-alone plant with a single-point 15 kV tie to the new 15 kV switchgear, and then to the host utility. Islanding capability is not currently included — the system proposed will allow the powerplant to supply its own power, and export the rest while running in parallel with the utility.

The 15 kV switchgear will include 5 cells rated for 1200 amp, 500 mVA, and 95 kV BIL bus; a 1200 amp plant tie breaker (52-GT); and two (2) 400 amp fused manual disconnects. The breaker cells will contain current transformers, withdrawable fused secondary potential transformers, and utility-supplied potential and current transformers. The breaker would be used to protect, isolate, and synchronize the gas turbine generator (GTG) unit to the powerplant 15 kV bus. The current transformers would be used for protective relaying for the GTG generator zone and for unit metering. The potential transformers will be used for metering, protective relaying, and synchronizing, in addition to input to the unit's AVR.

An isolation transformer (TG) provides isolation for the powerplant equipment. This will be an oil-filled, 13,800 V/13,800 V, delta/delta, 11 mVA/14.666 mVA, onan/onan unit. It will include cooling fans with temperature gages and alarms. Thus equipped, the transformer will be capable of carrying the entire GTG output.

An oil-filled, 13,800/480 V station transformer will also be used to handle the entire 480 V load of the powerplant. This will be a delta/Y grounded unit rated for 1000 kVA. This transformer will directly feed the plant's 480 V motor control centers.

The 480 V motor control centers (MCCs) will contain all the starters for all the individual GTG 480 volt motors, the 24 Vdc battery charger, the batteries and distribution system, the plant 48 Vdc protective relay and plant switchgear battery charger, batteries and distribution system, the unit's 480/120 V transformer, the unit's 120-208 V process distribution board, the GTG starting motor variable frequency control starter, and auxiliary control relays.

It is noteworthy that all MCC breakers and disconnects are lockable in the open position and that all size 0, 1, and 2 motor starters are withdrawable to provide safety and visible isolation.

The GTG unit control panel and electrical protective relay panel will be located in the powerplant control room. These panels include the digital GTG control panel, and electrical protection relay panel, and the powerplant utility electrical protection relay panel. The digital GTG control panel will monitor and control the entire GTG skid, including engine starting, operating and stopping, plus all skid auxiliaries, such as the fuel system, lube oil system, fire protection system, vibration monitoring system, skid ventilation and engine water wash systems, etc. The control is based upon an Allison-furnished digital engine control unit, which ties into a USTC-furnished Allen Bradley interface unit, and includes meters, indicators and switches mounted into a dedicated control panel. All operator controls and actions for the individual skid are initiated from this panel.

In addition, the panel will also control the natural gas booster compressor, the instrument air system, and building auxiliaries, such as ventilation, fire alarms, electrical systems and powerplant interface metering.

The entire powerplant will be designed to be operated by one person. The gas turbine control system will provide warnings and shutdowns to the main control panel when potentially hazardous GTG conditions develop (overtemperature, overspeed, excessive vibration, etc). Suitable monitoring for all other plant equipment will also be provided. Local instrumentation will be provided to provide status indications as required by code, to provide a safe, efficient, readily operable powerplant.

5.3.1.5 Fuel System and Gas Compressor

All fuel control and metering valves and the 3 micron filter are skid mounted for ease of access when servicing is required.

A natural gas boost compressor is required to support the Allison ATS because of the high pressure ratio at which the engine operates. This boost compressor, located outside the engine enclosure, will raise the natural gas supply pressure. For this conceptual design study the gas compressor selected was sized for full power operation at ambient temperatures from -7°C to 38°C (20°F to 100°F). A slightly larger unit may be required in certain geographic locations if full power is needed at lower ambient temperatures.

5.3.1.6 Lubrication System

The ATS utilizes a common lube system for the gas turbine engine, starting system, reduction gearbox, and the generator. The reservoir contains an immersion heater, temperature sensor, level gage, and level switch.

Oil is drawn from the reservoir by a gearbox-mounted, shaft-driven pump and circulated through a fin-fan type air to oil heat exchanger and a duplex filter. A thermostatic valve bypasses oil around the cooler to maintain an oil supply temperature of 49°C (120°F). The oil pressure is regulated to 172 kPa (25 psi) to supply the gearbox and generator. A separate AC motor-driven multielement pump is used to supply oil to and scavenge oil from the engine. This pump has one pressure element and four scavenge elements, one for each of the engine's sumps. Pressure gages, switches, and magnetic plugs are provided to monitor the system. In the event of abnormal conditions, one of the safety devices will either trip an alarm or effect a shutdown. A separate AC motor driven pre/post-lube pump is also provided to supply oil to the gearbox and generator during start up and coast down.

In the past Allison's aero derivative industrial engines have used accessory gearbox driven oil pumps and engine mounted filters, pressure control valves, and pressure regulating valves. These components, specifically designed for flight engine environments and requirements, are generally more expensive than comparable commercially available components. In the case of the ATS engine, Allison plans to specify the requirements for these components to the packager who will select, procure, and mount them in the skid. There is no need for an accessory gearbox on this engine since electric motor-driven pumps are to be used in the lube system.

The lube system also provides the working fluid, at the required pressure, for the compressor variable geometry actuating systems.

5.3.1.7 Safety

The fire suppression will be a CO_2 automatic discharge system to protect the GTG enclosure. Actuation may come from any of four thermal sensors, or either of two manual pull switches, or either of two ultraviolet flame detectors.

When activated, the fire suppression system will shut down the engine. Also, all enclosure openings and vent fans will be closed and shut off, respectively, in order to keep the CO_2 concentration to at least 30% by volume within the GTG enclosure.

The thermal sensors will be rate compensated, compact, hermetically sealed devices, with stainless steel sensing elements. The temperature setting is factory set and tamper-proof. The sensors will close an electric circuit when the enclosure air temperature reaches a pre-set level, or when the temperature rises above a pre-set rate (typically 15°F per minute). The detectors will be FM or UL approved.

The CO_2 cylinders are located adjacent to the GTG skid and are furnished by the Purchaser.

The control unit for the fire suppression system will be located in the GTG control cabinet. When actuated, the system will provide power for extinguisher operation, set off audible and visible alarms, shut down the engine and vent fans, and close the enclosure vents.

5.3.2 Reliability, Availability, and Maintainability (RAM)

5.3.2.1 System Reliability

5.3.2.1.1 Skid and Balance of Plant

Reliability has been taken into account during the design of the ATS powerplant package. For example, the air inlet system will be constructed of stainless steel, rather than painted carbon steel, because this increases durability and does not require repainting or other maintenance. Similarly, the engine starter is a simple AC electric motor, thus avoiding the problems of a hydraulic system such as leaks and foreign object damage. The many components of a hydraulic system are gone, thus improving reliability. Also, the electric generator will include conservatively designed bearings, which keep bearing loads and speeds low, in addition to the "integral pole" rotor design, which has proven to be very rugged and reliable. Experience in gas turbine packaging has provided Allison's packagers with much knowledge in the design of reliable systems and the selection of reliable equipment. The reliability of the ATS package should be equal to or better than that of previous Allison-powered systems.

5.3.2.1.2 Engine

Allison's objective with regard to reliability is to design the ATS engine not only to meet but to exceed existing reliability figures for Allison industrial engines. This will be accomplished by taking a conservative design approach in the compressor section and mechanical components areas of the engine. The simplified lubrication system and the elimination of the accessory gearbox, typically found on aero-derivative industrial engines, are examples of reduced complexity areas that will lead to improved reliability.

5.3.2.2 System Availability

System availability percentages are accepted indicators of reliability. The current market expectation for industrial gas turbine skids is 97% availability exclusive of scheduled downtime. Allison's current systems meet or exceed this availability. Although it is realized that this is a high percentage, it is felt that the simplified designs and use of existing proven components in certain areas of Allison's ATS will result in a system availability exceeding 98%.

5.3.2.3 System Maintainability

5.3.2.3.1 Skid and Balance of Plant

While reliability and availability go hand-in-hand, maintainability does not. Equipment may be very reliable and offer good availability, yet it may be hard to service when maintenance is required. The electric starter motor may be easily removed and replaced when required, while its variable frequency controls are located in an easily accessible cabinet in the control room. As another example, the speed reduction gearbox offers complete replacement of the main rotating elements through the side of the GTG enclosure. In general, the ATS package is designed to facilitate maintenance. Common maintenance items like fuel or lube oil filters will permit easy replacement and normally include differential pressure gages to indicate when maintenance is required. Lube oil pumps and coolers are selected with the best materials for the intended service and are always mounted for ready maintenance. Skid piping, valves, instrumentation and fittings are arranged in logical order, and are positioned for ready maintenance. The skid will include overhead cranes suitable for complete engine removal. The engine or gearbox "gearset" may be removed from the enclosure through removable doors and mounting posts. The maintainability of the ATS package will be as good as, if not better than, that of previous USTC genset units.

5.3.2.3.2 Engine

Allison's objective is to design the ATS engine to make field maintenance as easy as possible while requiring a minimum amount of downtime. This will be accomplished by incorporating a modular design that will allow easy access to major components and subsystems, thereby facilitating repair and/or replacement in the field. For example, the orientation of the silo combustion system is such that the liner components can be changed without major disassembly of the engine. Removal of the dome and the outer case allows access to these parts. The LP compressor and the power turbine will be removable as modules. After removal of the power turbine, it will even be possible to service HP turbine components. The ATS design will also allow easy access to thermocouples and fuel premix modules as well as to the skid mounted fuel and lube system components. It is also intended that multiple borescope access ports and lube system magnetic chip detectors in each sump's scavenge line will be incorporated to aid in troubleshooting and problem isolation.

6.0 CONCLUSIONS

Allison has completed conceptual design of an ATS that meets all requirements of the ATS program including high efficiency, low emissions, cost of electricity, and RAM levels comparable with today's systems. Allison has selected technologies for ATS that achieve breakthroughs in industrial engine firing temperature and emissions, yet are realizable to a schedule compatible with a year 2000 market introduction.

The GFATS design is based on turbine technology demonstrated under Task 8 of this program and combustion technology whose primary elements have been rig demonstrated as being realizable in the required timeframe. The Allison engine design concentrates technology on only those components where high payoff is available: the low emission combustor and high firing temperature turbine. The compression system is proven T406/AE 2100 existing aerodynamics with a boost compressor derived from a very successful unit demonstrated for flight engines.

The turbine engine is designed for ease of packaging as an industrial system for both electrical power and cogeneration applications. The end users, packagers, and overhaul facilities will not perceive this product to be different from current industrial gas turbine systems. The engine looks the same and acts the same right down to exhaust temperature levels, which do not require upgraded HRSG equipment in cogeneration applications. No new external support equipment such as water sources or heat exchangers are needed. The ATS provides significantly improved efficiency, power output, and emissions in the same size package as today's small industrial engines.

Allison has conceptually designed a competitive GFATS. Allison is committed to demonstration of this technology within the ATS program master schedule.

7.0 ACRONYM LIST

AEP	Allison electrophoretic process
AGMA	American Gear Manufacturers Association
ATS	Advanced Turbine System
AVR	
Btu	British thermal unit
CO	carbon monoxide
CVG	compressor variable geometry
dBA	adjusted decibel
DOE	Department of Energy
DS	directionally-solidified
EDM	electrodischarge machining
ESA	Electro-Spark Alloy
FADEC	full authority digital electronic control
FRFS	film-riding face seal
GFATS	Gas Fired Advanced Turbine System
GPM	gallons per minute
GTG	gas turbine generator
HCF	high cycle fatigue
HP	high pressure
hp	horsepower
HRSG	heat recovery steam generator
J	joule
kg	kilogram
kVA	kilovolt-ampere
kW	kilowatt
L/min	liters per minute
LCF	low cycle fatigue
LP	low pressure
LVDT	linear variable differential transducer
MCC	motor control center
METC	Morgantown Energy and Technology Center
MJ	megajoule
mVA	millivolt-ampere
MW	megawatt
N	newton
NOx	nitrogen oxide
O.D.	outer diameter
PVD	physical vapor deposited
RAM	reliability, availability, and maintainability
Rc	pressure ratio
RIT	rotor inlet temperature
rpm	revolutions per minute
RTSB	rear turbine bearing support
SOW	statement of work
TBC	thermal barrier coated
TG	isolation transformer
UHC	unburned hydrocarbons
USTC	U.S. Turbine Corporation
Vdc	volts direct current

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