Advanced Turbine Systems Program

Topical Report

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By
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at

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TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
I	Summary.....	1-1
II	Introduction.....	2-1
III	Advanced Turbine System/Cycle Configuration	3-1
	3.1 Choice of Engine Cycle	3-1
	3.2 Single Versus Two-Spool Engine Considerations	3-2
	3.3 Performance of Selected ATS Systems.....	3-3
IV	Advanced Materials and Advanced Cooling Technology to Achieve ATS High Efficiency.....	4-1
	4.1 Single Crystal Materials Description.....	4-1
	4.2 Processing.....	4-4
	4.3 Strength	4-7
	4.4 Oxidation/Corrosion.....	4-7
	4.4.1 Oxidation	4-7
	4.4.2 Corrosion	4-9
	4.5 Advanced Aero Engine Turbine Cooling Technologies.....	4-9
	4.6 Ceramic Technology	4-12
V	Turbine Design	5-1
	5.1 Turbine Aerodynamic Design.....	5-1
	5.2 Thermal Control System.....	5-2
VI	Cooling and Materials Technology To Improve Thermal Efficiency	6-1
	6.1 Analytical Method	6-1
	6.2 Turbine Cooling Configurations.....	6-2
	6.3 Turbine Cooling Studies	602
	6.3.1 Assumptions	602
	6.3.2 Airfoil Parametric Studies.....	603
VII	Advanced Turbine System Performance Results.....	7-1
	7.1 Airfoil Surface Temperature—Metal and Ceramic Turbines	7-1
	7.2 Current Technology Versus Advanced Technology Castcool	7-2
	7.3 Wall Thickness Effects	7-4
	7.4 Liquid Cooling Alternatives	7-4
	7.4.1 Liquid Impingement Turbine Vane Cooled Vane	7-4
	7.4.2 Injection Cooling of Compressor Discharge Air.....	7-5
	7.5	7-5
VIII	Emissions	
	8.1 Parametric Evaluation of Premixed Combustion Concept.....	8-1
	8.2 Premixed Combustor Design Approach.....	8-5

TABLE OF CONTENTS (cont)

<u>Section</u>	<u>Title</u>	<u>Page</u>
XI	Cost and RAM Estimate Process	9-1
X	Market Potential and Commercialization Plan	10-1
	10.1 Assessment of the Potential Market	10-1
	10.2 Power Generation Market	10-1
	10.3 Factors Influencing Industrial Gas Turbine System Commercialization	10-1
XI	Coal-Fueled Reference System	11-1
	11.1 Performance of Coal-Fueled Reference System	11-1
	11.2 Modification of ATS for Coal-Fueled Operation	11-3
	11.3 Description of the Allison Rich-Quench-Lean Coal Combustion System	11-5
XII	Program Recommendations for Phase II	12-1
	12.1 Summary of Phase II Program	12-1
	12.2 Summary of Phase II Program	12-2
	12.3 Summary of Phase II Program	12-4
	12.4 Summary of Phase II Program	12-6
	12.5 Summary of Phase II Program	12-8
	12.6 Summary of Phase II Program	12-9
	12.7 Summary of Phase II Program	12-10

LIST OF FIGURES

Figure	Title	Page
3-1	Parametric study of utility size gas turbine Brayton cycles	3-1
4-1	Chemical etching reveals the grain structure of conventional equiaxed, directionally solidified, and single crystal turbine blades for the	4-2
4-2	These conventional single crystal airfoils, typical of advanced engine airfoils, were used to test	4-5
4-3		4-6
4-4	All effort associated with process development for casting or bonding transpiration-cooled components was funded by Allison's existing IR&D programs.....	4-6
4-5	Sample turbine vane in Castcool configuration with cutaway showing cooling passages cast into the blade skin	4-7
4-5	 showed superior stress rupture properties over equiaxed alloys and	4-8
4-6	 single crystal alloys	4-8
4-6	 curves for	4-8
4-7	 shows the average material diameter loss at	4-8
4-7	 the incremental improvement in	4-8
4-7	 is clearly shown by the top,	4-8
4-7	 °F corrosion pin appearance after	4-10
4-8	 hours of	4-10
4-8	Average penetration on	4-10
4-9	hours of	4-11
4-9	Advanced turbine cooling technology trends	4-11
5-1	ATS aerodynamic flow path for the ceramic and metallic baseline cycles	5-1
5-2	Advanced	5-3
6-1	 maximum temperatures for the metallic turbine baseline design (i	6-3
6-2	 maximum temperatures for the ceramic turbine baseline design (includes	6-4
6-3	Effect of airfoil surface temperature on turbine cooling requirements	6-4
6-4	Effect of airfoil	6-6
6-5	Effect of airfoil	6-6
7-1	Effect of	7-2
7-2	Effect of	7-3
8-1	Arrangement of reactors in	8-2
8-2	 kinetic model AGT100 premixing combustor data	8-3
8-3	Predicted emissions for ATS	8-4
8-4	Predicted emissions for ATS	8-4
11-1	ATS	11-4
11-2	 system cross section.....	11-4

LIST OF FIGURES (cont)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
11-3	External Combustor turbine entry duct.....	11-6
11-4	Photo 1. Cooled wall flow of air vents in combustor.....	11-7
11-5	Photo 2. Cooled wall flow of air vents in combustor.....	11-7
11-6	Photo 3. Cooled wall flow of air vents in combustor.....	11-7
11-7	Photo 4. Cooled wall flow of air vents in combustor.....	11-7
11-8	Photo 5. Cooled wall flow of air vents in combustor.....	11-7
11-9	Photo 6. Cooled wall flow of air vents in combustor.....	11-7
11-10	Photo 7. Cooled wall flow of air vents in combustor.....	11-7

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
3-I	ATS system performance.....	3-4
4-I	Alloy selection rationale	4-3
4-II	Composition and physical properties of single crystal alloys	4-4
4-III	Material goals and accomplishments	4-5
5-I	ATS design point aerodynamic requirements	5-1
5-II	ATS design point velocity diagram parameters	5-2
7-I	Effect on simple cycle thermal efficiency of identified technologies	7-1
7-II	Effect of utilizing current forced-convection cooling technology on system performance	7-3
7-III	Effect on performance of utilizing castings in turbine	7-4
7-IV	Effect on performance of second vane	7-6
7-V	ATS design summary	7-6
9-I	Economic assumptions	9-2
11-I	Metallic turbine ATS performance.....	11-2
11-II	ATS design point requirements	11-3
11-III	ATS design point parameters	11-4

I. SUMMARY

The Allison Gas Turbine Division (Allison) of General Motors Corporation conducted the Advanced Turbine Systems (ATS) program feasibility study (Phase I) in accordance with the Morgantown Energy Technology Center's (METC's) contract DE-AC21-86MC23165 A028.

This feasibility study was to define and describe a natural gas-fired reference system which would meet the objective of $\geq 60\%$ overall efficiency, produce nitrogen oxides (NO_x) emissions 10% less than the state-of-the-art without post combustion controls, and cost of electricity of the N^{th} system to be approximately 10% below that of the current systems. In addition, the selected natural gas-fired reference system was expected to be adaptable to coal.

The Allison proposed reference system feasibility study incorporated Allison's long-term experience from advanced aerospace and military technology programs. This experience base is pertinent and crucial to the success of the ATS program. The existing aeroderivative technology base includes high temperature hot section design capability, single crystal technology, advanced cooling techniques, high temperature ceramics, ultrahigh efficiency turbomachinery components design, advanced cycles, and sophisticated computer codes.

We at Allison conducted preliminary conceptual evaluations of four different cycles; (1) the intercooled recuperative cycle, (2) the modified humid air turbine cycle, (3) the thermochemical recuperation cycle, and (4) a combined cycle. Allison's preliminary selection for this study consisted of a conventional combined cycle system. In this feasibility study Allison proposed a system with which the utility industry is currently very familiar and a configuration which would minimize any reluctance to its use by potential customers.

The reference system presented in Sections III and VII of this feasibility study consists of a conventional combined cycle system with an advanced gas turbine and state-of-the-art bottoming cycle. The gas turbine is sized for a nominal 140MW utility power generation application. Two different versions of the gas turbine were evaluated; a metallic gas turbine cycle and a ceramic gas turbine cycle. The metallic gas turbine would operate at a $^{\circ}\text{F}$ turbine inlet temperature and the ceramic gas turbine would operate at $^{\circ}\text{F}$ turbine inlet temperature. Both systems met the Phase I performance goal of $\geq 60\%$ overall efficiency. Emissions predictions as shown in Section VIII also meet the program objective. The operating and capital cost estimates presented in Section IX are preliminary, however, these also demonstrate the potential for meeting the cost objectives of the program.

Allison is committed to participating in the ATS program through the commercial deployment phase. Allison's industrial gas turbine business strategy promotes continuous assimilation of critical aerospace technology into gas turbines for power generation and cogeneration. The overall goals of the ATS program are consistent with Allison's industrial business strategy and would enable us to make revolutionary improvements in current industrial gas turbines. Just how the Allison business strategy for industrial gas turbines works is illustrated in Section X of this report. Market potential of ATS and a viable commercialization plan are briefly discussed in this section. Allison has identified some of the factors which would influence the commercialization of advanced industrial gas turbine systems.

Section XI presents a preliminary assessment of a coal fueled reference system which would be compatible with the natural gas-fired system. A brief description of proposed modifications to the gas-based system is also provided. It is Allison's opinion that the coal fueled reference system would require minimum configuration changes, and would meet the power and emissions goals.

Allison believes in the value of team participation in the ATS program. To meet this objective, Allison plans to team with a utility turbine manufacturer during Phases II through IV of the ATS program. Allison's advanced technology would be applied to industrial as well as large utility gas turbines to meet the program goals. The scalability of advanced technology features will be considered wherever possible to minimize the overall program costs. With this team arrangement in mind, Allison developed preliminary recommendations for the advanced technology projects to be demonstrated during Phases II through IV. These plans are outlined in Section XII. Included here are estimates of schedules and costs of mainly the Phase II conceptual design of the reference system and technology development projects. At this point, it would not be meaningful to provide any estimates on the individual phases of the remaining program (Phases III and IV).

Based on Allison's experience with the development of advanced military engines, it is Allison's estimate that the total program for an industrial ATS system from technology development to full-scale demonstration would cost approximately _____ million. Extrapolating the technology to large (140+ MW) utility turbines, Allison's estimate for combined industrial and utility turbine development program would be approximately _____ million. If the industrial and utility turbine programs are combined in technology development and demonstration phases, the total cost of the two programs would decrease substantially. Thus it is Allison's objective to conduct the two programs with scalable technology demonstrations with a utility turbine manufacturer and reduce the overall cost of a combined program.

Allison is confident that METC's ATS program's challenging goals of high efficiency, low cost, and cleaner environment can be achieved through the use of the advanced cycle concepts presented in this document.

II. INTRODUCTION

This is the topical final report on Phase I of the U.S. Department of Energy (DOE), Morgantown Energy Technology Center's Advanced Turbine Systems program. The Allison Gas Turbine Division of General Motors (Allison) initiated system scoping and feasibility studies as part of a contract modification to an existing contract under Contract No. DE-AC

This final report contains performance analysis of the advanced combined cycle systems to meet the DOE specified performance objectives of thermal efficiency of 60% or higher and low NO_x emissions. The analysis was based on a 140MW (nominal) utility combustion turbine with a conventional bottoming cycle.

In accordance with the goals of the DOE program, improvements in the gas turbine were the primary focus of Allison's activity during Phase I. Two types of advanced combined cycle systems were selected for the analysis. These are the proposed baseline systems. The first proposed system incorporates a high pressure ratio, single-shaft metallic turbine, with a rotor inlet temperature of F . The hot section utilizes single crystal and Castcool®* airfoils. The second system is also a high pressure ratio, single-shaft machine. This one however, contains a ceramic turbine with a rotor inlet temperature of F , and uses ceramic airfoils in and .

It is important to point out that advanced materials and advanced cooling technology are essential to meet the high efficiency objectives of the advanced turbine systems program. These two key technologies form the basis of the Allison selected cycle for the advanced combined cycle system program which is described in this document. Sufficient details on the application of these two important technologies are provided in various sections of the document.

Allison plans to team with a large utility turbine supplier during Phase II. It is Allison's intent to work jointly on advanced turbine systems in which most of the critical technology could be scalable between industrial and utility turbines. Allison is considering to utilize the advanced combustor technology of the utility turbine partner in this program. This arrangement would allow the team to generate concurrent designs and hardware for advanced utility and industrial turbines. During Phase II, some of the critical technology and components will be demonstrated in industrial sizes in order to keep the overall cost down without compromising on program objectives. Demonstration of ceramic airfoils and single crystal/Castcool airfoils however, would be done by using utility turbine size components. When industrial turbine size components are demonstrated, the program intent will be so that results could be scalable to a utility turbine. For industrial turbines, the objective would be to achieve an efficiency improvement of 15% greater than the 1991 vintage efficiency of industrial turbines as specified in the program objectives.

This feasibility study has identified a clear need for the development and evaluation of advanced technologies which are critical and necessary to enable the advanced combined cycle systems meet the ATS objectives. Allison proposes the following critical technology/components for further evaluation during Phase II, through design, development, fabrication, and testing.

* Castcool is a registered trademark of General Motors Corporation.

A brief description of these critical technology/components is presented in Section XII of this report. Also presented in Section XII are tentative schedules and rough order of magnitude costs for each of these recommended programs.

Allison conducted preliminary conceptual evaluations of other cycles, such as thermochemical recuperation as an alternate, to determine its merit in ATS applications. At this point, however, only a conceptual discussion of these alternate cycles is included in this report.

The Phase I Contract authorizes Allison to conduct system scoping and feasibility studies for the ATS project. Four specific tasks are delineated for Phase I. These are:

1. Selection of a natural gas-fired reference system
2. Description of natural gas-fired reference system
3. Conversion to a coal fueled reference system
4. Reporting.

Allison has completed the selection of a reference system in accordance with Task 1 above, which includes reference system cycle characteristics, a generic description of emissions characteristics, preliminary indication of capital and operating costs, and RAM. A description of the reference system and its projected performance characteristics are presented in Section III. The ATS performance results are presented in Section VII. Emissions are defined parametrically in Section VIII. Operating and capital costs and RAM discussion are outlined in Section IX. A commercialization plan and identification of potential market opportunities for the ATS in the industrial market sector is presented in Section X. Conversion to coal-fueled reference system is presented in Section XI. A best estimate of development needs and critical components/technology programs for Phase II is provided in Section XII of this topical report.

III. ADVANCED TURBINE SYSTEM/CYCLE CONFIGURATION

Allison chose the advanced combined cycle to serve as a baseline. This is the current *cycle of choice* for gas turbine utility power production. Allison has also chosen to concentrate initial study efforts on the hot section. Historically, hot section technology has paced engine development and, therefore, becomes critical path items and key technologies in an ATS development program.

Compressor technology has been chosen within current design state-of-the art (SOA). Allison is an industry leader in high pressure ratio axial compressor design. The pressure ratio all-axial compressor developed for the T-406 engine (V-22 Osprey) is an example of this technology. Allison has also designed compressors with a pressure ratio.

3.1 CHOICE OF ENGINE CYCLE

Figure 3-1 shows the thermal efficiency potential of simple Brayton cycles in the usual format with turbine firing temperature and overall pressure ratio as variables. Superimposed on this plot is a line of constant exhaust gas temperature. Current SOA in boiler technology is represented by 1100°F (1200°F representing advanced systems) with higher pressure ratio cycles at given firing temperatures reducing exhaust gas temperature to the bottoming cycle.

Figure 3-1. Parametric study of utility size gas turbine Brayton cycles.

This figure yields the following conclusions:

- An increase in cycle pressure ratio to [] from SOA of 10 [] provides significant improvement in simple cycle thermal efficiency ($\approx$ []). To provide optimum combined cycle performance it is best to hold at least 1100°F boiler inlet conditions. This higher pressure ratio should therefore be accompanied by a significant increase in firing temperature over current systems to optimize the combined cycle performance.
- Firing temperature (with underlying assumption of cooling flow increasing with firing temperature) is also a significant thermal efficiency driver. As will be shown in the body of this report, Allison has advanced hot section technology in development which can significantly reduce required coolant flows at high firing temperatures, thus improving thermal efficiency of the simple cycle.
- High firing temperatures provide high specific power engines. Although engine size per se may not be a factor in utility installation, capital purchase cost of utility turbines is a major factor. A []% increase in specific power results in a []% dimensional decrease in compressor systems. Turbine stages are even more strongly affected due to increased gas pressures. Component size is a significant cost driver of utility gas turbines.

Based on these conclusions, Allison has chosen to study the turbine section for a simple cycle at pressure ratio [] and two firing temperatures, [] and [] °F. Allison decided to size the ATS gas generator at 140MW to represent a typical utility turbine size for late 1990s application. These two cycles will serve as baselines for all further trade studies.

The [] °F baseline cycle incorporates ceramic technology in the turbine []. Allison has significant ceramic experience in small gas turbine engines (automotive) and has proposed the DOE (DOE []) to construct a 10MW class industrial engine utilizing this technology in larger scale. Application to the ATS system would be a further development of this technology.

The [] °F cycle incorporates an all-metallic turbine utilizing Allison's Castcool technology in single crystal material. This technology is a refinement of the Lamilloy®* blading technology currently being applied to the Allison/Air Force Advanced Turbine Engine Gas Generator (ATEGG) demonstrator engine, the highest turbine temperature capable core in the world.

Section IV provides more detail on this technology.

3.2 SINGLE VERSUS TWO-SPOOL ENGINE CONSIDERATIONS

Two-spool systems offer the advantage of being able to operate the compressor and turbine at their own speeds, i.e., not at the 60Hz utility turbine output speed. The disadvantage is the increased complexity of the multiple shaft system. Allison opted for the single-spool configuration because today's compressor technology can accomplish [] pressure ratio on a single shaft. The higher complexity multiple shaft systems are not required. Pressure ratios in the [] range would require multiple shaft configurations.

* Lamilloy is a registered trademark of the General Motors Corporation.

3.3 PERFORMANCE OF SELECTED ATS SYSTEMS

This section presents the performance of the fully developed ceramic and metallic ATS gas generators. This performance includes all performance improvements for which ATS Phase II programs have been defined (Section XII of this report).

Combined cycle performance is also given. It must be noted, however, that the steam turbine performance quoted represents Allison's understanding of the performance of this system. In Phase II Allison's aeroderivative gas generator will be combined with an advanced bottoming cycle design of a team member to produce a final ATS system.

The steam turbine performance is based on:

1. **A stack temperature of 250°F** Determined to be feasible with clean fuel and effective engine inlet airflow filtering system. Acid production in exhaust gases would be greatly reduced.
2. **Maximum steam temperature and pressure** These variables were established to obtain the proper balance of evaporator pinch point, stack temperature, and maximum cycle performance. Process steam heat content was *not* included in the quoted thermal efficiency.
3. **Steam turbine efficiency** A level of was determined to be aggressive but achievable in an advanced system.

Table 3-I presents a summary of the fully-developed ATS system performance.

Overall system optimization will continue during Phase I to work toward achieving system thermal efficiency of 60% (LHV).

Table 3-I.
ATS system performance.

<u>Parameters</u>	<u>Fully Developed Ceramic ATS</u>	<u>Fully Developed Metallic ATS</u>
Compressor		
pressure ratio		
polytropic efficiency		
inlet airflow (lb/s)		
inlet pressure loss (in-H ₂ O)		
Combustor		
pressure drop (%)		
Turbine		
efficiency		
expansion ratio		
output power		
firing temperature (°F)		
Exhaust diffuser		
pressure loss (% total)		
exhaust temperature (°F)		
Steam turbine		
maximum temperature (°F)		
maximum pressure (psia)		
exhaust pressure (psia)		
flow (lb/s)		
stack temperature (°F)		
evaporator pinch point (°F)		
output power (MW)		
efficiency		
Overall system		
output power (MW)		
system thermal efficiency (LHV)		
gas generator thermal efficiency (LHV)		

IV. ADVANCED MATERIALS AND ADVANCED COOLING TECHNOLOGY TO ACHIEVE ATS HIGH EFFICIENCY

Allison has utilized the two baseline engine cycles described in Section III to study the impact of applying various technologies to the simple cycle with the intent of improving its thermal efficiency. These technologies and their impact are presented in the body of this report. This section summarizes Allison turbine materials and processes capability, including single crystal, ceramic, and advanced cooling technologies. The products of this technology are the turbine blades and vanes which are key to realizing the baseline engine cycles chosen.

The single crystal materials have the potential of offering both improved strength and corrosion/oxidation resistance in ATS. Improved strength allows operation of turbine blades at higher bulk metal temperatures (reduced cooling flows) than current technology, while retaining life capability. Oxidation/corrosion resistance is vital to achieving life at the elevated metal temperatures. These materials combined with Allison casting technology can produce cooling schemes which approach the effectiveness of transpiration cooling, also resulting in reduced cooling flow requirements.

Allison has selected the Castcool process for manufacture of turbine blades and vanes in Allison's metallic ATS cycle. This is a process through which blades and vanes are cast net-shape from single crystal materials to a cooling configuration that approximates transpiration effectiveness. This process is a derivative of the Lamillo process more fully described in this section. Allison has selected its single crystal material for this application. This material offers strength, oxidation resistance, and fabricability.

Ceramic materials offer the ability to achieve ATS firing temperatures without significant cooling of the first blade and vane. Reduced cooling means high thermal efficiency and mechanical simplicity.

4.1 SINGLE CRYSTAL MATERIALS DESCRIPTION

Since the introduction of the gas turbine engine in the 1940s, the key to improving engine performance has typically occurred by increasing the turbine inlet temperature (TIT). The TIT is the temperature of the gas upon entry at the first-stage turbine vane. Traditionally, about 1/3 of the TIT increase has occurred due to advanced cooling concepts and 2/3 from material improvements. Allison single crystal materials and advanced casting capability offer the potential to improve both.

The material and casting technique improvements that have taken place during the past 50 years have enabled the gas turbine engine industry to progress from conventional equiaxed castings to directionally solidified parts and finally to single crystal engine airfoils. The Allison T56-A-427 second-stage turbine blades shown in Figure 4-1 illustrate the three different grain structures. Each casting technique advancement has yielded higher TITs and lower cooling air requirements.

Conventional polycrystal or equiaxed vacuum melted alloys were cast into turbine blades and vanes in the mid-1940s and were produced by pouring liquid metal at 2400°F into ceramic molds. The liquid metal rapidly freezes creating thousands of small equiaxed crystals.

Directionally solidified (DS) castings, developed during the 1960s, consist of columnar crystal structures that are oriented parallel to the growth axis. DS castings are produced by heating the ceramic mold to 2400°F after the mold has been positioned on a water-cooled metal chill plate. When the

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Figure 4-1.

$^{\circ}\text{F}$ liquid metal is poured into the mold, solidification occurs at the cold chill plate interface. The mold is then slowly withdrawn from the $^{\circ}\text{F}$ furnace, allowing the metal inside to directionally solidify from bottom to top.

As noted earlier, the performance of turbine engines is closely tied to the maximum metal temperatures allowed in the hot section. Single crystal investment castings combine the unique properties of single crystal superalloys with cost effective manufacturing to produce complicated net shape airfoils. Single crystal investment castings allow engine designers to improve performance, reduce specific fuel consumption, and increase part life on engine components.

melting point, the homogenization heat treat temperature has increased, the strength of the alloy has increased, and ultimately, the maximum use temperature of the casting has increased.

Environmental resistance is another important property that must be integrated into new generations of single crystal alloy designs. Typically, a coating is applied to engine parts to improve environmental resistance. For many types of advanced airfoils, coatings are detrimental to the performance of the airfoil. Coating application is complicated by the presence of cooling holes, which can become restricted and thus result in reduced cooling flow. Coatings often lead to embrittlement and variations in thermal expansion that result in fatigue problems. Coatings may also degrade mechanical properties through chemical interaction and added thermal cycles associated with their application.

Combining the ultra high strength-oxidation resistant single crystal alloy with the best available airfoil cooling concepts creates engine components that can meet the demands of the utility gas turbine industry.

Table 4-I compares several single crystal alloys. Based on fabricability, environmental resistance, strength, and commercial availability, it demonstrated that it was the most promising alloy for development of ultrahigh performance fabricated transpiration-cooled airfoils. Table 4-II compares the composition of several of these alloys.

TABLE 4-I.
Alloy selection rationale.

Rating Definition: 3 Exceeds Requirements
 2 Meets Requirements
 1 Fails Requirements

Second Generation Alloy

Performance Area

Heat Treatment and Fabrication
Castability
Oxidation Resistance
Stress Rupture °F/ksi
Alloy Availability
Score

TABLE 4-II.
Composition and physical properties of second generation single crystal alloys.

Element

Density (lbs/in.3)

_____ and its derivative _____ are the latest generations of single crystal materials developed under various contracts. _____ was designed for advanced airfoil applications where maximum turbine blade strength and high temperature environmental capabilities were required. _____ narrowly missed oxidation resistant goals established by Allison which were required for transpiration-cooled airfoil cover sheets. Allison modified the _____ chemistry to incorporate oxidation resistance with ultra high strength properties. The modified alloy is designated _____. Table 4-III compares _____ to the Allison _____ material. The strength and oxidation properties of Allison _____ material make it an excellent candidate for use in ATS systems.

4.2 PROCESSING

A major objective of recent Allison research was to demonstrate that the selected alloy could economically be cast and fabricated into the most demanding, ultrahigh performance fabricated single crystal airfoils capable of fully meeting _____ goals. To meet these goals _____ was tested in a series of increasingly difficult single crystal airfoils that represented a wide variety of complicated shapes (Figure 4.2). Final fabricability studies centered around _____^{110*} response to thermal processing and bonding during the transpiration-cooled airfoil assembly. Processing of these materials to the Advanced Aero Engine requirements indicates the producibility of complicated shapes. Utility turbines, of course, present additional problems which Allison would address in the ATS Phase II program described in Section XII of this report.

* Crystalfoil is a registered trademark of The General Motors Corporation.

TABLE 4-III.
Material goals and accomplishments.

Property

Stress rupture life
(2000°F/10 ksi)

Metal use temperature increase
(based on 1000°F/10 ksi)

2000°F dynamic oxidation (after
100 hours)

Demonstrate producibility

Figure 4.2. These conventional single crystal airfoils, typical of advanced engine airfoils, were used to test producibility, leading to the ATEGG Phase II airfoil.

castings were required to fabricate ATEGG Phase II prototype transpiration-cooled airfoils. [redacted] alloy was used for the ATEGG Phase II prototype blade spars, while [redacted] was favorably cast into thin ATEGG Phase II prototype airfoil-shaped [redacted]. The ATEGG Phase II prototype split [redacted] blades and [redacted] are shown in Figure 4-3. Casting yields and quality levels were excellent. Allison's unique [redacted] single crystal manufacturing processes eliminate the typical problem associated with both [redacted] observed in conventionally cored single crystal casting processes.

The fabrication of the [redacted]-piece transpiration-cooled airfoil offers the greatest cooling efficiency available. This design requires [redacted] thick oxidation resistant [redacted] in cast-in holes and Lamilloy cooling patterns to be braze bonded to [redacted] par halves. Process verification was accomplished by casting several molds of ATEGG Phase II prototype [redacted]-piece blade components from different heats of [redacted] alloy. The yields of [redacted] for the [redacted] spar casting process and [redacted] for the [redacted] thin airfoil sheet casting process were excellent for small quantity, ultrahigh performance single crystal airfoils. The thin airfoil sheet yield was reduced by [redacted] compared to [redacted] process, but the quality of the casting was excellent.

Figure 4-4 shows a cutaway of a sample vane in Castcool configuration. The Castcool configuration offers nearly the same cooling effectiveness as the Lamilloy technology without having to resort to building a turbine blade or vane from several sheets. The ATS cycle was selected at [redacted]°F firing temperature, which is significantly below Allison's advanced fighter engine technology. This reduced temperature allows us to select the [redacted] configuration over the Lamilloy product. Section

Figure 4-3. ATEGG Phase II Prototype fabricated transpiration-cooled airfoil components. All effort associated with process development for casting or bonding transpiration-cooled components was funded by Allison's existing IR&D programs.

Figure 4-4. Sample turbine vane in Castcool configuration with cutaway showing cooling passages cast into the blade skin.

3.4 provides more detail on the heat transfer (cooling) effectiveness of these products. Castcool has the potential of providing both the cooling effectiveness required in ATS and the cost and producibility required of a commercial product. This Castcool derivative of Allison single crystal technology is Allison's choice for turbine vanes and rotors in the metallic turbine configuration.

4.3 STRENGTH

Mar M-247 is a material with significant stress rupture strength advantage over current utility gas turbine materials such as INCO-718. As can be seen in Figure 4-5, the single crystal alloys offer significant improvements over this MM-247 alloy. The [] offers a [] life advantage at the condition shown. The single crystal alloys offer a tremendously improved design capability over current utility turbine materials.

4.4 OXIDATION/CORROSION

4.4.1 Oxidation

The Allison [] material exhibits good oxidation characteristics over the time period tested. The accelerated test results depicted in Figure 4-6 show the [] material to have a significant advantage in uncoated form. One key need is to demonstrate this property over the lifetimes expected of turbine blades/vanes in utility gas turbine engines. Blade lives of [] hours are typical in current utility engine applications, and with rework, are often extended to [] hours. A comprehensive testing program utilizing actual hardware is required to determine the capability of these single crystal materials to resist oxidation.

COMPARATI

PTURE LIFE

Figure 4-5. [] showed superior stress rupture properties over [] alloys and [] alloys.

Figure 4-6 [] dynamic oxidation curves for [] and [] shows the average material diameter loss at [] intervals. The incremental improvement in oxidation resistance from [] to the [] line relationship.

4.4.2 Corrosion

Hot corrosion resistance is a concern for any engine components that must operate in temperature ranges of 1800°F where exposure to sea salt and sulfur occur. Most blade and vane engine components operating under these corrosive environmental conditions are coated to protect and shield the base airfoil material from corrosion. Coating failure through foreign object damage (FOD), rub, or normal wear-and-tear is common. If blade alloys do not exhibit good uncoated baseline corrosion resistance, premature blade failures could occur when normal coating failures occur. Accordingly, uncoated 1800°F hot corrosion tests were performed by Allison on [] and [] to document and compare the uncoated corrosion resistance to other alloys.

The hot corrosion test was conducted at 1800°F with [] ppm sea salt concentration and [] sulfur concentration for a test duration of []. The [] diameter specimens were rotated at [] rpm in the combustion flame. The corrosion pins were removed once every [] hours to produce a thermal shock before being returned to the rig for continued testing.

Uncoated [] and [] exhibit superior hot corrosion behavior compared to the first generation single crystal alloy [] and equiaxed MM247 after [] hours of hot corrosion testing. A photograph showing the appearance of the [] diameter pins is shown in Figure 4-7. The relative penetration caused by the corrosive environment on each of these alloys is shown in Figure 4-8. Corrosion pins representing two different [] heats of alloy performed identically in the [] hour hot corrosion test. This repeatability suggests that there should not be any [] variation in [] response to heat corrosion testing. The surprisingly good corrosion resistance of [] with its [] content, confirms that a complicated balance of chemical element interactions is responsible for [] excellent corrosion resistance. No simple interaction of a single element could explain or predict this phenomenon.

Allison is convinced that a two-pronged attack on corrosion must be carried out to realize the ATS gas turbine cycle. The best materials for corrosion resistance must be chosen, and improved filtering of engine inlet air must be accomplished. The levels of salt and sulphur the engine sees must be reduced. Allison has proposed a filter development program (Section XII) to address this issue.

4.5 ADVANCED AERO ENGINE TURBINE COOLING TECHNOLOGIES

The program proposed in Section 12.2 of this report involves assessment of the potential gains to be achieved by introducing advanced aero engine high pressure turbine cooling concepts into large-scale utility gas turbine engines. Demonstrated aeroengine cooling performance trends for several advanced turbine vanes and blades are shown in Figure 4-9. The trends shown in Figure 4.5-1 demonstrate the significant cooling performance gains potentially achievable by incorporation of advanced [] cooling approaches, such as Lamilloy or Castcool. The results shown in Figure 4-9 indicate that the advanced Lamilloy/Castcool systems [] compare [] to ideal transpiration cooling approaches and are considerably improved over current state-of-the-art convection/film systems, representative perhaps of the LM6000 class utility machines. As noted previously, Allison has chosen the Castcool configuration for utility engine application. Figure 4-4 shows a turbine vane in Castcool configuration.

[redacted] [redacted] [redacted] [redacted]

Figure 4-7. [redacted]°F hot corrosion appearance after [redacted] hours of exposure on [redacted] and [redacted]

AVERAGE PENETRATION [redacted]

[redacted] Sulfur, [redacted] ppm Sea Salt, [redacted] Hour Test

ALLOY [redacted]

Figure 4-8. Average penetration on [redacted] after [redacted] hours of [redacted]°F hot corrosion testing with [redacted] sulfur and [redacted] ppm sea salt.

Figure 4-9. Advance turbine cooling technology trends.

The cooling performance levels represented by the Lamilloy/CastCool systems have the potential of further improvement in utility-size turbines to the extent that the intrinsic cooling feature sizes (internal geometric features, surface hole size, surface hole spacing, etc) can be maintained at (or close to) aero engine levels even as the flow size (and airfoil external chord/span size) increases to utility turbine levels. In this circumstance, cooling circuit features, channel heights, hole spacings, and boundary layer thicknesses remain small relative to increasing external (gas side) boundary layer thicknesses, effectively increasing the level of internal (cooling circuit) heat transfer coefficient relative to external (gas side) heat transfer. In the context of Figure 4-9, first order arguments will show that if cooling geometry feature size and cooling flow/gas flow ratio were maintained constant as airfoil (external) size is scaled up, the parameter $\frac{h_c}{h_g}$ would increase by approximately $\sqrt{\text{scale increase}}$ to the $\sqrt{\text{scale increase}}$ (or flow size scale $\propto \sqrt{\text{scale increase}}$ to the $\sqrt{\text{scale increase}}$). Based on the cooling performance trend line shown, cooling $\frac{h_c}{h_g}$ would thereby increase resulting in decreased cooling flow requirements and a higher thermal efficiency cycle.

These cooling performance gains are potentially very significant since flow-size scale relative to the demonstrated points shown in Figure 4-9 can be as much as a factor of $\sqrt{\text{scale increase}}$. However, it must be recognized that manufacturability/castability constraints, structural durability considerations, and operability concerns relating to $\frac{h_c}{h_g}$ will probably require some scale-up in internal cooling feature size and outer surface wall thickness, limiting the potential cooling performance gains to some degree. The focus of the proposed program is to conduct trade-off and preliminary design studies in combination with simple heat transfer $\frac{h_c}{h_g}$ tests to quantify these issues and establish a basis for a follow-on full-scale design effort.

4.6 CERAMIC TECHNOLOGY

Allison has successfully designed, developed, fabricated, and tested ceramic monolithics and ceramic matrix composite (CMC) components for various automotive and advanced military gas turbine engines.

Three static components, i.e., gasifier turbine vane, inner backplate, and combustor, were developed and evaluated during the Advanced Gas Turbine (AGT) program funded by the DOE. Furthermore, in the current Advanced Turbine Technology Applications Project (ATTAP) a gasifiers rotor has been developed using 3-D braiding/winding textile weaving preform fabrication methods.

The Advanced Turbine Rotor Design (ATRD) program developed and spin-tested a [] rotor by integrating analytical mechanics, [] fiber/matrix compatibility, and composite properties for IHPTET applications. The rotor was successfully burst tested within [] of the predicted speed.

In addition, under contract to the USAF, Allison has developed [] large annular combustor liners using []. An initial set of [] consisting of four inner and outer rings, was fabricated by []. This nonmetallic combustor program is aimed at far-term applications on high temperature rise combustion systems and is awaiting rig test.

Allison also responded to a DOE request for proposal (RFP) (DE-RP02-92CE40960) to design, build, and test ceramic turbine components for industrial engine application.

Allison also responded to a DOE RFP (DE-RP02-92CE40960) to design, build, and test ceramic turbine components for industrial engine application.

Completion of several of these programs has allowed Allison to develop significant capability in the ceramic composites and monolithics design area. Allison has the tools to accomplish ceramic component designs.

Allison has gained vast design and manufacturing experience with both the monolithics and ceramic composites. Based on significant advances made in properties and producibility of ceramic components, Allison believes [] are more advanced in their development stages and would be the [] material for Allison.

V. TURBINE DESIGN

5.1 TURBINE AERODYNAMIC DESIGN

Preliminary design studies identified a [] air-cooled, [] turbine which satisfied the design requirements for the ATS metallic and ceramic configurations. The aerodynamic design requirements for both configurations are shown in Table 5-I. The [] aerodynamic turbine flow path for both baseline cycles is shown in Figure 5-1.

Table 5-I
ATS design point aerodynamic requirements.

Parameter	Metallic	Ceramic
Rotor inlet temperature, T_t -°F		
Inlet total pressure, P_t -psia		
Inlet equivalent flow, $w\sqrt{\theta_{cr}}/\delta$ -lbm/sec		
Equivalent work, $\Delta h/\theta_{cr}$ -Btu/lbm		
Equivalent speed, $N/\sqrt{\theta_{cr}}$ -rpm		
Inlet actual flow, w -lbm/sec		
Actual work, Δh -Btu/lbm		
Actual speed, N -rpm		
Total-total expansion ratio- Re_{t-t}		
Goal total-total efficiency-%

Figure 5-1. ATS

for the ceramic and metallic baseline cycles.

The baseline turbine system employs highly efficient cooling techniques in [] and advanced materials to minimize cooling air requirements. A detailed discussion of the turbine cooling is found in subsequent sections. Stages [] incorporate rotor blade tips with [] to reduce overtight leakage losses and provide high aerodynamic efficiency. The ATS turbine is characterized by moderate stage equivalent work and loading levels. An inlet hub/tip radius ratio of [] and [] diameter flow path were utilized to maximize [] wheel speed and maintain acceptable rotor [] flow turning in each stage. The design point velocity diagram parameters are provided in Table 5-II.

The baseline turbine design was used to assess the impact of allowable metal temperature and cooling configuration on the turbine cooling flow requirements and aerodynamic efficiency. These assessments included the impact of the coolant flow mixing losses and pumping work on turbine performance. A detailed discussion of the turbine cooling studies is provided Sections VI and VII.

5.2 ACTIVE TURBINE TIP CLEARANCE CONTROL SYSTEM

Allison has successfully rig validated over [] compressor efficiency gains utilizing active tip clearance control on the [] compressor used in Allison's world famous 250-C30 helicopter engine. Even greater component efficiency gains are anticipated by applying Advanced Turbine Tip Clearance Control Systems (ATTCCS) to large industrial gas turbine stages because of significant reductions in high temperature, high pressure gas leakage. An additional benefit would be elimination of tip shrouds on the blade, simplifying the mechanical design with improved performance.

Much of this previous active compressor clearance control technology is directly related to the ATTCCS since both systems utilize similar components. The turbine system will use the same control system software and hardware, [] as utilized in the compressor program. However, while the compressor system used [] to move a relatively small lightweight rotor assembly, the turbine system uses [] to move part of the turbine case, a more practical approach for tip clearance control on large, heavy industrial turbine rotor assemblies.

Table 5-II
ATS design point velocity diagram parameters.

Parameter	Metallic	Ceramic
Stage equivalent work, $\Delta h/\theta_c$ - Btu/lbm		
Power split - %		
Load coefficient, $g\Delta h/U_m^2$		
Flow coefficient, V_x/U_m		
Rotor hub turning, $\Delta\beta$ - degrees		
Rotor reaction $\Delta P_{rotor}/\Delta P_{stg}$		
Turbine exit mach number - M_v		
Turbine exit swirl, α - degrees		

A schematic drawing showing the ATTCCS incorporated into a generic turbine configuration is shown in Figure 5-2. The system works as follows: tip clearance sensors mounted on the turbine shroud (not shown) provide clearance information to the [redacted] which, through a power supply, outputs current to the [redacted]. Three [redacted] connected to the blade track move the blade track axially. The tapered blade tips permit tip clearance variation with axial blade track movement. Seal rings provide sealing between the flow path and the cooling air cavity. The blade track can be equipped with an abradable material which can withstand slight blade rub, or it can be made from a composite material to decrease weight and reduce cooling air requirements. The [redacted] pull on the shroud against the [redacted] caused by the [redacted] pressure differential. A mechanical stop prevents the shroud from contacting the rotor in the event of [redacted] failure.

Another Allison high temperature aircraft magnetic bearing system development IR&D program also provides synergism with this ATTCCS development program. This longer range magnetic bearing development program is supplying important data regarding high temperature magnetic material design properties, rig validation of Allison's patented [redacted] design procedures, control system hardware and software improvements, rotor and control system modeling experience, and reliable high temperature wire coatings.

Development of ATTCCS for large industrial gas turbines will substantially increase gas turbine engine performance. Section VII provides details on performance improvement from [redacted] points in turbine efficiency. Turbine tip clearance leakage is a major turbine loss parameter. Allison's ATTCCS improves engine performance by substantially reducing turbine tip operating clearances. These performance benefits save fuel, reduce operating expenses, and improve engine durability and reliability.

Figure 5-2. Advanced turbine tip clearance control system schematic for [redacted] blade.

VI. COOLING AND MATERIALS TECHNOLOGY TO IMPROVE THERMAL EFFICIENCY

6.1 ANALYTICAL METHOD

Consideration of high TIT operation for advanced turbine engine concepts requires a realistic preliminary assessment of potential flow-path cooling concepts in terms of expected cooling performance. It is important to properly assess the relative advantages of one airfoil cooling scheme over another in order to determine the system performance trade-offs.

The principal measure of cooling system performance is expressed as the ratio of airfoil cooling airflow required to compressor inlet flow. Percentage cooling airflow requirements are known to be strongly influenced by turbine aerodynamic design, structural design and materials, and cycle pressure and temperature conditions.

For preliminary design purposes, turbine cooling requirements are established on the basis of simple overall procedures, which essentially equate the load on any cooled structural component to the absorption. The simplified basic equations express the ratio of airflow required to flow in terms of principal turbine and cycle parameters and cooling scheme characteristic parameters. The equations for cooled airfoils are:

convection

Lamilloy

where:

- alpha = Blade row acceleration parameter
- C1 = empirically derived constant corresponding to a detailed airfoil/cooling scheme design at design conditions
- C2 = empirically derived constant relating the etat for a detailed internal cooling scheme design to known cooling circuit parameters
- etat = cooling scheme thermal effectiveness = $f(C2)$
- F = airfoil wall temperature gradient parameter, $(T_w - T_c)/(T_g - T_c)$
- sigma = blade row solidity parameter
- Re = blade row characteristic Reynolds number
- Tc = coolant supply temperature
- Tg = gas stream relative total temperature
- Tw = airfoil wall surface temperature
- Wc = coolant flow rate
- Wg = primary stream flow rate at blade row inlet

Cooling flow requirements for stator endwalls, blade tracks, and rotor platforms are estimated from an experimentally-derived equation for Lamilloy walls:

where

q_{pc} = coolant specific heat
 G_c = blowing rate, lbm/sec/sq-in.
 h_g = flat plate heat transfer coefficient, $.037 (kg/x) (Re)^{.8} (Pr)^{.333}$

The engine cycle and turbine aerodynamic parameters for these calculations come directly from the turbine preliminary design velocity diagrams as described in Section V Turbine Designs.

6.2 TURBINE COOLING CONFIGURATIONS

Two turbine configurations were chosen (see Section III for rationale) for cooling parametric studies. Both are [] configurations with primary differences being their design point operating temperatures and materials. The turbines, described in detail in Section V have essentially the same [] flow paths, with slightly differing [] and aerodynamics. The configurations are referred to as metal and ceramic, for their structural/cooling characteristics.

The [] metal turbine operates at a design point rotor inlet temperature of [] and employs state-of-the-art Castcool technology in the [] vane and blade. The airfoil cooling schemes in the [] stages are current technology forced convection designs. For the airfoils in stages through [] the baseline wall thickness was assumed to be []. These relatively [] walls are typical in current utility turbine design. Alternative cooling schemes were considered for the first-stage blade and second-stage vane to determine performance tradeoffs.

The ceramic turbine employs ceramic airfoils in the [] blade row and [] vane row and operates at a design point rotor inlet temperature of [] F. The [] vane cooling scheme is again Castcool, while the [] blade row through [] airfoils employ current technology forced convection cooling schemes. The baseline wall thickness was assumed to be [] for the non Castcool metal airfoils.

6.3 TURBINE COOLING STUDIES

6.3.1 Assumptions

Throughout the turbine cooling studies, common cooling criteria were assumed for the endwalls, blade tracks, and rotor disks of the metal and ceramic configurations. The endwalls and blade tracks were required to be cooled to a surface average temperature of [] F [] C, and the rotor disks were assumed to be maintained at [] F.

The sources for cooling air are [] compressor bleed stations at compressor discharge pressure []. The [] airfoils, endwalls, and blade tracks, and the rotor disks of all [] were assumed to be cooled with CDP air. The [] airfoils, endwalls, and blade tracks were cooled with [] air, and all cooling circuits downstream used [] air.

The cooling air for all surfaces except the [] vanes was assumed to be cooled from compressor discharge temperature to [] F by a boiler []. The pressure drop associated with this [] is unacceptable for the [] vane cooling scheme, so compressor discharge air is used directly.

6.3.2 Airfoil Parametric Studies

6.3.2.1 Airfoil Surface Temperature

The cooling requirements for both the metal and ceramic turbines were determined for [] cooling levels corresponding to airfoil surface average temperatures of [] F, [] F, and [] F. Today's technology is represented by [] application of advanced single crystal materials of higher strength. For the metal, non-Castool airfoils, a common baseline wall thickness of [] was assumed.

The maximum temperature distribution through the metal and ceramic turbines are shown in Figures 6-1 and 6-2. In both cases the pattern factors [] were assumed to be [] for vanes and blades, respectively.

These figures essentially define the gas-side heat load in the two turbine designs. These figures also show [] cooling for the [] cooling levels examined. Application of advanced materials can reduce the [] requiring cooling from [] for the metal turbine, and from [] for the ceramic turbine.

Figure 6-3 shows the effect of [] cooling level on total turbine cooling requirements for the metal and ceramic turbines. The [] cooling flows are for [] cooling. [] cooling does not affect turbine or cycle thermal efficiency since the coolant reenters the gas stream upstream of the [] turbine rotor.

TEMP
(OF)

TE93-105

Figure 6-1.

maximum temperatures for the [] turbine [] design []

TE93-106

Figure 6-2. maximum temperatures for the turbine baseline design

TE93-107

Figure 6-3. Effect of temperature on turbine cooling requirements.

The differences in the [] cooling requirements reflect the benefits of [] in the [] and [] and are significant, cutting total [] cooling nearly []. Also evident in this figure is an apparent tradeoff between the [] turbine at the [] F wall [] temperature level and the [] turbine with [] at the more [] F.

6.3.2.2 Current Technology Versus Castcool

The advantage of choosing Castcool technology over current forced-convection technology for the [] was examined []. The surface temperature criteria [] was assumed to be [] F and the [] thickness of [] was assumed. Results show that the Castcool technology reduces required cooling flow by [] below that of conventional technology.

6.3.2.3 Wall Thickness Effects

Early in the turbine cooling studies it was evident the airfoil wall temperature gradients were large for the [] thickness of [] driving the cooling requirements up significantly for the [] and []. For this reason, the effect of wall thickness was examined for the [] turbine with airfoil surfaces at [] F. The wall thicknesses studied were between [], which is a relatively [] casting for the scale of the airfoils required, and [] the [] thickness assumed.

The effect of wall thickness on [] temperature gradients was examined for the []. While the effect was found to be relatively small for the [] and [], the benefit of [] castings is significant for the []. Figure 6-4 shows the effect of airfoil wall thickness on the wall gradient factor, which is essentially a multiplier of the cooling flow requirement. The [] gradient factor is reduced approximately [] by using []. The effect on cooling flow requirements is seen in Figure 6-5. For the [] vane, [] wall castings mean a reduction in cooling flow []. The [] blade effect is a [] more [], effect showing a payoff of only []. With the slight reductions in the [] stage airfoil cooling required, [] castings show potential for a total cooling flow reduction of [].

6.3.2.4 Liquid Cooling Alternative

This study was initiated based on the evidence of large wall gradients in the [] airfoils at the [] thickness. Alternatives to current technology forced convection air cooling were considered for the [] vane, based on Allison experimental experience with simple [] air cooling schemes.

Concept The direct liquid cooling technique applied here is an innovative concept for cooling turbine engine components. This concept was initially developed to use [] as the liquid coolant; however, [] can be used instead. The concept utilizes a two-phase mixture of air and liquid, where the [] is [] during the cooling process. This process provides a very large [] by taking advantage of both the [] rise and the [].

The technique utilizes [] in-air mixture which [] on the [] surfaces of high temperature turbine engine components to produce [] heat transfer rates.

93-108, Figure 6-4
22

Figure 6-4. Effect of airfoil wall thickness on wall gradient factor for metallic blade and vanes.

TE93-109

Figure 6-5. Effect of airfoil wall thickness on cooling requirements for metallic blade and vanes.

In the case of liquid fuel, the complete [] combined with surface temperature high enough to [] the [] the contact time between [] and the hot wall. This allows the fuel to be used for cooling purpose without []. The air/[] mixture is then routed out of the turbine vane or blade directly into a [] combustor, thus providing a []-air mixture to the combustor.

In the case of [] as the liquid coolant, the air-[] mixture can be routed to the combustor as in the case of liquid fuel or allowed to enter the gas flow path by a trailing edge ejection type scheme. The possibility of utilizing the [] or [] under these conditions provides a highly significant increase in available cooling for turbine components.

Advantages The advantages of this concept are numerous. The significant increase in available coolant [] provides the designer the option of [] cooling flow requirements at [] firing temperatures while maintaining component wall temperature at desired levels.

In the case of air-[] coolant mixture ejected through the [] the coolant air requirements are significantly less than air-only cooling mechanism due to the [] availability in []. Work is extracted from the coolant in turbine stages downstream of the [].

Air Impingement Cooling The []/air turbine cooling technique is a young, emerging technology that offers considerable promise, but will require development. Dr. Marius Paul, of Engine Corporation of America, has had previous experience with the concept and is serving as a consultant to Allison.

Initial efforts at Allison on the liquid cooling concept were performed under an IR&D program. These efforts initially focused on identifying the physics of the process and providing the necessary analytical background to develop a model of the process. Later in the program, a preliminary design evaluation was performed to determine the performance benefits that could be achieved with the [] cooling technique if it was applied to Allison's high temperature []. In this study it was shown that by using fuel cooling in the turbine rotor, the specific thrust can be increased by nearly [] over the [] design, which employed the most advanced air-cooled technology. The []-cooled design represented a [] improvement in specific thrust over the baseline air-cooled design and would nearly match the performance of a [] engine, thus providing an alternate approach in the event the required [] materials were not available.

Initial experimental efforts with the technique were performed under the Air Force contract [] where the concept was successfully demonstrated for stationary applications. Initially, using [] as the coolant, the wall temperatures of a cylinder simulating a vane were maintained below [] F with external gas temperatures above [] F. It was shown that [] can be [] from the airfoil wall in the temperature range of [] F without [].

Both analytical and experimental studies are currently being performed under NASA contract []. Under [] of the contract, a first order analytical model of the heat transfer and fluid flow process associated with the [] cooling technique was developed. It was based on the preliminary analysis of the concept that was developed under Allison IR&D as described above. It has been used extensively in preliminary design analysis, including the work being done on air/[]-cooled vane cooling studies reported herein, to evaluate the potential benefits of the concept for specific applications.

Essentially, the model performs a steady-state energy balance, accounting for evaporation of the [] within the airfoil. The model utilizes a finite difference-type scheme with the assumption of steady flow and [] dimensional heat transfer through the airfoil wall. As a [] model, the spanwise conduction along the airfoil is [], but accounted for is the conduction through the wall to the radial ribs on the impingement tube. Given specific engine and coolant conditions as input to the model, the program predicts airfoil wall temperature and coolant exit temperature. This model has been verified against the experimental data obtained in the static rig test operated under the Air Force contract []. It has proven versatile in estimating the level of cooling that can be achieved in specific designs and provides input to performance analysis programs to identify the benefits associated with this cooling concept.

The experimental portion of NASA contract [] will be completed by the end of CY92 and will result in the evaluation of the concept in a rotating environment simulating blade-cooling applications. This verification will be performed at rotational speed up to [] rpm and at external gas temperature up to [] °F.

A preliminary design study of an advanced engine concept to demonstrate potential payoffs was performed under NASA contract NAS- []. This study indicated that [] cooling can be a viable alternative to dependence on development of new high temperature materials.

The use of a []/air-cooled vane at the []/air ratio provides a significant reduction in air-cooling requirements for the metal turbine at $T_w = []$ °F. Total turbine cooling flow is reduced by [] (W_c/W_{comp}) from the [] metal turbine with a current technology forced convection cooling scheme in the [] vane. The higher technology level and cost of the []/air-cooling scheme is comparable to Castcool, but a comparable study of the metal turbine with a Castcool [] vane shows a savings of [] cooling flow. The []-cooled technology can have a significant impact on performance.

[] Injection Cooling of Compressor Discharge Air An alternate [] cooling scheme is to inject [] into the coolant air before it enters the airfoil. In this method when using [] airfoils, the mixing region has to be designed to avoid [] entering the airfoil. Any [] in the airfoil could cause uneven cooling with eventual airfoil failure due to mechanical stress. An advantage of this scheme is that internal design of the airfoil is the same as standard air-cooled designs, however, this cooling method does not make use of the efficient [] off the airfoil walls.

Impingement Cooling with [] The same cooling concept can be used with [] and [] mixture as the coolant media. Preliminary evidence indicates that [] will be necessary with the [] to ensure that [] does not occur. As long as some [] is present (even []) in sufficient quantity, [] will be formed instead of [] during [] of [] in a hot environment. The major advantage of this scheme is that no compressor discharge air will be needed to cool the vanes and, hence, improve the cycle efficiency. Also the process will be [] since the heat that is removed from the turbine vanes is returned to the cycle when the coolant [] the system through the [].

VII. ADVANCED TURBINE SYSTEM PERFORMANCE RESULTS

In the previous sections the aero engine technologies which should be applied to future utility size turbine engines were defined. This section quantifies their impact on simple cycle thermal efficiency. The following Table 7-I summarizes the results.

Table 7-I
Effect on simple cycle thermal efficiency of identified technologies.

Technology	Percent thermal efficiency increase	
	Baseline ceramic turbine	Baseline metallic turbine
Higher cycle pressure ratio		
Higher firing temperature		
Ceramics		
Single crystal materials		
with filter technology		
Castcool blade cooling		
Water/air-cooled vane		
blading		
Active turbine clearance control		
	$\Sigma =$	$\approx$ LHV

These cycle improvements result in a simple cycle at approximately thermal efficiency, more than better than current state-of-the-art. This cycle when combined with a purpose designed advanced steam turbine bottoming cycle can achieve the 60% thermal efficiency (LHV) desired for next generation utility turbines.

Although thermal efficiency is a key parameter used to judge advances in performance, it is not the only one. As noted in Section 3.1, the pressure ratio and firing temperature, combined with advanced turbine materials and cooling systems, also results in a lb/sec machine at 140MW. Current units in this class are more than lb/sec flow machines. This reduction in flow size will result in capital and operating cost savings due to reduction in size of parts. Material and machining costs will be reduced accordingly.

7.1 AIRFOIL SURFACE TEMPERATURE —METAL AND CERAMIC TURBINES

The effects of airfoil surface temperature on gas generator (simple cycle) and system performance (combined cycle) for a 140MW gas generator are shown in Figure 7-1. The turbine shows clear advantages in both gas generator and system efficiencies at the airfoil surface temperature of °F. The turbine continues to provide increased performance for the gas generator at the higher allowable airfoil surface metal temperatures although its advantage diminishes.

Figure 7-1. Effect of allowable temperature on simple and combined cycle thermal efficiency (140MW engine).

Applying improvements in metallic materials technology allows the metallic simple cycle thermal efficiency to approach [] thermal efficiency of the ceramic gas turbine. Thermal efficiency as a combined cycle plant presents a different picture. Reducing [] cooling flow by applying higher technology materials modifies the simple cycle sufficiently that the comparison of thermal efficiency of Figure 7-1 as a combined cycle plant is not entirely consistent. Figure 7-2 shows how [] gas temperature and mass flow (enthalpy) change for the 140Mw gas generator. The metallic engine at []°F firing temperature has [] gas temperatures at approximately []°F versus []°F for the []°F firing temperature ceramic cycle with advanced materials. A []°F [] turbine cycle implies material upgrades in the steam bottoming cycle. Current systems operate near []°F into the boiler.

7.2 CURRENT TECHNOLOGY VERSUS ADVANCED TECHNOLOGY CASTCOOL FIRST-STAGE BLADE

The use of Castcool technology in the [] blade reduces the chargeable cooling flow by []% over a current forced convection scheme with a baseline wall thickness of []. This technology provides an increase in gas generator thermal efficiency (LHV) from [] or nearly [] and an increase in combined cycle (LHV) thermal efficiency from [] to [] for a 140MW gas generator. The mass flow requirement drops from [] to [] lbm/s and the exhaust gas temperature increases slightly from []°F to []°F. See Table 7-II.

Figure 7-2 Effect of allowable temperature on gas temperature and engine airflow size (140MW engine).

Table 7-II
Effect of utilizing current forced-convection cooling technology on system performance.

Metallic Turbine - 2200°F Firing Temperature
Maximum Blade Metal Temperature - 2200°F
Engine Size - 140MW Gas Generator

Parameter	Baseline cycle Castcool	Baseline cycle with current technology
Total output power (MW)		
η_{th} gas generator (LHV)		
η_{th} combined cycle (LHV)		
Engine mass flow (lbm/s)		
Exhaust gas temperature (°F)		
$\Delta\%$ cooling flow		

7.3 WALL THICKNESS EFFECTS

The system performance effects achievable by using [] castings were found to be slight improvements in gas generator and combined cycle efficiencies from [] to [] and [] to [] respectively. The mass flow requirement was reduced from [] to [] lbm/s (kg/s), and a slight gas temperature increase from []°F to []°F was realized. See Table 7-III.

7.4 LIQUID COOLING ALTERNATIVES

7.4.1 Impingement [] Air [] Turbine [] Cooled

The first-order [] cooling model developed under NAS [] was used to predict the requirements to cool the [] of the metallic []°F RIT turbine design with []/air mixture. The model's subroutines which consider [] properties were modified to account for [] properties instead of []. Different [] to coolant air (LAR) mass flow ratio were used in a parametric study and a LAR of [] was considered appropriate to obtain the best []. To maintain an average wall temperature of []°F, the cooling air requirements were 1.33% of the compressor airflow with a [] AR of []. Using this cooling requirement and assuming that the air-[] coolant mixture is discharged into the turbine flow path through the trailing edge, a performance analysis was done. When compared with a standard air cooled [], there was a [] decrease [] of [] to [] in cooling air requirements for the [] vane; total (net) turbine cooling flow decreased by [] of W_{comp} . Table 7-IV summarizes the results of this analysis. An increase in gas generator thermal efficiency of more than [] is achieved.

Table 7-III
Effect on performance of utilizing [] castings in
turbine [] blade and vane.

Metallic Turbine - []°F Firing Temperature
Maximum Blade Metal Temperature - []°F
Engine Size - 140MW Gas Generator

Parameter	Baseline cycle [] ch wall	Baseline cycle with [] h wall
Total output power (MW)		
η_{th} gas generator (LHV)		
η_{th} combined cycle (LHV)		
Engine mass flow (lbm/s)		
[] gas Temperature (°F)		
$\Delta\%$ cooling flow		

Table 7-IV
Effect on performance of [] air cooled [] vane

Metallic Turbine - [] F Firing Temperature
Maximum Metal Temperature - [] °F
Engine Size - 140MW Gas Generator

Parameter	cycle with air-cooled []	cycle with []-air cooled []
Total output power (MW)		
η_{th} gas generator (LHV)		
η_{th} combined cycle (LHV)		
Engine mass flow (lbm/s)		
gas temperature (°F)		
$\Delta\%$ cooling flow		

7.4.2 [] Injection Cooling of Compressor Discharge Air

An alternate [] vane cooling scheme may be possible by using a [] mixture for the [] vane coolant. [] mixed with compressor discharge air can create a [] mixture at [] °F for [] vane cooling. This mixture can provide a [] in cooling air required for the baseline metal turbine at $T_w = []$ °F.

At the pressure and temperature of the coolant air entering the [] vane, up to a LAR of [] can be injected and still [] all the []. The final air [] mixture will be entering the blade at [] °F. Using this mixture for [] vane cooling can provide a [] in cooling air required for the baseline metal turbine at [].

This []% [] is [] the [] shown for the [] in case of Section 7.5.1 and, thus, will provide [] the benefit shown in Table 7-IV.

Liquid Impingement Cooling with []

This procedure was not studied sufficiently to quantify its potential impact. Future studies will accomplish this task.

7.5 ACTIVE TURBINE TIP CLEARANCE CONTROL

Allison design guidelines allow [] inch per [] blade row diameter as tip clearance in typical aero engine turbine designs. An analysis of the tip losses shows that active control of this level of clearance can achieve a [] point turbine efficiency improvement. This alone is worth [] in simple cycle thermal efficiency.

Allison has information on one operational utility gas turbine model which indicates that tip clearances may be significantly greater than []. This additional tip clearance may be used as a

buffer to prevent rub which can induce vibratory stress or even flutter. Active clearance control can eliminate rub and therefore the need for this additional clearance. In this specific example Turbine efficiency could be improved up to points or % thermal efficiency.

The following table (Table 7-V) shows base and active control clearances assumed for this study.

Table 7-V.
ATS design tip clearance summary.

<u>Stage</u>	<u>Blade height (in)</u>	<u>Blade row diameter (in.)</u>	<u>Tip clearance</u>	<u>Tip clearance</u>
--------------	--------------------------	---------------------------------	----------------------	----------------------

$$\Delta\eta_{\text{turb}} =$$

VIII. EMISSIONS

The current state-of-the-art gas turbine combustion liners mostly operate under the mode of operation in which fuel/air mixing and combustion processes take place simultaneously. The large regions of near stoichiometric flame temperature in the primary zone of the liner are consistent with the design of the liner. In addition, current methods use large amounts of cooling and dilution air to ensure acceptable wall temperature levels and to control [] at the combustor exit. This approach has historically worked well to control burnout of CO and unburned hydrocarbons (UHC), and to optimize combustion efficiency, ignition, pattern factor, and lean blowout goals. However, the high temperature regions in the primary combustion zone are for the most part responsible for the production of high thermal NO_x which has an exponential dependency on temperature.

For the ATS reference system, the emissions goals for nitrogen oxides are 10 ppm on dry basis corrected to 15% oxygen, and for carbon monoxide and unburned hydrocarbons 20 ppm on dry basis corrected to 15% oxygen. In order to achieve these low emission goals, without the use of diluent or postcombustion controls, the conventional [] combustor design approach must be replaced with the premixed design approach in which fuel and air are premixed ahead of the primary combustion zone to produce extremely uniform, lean, fuel-air mixture. A key question, however, is whether the premixing combustion approach can meet the present emissions goals in practical combustion devices under the proposed high turbine inlet temperature and high pressure operation of the ATS.

8.1 PARAMETRIC EVALUATION OF PREMIXED COMBUSTION CONCEPT

A parametric study was performed to predict emissions using a detailed chemical kinetic computer code. The Allison combustion reaction kinetics computer code [] combines a variety of finite-rate hydrocarbon combustion reaction mechanisms with modular models based on combinations of perfectly stirred reactors and plug-flow reactors.

The original reaction mechanism consisted of a global reaction of hydrocarbon fuel to H_2 and CO coupled with a detailed mechanism for the oxidation of these species to H_2O and CO_2 plus a mechanism for the formation of nitrogen oxides. Subsequently, detailed reaction mechanisms for the combustion of methane and of propane have been incorporated as options.

The concepts involving the [] and plug flow reactor (PFR) have long been employed as means to analyze combustion processes in gas turbine combustors. Briefly, the [] is characterized by the assumption that all constituents and products of the reaction are mixed together instantaneously and intimately in the reactor volume. The reactor thus has no flame front or flame speed. The combustion reaction takes place throughout the stirred reactor volume, and the reactor is characterized by a uniform temperature and composition. A PFR may be thought of as reacting flow passing through a tube with no back mixing. It may be approximated by a large number of small [] in series.

By the assumption of instantaneous mixing and reaction, the chemical kinetic equation which describes the reactions taking place in the [] can be written as algebraic equations rather than the differential equations required by a dynamic model. A [] iteration is used to solve for the composition of a []. In addition to reaction rate and enthalpy, fuel/air ratio, inlet temperature, pressure, and mean residence time. If the reactor volume and inlet flow rate are provided, the mean residence time is calculated.

Several models of gas turbine combustors have been developed by arranging [] and PFRs in various series and parallel combinations. These have been incorporated into the [] computer code. In addition, a model of the user's choosing can be fashioned as part of the input data stream.

For the purpose of this study [] was configured as shown in Figure 8-1. The upstream end of the reaction zone of a premixing combustor is modeled as [] reactors in parallel, [] representing the [] zone on the axis of the combustor and the other the [] region near the combustor wall. Of the fuel flow and combustion air, [] was allotted to the [] zone with the remaining [] % entering the [] region. These [] streams [] enter a plug flow reactor representing the downstream region of the [] zone. Next, there is provision for the addition of [] air, if any, and the mixture enters another plug flow reactor representing the [] of the combustor.

Initially, [] was validated by applying it to emissions data obtained with the Allison AGT100 combustor. This combustor was developed for the AGT100 engine, a 100 horsepower, two-shaft, [] gas turbine engine. [] volumes in [] were set to represent the AGT100 combustor and several points were modeled over a range of combustor reaction zone temperatures. In this case, the fuel was DF-2. The results are shown in Figure 8-2. [] predictions matched the measured emissions data quite accurately with the exception of slight over-predictions of [] at low reaction zone temperatures and [] at high temperatures. Overall, the application of [] to the AGT100 data yielded accurate to slightly [] results.

Next, the model was applied to the natural gas-fired reference system. Base load conditions for both metallic and ceramic turbine cycles were modeled, but part load conditions were not included in the study. As a starting point, a combustor volume was selected that provided equivalent reference velocity [] and residence time [] as the AGT100 combustor. Coincidentally, for natural gas-fired reference system operating conditions these assumptions yielded [] combustors [] diameter and [] length, which is very close to the size of combustion systems in current large industrial gas turbines. An equal volume was allotted to the dilution zone to represent transition ducts leading from the combustors to the turbine. Although conceptually the volumes selected are representative of a can-annular combustion system, the analysis is also applicable to a single large external combustor, provided the volumes are the same. The external combustor may be more appropriate in the case of a low-Btu gas fuel, particularly from the standpoint of manifolding large volumes of fuel to the combustor. For this study it was assumed that all combustor air was premixed with the fuel; there was no dilution air so [] temperature in the [] was equal to the turbine inlet temperature. Natural gas was modeled as pure methane.

Figure 8-1. Arrangement of reactors in [] kinetic code for modeling premixing combustors.

TE93-113

Figure 8-2. Validation of kinetic model AGT100 premixing combustor data.

Results of the parametric study for the [] turbine cycle are plotted in Figure 8-3. To meet CO and NO_x goals emissions must fall within the box indicated on the plot. UHC was assumed to be small with respect to CO, based on test results with AGT100 and other premixing combustors. Therefore, the sum of CO and UHC will meet the 20 ppmvd goal, if CO falls within the box with some margin. Combustor operating conditions are indicated on the plot.

At all points modeled CO is less than half of its goal. However, at the starting point NO_x exceeded its goal. Pressure, temperature, and combustor volume were all varied about the starting point. Reduction of pressure to [] atmospheres, which is equivalent to [] industrial engine pressure ratios, reduced NO_x from [] ppmvd with very little increase in CO. Reduction in combustor volume (or residence time) to [] of its initial value reduced NO_x from [] ppmvd with no increase in CO. The largest reductions in NO_x were obtained with decreases in gas temperature, however, this requires a corresponding decrease in TIT. Temperature was reduced until equivalent to the TIT of the [] engine cycle at which point NO_x emissions below [] ppmvd were predicted. Reductions in temperature also reduced CO emissions. Two points were run with both reduced temperature and reduced volume and are indicated on the plot.

The results of this study show that emissions goals can be met without changing [] turbine operating conditions by selecting a combustor volume equal to [] that of the initial []. At this point CO is predicted to be [] ppmvd as compared to its goal of 20 ppmvd and NO_x is predicted to be [] ppmvd as compared to its goal of 10 ppmvd.

Results of the parametric study for the [] turbine cycle are plotted in Figure 8-4. In this case predicted emissions were so low at the starting point that temperature was not reduced further. Reductions in pressure and volume slightly reduced NO_x and increased CO emissions. At the starting point CO and NO_x are both predicted to be [] ppmvd.

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8.2 PREMIXED COMBUSTOR DESIGN APPROACH

The results of the parametric study show that the emissions goals can be met at base load on natural gas fuel at both metallic and ceramic turbine cycle operating conditions, provided a properly designed combustion system is utilized.

There are two major operational issues in the operation of a combustion system. First, the combustor must be operable throughout the gas turbine engine cycle from idle to 100% power. During the turndown operation of the combustion system, flame stability must be maintained for the lowest power operation when the fuel/air ratio is lowest. Second, during the lean, low temperature combustion zone operation, the cooler combustor walls introduce quenching effects on the reaction involving CO and UHC, thereby, resulting in increased emissions. These two issues can be addressed by using a combustor and a concept and/or a . Maintaining high combustor wall temperature and use of will substantially improve combustion flame stability, the range of turndown operation of the combustion stem, and will help achieve the target goals for CO and UHC. Another way, if needed, to improve the range of turndown ratio is with in which a portion of air introduced into the premixing and the primary combustion zones is power level. Allison's experience in the combustor technology is also applicable for the combustion development effort in this project.

A number of combustion configurations, specifically in regard to method of fuel injection, premixing designs, and variable geometry concepts, are feasible. Based on its extensive past emission development experience, Allison believes that economically viable and successful ultralow NO_x combustion system is feasible with Allison's combustor concept. The system will use a number of that incorporate a fuel injection system with a design. A will be incorporated into a small, to combustion in addition to providing the ignition source for the staged fuel sequencing. By using fuel combination with advanced fuel injectors and to optimize fuel/air mixing, it becomes possible to selectively control combustion stoichiometry over the range of engine operation. The concept then provides the potential to minimize the production of CO and UHC at low power operation and nearly eliminates the production of NO_x at high power conditions.

IX. COST AND RAM ESTIMATE PROCESS

The approach taken by Allison to assess the impact of advanced technology on product cost is a simplified one since there is no conceptual design of the reference system to be evaluated for capital cost. This approach should be consistent with the definition of the program which is a feasibility study.

The Electric Power Research Institute's Technical Assessment Guide (TAG) method was used for computations to determine the cost of electricity (COE). The costs developed in this section represent the production cost of the Nth unit of the ATS gas turbine system. The following equation (9.0-1) identifies the major components of COE:

$$\text{COE} = \text{COE}_{\text{cap}} + \text{COE}_{\text{fom}} + \text{COE}_{\text{f}} + \text{COE}_{\text{v}} \quad (9.0-1)$$

Where:

COE_{cap} = capital contribution (fixed charge rate x invested capital [\$/kW])

COE_{fom} = fixed operation and maintenance contribution (levelization factor x fixed operation and maint. cost [\$/kW yr])

COE_{f} = fuel contribution (3.413 X levelization factor x fuel cost [\$/MMBtu])

COE_{v} = variable operation and maintenance contribution (levelization factor x 1000 x variable O & M cost [\$/kW hr])

Economic assumptions for COE computations are those used by DOE/METC for COE evaluations and are presented in Table 9-I.

The steps followed in assessing the capital cost were to (1) determine the incremental cost of advanced technology components on an Allison gas turbine, (2) modify the total cost of an Allison industrial gas turbine to reflect the capital cost change, (3) using the ratio of an Allison industrial gas turbine components to utility gas turbine components, determine the change in a utility turbine cost, (4) compare the cost of a 1991 utility production gas turbine to a utility turbine which would incorporate the advanced technology and components. This procedure provided an order of magnitude change in the production turbine costs in \$/kW.

Table 9-I.
Economic assumptions.

<u>ITEM</u>		<u>FACTORS</u>			
Project life		years			
Book life		years			
Tax life		years			
Federal & state tax rate		%			
Tax depreciation method		ACRS			
Investment tax credit		%			
Financil Structure					
Type of security	<u>% of total</u>	<u>Current \$ cost %</u>	<u>Ret. %</u>	<u>Constant \$ Cost%</u>	<u>Ret. %</u>
Debt					
Preferred stock					
Common stock					
Discount Rate (cost of capital)					
Inflation rate, % per year					
Real escalation Rates (over inflation)					
Fuel, % per yer					
Operating & maint. % per yr					

The natural gas-fired reference system in Allison's case is an advanced combined cycle combustion turbine. The advanced gas turbine is configured to use single crystal Castcool materials and advanced cooling technology, and generate a net of 140MW. Major hardware changes in the gas turbine engine would be in the hot section and increased compressor stages. The high pressure ATS turbine requires less mass flow, and will be smaller in overall dimensions compared to a current production turbine.

These reduced dimensions would mean the airfoil sizes in the ATS turbine will be smaller than for current production turbines generating the same power. Smaller physical sizes of the airfoils would tend to bring the production costs of the ATS turbine below the cost of airfoils for current turbines.

Using the procedure outlined above, order of magnitude estimates were generated for the cost of a production ATS gas turbine compared to the cost of a 1991 vintage production gas turbine. The overall cost of the hot section of the ATS turbine increased by over [] due to the sophisticated []

technology, advanced cooling techniques, and for one more stage added in the turbine hot section. The turbine section cost still represents approximately of the overall cost of a complete production ATS gas turbine. The increase in compressor cost due to additional stages would be offset by a smaller overall compressor. A increase in the cost of compressor was estimated for this modification. In terms of \$/kW, the total cost of the advanced technology ATS gas turbine was estimated to be approximately below the cost of a comparable production gas turbine with current technology.

It should be emphasized that the estimates generated for the airfoils represent very crude extrapolations at best. Currently, there is very limited experience with similar systems in production. Most of these advanced concepts are rather in early development phases. Because of this uncertainty, the higher multipliers used to estimate the cost of the hot section are conservative. It is anticipated that production costs of airfoils by the year 2000 s should be more cost competitive than assumed here.

The COE_{cap} fraction in Equation 9-1 could be assumed to provide a reduction of in \$/kW for the ATS turbine over a current production gas turbine of the 1991 vintage. This reduction in \$/kW of the capital cost contribution would also influence the COE_{fom} fraction.

The COE_{fom} fraction represents fixed operation and maintenance costs. For operation with natural gas as the main fuel, the plant labor requirements would change for the ATS. This is caused by the factor in the COE_{fom} fraction which is based on \$/kW yr. It is assumed that since the ATS is a production system, fixed maintenance costs and miscellaneous fixed costs would also vary with the \$/kW YR. compared to a 1991 vintage production turbine. Overall the impact of reduction in \$/kW in capital cost would reduce COE_{fom} costs by s well, since the \$/kW yr. would go down by

The COE_f fraction in Equation 9-1 would likely be the single component most affected by advanced technology. The ATS turbine fuel efficiency in terms of kW/MMBtu produced would be higher than for current production turbines. This is due to vast improvement expected in the gas generator thermal efficiency and heat rate. The estimated thermal efficiency of the ATS gas generator would be about better than the state-of-the-art. This advantage would result in a decrease in fuel consumption of for the ATS. A saving in the fuel cost would directly reduce the overall COE_f by

The last fraction COE_v in equation 9-1 is dependent on \$/kW hr. This fraction would be reduced by the reduction in the capital cost of the ATS gas turbine.

Adding up the total changes in each of the fractions making up the overall COE provides the following:

$$COE \text{ (ATS gas turbine)} = [(COE_{cap} + COE_{fom} + COE_v) \cdot (COE_f)]$$

Where COEs mentioned in parentheses are for the 1991 vintage production gas turbines.

The above analysis illustrates the cost of electricity of the ATS gas turbine would be lower than the COE for current production gas turbines.

The issue of reliability, availability, and maintainability would be unaltered or improved when the advanced technology and components are used in the ATS gas turbines. Allison's experience with the military and aerospace hardware tends to support this hypothesis. As more and more advanced technology is incorporated in production engines, RAM also seems to either stay the same or improve.

X. MARKET POTENTIAL AND COMMERCIALIZATION PLAN

10.1 ASSESSMENT OF THE POTENTIAL MARKET

Allison's proposed advanced turbine system configuration is sized for the electric utility and independent power producer application markets. Allison's plan is to develop an advanced turbine system in which the advanced technology can be demonstrated in its full-scale industrial gas turbine. The full-scale industrial demonstration size will also serve as a size for turbines. Allison's currently to that size.

Allison will add the new AIS developed gas turbine to its industrial market. Allison's objectives will be to advance the combustion turbine power generation technology through a revolutionary improvement process to more efficient, cost effective, environmentally superior systems.

Allison is convinced that the advanced aeroderivative gas turbine system technology power plant fits a variety of market requirements. A substantial market exists and will further develop globally for power modules rated between 100MW and 250MW, which are easy to transport and suitable for fast installation. An end user, however, must be convinced that the distinct advantages of high efficiency systems warrant taking the risks associated with new technology. It is expected that during Phase II of this program, customers' level of acceptance of advanced systems will be investigated in developing a more comprehensive commercialization plan for the large gas turbine. Allison will also study to determine an optimum size for the industrial market sector.

10.2 POWER GENERATION MARKET

The world market for gas turbines has increased more rapidly than the global gross domestic product. A recent article in *World Cogeneration* (Summer Issue - Vol.4, No. 3) indicates that the global market for power generation should grow at an average annual rate of around through the year 2001, representing gigawatts of anticipated additions. The Electric Power Research Institute's estimates indicate the total U.S. market will be a strong one, requiring an additional gigawatts of new capacity in the next years. According to Utility Data Institute (UDI), the United States' new capacity during 1990-2000, utilizing natural gas as the primary fuel, is projected to be about GW. An additional capacity of GW is projected to be coal based.

Availability of clean fuels, especially natural gas, has spurred on development of clean power plants, where coal has been a dominant fuel before. This appears to be the case in Latin America and the Asia-Pacific region. Capability of advanced gas turbines which could also be operated on clean coal would add considerably to a rapid conversion of current power plants to cleaner burning gas turbines.

Key drivers of the utility and independent power production markets are reserve margins, electric growth rate, retirements, imports, and demand side management. The 1990 Clean Air Act Amendments will also influence this market sector when compliance with Phase II of this act (mandated by the year 2000) would necessitate the use of gas turbines to generate clean power.

10.3 FACTORS INFLUENCING INDUSTRIAL GAS TURBINE SYSTEM COMMERCIALIZATION

Allison's primary business is in the industrial sector. Approximately of the new industrial market utilizes gas turbines. Therefore, the commercialization plan outline presented here focuses on the application of gas turbines for cogeneration and industrial markets.

Approach The Allison approach to assessing the industrial market consists of a strategy which reviews potential markets by the specific industry code, reviews regions of the country where the market may be attractive, and then generates a plan. Allison generally concentrates on five energy intensive industries -- paper and pulp, food and kindred products, chemical, petrochemical, and metals. Allison selects regions with relatively high energy cost, availability of natural gas, high growth, concentration of industries, and favorable state laws.

Candidate plants are selected and ranked, using project internal rate of return as a measure. Corporate and divisional contacts are made, middle and upper managements are involved, the product is tailored to site-specific applications and requirements, and those projects offering high potentials are pursued with individual contacts at plant and corporate levels.

Cogeneration The elements which are essential in determining cogeneration markets are the potential and actual size, and other considerations which dictate the application of cogeneration systems would be based on operating cycles, cost, and potential savings resulting from a substitution of a cogeneration system for existing process steam source. These systems should also be analyzed for a specific application against a gas turbine cogeneration system. These systems include from small cogens, diesels, steam turbines, and gas engines to availability of electric power to generate steam.

The cogeneration market is primarily regional. It offers a high potential in regions where electric rates are high, buy back rates are attractive, favorable regulatory climate is available, and the region has limited electric reserve margins.

Cogeneration Benefits Cogeneration offers the benefit of simultaneous production of process steam and electric power. The standard module is about 1 MW size, has low construction costs, and can be operated as a dual fuel unit -- natural gas and oil. Allison's current products demonstrate high availability, essential to a base load cogeneration application. Additionally, a cogeneration plant offers favorable turndown flexibility, and redundancy, it is a reliable source of power, and it has a very attractive pay-back (generally of three years or less) and return on investment potential.

The issues which would tend to adversely impact the industrial market are utilities unwilling to interconnect with cogenerators, a low price for excess power generated by cogenerators, high cost of back-up power, and specific regulations in a given state or locality which might prevent operation of cogeneration facilities.

The development of Allison's commercialization plan for the application of advanced gas turbines in the industrial sector will require examination of the fundamental elements of geographical regional issues, fuel availability, regulatory constraints and encouragement, customer preferences, financing, tax concerns, capital cost of the system, and system reliability, availability, and maintainability.

XI. COAL-FUELED REFERENCE SYSTEM

This section provides a summary of the analysis performed to determine requirements for conversion of ATS to a coal-fueled system. The Allison rich-quench-lean (RQL) coal combustion system is described in some detail in Section 11.3. The fuel produced by this process is a large quantity of low Btu gas which is supplied to the last stage of the combustor for a final lean burn. The combustion of coal results in a higher mass flow in the turbine section of the coal-fueled ATS at the same firing temperature and pressure observed in the natural gas-fired system. This higher mass flow results in three main modifications to the gas turbine:

1. The turbine design must be modified to accept and utilize the flow at performance.
2. The low Btu gas properties combined with a turbine yield across the turbine; i.e., steam cycle inlet temperature.
3. The modified turbine inlet and exit conditions result in turbine design modifications and bottoming cycle changes to accept the flow at temperature.

Results of the turbine design modifications are presented in Section 11.2 for the ATS. As noted, the natural gas fired system feasibility study showed the turbines can utilize the same flow path. Thus, Allison chose to study only the turbine system as representative of the changes required for conversion to a coal-fueled system.

A comparison of performance data for the ATS between natural gas and coal-fueled systems is presented in Section 11.1.

11.1 PERFORMANCE OF COAL-FUELED REFERENCE SYSTEM

Table 11-I presents a summary of the key performance parameters of the coal-fueled and natural gas-based systems. The most obvious differences are in the through the turbine (and therefore, through the bottoming cycle) and the exhaust gas temperature.

The additional results in a change in turbine output power of a significant in gas generator thermal efficiency. This is due to the turbine exhaust temperature. Significantly more is in the for use in the bottoming cycle.

Overall efficiency of the system drops by approximately points because of imperfect recovery of the additional. This additional is the result of the and. The is chiefly due to the water quench required to cool coal combustion products to a low enough temperature to effect ash removal. There are some studies which have investigated elimination of the steam bottoming cycle in the coal-fueled configuration. The turbine waste heat would be used to make steam for the quench process. The additional use of water in the coal system would also make a water recovery device in the exhaust desirable and probably necessary.

Table 11-I.
turbine ATS performance.

<u>Parameters</u>	<u>Natural gas-fired fully developed ATS</u>	<u>Coal-fueled fully developed ATS</u>
Compressor		
pressure ratio		
polytropic efficiency		
inlet airflow-lb/sec		
inlet pressure loss (in-H ₂ O)		
Combustor		
pressure drop-%		
Turbine		
efficiency		
expansion ratio		
output power-MW		
firing temperature - °F		
inlet corrected gas flow-lbm/sec)		
exit corrected gas flow-lbm/sec		
Exhaust diffuser		
pressure loss-%total		
exhaust temperature - °F		
Steam turbine		
max. temp.-°F		
max. press.-psia		
exhaust press.-psia		
flow-lb/sec		
stack temp.-°F		
evap. pinch pt. °F		
output power-MW		
efficiency-%		
Overall system		
output power-MW		
system thermal eff. %-LHV		
gas generator eff. %-LHV		
system thermal eff. %-HHV		

It should be noted that the _____ °F _____ gas temperature with the coal-fueled ATS will have ramifications in the mechanical and aerodynamic design of the _____ cycle. Materials to handle the _____ temperature and heat recovery _____ duct size selection to prevent _____ with the _____ mass flow system will be a concern.

In Section 11.2, it will be shown that it is possible to design a turbine flow path to accomplish both the coal-fueled and gas-fired system requirements. Allison has not determined that a bottoming cycle design exists which will do the same. However, Allison fully expects that there is a compromise design for the steam cycle.

11.2 MODIFICATION OF ATS FOR COAL-FUELED OPERATION

Preliminary design studies have identified a [] turbine which satisfies the design requirements for the ATS gas-fired and coal-fueled applications. The [] design requirements for both applications are shown in Table 11-II. The [] turbine flow path is shown in Figure 11-1.

Table 11-II.
ATS design point [] requirements.

<u>Parameter</u>	<u>Gas-fired</u>	<u>Coal-fueled</u>
Rotor inlet temperature (Tt)-°F		
Inlet total pressure (Pt)-psia		
Inlet equivalent flow ($w \sqrt{\Theta \alpha}$) -Btu/lbm		
Equivalent work ($\Delta h / \Theta \alpha$) -Btu/lbm		
Equivalent speed ($N / \sqrt{\alpha}$) rpm		
Inlet actual flow (w)-lbm/sec		
Actual work Δ -Btu/lbm		
Actual speed(N) rpm		
Total-total expansion ratio- Re _{t-t}		
Goal total-total eff.-%		

As a result of the [] flow of the coal-fueled application, the turbine [] flow path was moved [] in the [] relative to the original ATS, [] from []. The turbine flow path will still be common for both coal-fueled and natural gas-fired applications. However, a [] for the coal-fueled cycle is required due to the [] let flow capacity difference. As shown in Table 11-III, the turbine stage aerodynamics are tailored to provide acceptable performance for both applications. [] for the gas-fired application was set to maintain acceptable [] throughout. The gas-fired application features [] flow at [] increasing to [] in the coal-fueled application.

Figure 11-1. ATS

: flow path.

TE93-116

ATS design, Table 11-III parameters.

Parameter	Gas-fired	Coal-fueled
Stage equivalent work ($\Delta h / \Theta_{cr}$) -Btu/lbm		
Power split, %		
Load coefficient ($gJ\Delta h / U_m^2$)		
Flow coefficient (V_x / U_m)		
Rotor hub turning ($\Delta\beta$)-deg		
Rotor reaction		
Turbine exit mach no. (M_n)		
Turbine exit axial M. No. (M_{vx})		
Turbine exit swirl (α)-deg		

11.3 DESCRIPTION OF THE ALLISON RICH-QUENCH-LEAN COAL COMBUSTION SYSTEM

The current RQL combustion system is shown in an expanded cross-section view in Figure 11-2. Coal/water slurry or dry coal is injected into the rich zone where it is vaporized and the combustible matter is converted to carbon dioxide, carbon monoxide, hydrogen and water producing a fuel rich gas. Gas temperature in the rich zone is allowed to rise to []°F by controlling the fuel/air mixture to a fuel equivalence ratio of []. Water is sprayed into the hot gas in the quench zone to reduce the average temperature to []°F before the ash laden gases pass through twin vertical cyclones. The cleaned fuel rich gas is passed to the lean combustion zone where it is mixed with a fresh charge of air and auto-ignites, raising the temperature to []°F. [] air is added to the gases to temper the combustion products to []°F before entry to the turbine section.

In the various proof of concepts tests conducted on this type of combustor design, Allison learned that the rich zone carbon conversion efficiency of up to [] was achieved, confirming the earlier bench test results.

For the ATS application, the lean combustion will be maintained at a higher temperature, up to []°F. There will be no addition of any [] past the [] zone.

The mating of the RQL combustor to the ATS turbine system will require modifications to the center section between the compressor and the turbine in the gas-fired ATS. A detail design of the transition section duct to accommodate the RQL combustor in an industrial gas turbine was generated by Allison on the direct coal-fueled turbine program. A schematic of this design is shown in Figure 11-3. The ATS gas-fired turbine will require similar modifications.

Figure 11-2. Full-scale combustion system cross section.

TE93-118

Figure 11-3. External combustor turbine entry duct.

XII. PROGRAM RECOMMENDATIONS FOR PHASE II

This section contains Allison's recommendations for future work to be performed on the Advanced Turbine Systems program during Phase II.

Specific programs are proposed by Allison to be conducted over a two year period in Phase II. These are:

Preliminary design of the advanced gas turbine and complete cycle evaluation of the advanced combined cycle combined cycle systems.

Design, fabricate, and test airfoils for a 1000°F rotor inlet temperature industrial/utility turbine.

Design, procure, and test inlet air filter(s) to capture incoming alkali and salt sprays to minimize hot corrosion.

Each program is structured to be complete in a two-year period. The specific statements of work, and schedules of tasks for each program are presented in their individual write-ups.

At this time, only a rough order of magnitude cost estimate is generated for each program. These cost estimates will be refined and revised as needed during the remaining period of the Phase I contract. Allison will submit the final costs in a formal format as part of the Topical report on Phase I.

A preliminary cost estimate for each of the programs recommended for Phase II is given below:

A time-phased milestone chart containing the programs is presented in Figure . This figure provides the startup dates, duration, and completion dates of key tasks for each program.

Figure 1 Phase II

It should be noted that [redacted] is essential to the overall Phase II program and forms the basis to the [redacted] programs. [redacted] generate [redacted] of the advanced gas turbine. This program's output will essentially [redacted] DOE is being advised that selection of [redacted] is necessary so Allison can generate [redacted] data to pro-

THE ADVANCED TURBINE SYSTEM (ATS) - A MAJOR COMPONENT OF THE ADVANCED SYSTEMS

This program will provide the [redacted] of the [redacted] to sufficient detail to identify the [redacted] [redacted] This program also provides the [redacted] required [redacted] in Sections [redacted] In addition to the [redacted] of an [redacted] system as the [redacted] Allison will also conduct a [redacted] of the thermo-chemical recuperation system as the [redacted] The latter will be performed in conjunction with the [redacted] Technology and [redacted] Corporation as [redacted] The following [redacted] performed during this program. The [redacted] program will require a total of [redacted] months. A milestone chart with the various tasks for the program defined in this section is presented in Figure [redacted]. A preliminary estimate of the cost of this program is [redacted].

The [redacted] will be initiated by [redacted] the requirements for the Advanced Turbine System in cooperation with the [redacted] for both the [redacted] and the [redacted] system requirements including [redacted] and advanced [redacted] performance characteristics generated by the [redacted] on the [redacted] system will feed into optimizing the system.

TE93-120

Figure 1. Project schedule for the program.

Allison will work [redacted] as the [redacted] for [redacted] who will provide design data which impact the design process such as life requirements, reliability, availability and maintainability, combustor pattern factor, cyclic operation, cold day/high power operation, compressor IGVs, and engine sizing.

A [redacted] design will be completed in sufficient detail to identify the [redacted] and [redacted] will be designed and [redacted] completed. This activity will result in identifying [redacted] and to ensure performance and design life can be achieved.

The design of the [redacted] will be provided by the [redacted]. The [redacted] is expected to meet [redacted].

Allison will complete a [redacted] design in sufficient detail which will identify [redacted]. This detail will be adequate to perform [redacted] and confirm the adequacy of [redacted].

Detail design procedure of a [redacted] is described in Section 12.2.

Cycle Design. This task will be accomplished by [redacted]. It will advance the state-of-the-art and impact the [redacted] gas temperature (firing temperature) in the gas turbine design.

Design of the engine layout will be generated as the final product of this program. This will provide sufficient details on proposed engine construction. Allison's members, who are more knowledgeable in the [redacted] will work [redacted] Allison on this task.

The [redacted] is ideally suited for expanding the [redacted] of advanced gas turbines. Allison has the unique capability [redacted]. The proposed program will utilize this [redacted] and in-house proprietary [redacted] of Allison to determine the adaptability of [redacted] to large utility airfoils with long life requirements.

The proposed [redacted] program consists of the [redacted] distinct tasks of preliminary [redacted] and [redacted] assessment, [redacted] demonstration and [redacted] manufacture testing [redacted] evaluation [redacted] and [redacted] design update.

An overall period of [redacted] is required to conduct this program. A milestone chart is included as Figure [redacted], depicting the various tasks and their duration. The estimated preliminary costs to conduct this program are [redacted].

The advanced [redacted] turbine airfoils will be configured utilizing the characteristics of [redacted]. In this task a preliminary design of the [redacted] will be generated. The specific activities will include [redacted] and [redacted] design of the [redacted].

Concurrent with the [redacted] activities, [redacted] manufacturing inputs will be provided to engineering for incorporation in the design on a continuous basis. This feature will enhance the [redacted] aspects of the [redacted] and enable proper utilization of anticipated [redacted] peculiar [redacted]. In addition, a [redacted] will be conducted in parallel. It is important to have the design of a [redacted] utilize not only the design aspects of [redacted] but also reflect the ability to produce the hardware within the constraints of the [redacted] technology.

This task will require [redacted] to complete.

Task 2 - Process [redacted] This task will be devoted primarily to the selection and establishment of specific process to be used in [redacted]. Economics, compatibility of [redacted] requirements with available [redacted] and timing to [redacted] a given [redacted] will be thoroughly evaluated. This task will result in an optimization of the [redacted] and demonstration of the selected [redacted] capability.

[redacted] will be to develop [redacted]. Using this technique, [redacted] will be made for use in the [redacted]. It is estimated that this [redacted] will require [redacted] to complete and will be initiated toward the [redacted].

Having made the [redacted] Allison will proceed with the [redacted] of actual hardware in this task. [redacted] will be [redacted] with design characteristics specified under [redacted]. A quality assessment of [redacted] will be made,

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will be run on bars with and without [redacted] to determine the ability to withstand [redacted] environment. The extent of [redacted] experienced by the [redacted] and resultant change of [redacted] will be determined.

Another [redacted] of tests will focus on evaluating [redacted] of the material. The [redacted] will be [redacted] at turbine temperatures encountered by [redacted] in actual operation. The test will be run for [redacted] duration to enable extrapolation of the [redacted] potential in a long term [redacted] [redacted]

The [redacted] series of tests will be structured to determine the [redacted] [redacted] part. In this test a detailed assessment of the [redacted] will be made to ensure that the [redacted] meet the objectives of the overall program.

This task will require a period of [redacted] of total time to complete. It will run [redacted] with the [redacted] tests.

The results of [redacted] and [redacted] series evaluation will be used to [redacted] turbine [redacted] designs [redacted] during Phase II. A final [redacted] design based on the [redacted] will be generated as part of the [redacted] of the advanced gas turbine program under Phase II. The duration of this task is estimated to be three [redacted]

The advanced combined cycle [redacted] turbine program will be structured to provide turbine performance and the corresponding turbine [redacted] The information generated in the preliminary design program for advanced combined cycle systems during Phase II will form the basis for this program. The [redacted] program will develop [redacted] candidate [redacted] and the recommended [redacted] for those [redacted] three-dimensional finite element models for [redacted] of the [redacted] mechanisms, [redacted] versus the projected life requirements, and [redacted] [redacted] [redacted] [redacted] Gas Turbine Development program is expected to serve as a guide in the preliminary definition [redacted] materials [redacted] A milestone chart with appropriate tasks [redacted] [redacted] is presented in Figure [redacted]

A proper costing of the total program would be possible after specific designs of [redacted] complete. With that constraint, it is estimated that the overall costs would be in the range of [redacted]

Specific [redacted] geometries will be analyzed for aerodynamic characteristics and compatibility with the objectives of the overall program. These [redacted] will be reviewed with [redacted] to incorporate [redacted] and recommendations in the design and [redacted] The designs may be modified to reflect these inputs. Several design iterations are anticipated prior to selection of [redacted] materials. Large utility size [redacted] would most likely require [redacted] stress levels [redacted] in [redacted] may impose additional constraints, which could result in [redacted] made out of [redacted] segments instead of [redacted] [redacted] will be designed to [redacted] on each other to provide the [redacted] and [redacted] with [redacted] between [redacted] of [redacted] may not pose a serious problem, however, it would be of major concern [redacted]

TES3-122

development and test program.

It is proposed that a turbine should be insulated and above the which can be and a which will the The exact which results in satisfactory at the temperature of the engine will be determined through the The feasibility of the and will be evaluated for their suitability in this application. The of more than material will likely be evaluated in the program.

Potential for ceramic will be defined. Suppliers will be contacted to for bench test evaluations and material properties determination. This task will proceed in accordance with Allison. The to be will be for a application. The of the poses a challenge from both design and fabrication standpoint. Discussions with have indicated that of the within their capabilities. Process development will be required to achieve satisfactory. The airfoils would make the manufacturing process easier and the quality of the product superior.

Allison plans to conduct bench scale testing of the different approaches, different to verify their. The series of tests will include frequency, and thermal exposure at load. characterization of the will be performed to verify analytical models and conformance to design requirements.

In addition, Allison plans to design, fabricate, install, and test [redacted] in an actual [redacted] gas installation. The purpose of this test will be to assess the [redacted] in a representative gas turbine [redacted].

The results from these [redacted] will be used as a guide in assessing the [redacted] in meeting the [redacted] objectives of the Advanced Turbine Systems program.

Preliminary experimental data and model evaluations indicate vast improvements in the overall performance of an advanced combined cycle system utilizing [redacted] versus [redacted] discharge only. A modest program on the use of [redacted] as the preferred [redacted] is proposed to refine the preliminary work already conducted. The test program results will then be adapted to [redacted] of advanced [redacted] turbines.

A turbine preliminary design incorporating a [redacted] as well as a design based on a [redacted] same [redacted] will be developed. The design(s) will incorporate all special [redacted] and [redacted] features required to ensure successful operation of the selected system. A preliminary assessment with the baseline [redacted] will be made.

An existing facility will be used to demonstrate the [redacted] concept. A new [redacted] will be designed and fabricated to test [redacted] incorporating the [redacted] applicable to advanced utility turbines. The test rig will be used to simulate [redacted] turbine [redacted] and [redacted]. The facility is capable of operating at gas temperatures above [redacted] °F, thus fully [redacted] the advanced turbine [redacted]. Pressures up to [redacted] psia can be achieved in the test section. A [redacted] will be designed to simulate the [redacted] that would be used in the advanced turbine.

Design, fabrication, instrumentation and installation of the test section is expected to require [redacted]. During this period the [redacted] will also be designed, fabricated, instrumented and installed. About [redacted] will be required to perform [redacted] of the facility and experimental hardware to ensure the quality of data that will be obtained.

A period of [redacted] of testing will be spent performing [redacted] tests. These tests will be used to develop an [redacted]. The same instrumented [redacted] of the [redacted] will be used in all tests. The [redacted] will be changed from test to test to obtain the optimum [redacted] configuration.

The final [redacted] of tests will focus on performing the [redacted] tests. This series of tests will address the [redacted] for the [redacted]. The [redacted] configuration developed during the [redacted] of testing will be used during the [redacted] tests. These tests will consist of using [redacted] of the same [redacted] as would be available in [redacted] installations. During this series of tests, the [redacted] will be monitored as a function of run time. Any degradation of [redacted] will be used to extrapolate the expected [redacted] of the [redacted] using this [redacted] concept.

Figure [redacted] contains a milestone chart showing the various tasks identified above. It is estimated that the overall cost of this experimental demonstration will be approximately [redacted].

Figure Experimental engine development and testing concept.

ADVANCED INLET AIR FILTERS

The two major challenges to long life of the hot section airfoils in gas turbines are base materials and inlet air filters. Base materials which are high in chromium, to provide protection from oxidation, are generally poor in their mechanical characteristics. At high operating temperatures, the base material is attacked by oxidation. Figure is a schematic diagram of oxidation versus temperature for typical base materials. Allison's experience indicates that a coating which is superior for protection would be susceptible to erosion. Similarly, a coating which would provide protection would erode more readily.

Hot gases entering the turbine contain various contaminants from products of combustion which are primarily present in the fuel and in the inlet air. In the ATS program, natural gas is the primary fuel of interest. Gas basically is a relatively clean fuel, with very low sulfur and other contaminants. Dry inlet air filters are utilized extensively to trap any particulates from entering the compressor. These filters, however, are ineffective in removing any vapors and aerosols.

A combination assembly of dry inlet filter and wet inlet air filter system is being considered to minimize the erosion which would attack the airfoil base. These filters will utilize a coating and operate to some extent as filters.

A component evaluation program is being proposed in Phase II in which specially designed inlet air filters will be tested for their capability to remove contaminants. In this program, Allison will work together with an inlet filter supplier. Allison will specify representative pressure drops, airflows, and different concentrations of sodium chlorides, sodium sulfates, sulfur, and other airborne contaminants which are likely to be encountered in the operating environment of gas turbines.

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Figure 12-7. Advanced Turbine Control System.

Design and Parts Fabrication. In conjunction with Allison's Industrial Gas Turbine and Advanced Turbine Control System, a scaled first-stage 501K van turbine rotor, standard case, and Advanced Turbine Control System will be designed and fabricated for incorporation into Allison's Research Laboratories Small Turbine Research Facility. This turbine test rig is specifically designed to investigate advanced turbine aerodynamic and Advanced Turbine Control System. The facility is also ideally suited to Advanced Turbine Control System concept screening. The deliverables from this task are technical drawings of the systems and complete sets of system parts.

Advanced Turbine Control System and Instrumentation. After completing hardware fabrication, the rig will be heavily instrumented and assembled initially Advanced Turbine Control System. The Advanced Turbine Control System will be Advanced Turbine Control System to enable a direct comparison of conventional Advanced Turbine Control System turbine Advanced Turbine Control System with the Advanced Turbine Control System Advanced Turbine Control System turbine efficiency at identical operating conditions. The deliverables for this task are the installations of the Advanced Turbine Control System in the Advanced Turbine Rig.

Advanced Turbine Control System and Instrumentation. First series of tests will be conducted with Advanced Turbine Control System to generate performance maps Advanced Turbine Control System Advanced Turbine Control System typical in industrial power turbines to obtain baseline performance curves. Advanced Turbine Control System Advanced Turbine Control System will be generated next at Advanced Turbine Control System Advanced Turbine Control System made possible by Advanced Turbine Control System. Comparison of these data will validate the direct performance improvements achievable with the Advanced Turbine Control System. Mechanical performance will be quantified in this task. The deliverables will include a series of turbine performance Advanced Turbine Control System and test results.

Advanced Turbine Control System and Instrumentation. A detailed plan will be generated in this task, incorporating the Advanced Turbine Control System Advanced Turbine Control System into an industrial gas turbine. The knowledge gained during the design, fabrication, and experimental activities will enable generating a detailed plan. The results of

improvements achieved in an industrial turbine will then be extrapolated to estimate the performance in turbines. The deliverables of this task will be a detailed for an industrial turbine and an improvement estimates for an advanced combined cycle utility turbine.