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Advanced Turbine Systems Program

Quarterly Report

February 1 - April 30, 1996

Work Performed Under Contract No.: DE-AC21-93MC29257

For
U.S. Department of Energy
Office of Fossil Energy
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Disclaimer

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EXECUTIVE SUMMARY

This quarterly report covers activities on key tasks of the Allison Advanced Turbine Systems contract DE-AC21-93MC29257, from February 1996 to April 1996.

Allison continued progress on the following tasks during this quarter:

* Task 5: Market Study
* Task 6: GFATS System Definition and Analysis
* Task 8.01: Castcool™ Technology Demonstration
* Task 8.04: Low Emissions Combustion System
* Task 8.07: Ceramic Vane Design and Evaluation
* Task 9.0: Program Management

SUMMARY OF SPECIFIC TASKS

Task 5.0: Market Study -- The objective of the market study is to focus on distributed generation prospects for an industrial ATS, utilizing the Allison ATS family as the primary gas turbine systems. During this quarter, Allison received comments from the Electric Power Research Institute personnel on the Statement of Work generated by Allison. EPRI agreed that the SOW was appropriate and complete. However, EPRI personnel indicated that the study would cost more than the amount stated in the SOW. Details of the status is presented under the specific summary of the task.

Task 6.0: GFATS Definition and Analysis -- The solid grid generation for the diffusers and the transition duct was completed. Application of the CFD code to the flowpath model for the diffuser design was also completed. The predicted flows indicate that the "turning" diffuser provides a better flow distribution. A heat transfer analysis on combustor outer case and transition duct wall was also performed.

The rapid prototype fabrication of the outer flowpath inner sleeve was successfully completed. The CADDS models with finer definition were created and converted to the .STL files. The aluminum castings for the outer case and transition duct are nearing completion, and will be ready for machining and instrumentation.

The study of carcass deflection from silo combustor is delayed pending completion of flow and heat transfer analyses.

The use of a one piece continuous blade track for the HP turbine was evaluated. A two-dimensional finite element heat transfer model was used to determine the cooling flow requirements. Stress analysis of the blade track designs indicated that segmenting the ring would be needed to reduce the thermal stress to within the allowable limits.

Verification of the mixed flow rotor 3 D analysis was completed. Good correlation increased confidence in the analysis of the ATS rotor. A rate of return analysis showed that the LP compressor could be cost competitive with the less expensive mixed flow rotor than with the two stage axial rotor design.

A 2 stage power turbine combined with the HP and LP turbines represent the latest ATS turbine configuration. It is estimated that reduction of stages in the turbine would save approximately $100,000 in the overall turbine costs.

A surge protection valve to protect from potential overspeed and infrequent compressor surges will be located on the combustor outer case and vent to the engine exhaust.

Creep rupture properties for coated CMSX-4 single crystal alloy for thin wall applications will start in early May. A total of one hundred test specimens will be tested.

Extended oxidation testing of coated turbine material specimens continued (IN 738, NiCoCrAlY coated specimens, and CMSX-4 +La, bare and Pt-Al coated pins). These tests will be concluded after accumulating approximately 8,000 hours. A summary of these tests is presented in the detailed section of this task.

The current study of Lamilloy thermal effectiveness consisted of three hole patterns. Test results of hole pattern variation on internal cooling performance are presented in graphical forms in the detail description of this task. The results show that the preferred hole pattern is the one with three rows of pedestals between a pair of cold/hot side holes, thus increasing cooling air contact with pedestal surfaces.

Work on TBC coated endwall showed a better overall thermal efficiency. The use of TBCs will be necessary to reduce the metal temperatures to levels permitting long life capability.

Work on the design requirements was initiated during this quarter. This sub-task is expected to be completed by the end of May, 1996.

Task 8.01: Castcool^{R} Technology Demonstration -- The Castcool^{TM} blade fabrication process enabled producing a total of 93 good quality blades which were fully inspected. The yield continued to show improvements. Yield continued to improve. These blades will be tested in the ATS Phase 3 gas generator tests. All blades will be inspected after the test to verify successful engine operation.

Detailed X-ray of defective blades showed cracks developed during final cleaning. The power level and frequency of the ultrasonic machine was sufficient to excite a panel mode in the thinnest area of the airfoil, resulting in cracking. Subsequent airfoil processing using lower powe ultrasonic cleaning approach has been successful.

Coating of vanes and blades was completed. Subsequent cold flow testing of blades demonstrated acceptable cooling flow levels. The vanes were determined to have excessive cooling flow reduction due to blockage. The low-flowing holes were enlarged. Cold flow recheck indicated these vanes to be acceptable for gas generator demonstration.

Final preparations were completed for integration of the seal into the gas generator test hardware. The seal will be assembled in the gas generator in May.

Blade tip bonding was completed during this period. a total of 17 tips with a bonded abrasive tip have been completed. total of 60 machined tips with a double braze, single crystal plate abrasive tip have been completed. These blades will be demonstrated in the ATS Phase 3 gas generator test to evaluate their durability.

Task 8.04: Low Emission Combustion -- Various combustor configurations were evaluated. Two silo combustion systems have been selected as potential candidates. One system is based on a traditional catalytic combustion concept. The other system consists of a premixer in the first stage followed by a catalyst.

Catalytica has completed feedstream contaminant testing of the two stage reactors. The results using salt and dust contaminations indicate some degradation of the catalyst may occur even at low exposure levels.

Flashback due to the ATS cycle is a concern. Extensive testing was done by modifying the standard module for the ultra low NOx program. In this study, parametric changes were made to the velocity field, mixing efficiency, and fuel-air concentration profile. The impact of these changes was recorded in terms of flashback propensity, NOx formation, pressure drop, and nozzle wall temperature. Eight different configurations were analyzed. This testing has helped in understanding the flashback phenomena. The results will be used in future module development for Phase 3.

Extensive LDA velocity measurements were made at ERC's atmospheric facility. These measurements were carried out to determine the interaction of swirling flows, velocity profiles at premixer/combustor interface, velocity profiles downstream of the module nozzle, velocity profile at the exit of the premixer, and particle size dependency of velocity measurements. The results indicated that particle size effects should be considered when interpreting velocity measurements from hardware. This testing helped in our understanding of the flashback phenomena and premixer design. The results will be used in module development for Phase 3.

Task 8.07: Ceramic Vane Design and Evaluation -- Activities for this task included : thermal and mechanical stress analyses of the vane and mount designs; long term vane life evaluations; evaluation of thermal shock tests for ceramic vanes; and design and drafting for the ceramic vanes and their mounts.

All maximum continuous power and emergency shutdown stress analyses have been completed. Stress levels and probability of survival values have been acceptable. Results show that maximum stresses occur at the trailing edge of the ceramic vane in the region of mid span. At the location of highest stress, material temperature is 1345 oF. The calculated fast fracture probability of survival exceeds 99.99 % for all vanes for the highest stress condition.

Although AS 800 (Allied Signal) and Sn 281 (Kyocera) are two promising ceramics for improved stress rupture lifetimes, there is currently insufficient long term stress rupture data for durations over 5,000 hours. Oak Ridge National Laboratories has agreed to provide long term data for these materials at test conditions suggested by Allison.

Current budget does not allow full vane sets from two suppliers. If additional funding is determined to be unavailable, then cascade rig fabrication and vane thermal shock tests should be eliminated in order to provide funds for vane sets of two ceramics.

The design and drawings of the ceramic vanes and their metallic mounts are complete. The final detailed dimension specification considers significantly different coefficients of thermal expansion between the ceramics vanes and metal mounts. The circumferential restraining pin was redesigned for a wedge shape. Also, truncating the back corner of the vane lower platform to accommodate the wedge shaped pin was helpful.

Task 9.0: Program Management -- The program management activity during this quarter was directed toward bringing the schedule and cost in line with the plan. The project is now in compliance with the revised schedule. The no increase in cost request by Allison to revise the schedule was approved by the DOE/METC Project Manager. The revision actually helps toward simplifying the tasks to be performed in Phase 3.

The Milestone Chart in Figure 1 contains the status of each program task.

MILESTONE SCHEDULE PLAN

DOE F1332.3
(11-84)

U.S. DEPARTMENT OF ENERGY

MILESTONE SCHEDULE ☐ PLAN ☐ STATUS REPORT

FORM APPROVED
OMB NO. 1901-1400

1. TITLE	2. REPORTING PERIOD	3. IDENTIFICATION NUMBER
Fig.1-1 ATS Phase 2 Extension	May 1995 - Aug. 1996	DE-AC-21-93MC29257 Mods 7,8

4. PARTICIPANT NAME AND ADDRESS
Allison Engine Company
P. O. Box 420
Indianapolis, IN 46206-0420

5. START DATE May 1, 1995
6. COMPLETION DATE Aug. 31, 1996

7. ELEMENT CODE	8. REPORTING ELEMENT	9. DURATION (1995: M J J A S O N D; 1996: J F M J J A S; FY 1997; FY 1998)	10. PER CENT COMPLETE a. Plan	b. Actual
P13105	Task 5.0	Market Study — Report ▽ (Aug 1996)	100	10
P13106	Task 6.0	GFATS System Definition and Analysis — Report ▽ (Jul 1996)	100	85
P13181	Task 8.01	Castcool — Report ▽ (Jul 1996)	100	100
P13184	Task 8.04	Low Emission Combustion System — Report ▽ (Jul 1996)	100	100
P131B	Task 8.07	Ceramic Vane Design and Evaluation — Report ▽ 3/98	100	46
P13109	Task 9.0	Program Management ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽ ▽	100	70

11. SIGNATURE OF PARTICIPANT'S PROJECT MANAGER AND DATE

DETAILED REPORTS ON INDIVIDUAL TASKS

TASK 5: DISTRIBUTED GENERATION MARKET STUDY

Progress Report for February 1996 - April 1996

A statement of work to conduct distributed generation market study was provided to the Electric Power Research Institute during the last quarter. A meeting was subsequently held at EPRI to review the scope of the study and to assess how this task might be compatible with the current EPRI study on distributed generation. The purpose of the study was to have a market study conducted on the potential application of the Allison ATS type advanced gas turbine in the distributed generation market.

EPRI reviewed the SOW and sent the comments in to Allison. EPRI stated that the SOW was comprehensive and the study should be conducted to include the tasks outlined. However, EPRI mentioned that the cost of the study would be $100,000 instead of the $40,000 indicated in the SOW.

A letter of request was sent by Allison to Mr. Leland Paulson, DOE/METC Project Manager, asking for his concurrence to increase the allocated cost for Task 5 from $40,000 to $100,000, without increasing the overall cost of the contract. Mr. Paulson provided the go ahead to Allison to increase the funding for Task 5. This approval authorized Allison to adjust the cost of the tasks within the overall contract, without increasing the total contract cost to DOE/METC.

Allison subsequently sent a revised request for proposal to EPRI, and asked EPRI to submit a formal proposal. This proposal will form the basis for a formal contract with EPRI. The contract will specify that EPRI must complete the tasks outlined in the DOE/METC approved statement of work generated by Allison, and in accordance with the funding and schedule.

TASK 6 QUARTERLY REPORT
FEBRUARY THROUGH APRIL 1996

6.01 Combustion Section Flow and Heat Transfer Analysis - This period the solid grid generation was completed for the both the "straight" and "turning" diffusers, and for the transition duct outer flowpath (i.e., outside the transition duct and inside the outer combustor case) using the previously generated Patran surface models of the involved components. Application of the CFD code to the solid grid outer flowpath model was completed for both the "straight" and "turning" diffuser designs. The predicted flow conditions will later be correlated with the rig test data from subtask 6.02. Work has begun to post-process the analytical data to prepare it for comparison to the rig test data. The predicted flows indicate that the "turning" diffuser provides a better flow distribution. However, design modifications will be required in Phase 3A to obtain the optimum flow conditions.

A heat transfer analysis was also performed. It assessed combustor outer case and transition duct wall temperatures and associated flow conditions. This completed the analytical effort on this subtask, except for generation of a Technical Data Report and completing the post-processing of the analytical data for comparison to the rig test data.

6.02 Combustion Section Scale Model Rig Test - Initial rapid prototype fabrication attempts were made early in this period. It was discovered that the CADDS model (an .STL file) definition was not fine enough for generating the surfaces of the four larger rig test parts (outer case, transition duct, and both diffuser designs). Also, the type of process selected, Selective Laser Sintering (SLS), was found to be unsatisfactory for these pieces. However, due to its smaller size and simpler shape, rapid prototype fabrication of the outer flowpath inner sleeve was successfully completed this period using the SLS process and the original .STL file.

To address the problems of the four larger rig test parts , their CADDS models were recreated with finer definition, and then converted to the necessary .STL files. Subsequent rapid prototyping of these parts using the finer model definition and a different process, Stereolithography (SL), was successfully completed. Unlike the outer case and the transition duct, both diffusers will be left in their plastic rapid prototyped form for the airflow rig testing. Dimensional verification of the plastic diffusers was done this period.

The rapid prototyped plastic outer case and transition duct were sent to Allison for visual review before being shipped to the aluminum investment casting vendor. The two parts then served as the patterns for making the molds in the investment casting process. The investment casting process was nearing completion at the end of the period. Following procurement early next period, the aluminum castings will be machined and instrumented to prepare them for rig usage. Airflow rig adaptive hardware fabrication was also nearing completion at the end of the quarter.

6.03 Study of Carcass Deflection from Silo Combustor - Work on this subtask has been delayed pending completion of subtask 6.01.

6.04 Reduced Turbine Cooling Flow Studies - The previous quarterly report outlined the fact that the secondary flow requirements for the ATS engine were too low to meet the life criteria for the engine. One obvious method to reduce cooling air was to reduce the clearances in the engine and it was noted that additional work was required to better define the practicality of using the reduced clearances. During the quarter, investigation of potential seal types for cavity sealing and their advantages and disadvantages in the engine was conducted.

Although Allison has used more expensive seals in the aircraft engines, the reliability versus cost does not always prove acceptable in the industrial application where long term reliability is key. Consequently, the standard labyrinth seal arrangement is desirable from a cost and reliability perspective. Investigation into this problem will continue, but the ATS engines will likely use a high percentage of labyrinth seals because of the industrial application.

6.05 Ceramic Blade Track Design - The objective of this subtask is to evaluate the use of a one piece continuous blade track for the first and second stages of the HP turbine. During this quarter, a two-dimensional finite element mesh was used as a heat transfer model for four preliminary designs. Heat transfer analysis was completed using a scaled 501-K combustion pattern, and the results indicated chargeable cooling flow is needed to reduce the maximum ceramic temperature to 2200°F for 16000 hour life.

Stress analysis was performed on the blade track designs using the finite element mesh generated for the heat transfer analysis. Maximum tensile stress from thermal gradients in the blade track were well above the range set for 16000 hour life. Segmenting the ring into six pieces reduced the stress levels to well within the acceptable range for survivability.

Since the continuous ceramic blade track will be unable to survive the temperature gradients imposed on it from the anticipated combustor pattern, this design is no longer being pursued. However, an investigation of a segmented ceramic blade track is being conducted in an effort to create a ceramic seal capable of meeting ATS life requirements.

6.06 Inlet Housing Loss Optimization - This task follows and benefits from the methodology recently developed and used for defining the radial inlet flowpath of another similar Allison industrial engine. Due to workscope reduction for this task, it was proposed to redirect this effort to optimize the inlet plenum flowpath upstream of the radial inlet housing to minimize losses resulting from inlet distortion.

After receiving estimates from the research lab for scale model work, it became apparent that the effort would not be within the available resources and schedule of this subtask. Also, such a program is not cost effective in light of the relatively small potential performance payoff. Inlet plenum design will be part of the skid design later in Phase 3 of the program. No additional work is planned for this subtask.

6.07 Study of Mixed-Flow LP Compressor - Verification of the mixed-flow rotor 3D viscous analysis was completed during this period. The verification was accomplished by applying the mixed flow rotor analysis technique to two previously designed centrifugal compressor rotors for which test data exists. Good correlation between the previously modeled impellers and the ATS rotor increased confidence in the analysis of the ATS mixed-flow rotor.

After several iterations, exit vane definition was completed based on 3D viscous analysis of the exit vane row. ATS mixed-flow rotor exit conditions predicted by the 3D viscous rotor analysis were used for this definition. The analysis indicates that the mixed-flow rotor will have to be moved forward approximately 3 inches to minimize turning losses before entering the HP compressor. Analytical efforts for this subtask were completed this period, which included off-design conditions. The detailed Technical Data Report was also completed and published this period.

A preliminary customer's internal rate of return (IRR) cost analysis showed that for a break-even condition, the LP compressor could be approximately 1% less efficient with the less expensive mixed-flow rotor than with the two stage axial rotor design. However, this applies before factoring in significant non-recurring capital equipment and additional rig test costs associated with the mixed-flow design. Risk of achieving the predicted performance must also be considered.

6.08 Increased LP Rotor Speed - The last quarterly report, covering the period from November 1995 through January 1996, stated that a three stage power turbine had been defined for the Allison ATS engine. This three stage turbine combined with the two stage HP turbine for a total of five turbine stages, one less than in the proposal engine. In the February monthly report it was erroneously stated that a two stage power turbine had been identified for the Allison ATS engine. In fact, the two stage power turbine has been selected for the reconfigured engine that is being developed under Phase 3A of the program. This reconfigured engine has a two stage HP turbine, a one stage LP turbine, and a two stage free power turbine for a total of five stages of turbine. The approximate $100,00 cost savings reported in February will be approximately $50,000 as was stated in the last quarterly report.

No further work will be done on this subtask.

6.09 Surge Protection Valve Study - Compressor surges, while infrequent, may occur in industrial gas turbine engines. In the event of a violent surge, severe damage to the compressor flowpath hardware can occur. The need for a surge protection valve has been established to protect the ATS compressor due to the relatively large volume of high pressure and temperature air in the silo combustor.

There is also concern for potential overspeed from the large amount of stored pressure energy resulting from electrical generator load loss. It has been identified that one valve can provide protection from either event. The valve will be located on the combustor outer case and vent to the engine exhaust. An initial study of the control requirements was performed in the previous period. No additional work was performed on this subtask during this period.

6.10 Update Design Sketches - This subtask covers revisions to the general arrangement drawing of the ATS engine which was created in Phase 2. Work done under Subtask 6.08 had previously identified a new three stage power turbine for the Allison ATS engine. Further studies conducted under Phase 3A have led to a more extensive reconfiguration of the engine. In short, Allison is developing an engine with a two shaft gas generator and a two stage free power turbine. The details of this reconfiguration, have been thoroughly discussed and reported under Phase 3A of the program. Since the detailed definition of this turbine is being done in Phase 3A, it is felt that the general arrangement being created in phase 3A is the proper place to show this configuration.

6.11 Effect of Thin Wall and Coating on Single Crystal Mechanical Properties - The objective of this subtask is to generate creep rupture properties for coated CMSX-4 single crystal alloy for thin wall applications. One hundred test specimens are to be tested, twenty-five with AEP coating, twenty-five with conventional Pt-Al coating, twenty-five with NiCoCrAlY coating, and twenty-five bare samples.

The NiCoCrAlY and Pt-Al coated specimens have arrived at the testing facility, and testing began on these in early May. Finish heat treating of the AEP coated and bare specimens is scheduled to be completed in early in May, putting their arrival at the testing facility at mid to late May.

6.12 Extended Oxidation Testing - Oxidation testing continued during April on all specimens in this program. Figure 1 is a summary of the testing that has taken place to date under Phase 2 and Phase 2 Add-on portions of the program.

Nickel-based alloys such as IN738 were identified as an airfoil base material in the Phase 2 proposal. Allison field experience indicates that the IN738 material does not have adequate oxidation resistance. Thus the IN738 samples were inserted to provide relative oxidation data.

A slot was made available in the rig as some other pin samples deteriorated. Two X-40 pins were inserted into the test to determine the relative oxidation life of cobalt-based alloys compared to nickel-based alloys. This testing will be used to better access material selections in the Phase 3 portion of the program.

Extended oxidation testing will be ended after the specimens from Phase 2 have accumulated 8000 total hours to allow adequate time for evaluation of the specimens and preparation of the final report.

PROGRAM PHASE	MATERIAL	COATINGS	HOURS
2	CMSX-4	Pt-Al, simple alumide, NiCoCrAlY	7920
	CM186	Pt-Al, simple alumide	7920
2 Add-on	IN738	Pt-Al, NiCoCrAlY	2920
		simple alumide	1128
	CMSX-4 + La	Pt-Al, simple alumide, bare	2920
	CMSX-3	NiCoCrAlY	2122
	X-40		85

Figure 1 -- Oxidation Testing Time on Coated Specimens

6.13 Castcool Heat Transfer Effectiveness Testing - The February-April period saw completion of the test samples and the corresponding thermal effectiveness testing. Figure 2 shows the effect of hole pattern variation on internal cooling performance, and also illustrates the three hole patterns that were tested; 4S, 4D, and 2D. In each diagram, black circles represent cold side holes, white circles represent hot side holes, and squares represent pedestals. Note that air flows in through the cooling circuit (cold side holes) and takes the most direct route through the passages between pedestals, to the hot side exit holes.

The preliminary effectiveness results plotted in Figure 2 indicate that the 2D hole pattern resulted in a significantly lower effectiveness than the 4S and 4D patterns, which produced about the same level of effectiveness. For the 2D hole pattern, there is only one pedestal (two passages around the pedestal) between any given pair of cold/hot side holes, thereby minimizing cooling air contact with pedestal surfaces. The 4D hole pattern puts three rows of pedestals between any given pair of cold/hot side holes, thereby increasing cooling air contact with pedestal surfaces. However, the arrays of pedestals on the diagonals between cold side holes (dead zones) remain essentially unwashed by cooling air.

Furthermore, the fewer holes per unit area in the 4D design increases the pressure drop and severely limits the maximum air flow through the sample. The 4S hole pattern produces the same level of cooling effectiveness as the 4D with much lower pressure drop over a wider range of cooling air flow, and virtually eliminates "dead zones." Based on these results, the 4S hole pattern is clearly the best of the three patterns considered here.

The effectiveness data collected to date was curve fit using the equation derived from an energy balance between the Lamilloy metal surfaces and the cooling air flow:

$$\eta = 1 - \exp\{-a(1/w)^{b}\}$$

where *w* is the mass flow rate of cooling air, *a* contains the product of overall convection coefficient and surface area, and *b* contains the Reynolds number exponent. Note that the equation for η is derived from a given physical configuration. The experimental data correlates well with the analytical prediction of the thermal effectiveness η, indicating that the data is valid. The ability to obtain the coefficients *a* and *b* along with a given coolant flow will permit the prediction of the η for a variety of conditions.

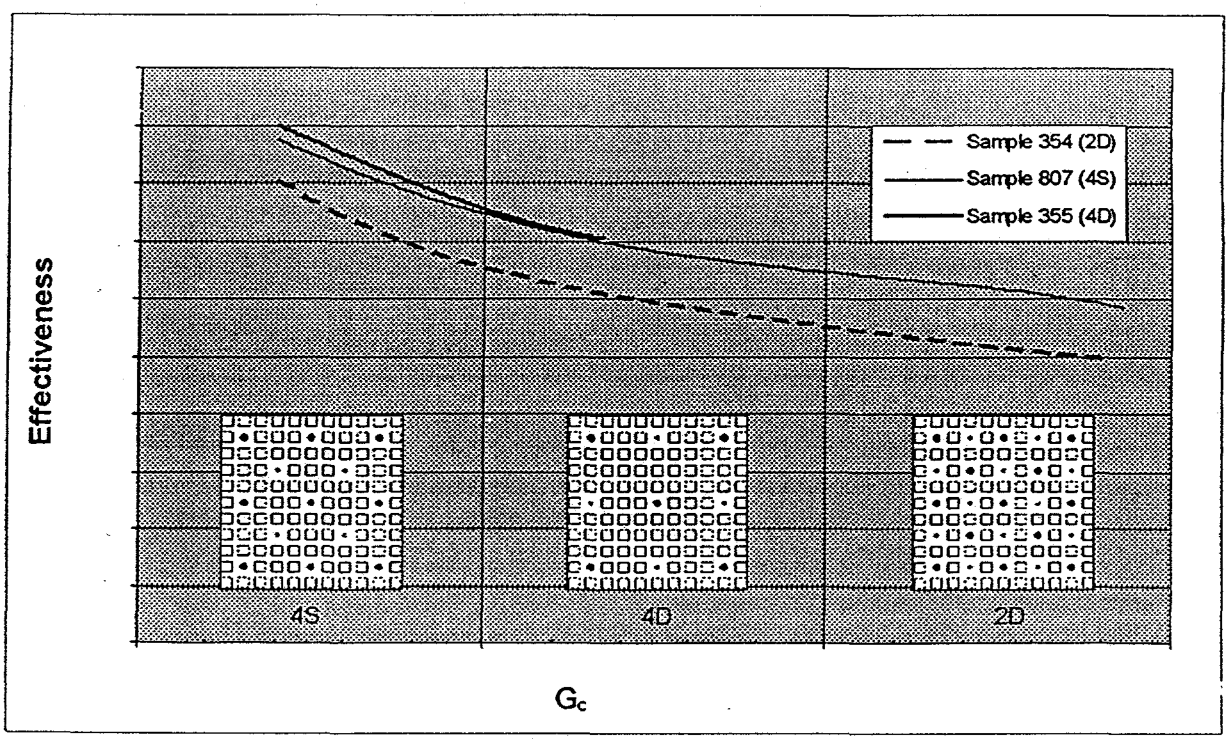


Figure 2 -- Effect of Hole Pattern Variation on Internal Cooling Performance

6.14 Thermal Barrier Coating of Turbine Vane Platforms The previous quarterly report detailed how the use of thermal barrier coating (TBC) can effectively reduce metal temperatures in a Castcool-type vane, when combined with smaller holes in the cooling circuit. This permits a slightly better overall thermal efficiency, though slight reductions in nonchargable air will not have a significant effect. The use of thermal barrier coatings will likely be necessary to reduce the metal temperatures to levels permitting long life capability. It remains to be seen just how well a TBC can be applied to the vane without clogging the small gas side cooling holes. Recall that the previous section mentioned that combining film cooling with a TBC could also produce a cost effective solution. It is recommended that further investigation into the application of TBCs be continued in the next phase of the program.

6.15 Design Validation - The first step in Allison's design validation process is the establishment of the design requirements document by the Chief Project Engineer. During this quarter work on the design requirements was initiated, and it is anticipated that the requirements will be completed in May. Following the publication of the design requirements the design criteria will be developed as a part of Phase 3A. According to Allison procedures the conceptual design review is to be conducted after the design requirements, the design criteria, and the general arrangement drawing are all completed. This review will also be accomplished in Phase 3 of the program.

INTER-ORGANIZATION

Allison

Allison Engine Company P.O. Box 420 Indianapolis, Indiana 46206-0420

To : S. Ali Address :

From : J. Skinner Date : May 18, 1996

Subject ATS Phase 2 Quarterly Progress Report for February - April, 1996 - Task 8.01

Task 8.01, Castcool™ Technology Demonstration was completed during the reporting period of February 1, 1996 to April 30, 1996. The progress made during this reporting period is summarized in the following paragraphs.

8.01.01 - Castcool™ Blade Fabrication (100% complete)

Objective:

Castcool™ turbine technology is a critical technology needed for the DoE's ATS program. Castcool™ is a manufacturing process that enables the casting of holes and intricate patterns in high temperature capable single crystal materials. Allison is using the Castcool™ process to manufacture turbine airfoils that utilize highly effective cooling schemes, such as Lamilloy®, in a cost effective manner to improve engine thermal efficiency.

Allison has been developing a Castcool™ blade that is directly applicable to the ATS turbine. Under an ATS Phase 2 task, Allison continued to refine the fabrication process initially developed under IR&D and cast a limited number of blades (56) and improved yield by 60% from the start of the effort. However, the fabrication process cannot be validated by making a small quantity of airfoils. A large enough sample needs to be made to verify the yield and overall quality of parts. This subtask was established to build upon the previous efforts and cast an additional number of engine quality blades and complete all detailed inspections of these castings. This includes visual inspections, ultrasound (for wall thickness), borescopes, x-ray (to examine internal features and deviations), chemistry analysis, metallography, water flow, and air flow tests. This data will be compared with the design intent and previous castings to validate the current process and identify potential process refinements that would be required to assure production readiness for ATS applications. As a side benefit, this task will fabricate blades that can used for other subtasks and for engine testing.

Progress:

Significant activity on this effort continued during this reporting period. To date, a total of 93 good quality blades have been finished and fully inspected. Yield continued to show improvement from earlier molds and has surpassed the levels demonstrated in the Phase 2 effort. Continued progress in the

AEROSPACE GROUP

area of wax assembly quality has been the result of continued effort by Allison's Single Crystal Operations working in conjunction with the assembly vendor.

During final inspection of the Castcool™ blades, cracks were detected along a 45° angle near the trailing edge. Detailed X-ray inspection found cracks in 14 of the blades, all in the same location on the airfoil. A review of the blades found that the cracks developed in the final cleaning of the parts. The blades were cleaned using an ultrasonic method. The power level and frequency of the ultrasonic machine was sufficient to excite a panel mode in the thinnest area of the airfoil wall, resulting in cracking in 14 of the airfoils. This area is in the trailing edge pin-fin cooling area, not in the Castcool™ part of the airfoil. Subsequent airfoil processing using lower power ultrasonic cleaning process has been successful. A review of the design and observed failure mode does not indicate a problem in engine operation, therefore, the remaining blades were cleared for demonstration in the ATS Phase 3 gas generator test. All blades will be inspected after the gas generator test to verify successful engine operation.

8.01.02 - Castcool™ HP Turbine Design Analysis (100% complete)

Objective:

In 1994, Allison completed testing of an ATS prototype turbine in the AE 301X turbofan engine under a Phase 2 task. This turbine, which featured Castcool™ technology first stage vanes, was successfully tested above the ATS turbine rotor inlet temperature goal of 2600°F. As reported in Phase 2 Annual Report, a significant amount of information and experience was gathered on this turbine from the test program. Future plans call for upgrading the turbine to incorporate Castcool™ first stage blades and running a durability test at even higher temperatures in a gas generator. This subtask has been established to evaluate the results of the previous test and analyze the design modifications to the turbine in relation to this future testing.

Progress:

Completion of this task was reported in the previous period. No new activity during this reporting period.

8.01.03 - Demonstration of Coating Castcool™ Airfoils with Pt-Al (100% complete)

Objective:

Under a previous ATS Phase 2 task, Allison evaluated several types of coatings for long term oxidation resistance. These results indicate that a platinum-aluminide AEP coating is the best solution for the first stage Castcool™ CMSX-4 airfoils. Allison has performed some demonstrations of applying this coating on Lamilloy® and Castcool™ disk samples, but not on actual Castcool™ airfoils. Under this subtask, Allison is developing and demonstrating the application of the platinum-aluminide AEP coatings on Castcool™ vanes and blades using existing assets.

Progress:

Coating of 4 Castcool™ vanes and 5 Castcool™ blades was completed. Subsequent cold flow testing demonstrated acceptable cooling flow levels in all 5 Castcool™ blades. These blades will be demonstrated in the ATS Phase 3 gas generator testing. The Castcool™ vanes were determined to have excessive cooling flow reduction due to hole blockage. The low-flowing holes were enlarged using a highly localized grit-blast procedure, demonstrated successfully on earlier Allison Lamilloy® airfoils. Following a successful cold flow recheck, these assets were also cleared for demonstration in the gas generator.

8.01.04 - Development of a Film-riding Face Seal (100% complete)

Objective:

Film riding seal technology has the potential to reduce seal leakage below levels demonstrated on brush seals with higher ΔP capability and longer durability due to the non-contacting design, making it an attractive technology for ATS applications. Allison has been developing this technology and has demonstrated these potential benefits on a seal rig. This task will take the "next step" and design, fabricate, and rig test an engine configuration film riding seal. This seal will replace the current three-stage brush seal at the compressor discharge location on the T406/AE engine compressor. After successful rig testing, this seal will be available for gas generator/engine testing. Allison is subcontracting John Crane Co. to fabricate and rig test the seal.

Progress:

Final preparations were completed for integration of the seal into the gas generator test hardware. The seal will be assembled in the gas generator in May for a June 1996 demonstration.

8.01.05 - Castcool™ Blade Abrasive Tip Development (100% complete)

Objective:

The Castcool™ blade design incorporates Lamilloy® cooling technology to cool an abrasive tip (for clearance control) with a minimal amount of cooling air. Two fabrication approaches are being evaluated for the blade tip:

(1) a Castcool™ tip with a bonded abrasive tip, and
(2) a machined Lamilloy® tip with a double-braze, single crystal plate/abrasive tip.

Under our completed ATS Phase 2 Castcool™ blade fabrication development effort, we successfully cast the Castcool™ tip on several development pieces. The data taken to date clearly shows a negative impact on casting yield with this approach. The need exists, therefore, to develop an alternative approach. This task will develop the process to put abrasive tips on both configurations, demonstrate these processes on a set of blades, and compare the finished part yield of both approaches and provide a recommendation for the ATS program.

Progress:

Blade tip bonding was completed during this period. A total of 17 Castcool™ tips with a bonded abrasive tip have been completed. A total of 60 machined Lamilloy® tips with a double-braze, single crystal plate/abrasive tip have been completed. These blades will be demonstrated in the ATS Phase 3 gas generator test to evaluate the durability of both configurations.

Allison

Allison Engine Company P.O. Box 420 Indianapolis, Indiana 46206-0420

TASK 8.04

Quarterly Progress Report for February-April 1996

Status

Task 8.04 is 100% complete.

Task 8.04.01: Catalytic System Pilot/Preburner Design and Test

Various ATS combustor configurations (silo-type, externally mounted canted can, annular, and canted annular) were evaluated. For the same combustor volume, the silo combustor provides the lowest total surface area and the highest backside convective cooling velocity for the same liner/casing gap. However, a silo combustor would require a large envelope for installation and a large catalyst diameter.

Two silo combustion systems have been chosen as potential candidates. The first system is the "traditional" catalytic combustion system which includes a pilot/preburner in the first stage, a premixer in the second stage followed by a catalyst. The high pressure, high temperature ATS cycle allows the consideration of a second system. This system consists of a premixer in the first stage followed by a catalyst and post-homogeneous combustion zone. The pilot and additional premixers are then located farther downstream. This configuration allows for a smaller catalyst as well as keeping the catalyst upstream of the acceleration and part-load combustion. Further analysis and testing under Phase III will enable a selection of the ATS combustion system.

Task 8.04.02: Catalytic Element Evaluation

Catalytica has completed feedstream contaminant testing of two-stage catalytic reactors. Both salt and dust contamination tests were conducted. For each of the accelerated tests, the salt or dust contaminant feed rate was adjusted so that a fifty-hour test exposed the catalyst to the same total contaminant mass as would 8000 hours of operation. All of the tests were performed at 501-KB7 full power conditions, but at a reduced pressure of 9.4 atm. The dust (silica or alumina particles) concentrations ranged from 4 to 13 ppbw (parts per billion by weight). For each half of the dust contamination testing, the catalyst was exposed on only one of two separate solutions of either silica or alumina particles. The salt contamination testing used a salt water solution. The results indicate some degradation of the catalyst may occur even at low exposure levels

Task 8.04.04: Aerodynamic Stabilized Premixer Development
Flashback:
Due to the extreme conditions in the ATS cycle, flashback and autoignition are a concerned. As a starting point in understanding the parameters involved in determining flashback, extensive testing was done by modifying the RSPN1.2L which is the standard module for the DOE 9 ppm program. We have significant experience with this RSPN1.2L premixer and choosing this design for a parametric evaluation would yield the greatest understanding of the variables that are influential in flashback.

The purpose of a premixer is to uniformly mix fuel and air prior to combustion. As such, a combustible mixture is always present to support a flame. Combustion within the premixer is suppressed by eliminating all ignition sources. The premixer design has a contraction at the discharge of the radial swirler that forms a throat with velocities sufficient to avoid flame propagation into the premixer that would act as an ignition source. In the optimum design, the axial velocity profile at the throat would match with the local fuel-air concentration profile to control upstream flow propagation into the premixer.

In this study, parametric changes were made to the velocity field, mixing efficiency, and fuel-air concentration profile. The impact of these changes was recorded in terms of flashback propensity, NOx formation, pressure drop, and nozzle wall temperature. The following paragraphs briefly describe the modifications and the results. All comparisons will be made to the baseline design.

RSPN1.2LM3 employs a standard module, but blocks the top 4 fuel holes on each tube to lean out the core airflow. This module did achieve better flashback margin, but at the expense of less mixedness, higher NOx, hotter liner walls, and a higher hotflow pressure drop.

RSPN1.2LET uses a standard swirler and fuel injection, but the nozzle contraction is smaller, increasing bulk throat velocity by 56%. Laser Doppler Anemometry (LDA) measurements, however, indicated that the throat velocity profile changed to give lower centerline velocities than the standard design. The module flashed back easily, even at lean conditions and high pressure drops. This module also had higher NOx, and a very hot nozzle.

RSPN1.2LENT uses a standard swirler and fuel injection, but eliminates the nozzle contraction entirely, with the hope that the velocity profile will flatten, reducing flashback tendency. However, the bulk velocity at the premix cup exit reduced by 44% allowing flashback at all tested conditions.

RSPN1.2LL uses a standard swirler and fuel injection, but the premix cup is lengthened .75" . This modification had no measurable impact on emissions or flashback. Cold flow atmospheric mixing measurements indicate that the mixing profile was unaffected by the increased length.

RSPN1.2LS takes a standard module design and reduces the fuel injection hole diameters to increase fuel pressure drop. Flashback margin appeared unchanged from a standard RSPN1.2L. However, slightly higher NOx, hotter walls and a lower Lean Blowout indicated an adverse affect on mixing performance.

RSPN1.2LEM4 uses a standard swirler, but employs smaller and fewer fuel orifices than the baseline design. This is in an effort to decrease fuel circuit ACd. The observed higher NOx and greater tendency to flashback can be attributed to the richer centerline fuel concentration at the nozzle throat, as measured by cold flow sampling measurements. It would appear that a lean center recirculation zone limits NOx emissions more effectively than does a perfectly flat mixture fraction profile.

RSPN1.2LEJ is a standard RSPN1.2LE module, but flows an air jet through the pilot fuel port located within the premixer and discharging along the module's centerline. This modification did not have a large impact on NOx or flashback resistance. However, it was observed that while the module resisted flashbacks at pressure drops greater than 2.7% (same as baseline), the module was seen to flash back again between about 4.5% and 7.5% pressure drop. This anomaly was only observed with this particular module and may be due to changing air splits between the main and pilot jet of air. The actual airflow splits for this module were not determined.

RSPN1.2LLSN uses a standard swirler and fuel injection, but has a shorter nozzle expansion. This module exhibits lower NOx, but similar flashback characteristics to the baseline RSPN1.2L. The liner walls were hotter and needed extra cooling due to the corner recirculation and combustion. This corner combustion may account for the lower NOx, but it is unknown how this zone may be affected by multiple module interactions.

This testing has aided in the understanding of flashback phenomena. The results will be used in future module development in ATS Phase III.

Atmospheric Velocity Measurements:

Extensive LDA velocity measurements were made at ERC's atmospheric facility. These measurements were carried out to determine (i) interaction of swirling flows between adjacent premixers in a parallel stage, (ii) velocity profiles at the premixer/combustor interface, (iii) velocity profiles downstream of the TRSPN module nozzle, (iv) velocity profile at the exit of the non-stabilizing premixer AMP2, and (v) particle size dependency of velocity measurements. The details of these measurements and the findings are presented in the following paragraphs.

Reacting and non-reacting velocity measurements were made on a parallel stage configuration with 3 RSPN1.2L modules. Both sets of measurements showed that a central recirculation zone exists along the centerline of each module. The gas velocity in between the modules is high. The swirling flows coalesce into a bulk swirling flow by about 9" from the nozzle throat exit.

Velocity at the nozzle throat or the interface between the premixer and the combustor have been made for a couple of premixer designs by providing optical access through 1/4" holes drilled in the side of the nozzle. Steps were taken to minimize the impact of this by sealing off the gap between the nozzle and the quartz liner such that the access hole does not provide a leak path. These measurements have provided the first data in this region and have been useful in improving modelling approaches. Further improvements can be expected from the use of the back-scatter technique since potentially, the need to drill the 1/4" holes will be eliminated.

Non-reacting velocity measurements were made downstream of the TRSPN nozzle expansion. The measurements are similar to those obtained with the Green Thumb (DOE 9 ppm) modules with the exception of the shape of the axial velocity profile close to the module at the centerline. The peak negative velocity is not located along the centerline in the recirculation zone but is slightly off-axis. This could be due to the fact that the TRSPN module has a nozzle with a shorter diverging section followed by a sudden expansion. The tangential velocity profiles also show a consistent difference close to the nozzle at the centerline. The peak tangential velocity occurs further away from the centerline here. At larger distances from the module, both axial and tangential velocity profiles are similar to those obtained with the Green Thumb modules.

ERC attempted velocity measurements on AMP2, the premixer with minimal swirl. They had a lot of difficulties getting any measurements in the region close to the premixer exit. The only satisfactory measurements they could get were away from the region of interest. The AMP2 design incorporates an axial swirler. The central hub is of similar size as the premixer exit. A similar 'hole' where no particles are present at the axis of the swirling flow has also been observed with the RSPN type designs. This problem is discussed below.

The inability to maintain particles in the center of the swirling flow of the RSPN type design suggests that the premixer design acts as a particle separator. In the case of the AMP2 hardware, the swirl is minimal and the particles perhaps do not follow the flow and run into the conical converging wall of the module. To confirm this, a particle size dependency of velocity measurements was investigated using a RSPN type design. Two particle sizes were evaluated: 1 micron and 0.3 micron. At the module throat, the smaller particles give a higher velocity. At the exit of the nozzle, the smaller particles give a lower peak velocity. These observations are consistent with the fact that the smaller particles have smaller inertia and can follow the flow better. At the throat, the flow has just been accelerated by the converging section of the nozzle. Smaller particles accelerate faster and hence register a higher velocity (closer to and perhaps lower than the actual velocity). At the exit of the nozzle, the flow has just been decelerated by the diverging section. The larger particles have a higher momentum and maintain their velocities longer and yield higher magnitudes. Unfortunately, very small sized particles can not be used since the signal drops off very rapidly. Thus the particle size effects should be borne in mind while interpreting velocity measurements from practical hardware.

This testing has aided in the understanding of flashback phenomena and premixer design. The results will be used in future module development in ATS Phase III.

TASK 8.7

ENGINE COMPONENT DESIGN AND EVALUATION

Quarterly Report for February, March, and April 1996

Objective: Since ceramics have not been used commercially for airfoils in industrial gas turbines, it would be beneficial to prove this technology first for current turbine inlet temperatures (approximately 1100 C (2000 F)) as a stepping stone to introduction at the very high ATS inlet temperatures in excess of 1427 C (2600 F). Accordingly, the objective of this task is to design, evaluate and demonstrate ceramic first stage vanes in an industrial turbine.

This task was established in June of 1995 through contract Mod A008 of the program.

Accomplishments: Activities for this task were in the following areas:

* thermal and stress analyses of the vane and mount designs
* long term vane life evaluations
* evaluations of thermal shock tests for ceramic vanes
* design and drafting for the ceramic vanes and their mounts
* presentation

Vane/mount analyses. All maximum continuous power and emergency shutdown stress analyses have been completed for the ceramic vanes using the three bounding combustor temperature patterns. Calculated ceramic vane stress levels and probability of survival values have been acceptable for all of these cases. The following Tables show results of the stress analyses. Maximum stresses in the vane are given for each condition along with the location of maximum stress, the material temperature at that location, and the probability of survival of all 60 vanes considering the statistical nature of the ceramic properties.

Figure 1 shows the thermal shock stress contours for the maximum inner gradient bounding combustor temperature pattern at about 0.9 sec after initiation of emergency shutdown. These conditions produce the highest calculated stress (30.2 ksi) of all the conditions evaluated. This stress, like maximum stresses for all the transient and steady state analyses, occurs at the trailing edge of the ceramic vane in the region of mid span. Because the vane is experiencing rapid cooling in the emergency shutdown cases, the material temperature is relatively low. At the location of the highest (30.2 ksi) stress, that materials temperature is calculated to be 1345 F. Table 1 shows that the calculated fast fracture probability of survival exceeds 99.99 % for all 60 vanes for this highest stress condition, as well as for all the other emergency shutdown combustor pattern conditions.

SUMMARY OF CERAMIC VANE STRESS ANALYSES

Table 1.

TURBINE EMERGENCY SHUTDOWN

Bounding Combustor Pattern

	Max. Inner Gradient	Max. Temp.	Max. Outer Gradient
Max. Stress (KSI/MPa)	30.2/208	24.5/175	28.9/199
Vane Set POS	>0.9999	>0.9999	>0.9999
Temp. at Max. Stress Loc.(F/C)	1345/729	1370/743	1350/732
Location	Mid Span Trail Edge	Mid Span Trail Edge	Mid Span Trail Edge

Table 2.

TURBINE MAX. CONTINUOUS OPERATION

Bounding Combustor Pattern

	Max. Inner Gradient	Max. Temp.	Max. Outer Gradient
Max. Stress (KSI/MPa)	24.5/169	17.6/121	21.8/150
Vane Set POS	>0.9999	>0.9999	>0.9999
Temp. at Max. Stress Loc.(F/C)	2160/1182	2330/1277	2260/1238
Location	Mid Span Trail Edge	Mid Span Trail Edge	Mid Span Trail Edge

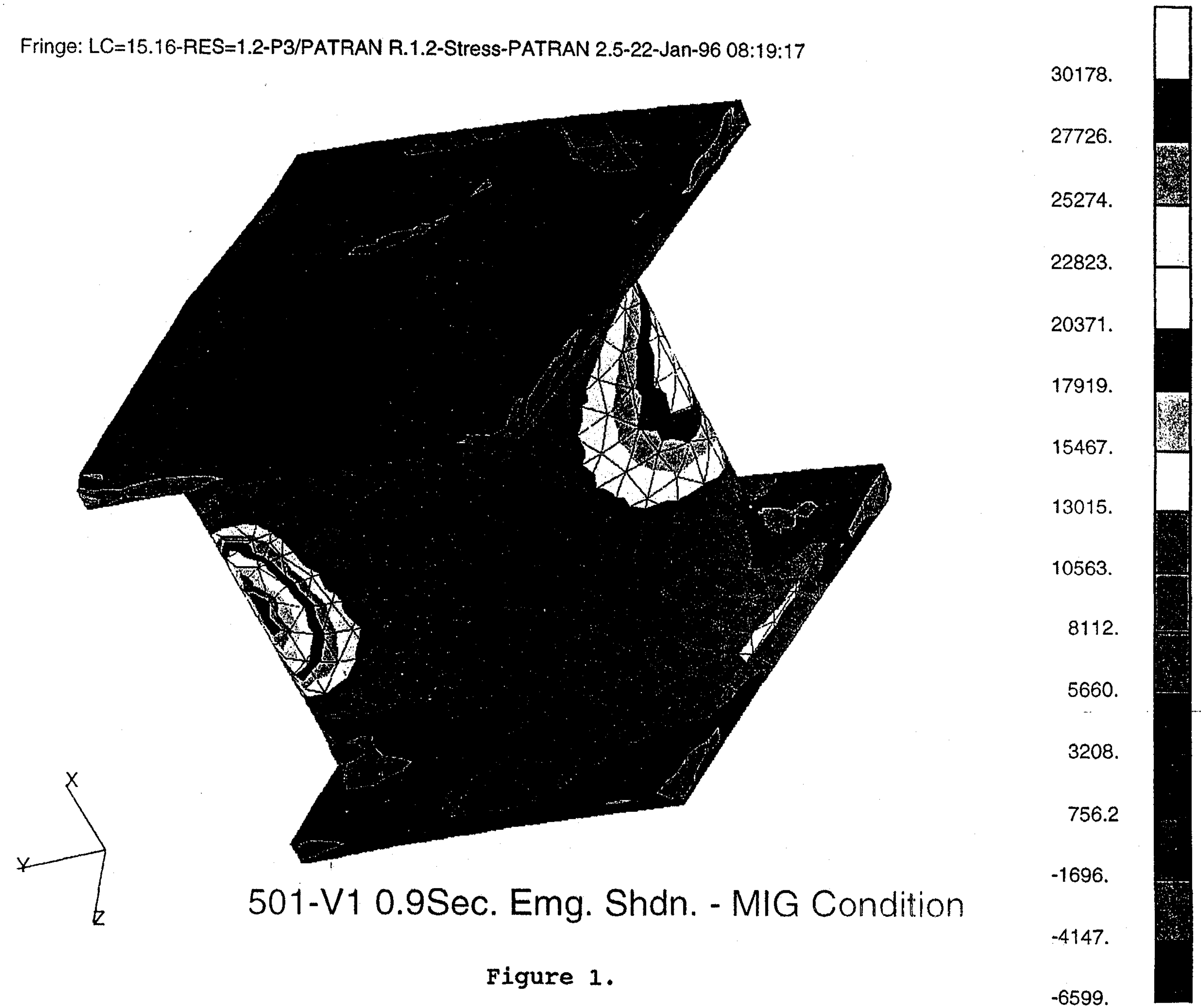
Figure 2 shows that the highest stress is 24.5 ksi at conditions of maximum continuous power and the maximum inner gradient bounding combustor temperature pattern. Table 2 indicates that this is the highest steady state stress calculated in the ceramic vane and that the fast fracture probabilities of survival exceed 99.99 % for all steady state conditions evaluated. The ceramic material temperature is about 2160 F at the trailing edge location of maximum stress. The highest continuous power stress is slightly lower than that (26 ksi) reported by Solar for their ceramic vane stress analyses.

Long term vane life. The analyses described above showed very good fast fracture probability of survival values. However, it is well known that ceramic long term stress rupture strengths at high temperatures are significantly lower than fast fracture strengths. NGK Insulators (Japan) silicon nitride material SN 88 appears to be the only ceramic that has survived stress rupture tests at the maximum steady state stresses and temperatures indicated above for durations in the 5000 to 10000 hr range needed for the turbine demonstration. DOE has given permission to utilize the NGK material. However, the NGK sales office in the U S indicated that their production capabilities are booked and an Allison appeal to the NGK home office in Japan to quote on vanes for this program has been denied. Consequently, no ceramic with adequate life shown in long duration materials tests is available to this program for the Allison 501 turbine demonstration at a commercial site.

Although AS 800 (Allied Signal) and SN 281 (Kyocera) are two promising ceramics for improved stress rupture lifetimes, there is currently insufficient long term stress rupture data for durations of 5000 to 10000 hrs necessary to verify their use in the engine demonstration at a commercial site. Oak Ridge National Laboratories (ORNL) has verbally agreed to provide long term data for these materials at test conditions suggested by Allison. These conditions are representative of the steady state stresses and temperatures calculated for the vanes which are shown in the Tables 2. Consequently, Allison would like to procure full vane sets of two materials and base the decision on which material to use in the engine on additional long term ceramics tests to be run at Oak Ridge National Laboratories (ORNL) during the approximately ten months needed for vane fabrication.

Thermal shock tests. A review of the Task 8.7 budget indicates that insufficient funds are available to procure full vane sets from two suppliers. The budget for the vane thermal shock rig fabrication and testing is the only sufficient source to accommodate the approximately $ 345 K additional cost for a second set of vanes (including spares and specimens).

If additional funding is determined to not be available, Allison will probably recommend elimination of cascade rig fabrication and vane thermal shock tests in order to provide funds for procurement of vane sets of two ceramics. The thermal shock tests



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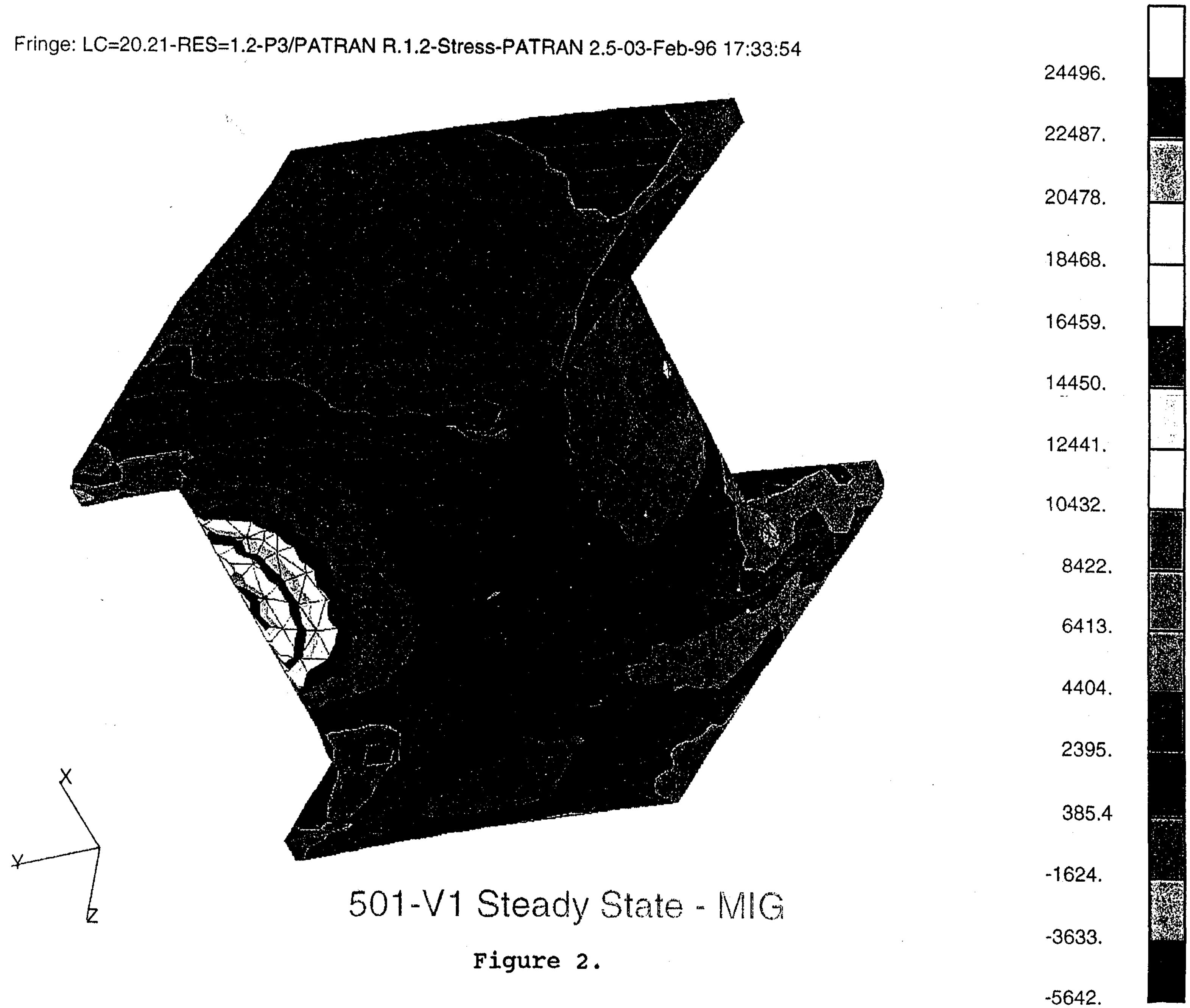
501-V1 0.9Sec. Emg. Shdn. - MIG Condition

Figure 1.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14450.
12441.
10432.
8422.
6413.
4404.
2395.
385.4
-1624.
-3633.
-5642.
X
Y
Z
501-V1 Steady State - MIG

Figure 2.

are probably not critical because stress analyses have calculated acceptable stress levels and probabilities of survival at turbine emergency shutdown thermal shock conditions.

Vane/mount design. The design and drawings of the ceramic vanes and their metallic mounts are complete except for checking and fine tuning the specification of a few dimensions and tolerances using results from thermal and stress analyses. The final detailed dimension specification considers significantly different coefficients of thermal expansion between the ceramics vanes and metal mounts. This results in differental thermal growths between the ceramic vanes and their metal mounts and opening of gaps from cold engine startup to steady state operating conditions. The extent of increase in circumferential and axial gaps was found to enable the vanes to rotate about the circular restraining pin by more than 8 degrees because the resultant aerodynamic load produces a clockwise torque on the vane with respect to the pin center. This is unacceptable because the rotation reduces the first vane passage throat area to restrict engine flow and significantly decrease engine power. Consequently, the circumferential restraining pin was redesigned for a wedge shape. The action of the resultant aerodynamic load tends to force the vane to the back channel surface to prevent rotation. Also, truncating the back corner of the vane lower platform to accommodate the wedge shaped pin is a much simpler and less expensive ceramic fabrication process than to produce a hole matched to a circular pin.

Presentation. The needs of this program for long term ceramics data were presented on April 18 at the ATS Materials Workshop on Long Term Testing. The purpose of this presentation was to stimulate acquisition of data to verify the long term life of a ceramic suitable for the Allison ceramic vane demonstration and commercial industrial turbine lifetimes.

Efforts Completed:

This task is estimated to be 46 % completed.

TASK 9.0 PROGRAM MANAGEMENT

Progress Report for February 1996 - April 1996

Allison continued program management of the ATS during this quarter. Allison submitted the draft Quarterly Report (November, 1995 - January, 1996). This report contained an overview of technical accomplishments and progress made on the program. Allison then submitted the final Quarterly Report after being notified by Mr. Leland Paulson, DOE/METC Project Manager, of the acceptance of the draft report.

Allison also submitted non-proprietary copies of the following topical reports to DOE/METC during this quarter:

- Final topical report EDR 17288A -- Task 6: ATS System Definition and Analysis.
- Final topical report EDR 17253A -- Task 8.4: ATS Combustion System.

A request was submitted to Mr. Paulson to allow Allison to submit one final report per the revised schedule, at the completion of all tasks except Task 5.0 and Task 8.07. The request also included an extension to complete Task 5.0, and an increased funding approval for Task 5.0 from $40,000 to $100,000, without increasing the cost of the overall contract.

At a Phase 3 program review meeting, Mr. Paulson asked Allison to submit the current scope of Task 8.7 and the funding requirements in accordance with the current contract. He and Mr. S. Waslo, DOE/EE Program Manager also asked Allison to provide a scope and cost summary for the continuation of the Ceramic Vane Design and Evaluation (Task 8.07) task in Phase 3. This information was submitted to Mr. Waslo per the request.

The overall program is within budget and on revised schedule.