ADVANCED HYDROGEN TURBINE DEVELOPMENT

PHASE 1

FIFTH QUARTERLY PROGRESS REPORT

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AC	Actual Cost
ACS	Advanced Catalytic System, Inc.
ACWP	Actual Cost of Work Performed
AN^2	Blade Annulus Area x Rotational Speed Squared
ASME	American Society of Mechanical Engineers
ASU	Air Separation Unit
BCWP	Budgeted Cost of Work Performed
BCWS	Budget Cost of Work Scheduled
BOP	Balance of Plant
CAD	Computer Aided Design
CCT	Compressor, Combustion and Turbine
CMC	Ceramic Matrix Composites
CPI	Cost Performance Index
CRM	Chemical Reactor Modeling
CTE	Coefficient of Thermal Expansion
CTQ	Critical to Quality
DLR	Deutsches Zentrum für Luft und Raumbart
DOE	Department of Energy
DoE	Design of Experiments
EPRI	Electric Power Research Institute
ENEL	Entre Nazionale per l’Energia Elletrica
EV	Earned Value
EVA	Earned Value Analysis
FOD	Foreign Object Damage
FTT	Florida Turbine Technologies
FY	Fiscal Year
GIT	Georgia Institute of Technology
GT	Gas Turbine
HADES	Hyperbaric Advanced Demonstration Environmental Simulator
HEE	Hydrogen Environment Embrittlement
HHV	Higher Heating Value

HIP	Hot Isostatic Pressing
HP	High Pressure
HRH	Hot Reheat
HRSG	Heat Recovery Steam Generator
HVOF	High Velocity Oxy-Fuel
IET	Integrated Energy Technologies
IGCC	Integrated Gasification Combined Cycle
IGTI	International Gas Turbine Institute
IGV	Inlet Guide Vane
IHE	Internal Hydrogen Embrittlement
IP	Intermediate Pressure
IPT	Integrated Product Team
ITM	Ion Transport Membrane
LCG	Low Calorific Gas
LEC	Levelized Electricity Cost
LCF	Low Cycle Fatigue
LP	Low Pressure
LTP	Long Term Program
NETL	National Energy Technology Laboratories
NPV	Net Present Value
O&M	Operation & Maintenance
OEM	Original Equipment Manufacturer
QFD	Quality Function Deployment
PV	Planned Value
R&D	Research & Development
RAM	Reliability, Availability and Maintainability
RE	Rare Earth
ROM	Rough Order of Magnitude
RDI	Research & Development Implementation
SAS	Secondary Air System
SCR	Selective Catalytic Reduction
SEM	Scanning Electron Microscopy
SOW	Statement of Work
SPG	Siemens Power Generation
SPI	Schedule Performance Index
ST	Steam Turbine
SSRT	Slow Strain Rate Tests
TAMU	Texas A&M University
TBC	Thermal Barrier Coating
TET	Turbine Exit Temperature
TIT	Turbine Inlet Temperature
UCF	University of Central Florida
UTRC	United Technologies Research Center
VOC	Volatile Organic Compounds
XRD	X-Ray Diffraction
YSZ	Yttria Stabilized Zirconia

DISCLAIMER

EXECUTIVE SUMMARY

Considerable progress has been made on the Advanced Hydrogen Turbine Development Project in the Phase 1 Fifth Quarter in the areas of combustion development, turbine conceptual design and materials development.

The focus was on efficiency enhancements, risk mitigation and design flexibility to achieve program goals and ensure program benefits to the power generation industry. This approach also puts emphasis on marketability of the developed advanced technologies in order to maximize the benefits to society and the environment. Increased efficiency will reduce fuel requirement and emissions per MW, minimize plant capital cost and improve the economic viability of an IGCC power system. Risks associated with advanced technologies will be mitigated by building on extensive Siemens gas turbine experience in IGCC applications and high temperature operation. Platform development approach will be used to minimize risk from new technologies and build on proven components. Extensive risk assessment and mitigation process on individual components and systems will be employed throughout the advanced turbine development. To achieve maximum design flexibility, the gas turbine will be designed to be adaptable to different IGCC plant configurations, gasifier designs and ASU types. Fuel flexibility will be built into the combustion system and the hot end to allow operation on hydrogen and syngas, as well as natural gas as a backup. Operational flexibility will be provided to allow adaptation to various duty cycles and polygeneration.

Plant performance calculations were completed for different engine development levels and air integration levels on both syngas and high hydrogen content fuels. Plant design and performance calculations are also being completed for different gasifier types and air separation technologies. Plant cost estimation for a syngas-based IGCC plant is in progress.

Major activities in the Efficiency Improvement Task included completion of the gas turbine thermodynamic performance results for several levels of air integration with syngas, and performance evaluation on high hydrogen content, syngas and natural gas fuels. Gas turbine hot section technology insertion studies are now underway to determine the optimal suite of technologies for the H2 engine. A separate evaluation of the potential benefits of ITM ASU is being performed.

The GT Integration Task focus has been iterating on the engine secondary air systems model and updates to the engine longitudinal section drawing. Modeling has identified key turbine areas where sealing improvements could be achieved. Secondary air systems studies were completed for the identified compressor disc cooling concepts. The latest revision of the engine longitudinal drawing was released. Increased annulus area turbine design is being evaluated for impacts to the engine.

Preliminary data has been obtained on ignition delay and flame speed for fuels with a high level of hydrogen. Aerodynamic design optimization studies and mechanical design and analysis were performed on a staged fuel injection system concept. Full scale basket testing of the axially staged concept has begun. Preliminary aero design has been completed on the syngas capable premixed combustion system. Long lead items have been released for hardware needed for a June, 2007, high pressure test on the syngas premixed combustion system. The fuel flexible Rich Catalytic Lean combustor

scale model was tested with an enhanced module configuration at F-Class temperatures and produced low NOx emissions on natural gas and syngas fuels.

The advanced transition design in CMC material was selected as primary approach and the steam-cooled design as the backup. The advanced transition development efforts focused on: detailed CFD analysis evaluation, identification of preferred manufacturing approaches through vendor interactions and preliminary feasibility trials, identification of preferred conceptual support and seal designs and aero validation test plan development.

The turbine aerodynamic meanline design was updated with more accurate leakage and turbine cooling air flow estimates. A 2-D throughflow analysis was completed and preliminary airfoil shape definition and midspan CFD analyses were carried out. Airfoil cooling concepts, prioritized during the previous quarter, were developed further for all turbine airfoils. To assess the feasibility of a cooled, high AN^2 fourth stage blade, a study was initiated to better understand the aerodynamic, cooling and structural challenges that must be resolved. The ability to economically manufacture a cooled airfoil is essential to the design viability. Therefore, a team of internal and external experts was constituted to review the turbine component conceptual designs for manufacturability. Definition of cooling experiments to be conducted at University of Central Florida and Texas A&M University was finalized. Testing is scheduled to begin early in the next quarter.

The Rotor team had focused their effort on identifying several rotor configurations that would satisfy the rotor mechanical integrity at the design pressure ratio. The list of potential “air cooled” compressor disc concepts was down selected to four concepts. A peer review of potential rotor materials was conducted and a primary path was selected.

A baseline 2-D longitudinal was created for all engine casings, incorporating a compressor, combustor, and turbine casing and a one-piece turbine vane carrier with the transition steam manifolds imbedded at the forward end. Several constraints, which will require additional design effort, have been identified, such as spacing of transition portals and rotor cooling air pipes without interference.

IN939 specimens, coated with four types of bond coats, each modified with a different a rare earth element, were cyclically tested at three temperatures in static air. The neodymium containing bond coat showed superior oxidation resistance compared to the other coatings. Two new TBCs met the room temperature conductivity target and showed no phase transformation at 1500 - 1850ºC. A peer review for the high temperature capable TBC was carried out (DOE Milestone No. 5). Based on information from Howmet, rare earth addition levels for alloy modification were calculated and four rare earth elements were procured for the first iteration of castings. Diffusion bonded (CM)247LC to Haynes 230 and 214 coupons have been sectioned for bond coat integrity evaluation. The bonded coupon central sections appeared to be well bonded with no cracks or porosity. Initial tensile tests showed very promising results. A literature review on hydrogen embrittlement has been completed. Preliminary results were obtained on TBC coated superalloy systems tested at 1000ºC in syngas environments. No TBC degradation was observed up to 500 hours of testing. A furnace cycle test at 1100ºC resulted in TBC spallation after 400 hours, compared to 1200 hours in air. The TBC, bond coat and substrate system is being focused to increase environmental and durability capabilities.

Auxiliaries progress achieved in this quarter included identification of key auxiliary systems, materials to be reviewed, alternatives for risk assessment and constraints from the gas turbine that affect integration. A second level cost estimate was also completed utilizing the initial cost estimate done in the third quarter of 2006.

Major activities under the Program Management Task included syngas-fueled gas turbine-IGCC plant capital cost estimation, completion of the Hydrogen Turbine-IGCC marketing web-survey, second Customer Advisory Board Meeting and the organization of DOE executive management visit at the Siemens Power Generation Orlando site. The Syngas-fueled gas turbine-IGCC plant capital cost estimations are in progress for several cases incorporating the advanced Hydrogen Turbine and one for the SGT6-6000G gas turbine. The results will provide information on the effect of % integration level and gas turbine efficiency on plant capital cost. A study carried out on the GT technology impact on IGCC plant coal consumption showed that advanced technology will significantly reduce coal consumption The survey results, which included input from 56 respondees, provided valuable information for the future development of the advanced Hydrogen Turbine and its incorporation into IGCC plants.

PROGRESS DURING REPORTING PERIOD

Introduction

Significant progress has been achieved in technology development in combustion, advanced transition, turbine and materials, as well as in Plant and GT Integration. To assess plant performance at different engine development phases, plant performance calculations were generated for three engine technology levels: current, near term and far term. Syngas-fueled plant performance calculations were also carried out at different air integration levels to ascertain the effect on plant performance and provide information for plant capital cost estimation for the different integration levels.

Gas turbine performance runs were generated for the ASU integration study and increased last row turbine blade annulus studies. Gas turbine technology insertion studies are underway to identify which technologies should be considered for incorporation in order to achieve optimum performance. GT Integration efforts concentrated on updating the secondary air systems models and the engine longitudinal section drawing. Secondary air systems models were completed for the selected compressor discs cooling concepts. Key turbine areas were identified where sealing enhancements could be achieved to improve turbine performance and mechanical integrity.

Ignition delay experiments were performed on syngas mixtures to provide test information for improving the existing kinetic mechanisms for fuels with high hydrogen content. Laminar flame speed tests were carried out on hydrogen and hydrogen-containing fuel mixtures to compare with available chemical kinetic mechanisms used in modeling and hence improve them. Premixed combustion system design was initiated to allow optimal performance on syngas and high hydrogen content fuels. A special transition was designed as a proof of the axially staged combustor concept. The fuel flexible Rich Catalytic Lean combustor scale model tested at F-Class temperatures produced low NOx emissions on natural gas and syngas fuels. The advanced transition design in CMC material was selected as the primary approach and the steam-cooled version as the backup design. The 2-D turbine flow analysis was completed. Preliminary airfoil designs were carried out, midspan CFD analyses were done and thermal analyses on some airfoils were completed. A feasibility study was initiated on the high AN^2 fourth stage blade design.

IN939 specimens coated with four bond coats, each modified with a different rare earth element, tested in static air at three temperatures behaved similarly with respect to weight change, but the neodymium containing bond coat showed superior oxidation resistance. DOE Milestone No. 5 was achieved with the high temperature capable TBC conceptual design. Two new TBCs tested at 1500-1850ºC exhibited no phase transformation. Four selected rare earth element additions to enhance ((CM)247LC superalloy capability were procured to support the upcoming casting trials. Initial tests on diffusion bonded ((CM)247LC to Haynes 230 and 214, to be used in fabricated airfoil development, showed very promising results. The literature review on hydrogen embrittlement of alloys used in the H2 Turbine was completed. TBC coated superalloy specimens were tested at high temperatures to determine their performance in syngas environments.

A study was conducted to determine the effect of efficiency on IGCC plant capital cost in \$/kW. The gasifier/ASU island technology, and hence its cost, were kept constant, but the gas turbine technology level was varied. The results confirmed the earlier expectations that efficiency increases will have a considerable impact in reducing the IGCC plant capital cost in \$/kW.

Another study was carried out to estimate the IGCC plant coal consumption variation with enhanced GT technology. The results showed that improved GT technology will significantly reduce coal consumption and hence emissions.

The second Customer Survey results were analyzed and the key findings were presented at the second Customer Advisory Board meeting held in Orlando during the November Future-Gen Conference. The survey results provided invaluable "voice of the customer" input to guide the Advanced Hydrogen Turbine development and hence ensure its success. A meeting was held in Orlando between DOE's Fossil Energy upper management team and Siemens management to discuss the H2 Turbine program, its future direction and Siemens gasification technology.

Plant Integration

Approach

In order to assess plant performance at different engine developmental phases, plant calculations were generated for four levels of engine technology: Current (SGT6-5000F), Near Term (FutureGen and G Shaft Limit), and Far Term (Advanced H2). Once the design point of the Advanced H2 engine is finalized, an improved bottoming cycle will be applied to further improve cycle efficiencies. Table 1 summarizes the assumptions for the component / system features, used in these calculations.

System	**Current**	**Near Term**	**Far Term**
Gasifier	Slurry Fed, Syngas Quench, Syngas Cooler	SAME	SAME
ASU	High Pressure with GT Air Extraction	SAME	SAME
AGR	Selexol	SAME	SAME
GT Fuel Conditioning	Moisturization, N_2 Dilution, high temperature pre-heating	SAME	SAME
HP ST Inlet Pressure	≈110 bar	≈170 bar	≈170 bar
HP / HRH ST Inlet Temperature	≈560ºC	≈600ºC	≈600ºC
Heat Sink Type	Wet Cooling Tower with 48mbar back pressure	Wet Cooling Tower with 38mbar back pressure	Wet Cooling Tower with 38mbar back pressure

Table 1. Plant Configuration and Technology Level Assumptions

Study of the GT air integration level for the far term engine design was conducted by running performance calculations with GT air extractions that provided between 30% and 90% of the total ASU air requirements. During this study, steam turbine selection was made from a finite set of existing designs. Therefore, steam conditions varied between runs.

In an effort to improve plant performance while burning high hydrogen content fuel, use of a different gasifier is currently under study. Key attributes of the two gasifier systems are shown in Table 2.

System	**Original Gasifier**	**Current Gasifier**
Fuel conveyance	Pumped H_2O slurry	Blown CO_2 transport
Gasifier Fuel Mixing	Two-stage: first stage is mix of O_2 and slurry, second stage is all slurry	Single stage with O_2, coal / CO_2, and steam
Syngas Cooling	Heat Exchanger to generate steam	Water quench

Table 2. Gasifier Differences

The use of Ion Transport Membrane (ITM) technology in far term power plants remains of interest to the plant performance determination. Plant performance for a syngas-based far term engine technology level will be studied with both cryogenic and ITM air separation technologies to determine the ITM technology impact on plant efficiency and output.

Plant calculations were all based on a configuration including two Gas Turbines and HRSGs, and one Steam Turbine.

Results and Discussion

Plant calculations for the various engine technology levels indicated significant increases in plant performance, both in terms of power and efficiency, with increasing engine technology. Performance on syngas fuel for the near term SGT6-6000G based plant as compared to a plant based on current operational F technology is approximately 3 percentage points higher in efficiency and between 15% and 50% more output. The far term plant performance on syngas fuel exceeds that of the near term plant by approximately 3 percentage points in efficiency and between 20% and 80% in plant net power. Similar improvements are also seen on hydrogen fuel. However, it was observed that the gasifier used in these studies did not yield optimal performance for high hydrogen fuel due to the high syngas methane content and low moisture content.

Plant calculations based on the different gasifier will be included in the next Quarterly Report, along with an evaluation of optimal plant configuration for both syngas and high hydrogen content fuels.

Far term plant performance calculations with syngas fuel show a tendency for higher output with reduced air extraction, as well as marginally higher plant efficiency with decreased GT air integration. In conducting this study, an attempt was made to use existing steam turbine designs. This resulted in an exaggeration of the efficiency deltas between low and high GT air integration, since the steam turbine pressures increased given the higher steam flows resulting from increased GT exhaust flows. Recalculation using “rubberized” steam turbine designs would show a less pronounced relationship between GT air integration level and plant efficiency, but would still exhibit the same trend due to differences in blading designs for the various air extraction levels.

Conclusion

Planned engine technology improvements offer significant plant performance enhancements, both in terms of plant output and efficiency. Further improvements in high hydrogen content fuel based plant performance using a different gasifier type are underway, as is a study on the impact of ITM air separation technology.

Efficiency Improvements

Approach

The overall approach includes three studies that are ongoing in parallel to determine the optimal IGCC system for the H2 Turbine. First, in order to optimize the ASU integration level, several levels of air integration were run in the baseline engine. The thermodynamic results are to be combined with economic analyses and evaluated in the context of technological risk to select the going-forward air integration level. Second, appropriate suites of gas turbine hot section technologies were identified and will be evaluated against one another to determine the performance achievable for competing technologies. Finally, Ion Transport Membrane air separation technology is being evaluated head-to-head with the cryogenic technology in the baseline cycle to determine the potential benefits.

Results and Discussion

Several levels of air integration between the gas turbine and the ASU were evaluated in the baseline H2 Turbine configuration. ASU integration levels of approximately 30%, 60%, and 90% were run in the thermodynamic model fired on syngas. For reference, a hydrogen-fueled baseline (using 75% ASU integration to yield similar air extraction demand as for 90% integration when firing on syngas), and a natural gas-fired baseline were also run. The results of the air integration study are currently being evaluated in the context of trading gas turbine power output against last row turbine blade flow capacity limits to determine the target integration level range for an advanced IGCC system.

While the above evaluation of air integration level is ongoing, the 90% air integration level case was selected to investigate several technology suites for the gas turbine hot section. Gas turbine hot section technology insertion studies such as these will have little impact on the selection of air integration level, and vise-versa. Therefore, these studies may be performed in parallel.

The gas turbine hot section technology insertion studies began with a re-calibration of the baseline assumptions for turbine stage work splits, cooling flows, leaks, and efficiencies, in order to incorporate the latest results from the turbine expander design team. Several technology suites were then formulated for evaluation against the baseline case of all-metal components. These technology suites include logical combinations of cooled cooling air (for air currently uncooled in the baseline case), alternative cooling air sources, CMC static components and TBC technology studies. From these cases, the going-forward suite of hot section technologies will be down selected and evaluated against the current baseline to indicate overall plant performance improvement.

Also, in parallel with the above two efforts, is an evaluation of the Ion Transport Membrane (ITM) air separation technology as applied to the 90% air integration case. This evaluation will quantify potential gains from the ITM ASU as compared to the cryogenic technology.

Conclusions

The current quarter efforts yielded the thermodynamic performance results for the ASU integration optimization. These results, combined with the baseline runs for both hydrogen and natural gas fuels, last row turbine blade design studies, and plant economics, will yield the air integration level range for the H2 Turbine IGCC plant. Technology insertion studies are underway to determine the optimal suite of technologies, and a separate evaluation of the potential benefits of ITM ASU is being performed.

GT Integration

Approach

The secondary air systems model has been updated with input from turbine and compressor system groups as outlined in the RDI plan. Figure 1 shows the secondary air systems model development process.

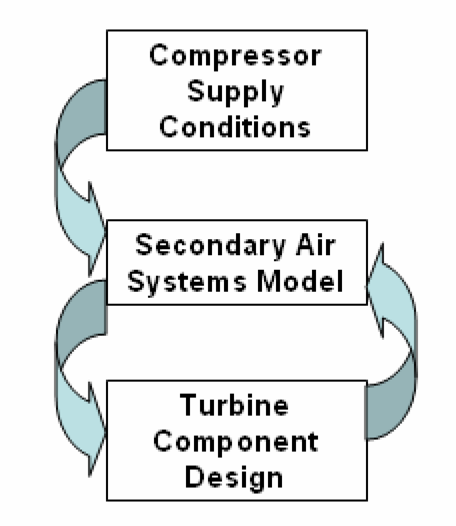


Figure 1. Secondary Air Systems Model Development

The modeling has identified key areas of the turbine where sealing improvements could be realized. Action is being taken to address these areas with advanced sealing approaches.

Secondary air systems studies were completed for compressor disc cooling concepts developed from the rotor workshop.

Revision 0 of the longitudinal section drawing has been released. High AN^2 (= Blade Annulus Area x Rotational Speed Squared) turbine blades are being evaluated for impacts on the engine longitudinal and overall envelope.

Results and Discussion

Secondary air system model iterations were used to identify compressor takeoff stages for turbine cooling. At higher pressure ratios the turbine leakage flow increases without additional sealing measures to mitigate. This secondary air system model review identified opportunities for improved sealing and leakage reduction. Turbine cooling supply pressures are being evaluated again to determine if lower pressure compressor stages can be used to adequately deliver the required cooling flow. Use of lower pressure stage also results in lower cooling air temperature.

With higher pressure ratio, the rear compressor stages operate above the current limit for steel discs without some active cooling or a change in material. Several concepts for cooling of the compressor rear stages have been developed on a conceptual basis. The more promising concept has been evaluated also in terms of secondary air system and found to be feasible in terms of delivery pressure and temperature. Further development of these concepts will include feasibility and engine performance impacts evaluation.

The Revision 0 release of the longitudinal cross section includes the most recent updates of the compressor, turbine and combustor. Rotor and casings are being updated to support the development of a preliminary engine model to evaluate the engine longitudinal thermal and mechanical behavior. Layout of the high AN^2 turbine has identified a concern in terms of the engine shipping envelope. This is being evaluated on an ongoing basis.

Syngas delivery pressure has been calculated for the 2010 and 2015 engines.

Conclusions

Preliminary selection of compressor delivery stages are adequate in terms of pressures and temperatures for turbine cooling. Further optimization will be done based on turbine component development progress.

It is feasible from a secondary air systems standpoint to cool the compressor rear stages and utilize steel discs.

There are no major issues with the overall engine layout. A concern regarding the shipping envelope for the high AN^2 turbine has been identified.

Component Development

Compressor

Completed the 16 stage, high pressure PR compressor through flow analysis with 565 kg/s and 590 kg/s inlet mass flows and accounting for revised bleed flow locations and bleed flow amounts based on input from secondary flow analysis. Starting with the basic PR design, work was commenced on the 17 stage, higher pressure ratio compressor design for both inlet mass flows.

Combustion

Approach

Four combustion system technologies are being considered for the H2 turbine program:

- Diffusion flame combustor
- Catalytic combustor
- Premixed combustor
- Axially staged system

Support will be obtained from Texas A&M University, Georgia Institute of Technology and University of Central Florida in performing technology level experiments. Various types of modeling (CRM, CFD, Pro/E, …) will be performed to evaluate the feasibility of different concepts. Results from the university work will be used for calibration of above mentioned models. Rig component testing of promising conceptual designs will be conducted. By the end of Phase 1, two systems will be down selected for further design and testing during Phase 2.

University Support

Ignition delay experiments in the University of Central Florida (UCF) shock tube have focused on the fuel obtained from the 90% CO_2 capture. The effects of temperature, equivalence ratio and pressure have been studied. Data has been obtained at pressures up to 50 atmospheres.

Data has also been obtained at the Georgia Institute of Technology for laminar flame speeds of pure hydrogen, hydrogen diluted with nitrogen and mixtures of hydrogen and carbon monoxide at elevated temperatures and pressures. Data has been obtained for strained and unstrained flames.

Design Work

The preliminary aero design of the syngas capable premixed combustion system has been completed and the rig test combustor long lead items have been released for manufacturing. The design modifications include changes in shape and angle of the premixing vanes as well as the flow path improvement in the premixing section. Detailed mechanical and aero design will continue in the next quarter.

Rig Testing

Full scale basket testing of the axially staged concept has begun and will be completed in January, 2007. Full scale basket testing will be performed on the premixed combustion system with hydrogen and methane mixtures in January, 2007. The small scale 60 tube catalytic combustion rig will be tested on hydrogen and methane mixtures in February, 2007. The goal of these tests is to determine the maximum hydrogen concentration that the design can operate on without flashback. Diffusion flame testing will continue in February, 2007, to evaluate potential basket and nozzle modifications. Full scale basket testing is planned on the new syngas premixed combustion system for June, 2007.

Results and Discussion

University Support

Ignition delay experiments have been performed on syngas mixtures using the UCF shock tube facility shown in Figure 2. Figure 3 compares the results of the UCF shock tube test results with previous flow reactor work performed at United Technologies Research Center (UTRC) and modeling studies using the existing chemical kinetic mechanisms. All of the available kinetic mechanisms over predict the ignition delays at temperatures of less than 1000°K. Additional work is necessary to improve the existing kinetic mechanism for fuels with a significant amount of hydrogen.

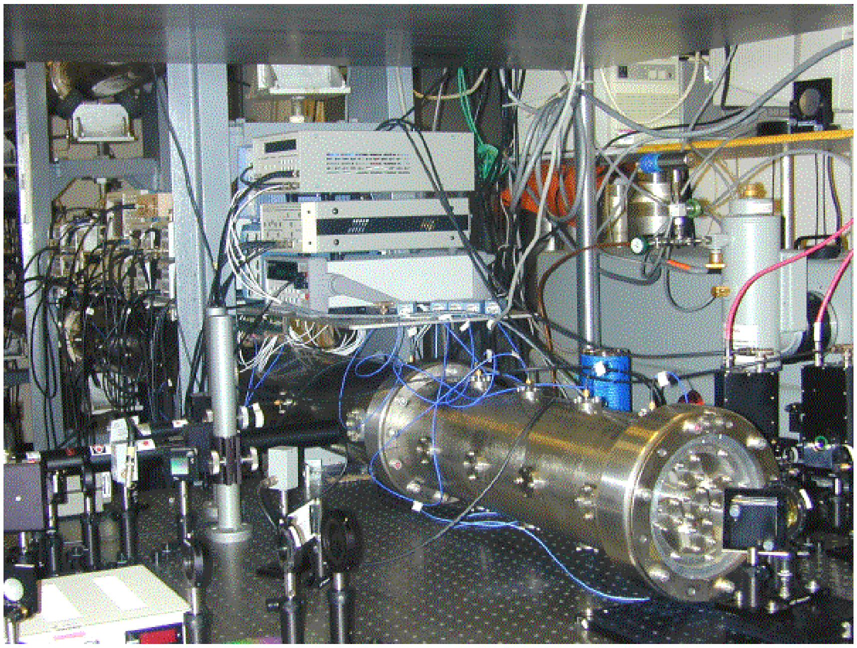


Figure 2. UCF Shock Tube Facility

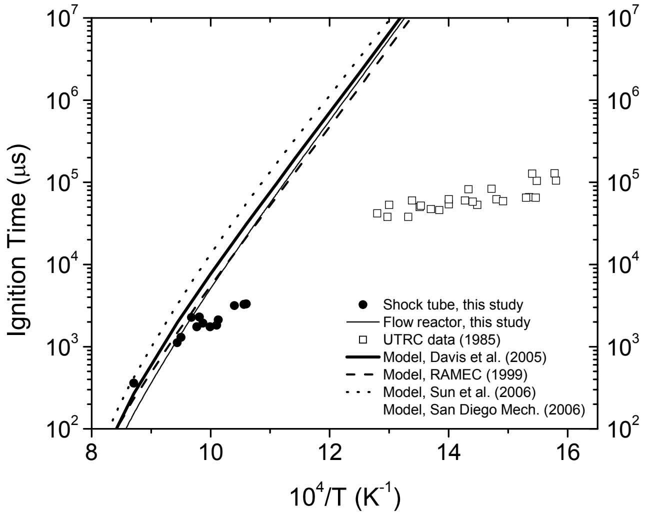


Figure 3. Syngas Ignition Delay – Comparison of Model Calculation to Experiments

This project has concentrated on the development of the data necessary to correct the chemical kinetic mechanisms for hydrogen rich fuels in the low temperature region. During this quarter all of the work was focused on the study of the effects pressure, temperature and equivalence ratio on the ignition delay of a fuel typical of 90 % CO_2 capture. This fuel is primarily hydrogen but contains small amounts of N_2, CO, CO_2 and CH_4. Data has been obtained at pressures up to 50 atmospheres. Work during the next quarter will focus on the effects of diluents on the ignition delay for the 90% CO_2 capture fuel. Figure 4 shows typical ignition delay data for the 90% CO_2 capture fuel. As part of this study, a laser absorption measurement system has been installed to measure water vapor concentrations in the shock tube. This is essential to obtaining the correct initial conditions for the studies of steam dilution.

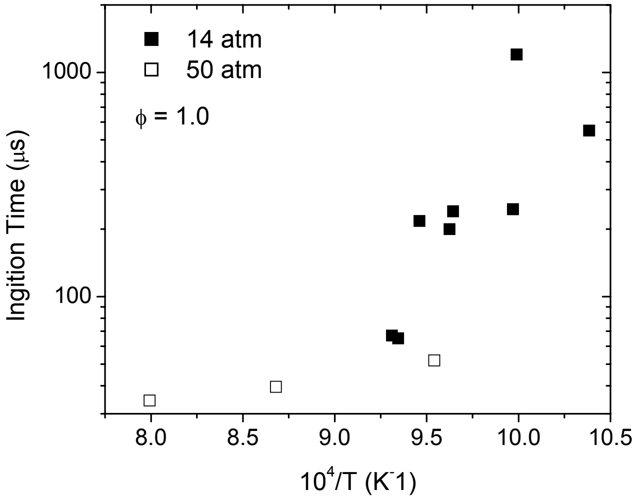


Figure 4. Ignition Delay Data for the Baseline Mixture

The laminar flame speed reactor at Georgia Tech is shown in Figure 5. With this geometry, a laminar flame is stabilized between the nozzle and the stagnation plate. Axial velocity measurements are performed in the flame region and a curve typical of Figure 6 is generated. From this curve, the laminar flame speed, Su, can be determined from the minimum velocity and the strain rate, K, can be determined from the maximum gradient in axial velocity. By adjusting the nozzle exit velocity it is possible to vary the strain rate and generate a curve of laminar flame speed versus strain rate which can be extrapolated to zero strain.

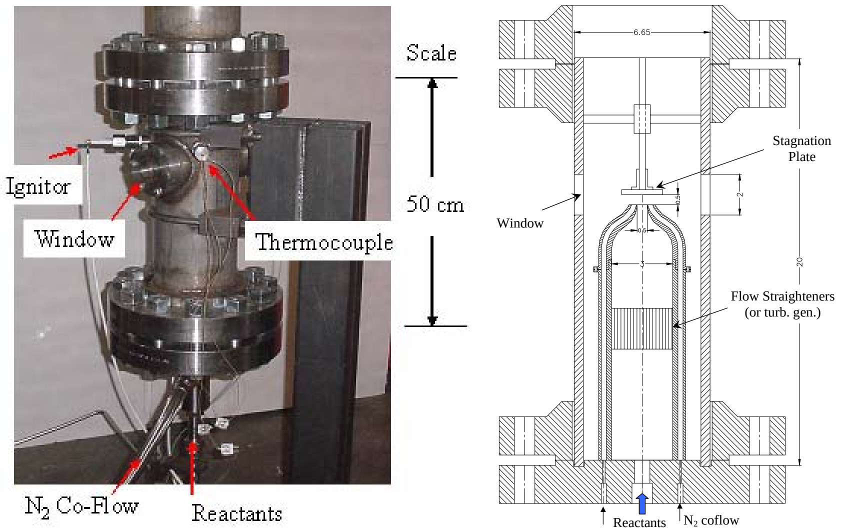


Figure 5. Laminar Flame Speed Rig at Georgia Tech

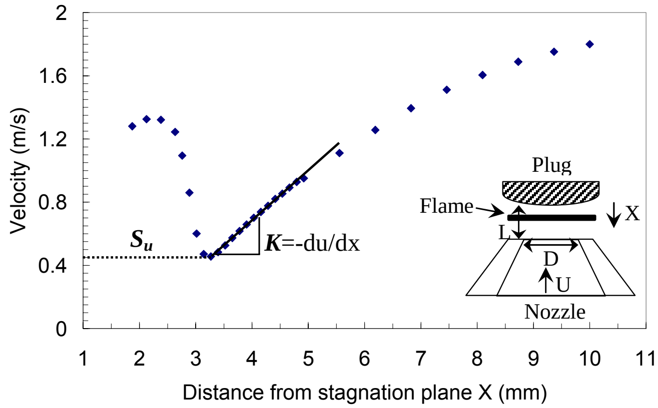


Figure 6. Measurement of Strained Flame Speeds

The stagnation plate can be removed to get the laminar flame speed of unstrained flames. At elevated pressures, it was necessary to use helium dilution on the unstrained flames in order to get a stable laminar flame.

Data has been obtained for the laminar flame speed of hydrogen, hydrogen diluted with nitrogen and for H_2/CO mixtures at elevated temperatures and pressures of up to 10 atmospheres. Experimental results for the strained flames were compared with the CHEMKIN OPPDIFF code and the unstrained flames were compared with the CHEMKIN PREMIX code. The chemical kinetic mechanisms used in the modeling were: GRI Mechanism 3.0, Davis H_2/CO mechanism, Dryer H_2-O_2 mechanism and Dryer C1 mechanism. Typical data is shown in Figure 7 for pure hydrogen flames. For this case, the GRI mechanism is closer to the measured values than the Davis mechanism.

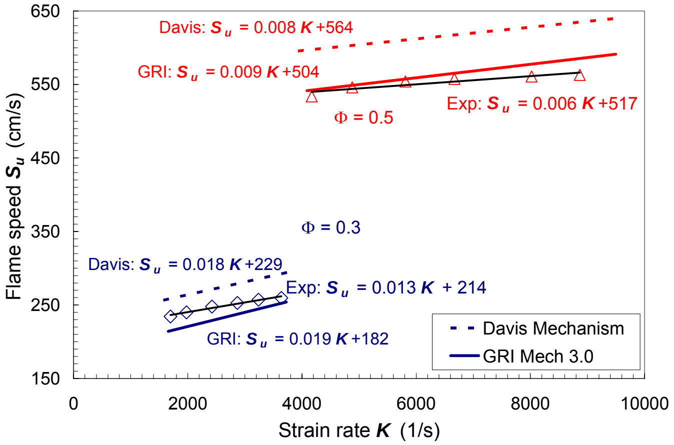


Figure 7. Laminar Flame Speed for Strained Hydrogen Flames

Design of a flashback resistant premixed combustor for fuels with high hydrogen content requires knowledge of the mixture turbulent flame speed. Future work will concentrate on measurements of turbulent burning velocity. The turbulent burning velocity will be determined as a function of the mixture composition, turbulence intensity and turbulence length scale. Construction of the turbulent flame speed rig is currently underway.

Design Work

Initial design work was performed on the premixed system to enable optimal performance on syngas and high hydrogen fuels. This design work is complicated by the significant differences in flow rates between the different fuels. Separate injection stages are required for natural gas, hydrogen and syngas. Preliminary mechanical design has been performed on the fuel injection system to enable operation on the wide variation in fuel flow rates required for natural gas, syngas and high hydrogen fuels. Significant changes to the fuel delivery system were necessary to accommodate wide differences in fuel flow between syngas, hydrogen and natural gas. Additional fuel stages were required. The preliminary fuel injector design is shown in Figure 8. The goal is to release the long lead items necessary for a test of this system in the May/June, 2007, time frame. Detailed design work will continue during the next quarter.

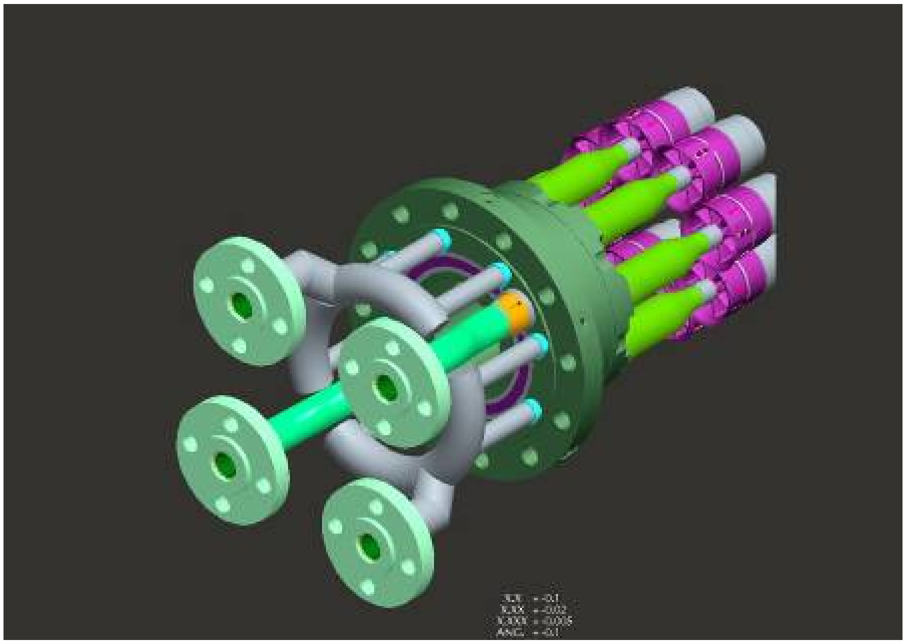
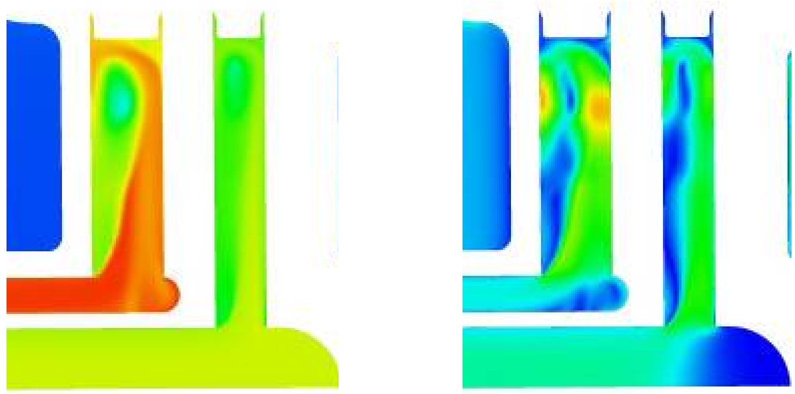


Figure 8. Preliminary Design of the Syngas Premixed Fuel Injection

CFD has been used as a tool for the fuel injection system design. The fuel flow calculations in the fuel injectors' internal passages were performed to minimize the pressure drops within the injectors and insure the flow is evenly distributed at the exit. Figure 9 shows the total pressure and Mach number distributions in the fuel injector internal passages. In this design, a large recirculation zone was formed in the radial feed channel to the injection holes. This resulted in a significant pressure loss and in a significantly non-uniform flow pattern at the injectors. By redesigning the fuel injector internals it was possible to eliminate the recirculation zone and the associated pressure loss.



a) b)

Figure 9. CFD Modeling of the Fuel Flow Through the Fuel Injection System [a) total pressure, b) Mach number

Rig Testing

Preliminary CFD calculations have shown that the addition of an axial stage in the transition can significantly reduce the NOx emissions compared to the current single stage design. The key to successful design of an axially staged combustion system is proper mixing of the axial stage fuel before combustion takes place. As a proof of the axially staged concept, a special transition was designed and built with an internal fuel manifold for testing of different axially staged concepts. Using the standard Siemens DLN burner and the axial stage transition, full scale high pressure testing will be conducted at the Siemens combustion test facility at ENEL.

All of the hardware necessary for the axially staged test has been fabricated and installed in the Siemens test rig at ENEL. Figure 10 shows the completed transition before installation in the test rig and Figure 11 shows the interior view of the transition. This transition was designed with removable fuel injection nozzles so that several different fuel injection patterns can be studied. Testing on this concept will continue through January, 2007. The testing will examine the effects of different fuel injection patterns, heat input in the axial stage and the effects of diluent on the axial stage. These tests will look at both methane and hydrogen fuel in the axial stage.

Figure 10. Transition with Axially Staged Fuel Injection

Figure 11. Interior View of the Axial Stage Transition

Siemens has been working on a Rich Catalytic Lean (RCL) design capable of operation on natural gas, syngas and high hydrogen fuels. The concept of this design is illustrated in Figure 12. In this concept the combustion air is split into two streams. Part of the air mixes with the fuel and reacts in the catalyst region while the remainder of the air is used to backside cool the catalyst. In this design the catalyst section is designed to operate in the fuel rich region above the mixture flammability limit. By operating the catalyst fuel rich, the RCL design has proven to have increased fuel flexibility and is more robust to transient operation than lean catalytic designs.

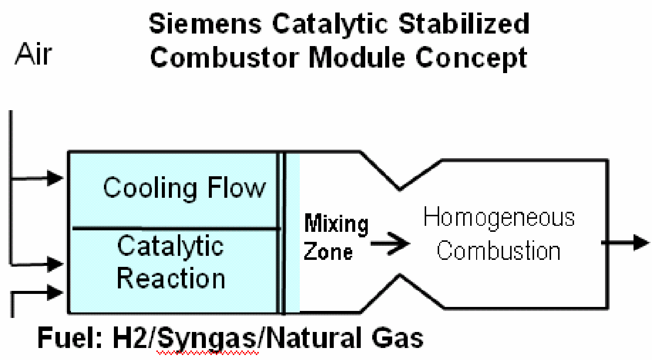


Figure 12. Rich Lean Catalytic Combustor Concept

Initial development of the fuel flexible RCL catalytic combustor has been achieved though scale module testing (1/6 basket scale) at the Siemens test facility in Lincoln. Two catalyst designs were available for testing during this campaign. The base design used a catalyst section composed of tubes, while the alternative design used a section composed of corrugated plate sections. The tube design has been tested extensively on natural gas and has proven to produce emissions in the range of 2 ppm NOx at F-Class firing temperatures. Initial testing was performed on syngas and the emissions were roughly 2.5 times that of natural gas and there was a flashback event when the firing temperature was increased to above G-Class temperatures. Analysis of this data showed that the syngas mixing was not optimal and that the velocities in the mixing zone were too low to prevent flashback. The tube module provided for this test was redesigned to improve mixing and increase the margin for flashback. The plate module provided for this test was an entirely new design which had never been tested previously.

The goal of these tests was to down select the final catalyst design to be used in the RCL fuel flexible catalytic basket verification test. During the tube module testing, damage occurred to the catalyst section when failure of the fuel control system resulted in pure hydrogen being introduced to the module during loading. This resulted in irreparable damage to the catalyst section. Initial testing performed on the plate design indicated that the fuel air mixing pattern in the catalyst section was not optimal. It was decided to redesign the fuel injection system before any further testing is done on this design.

Current funding situation does not allow for the construction of a replacement for the catalytic section. Additional catalytic testing on the tube design is planed for Casselberry Lab in February, 2007. These tests will be with methane and mixtures of methane and hydrogen. The test results will then be used to confirm the tube module performance. The plate module did not sustain serious damage and replacement parts are available for additional testing. The fuel delivery system redesign for the plate module is currently ongoing. Once the design is completed, additional testing will be performed to verify this design on both natural gas and syngas.

Conclusion

Design and hardware preparations continue for the upcoming high pressure rig tests, which will be completed in the next quarter.

Advanced Transition Integration

Approach

The conceptual work associated with the steam-cooled configuration has been highly successful and the design approach is considered feasible. However, due to long term benefit growth potential, reduced plant system complexity, and advancement of corporate technology in a critical field, the primary approach for the advanced transition system has been redirected from steam-cooling to CMC. Further, CMCs are considered well suited for this application. Other than the limited manufacturing and materials development efforts associated with the steam-cooled design, most conceptual design efforts done to date are directly applicable and necessary for CMC as well. Steam-cooling will be maintained as a viable secondary option.

The advanced transition development effort is internally funded by Siemens. The progress and results from the development effort are being integrated into the DOE Advanced Hydrogen Turbine. Weekly meetings were held to discuss status, actions, issues and concerns on the advanced transition development. In addition to the Integrated Product Team members, other experts participated in brainstorming meetings to provide non-subjective and unbiased opinions and ideas.

For the conceptual design review, basic manufacturing and analytical feasibility must be demonstrated. To achieve this, the approach has been to engage and work with vendors with expertise in the identified potential manufacturing approaches. For analytical feasibility studies, more sophisticated fluid and structural models were created and boundary conditions more accurately determined. Aero feasibility demonstration rig testing will be conducted for risk mitigation as will full temperature full pressure rig testing.

The departure from the standard transition design requires that the conceptual design phase consists of a series of design reviews, rather than a typical single review, to assure proper design configuration and risk identification early on. This will reduce the need for design changes later in the development process when such changes are significantly more costly (both financially and to schedule). A review of the overall conceptual approach will take place in January, 2007. Conceptual design reviews of more specific design aspects will be conducted throughout 2007.

Results and Discussion

Reacting flow, couple component transient CFD results, analytically verify the concept's feasibility. However, detailed evaluation of results identified potential areas of concern. Revisions to the transition geometry were generated in response and are under evaluation. The revised geometry potentially has other significant benefits. Preliminary results of this revised geometry will be presented at the conceptual design review in January.

Manufacturing feasibility, welding and formability tests on targeted advanced materials were completed. Results were highly successful. Photographs are provided in Figure 13. Manufacturing vendors were heavily engaged during the quarter and were instrumental in identifying preferred configurations to develop for the more complex aspects of the design.

Figure 13. Photographs of Welding and Formability Trials

A preferred inlet support design was identified based on several factors, including preliminary stress analysis, assembly considerations and spatial requirements. The design is new for the inlet support, but somewhat similar approaches have been used elsewhere. Preferred seal concepts have also been identified.

Aero validation rig development continues at the University of Central Florida (UCF). The rig utilizes much of the existing SGT6-6000G row 1 vane film cooling rig. CFD analysis for the transition exit diffuser design was completed in the previous quarter. Test piece hardware is now being fabricated.

Preliminary full temperature, full pressure rig development efforts were begun in coordination with the Combustion team.

Conclusion

Advanced transition design in CMC material was selected as primary approach. Significant progress has been made regarding overall conceptual design configuration, inlet support and exit seal approaches, manufacturing feasibility and preferred fabrication approaches, and identification of potential aero risks and mitigations.

Summary of Significant Accomplishments

- Conceptual design review report written.
- Preliminary manufacturing feasibility tests successfully completed.
- Preferred inlet support and exit seal approaches down selected.
- Potential aero risks identified from coupled transition-turbine steady and unsteady CFD analyses, with mitigation actions identified.
- Preferred manufacturing approaches identified for more complex aspects of design.
- The primary advanced transition design approach was redirected from steam cooling to CMC.

Turbine

Approach

The intent of this task is to prepare conceptual design solutions for components of the Advanced H2 Turbine, conduct studies to evaluate and quantify the benefit of the various concepts, and to conclude with the selection of design concepts to be pursued in Phase II. This activity is focused on development of component technology critical to successfully achieving the aggressive performance goals of this turbine: aerodynamics, airfoil cooling and sealing. Activity this quarter included: support of overall engine cycle studies and secondary flow system modeling, turbine airfoil cooling concept development and analysis, ceramic matrix composite (CMC) component feasibility studies, conducting initial studies of the high AN^2 row 4 blade, design-for-manufacturing assessment of airfoil cooling concepts and continuation of experimental heat transfer research on cooling technologies under consideration in the H2 Turbine.

Results and Discussion

The turbine meanline aerodynamic design completed in the previous quarter was updated to include the latest cooling and leakage air flows. Earlier results were based on leakage flow estimates calculated within the turbine meanline code. This update applied results of the recently available engine secondary air flow model, which yields a more accurate and detailed breakdown of chamber pressures and temperatures, leak paths and flow rates. The latest meanline model also included the most current cooling flow estimates that have been adjusted based on coolant supply conditions also provided by the secondary air flow model. The output of the turbine meanline code, which in addition to overall turbine performance data such as power, efficiency and exit temperature, also provides detailed data for each stage of vanes and blades, such as stage loading, velocities, pressure and temperature. These results were then released for updates to the engine cycle model and detailed turbine component feasibility studies. In addition to the baseline turbine design, aerodynamic designs were updated for the higher flow turbine, as well as for various technology insertion scenarios in support of ongoing engine cycle studies.

For the refined meanline aerodynamic baseline turbine design, a 2-D through flow analysis was conducted. This was followed by preliminary airfoil shape definition, loading, and midspan CFD analysis of each airfoil row. The geometry and analysis results for the row 2 blade are shown in Figure 14.

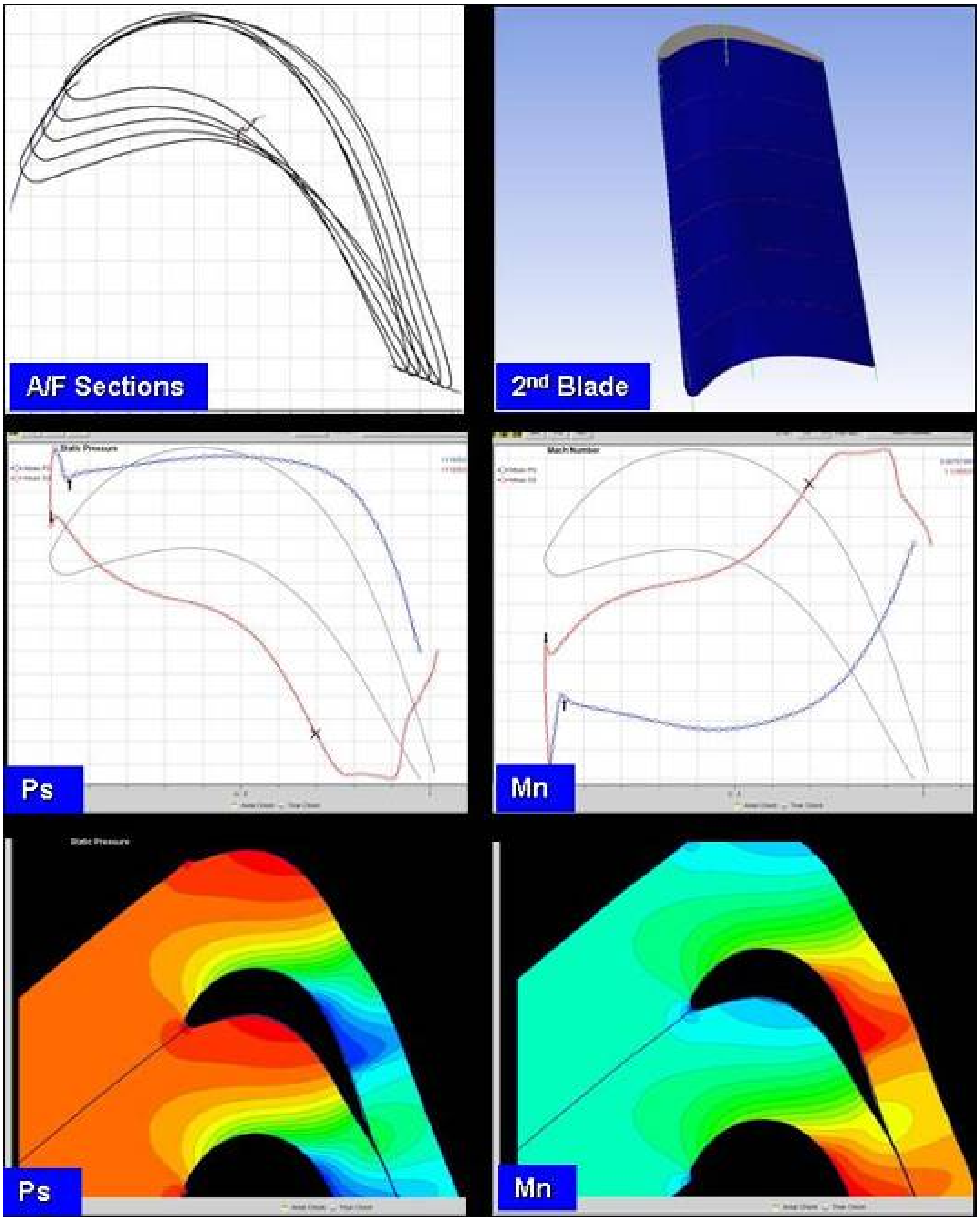


Figure 14. Preliminary Geometry and Analysis of the Row 2 blade

Further development of the airfoil cooling concepts prioritized during the previous period was initiated in this quarter. For each airfoil row a concept was identified based upon criteria including performance, durability, manufacturing and cost. For two components, the row 1 blade and row 2 vane, a second concept was also selected for the purpose of providing a more quantitative comparison of required cooling flows and calculated component life.

The analysis process for each airfoil row is similar. Based on the initial heat transfer design, 2-D CAD geometry of the airfoil midspan section is prepared. These sections account for manufacturing practice relating to alloy, wall thickness, taper, and casting die draft angles. From these scaled sections the internal conditions and geometry are iterated on, to result in a configuration and a set of internal heat transfer boundary conditions. One-dimensional heat transfer analysis is then used to calculate local metal temperatures for various locations on the airfoil as well as the heat up of air passing through the cooling circuit. Results are compared to maximum allowable temperatures at the TBC surface and interface (bond coat). Temperature predictions are also made for local TBC spallation to assess airfoil oxidation life.

In addition to the 1-D thermal analysis, 2-D or 2.5-D finite element analyses are being conducted for selected concepts. For the 2.5-D models, the midspan section geometry is being extruded and one unit of periodic spanwise internal features added. ANSYS FEA models are constructed on these solid models and loaded to simulate expected thermal and mechanical boundary conditions. Thermal and structural analyses of these models are then used to calculate the component LCF, creep and oxidation lives.

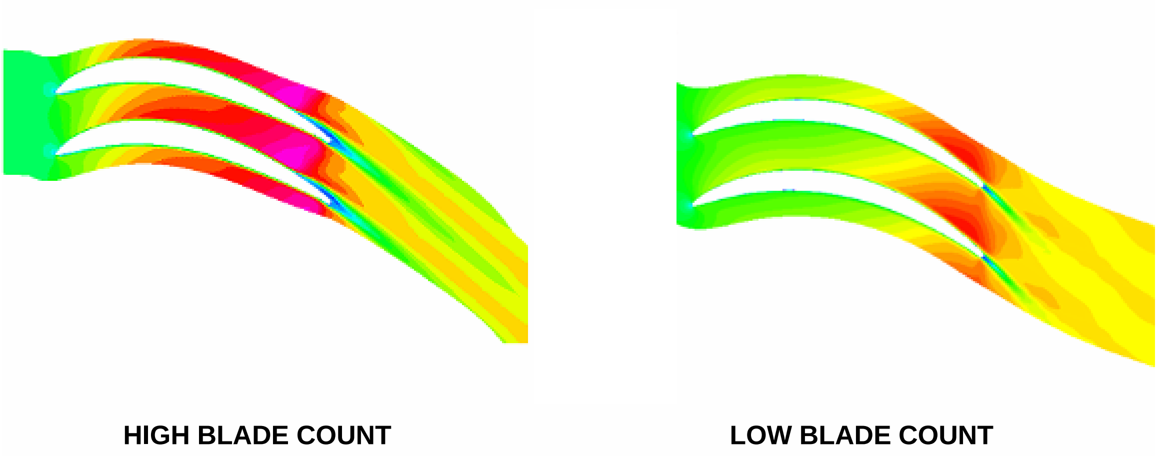
During the previous quarter the thermal/structural analysis process has been completed for the row 1 blade (1 of 2 concepts under consideration), the row 2 vane (1 of 2 concepts under consideration), the row 3 vane and the row 4 blade. Results indicated that the cooling design for each concept is feasible for the current engine cycle and cooling flow allocation. Work on the remaining airfoils, i.e. another row 1 blade, the row 2 blade, another row 2 vane, the row 3 blade, and the row 4 vane are in progress, and will be completed during the next quarter.

The feasibility of constructing ring segments in a ceramic matrix composite material was initiated this quarter. For the row 1 ring segment, thermal calculations show no benefit for reducing cooling flow using CMC and the loading is very high for the CMC capabilities. A cooled metal concept will be developed for this component during the next quarter. Row 2 and row 3 CMC ring segments both appear feasible, with favorable benefit in reducing cooling flow (by up to 75% for row 2 and 100% for row 3). Further evaluation of potential benefits in cooling reduction from these components will be conducted to determine development focus. Concept development on these components will start next quarter and will also include cooled metal concepts for baseline comparisons.

High flow rate engine cycles studied during the previous quarter are predicated on the capability to design larger turbine blades. To assess the feasibility of a cooled, high AN^2 fourth stage blade for the H2 Turbine, a concept study was begun this quarter, which is expected to expand on one or more of the brainstorming ideas mentioned in the last quarterly report. In order to better understand the aerodynamic, cooling and structural challenges to be satisfied, an initial concept was established. For the purpose of this preliminary analysis, this initial concept was allowed to neglect vibration criteria and production manufacturing capabilities that will be addressed later.

Analysis results for this initial concept indicate that due to the increase in blade pull stress, airfoil root section area must be increased beyond the limit that allows for the aero design criteria for blockage to also be satisfied. Reducing the blade count improves this somewhat due to the corresponding increases in gap and airfoil chord. Contour plots of CFD analyses showing excessive flow velocity due to blockage are shown in Figure 15.

Cooling for this blade concept is with two radially flowing core passages. Shown in Figure 16, the passages become very thin toward the tip, which increases the internal flow velocity and also represents a significant casting challenge. Figure 17 shows that based on the calculated pull and metal temperatures for an uncoated, tip-shrouded blade, the pull stress exceeds both creep and strength limits for almost the entire span. Configurations with part-span shrouds (snubbers), or shroudless blades appear promising, if manufacturing and stage vibration concerns can also be mitigated.



HIGH BLADE COUNT

LOW BLADE COUNT

Figure 15. Increased Span Row 4 Turbine Blade Flow Blockage Comparison at 10% Span

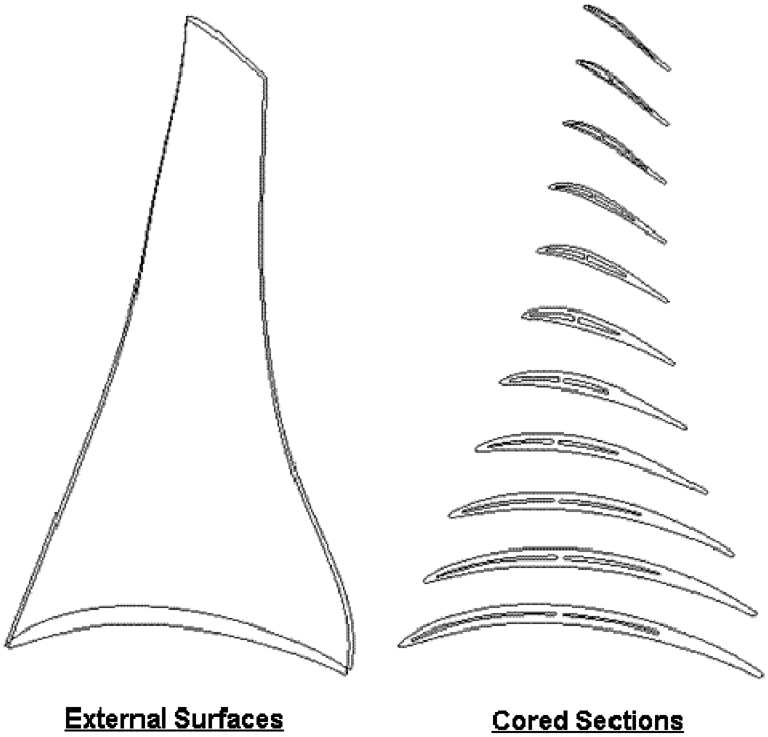


Figure 16. Initial Concept - Increased Span Row 4 Turbine Blade Contours

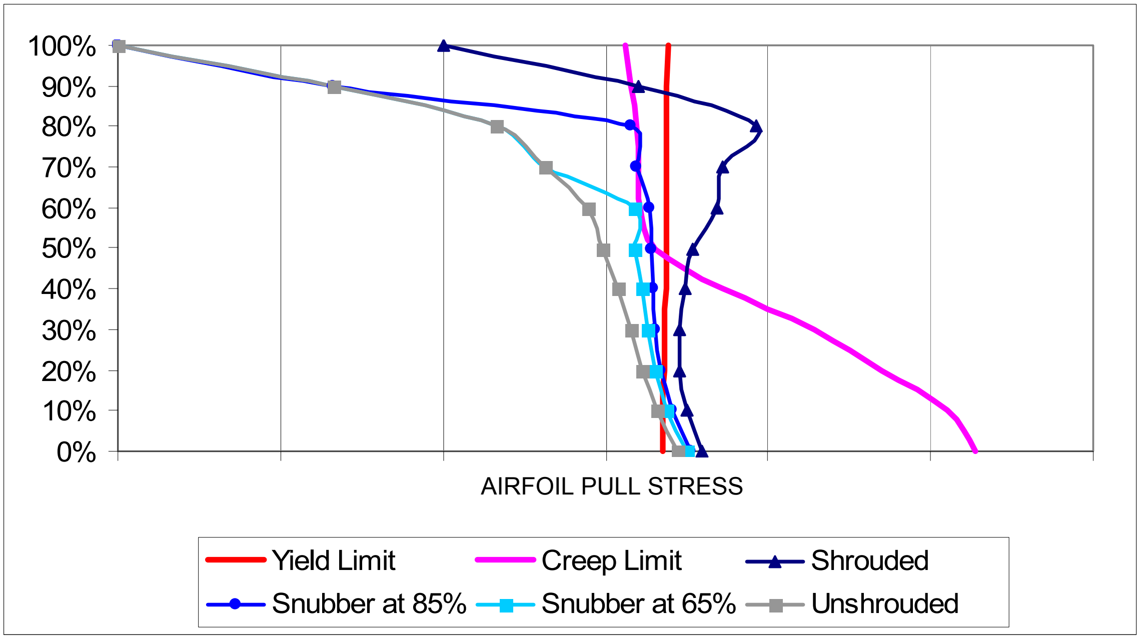


Figure 17. Initial Concept – Increased Span Uncoated Row 4 Turbine Blade Structural Assessment

The ability to manufacture a cooled turbine component, and do it economically, is essential to the design viability and as such the manufacturing process and ability to manufacture an airfoil must be thoroughly examined throughout the design process. As a consequence, a team of internal and external industrial experts was assembled to review the prioritized conceptual designs for the turbine components. The purpose of the review was two-fold:

1. Discuss the manufacturability of the prioritized cooling concepts and the industry's experience with similar designs.
2. Identify manufacturing technology gaps to be addressed early on to enable successful component manufacture utilizing these cooling concepts.

The general opinion based on Siemens and industrial experience was that to cast components with such complex cooling geometries, it will be important to focus on the following technology thrust areas:

- Casting Process Development
- Defect Tolerance Limits
- Post-Cast Process Development

Within the casting process development, issues such as ceramic core development, ceramic shell development, wax development, solidification conditions and crystal growth are considered. Process steps such as crystal growth, solidification conditions and wax development treatment can be easily addressed, given Siemens experience with casting relatively complex geometries. The main focus in this area will, therefore, be in ceramic core development.

To cast a cooled turbine component, first a ceramic core is made of the internal features. The core is critical in obtaining the necessary cooling performance of the component. Conventionally the core itself is manufactured by either injection molding (low pressure or high pressure) or transfer molding. In both processes, precision dies are required. The directions in which the segments of the dies are pulled apart to remove the core are fundamental in designing the cooled airfoil. It does certainly impose limitations on the core design to ensure that the various die segments can be withdrawn without interference. With near wall cooling and other advanced cooling schemes, the conventional core production methods alone will not be able to meet the requirements of the advanced designs. Therefore, advanced ceramic core manufacturing methods will be required for this program.

The area of defect tolerance limit addresses microstructure/property relationships and performance/acceptance criteria. Establishing the tolerance level and allowable defect in turbine airfoils with such intricate cooling schemes will require continued close coordination between airfoil designers, casting suppliers and material engineers. The complete elimination of defects is very difficult in large component sizes for some alloy compositions, however it is important to characterize defect effects. This activity will assess the performance loss associated with having defects present so that proper defect tolerance levels are specified, which ensure adequate performance and maximize casting yield.

The post-cast area addresses issues such as heat treatment, HIP and nondestructive inspection. Siemens has good experience with heat treatment and HIP requirements for a wide variety of alloys used in industrial gas turbines. The main focus in this area will be in nondestructive inspection technology. This will be done in tandem with the defect tolerance limit. For the proposed intricate designs, it is important to have an inspection technology in place to detect the allowable defects easily. This will minimize the number of cut-ups required for inspection. In the long run, this will help in reducing the component costs.

Definition of the experiments to be conducted by universities was finalized this quarter and Statements of Work issued to both the University of Central Florida (UCF) and Texas A&M University (TAMU).

The primary objectives of the UCF study are to provide experimental data to support the advanced internal cooling conceptual designs with minimal pressure drop and highest heat transfer at a given mass flow rate. To achieve this objective the project has been split into two tasks. The first task involves the experimental study of the blade leading edge internal cavity using advanced turbulator configurations, while the second task involves an experimental study of the blade trailing edge internal cavity. A comprehensive parametric investigation will be performed for both tasks to study heat transfer and pressure drop over the test model. A total of 60 cases are being planned for each task including tests for 3 Reynolds numbers, 3 Mach numbers and several geometry configurations.

The project is currently on schedule to begin experimental testing early in the next quarter. The detailed design for both test models was provided to UCF by Siemens. Drawings were prepared by UCF based on the dimensions provided to them by Siemens. Detailed instrumentation, layout and boundary conditions for both test models have been discussed and agreed to. Fabrication of both test models has also been initiated.

Two primary objectives have been defined for the TAMU study. The first objective involves a feasibility study to investigate different internal cooling designs using leading edge impingement by addition of turbulators to enhance heat transfer while the second objective involves the study of an advanced external cooling conceptual design for the blade tip with minimal leakage flow and heat transfer along with minimal usage of coolant. A high tip leakage flow increases aerodynamic losses as well as makes the blade tip susceptible to thermo mechanical fatigue cracking and oxidation due to high metal temperatures. The new proposed blade tip design will help in minimizing tip metal temperatures and also meet oxidation limitations for advanced turbine component design applications. Experimental investigations along with CFD simulations are planned for the blade tip study. The CFD investigations will validate and compare predictions with other typical blade tip geometries as well as optimize the proposed advanced blade tip design. The CFD investigations will be supported by experimental investigations on the blade tip. A new transonic, high pressure ratio cascade will be designed and constructed to investigate heat transfer and film cooling on an advanced blade tip design at near engine flow conditions. Pressure measurements are to be performed on the blade tip and the shroud to quantify the leakage flow over the tip with and without film cooling. The results from the new tip design will be compared against a baseline test with a typical squealer tip.

The project is currently on schedule to begin experimental testing early in the next quarter. The detailed blade tip design and the boundary conditions were provided to TAMU by Siemens. Drawings for a cascade based on the provided information were prepared by TAMU. The cascade 3-D conceptual design is shown in Figure 18. Detailed instrumentation, layout and scaled flow conditions for the cascade have been discussed and agreed to. Fabrication of the cascade has also been initiated. CFD simulations have begun and grid construction/optimization is ongoing. Preliminary CFD results are expected in the next quarter.

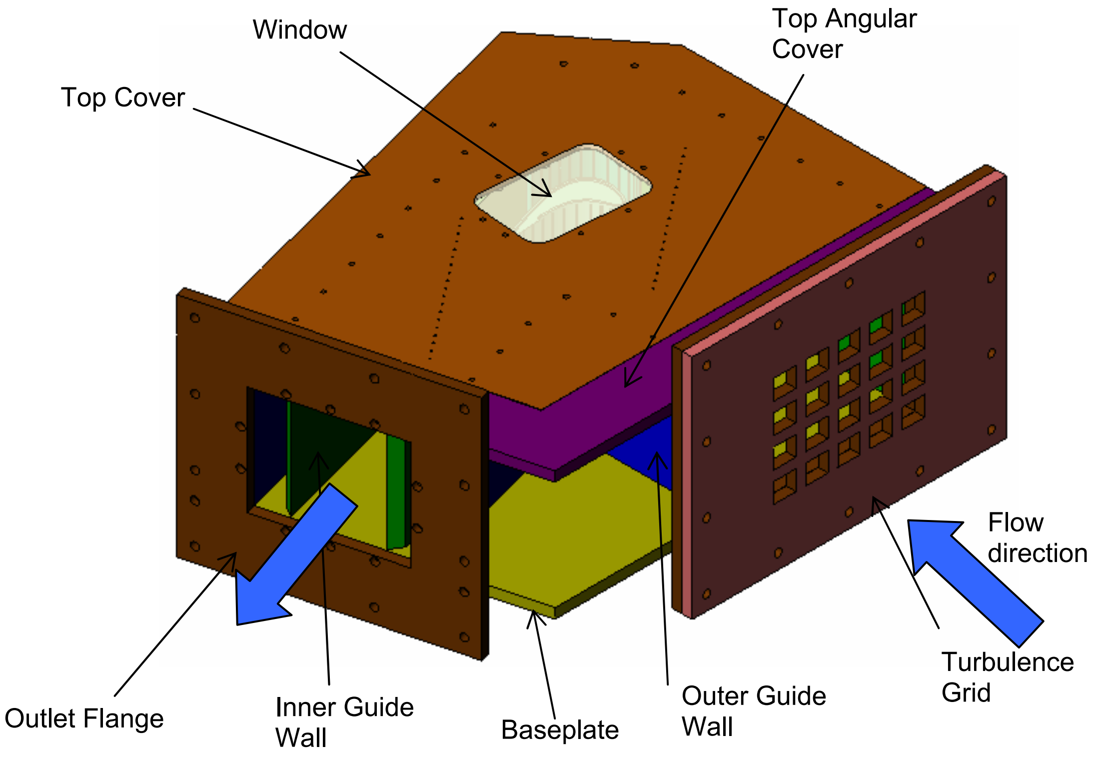


Figure 18. 3-D Model of the Blade Tip Cascade at TAMU

Conclusions

The turbine meanline aerodynamic design was completed with more accurate leakage and cooling air flows. A 2-D throughflow analysis was conducted, followed by preliminary turbine airfoil shape definition and midspan CFD analysis for each airfoil row.

Further development of cooling concepts, prioritized in the previous quarter, was carried out. Thermal analyses on some airfoils were completed and are in progress on the remaining ones. A study was initiated to assess the feasibility of a cooled, high AN^2 fourth stage turbine blade, in order to better understand the aerodynamic, cooling and structural challenges.

A team of internal and external experts was formed to review the turbine component conceptual design manufacturability.

Definition of cooling experiments at UCF and TAMU was finalized. Testing is scheduled to begin early in the next quarter.

Rotor

Approach

Several rotor configurations that will satisfy the rotor mechanical integrity at the elevated pressure ratio were identified. The list of potential "air cooled" concepts was reduced down to 4 concepts. A Peer Review of potential rotor materials was held and a primary path was selected.

Results and Discussion

More than 10 air cooled rotor concepts that were brainstormed in the previous reporting period were reduced down to four during this reporting period. All four concepts will be evaluated from a cost, mechanical integrity and performance considerations.

Milestone

Develop Rotor Cooling Concepts Layouts, completed on 11/30/2006.

A materials peer review was held on December 11th where all standard Siemens rotor materials were compared based on mechanical integrity, cost, performance and risk. The Peer Review Team was made up of rotor experts, materials experts and forging experts. The issues associated with the IN706 / IN718 family of Nickel based rotor alloys were discussed and the decision was made to remove the Nickel based materials from our materials list. The focus will be on steel based materials and use of cooling air to keep the metal temperatures within the "max use" temperature limits.

The rotor design will follow the following order of preference:

1. Air cooled steel disc construction.
2. Un-cooled compressor using steel discs and possibly higher chrome content steels in the rear stages.
3. Un-cooled compressor using steel discs and hybrid rear compressor discs. The hybrid discs may be dual heat treat discs, or dual chemistry discs. This path may require a materials development program, for which currently no budget exists.

Conclusion

Cost, performance and mechanical integrity considerations dictated that an "air cooled" compressor disc configuration will be designed and conventional steel rotor material will be utilized, if possible. Nickel based materials (IN706 & IN718) have been eliminated.

Casings

Approach

The approach for designing the Compressor, Combustion and Turbine (CCT) cylinder is a step-by-step process of adding features and rearranging the layout. First, the basic geometry of the CCT cylinder was constructed and designed to mate up with the Compressor and Exhaust Cylinders. The CCT is required to accommodate numerous interfaces with other components. Therefore, these interfaces are applied to the CCT base model and associated interferences are worked out. For example, the portals for the Advanced Transition were input into the CCT model, followed by the rotor cooling air pipes. The shape and geometry of the advanced transition causes these features to overlap, therefore a redesign effort will be made to determine what changes are possible to accommodate both component interface requirements (see Figure 19).

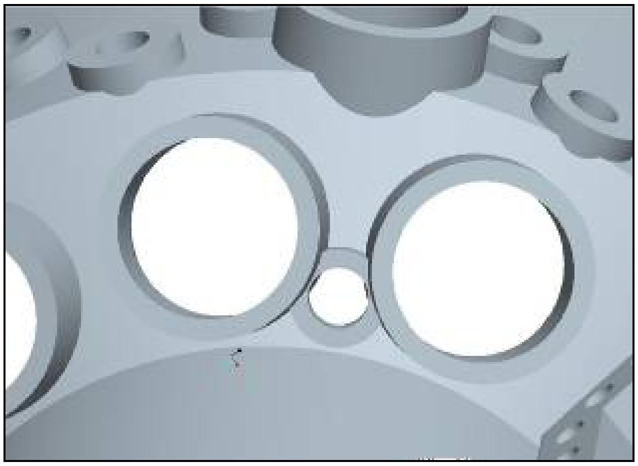


Figure 19. CCT Cylinder – Portal Interference with Rotor Cooling Air Pipe

The approach to designing the Turbine Vane Carrier is similar to the CCT cylinder. A step-by-step process of adding features will be followed, until all necessary requirements are incorporated.

Results and Discussion

The primary goal in this quarter was to provide a baseline 2-D longitudinal layout of the casings, to establish the spacing with interfacing components. To accomplish this goal, several decisions had to be made regarding the general configuration for certain components. Some of these components were the Compressor, Combustor, and Turbine sections of the outer casings (see Figure 20 and Figure 21). The combustor section of this engine has a decreased axial distance, in proportion to other Siemens engine frames. This change results in a reduced space for piping and other components which interface at the combustor section, such as rotor cooling air pipes, combustor shell extraction pipes, manways, etc. The decision was made to go forward with a CCT-style outer casing. This style of casing involves one outer casing cylinder stretching from the compressor exit region to the turbine exit region. The use of such a large casing will cause an increase in manufacturing cost, as well as a decrease in outage convenience, as the entire CCT case must be removed. However, the elimination of the vertical joint between the combustor and turbine sections will allow sufficient space for all necessary casing interfaces, as mentioned above. Maintaining similar casing interfaces as in previous engine frames keeps the design of these components within Siemens' range of experience.

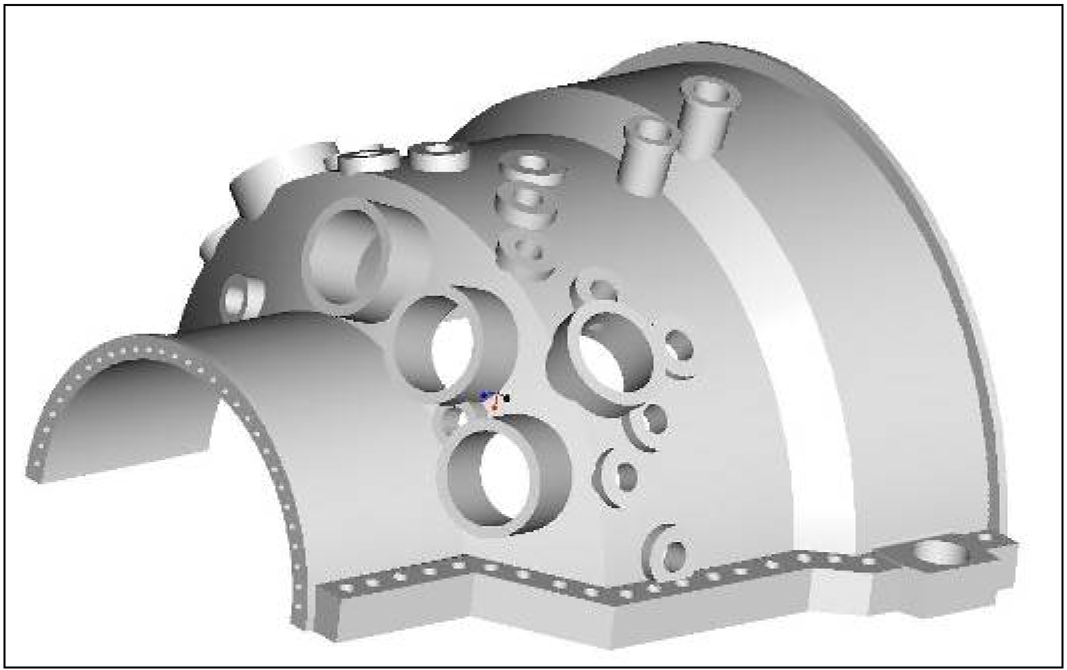


Figure 20. CCT Cylinder – Partially de-Featured

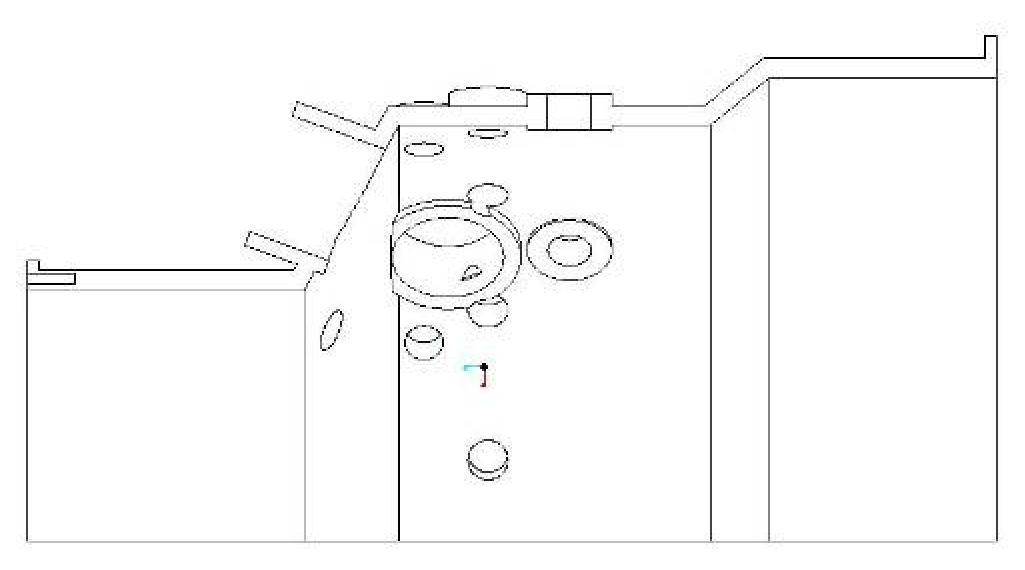


Figure 21. CCT Cylinder – Longitudinal Cross-Section

Another configuration that was selected as the primary path was a one-piece Turbine Vane Carrier. This type of vane carrier is based on the Siemens harmonized approach.

The one-piece vane carrier advantages are elimination of gaps between stages and design simplicity by reducing parts and assembly steps.

The advanced transition design to be incorporated into the Hydrogen Turbine will be fabricated in CMC material as the prime approach. Steam-cooled advanced transition will be considered as the back-up design. If required, steam cooling can be accommodated by embedding steam manifolds in the Vane Carrier forward section (see Figure 22).

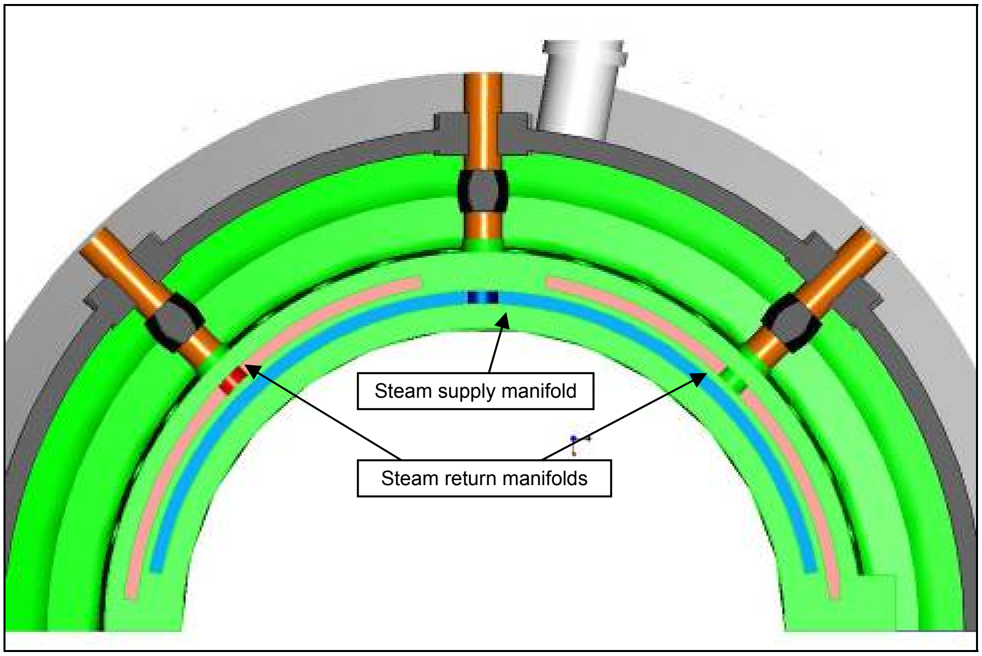


Figure 22. CCT Cylinder – Axial Cross-Section, Showing Steam Manifolds

Conclusions

The baseline layout of the CCT case and the Turbine Vane Carrier was completed, creating the foundation for the overall engine layout. This is important, as the details of the design can begin to take form. The 3-D layout of these two components will take shape, as all interfacing components are designed.

Actual or Anticipated Problems or Delays and Actions Taken to Resolve Them

In the current layout of the CCT case, the maximum radius exceeds the shipping envelope for rail car transportation. As seen in Figure 23, the Turbine Support represents the widest part of the case. To meet the shipping limitation, the configuration of the Turbine section may be altered. The turbine support could be repositioned, or the Vane Carrier support system may be altered such that the aft end of the CCT case can be brought radially inwards.

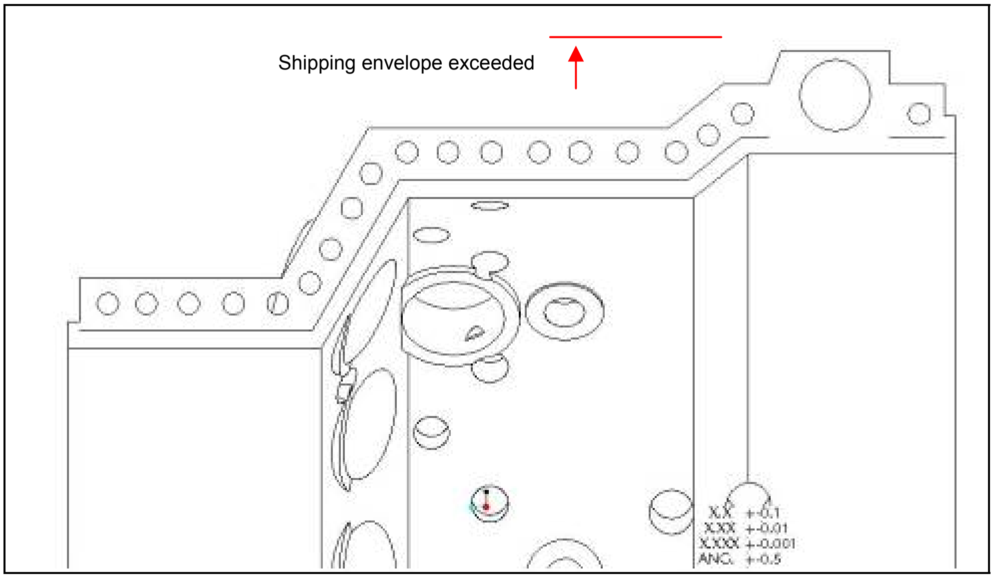


Figure 23. CCT Cylinder – Horizontal Joint

Materials Development

Approach

During the first quarter FY07 the focus of the materials and coatings activities has been on the following sub-projects:

- High temperature bond coats
- High temperature capable TBCs
- Rare earth alloy modifications
- Fabricated airfoils for near wall cooling

The efforts associated with hydrogen embrittlement Materials sub-project have been suspended, however the results of the literature review have been compiled and are published within this report.

In addition to the four material sub-projects highlighted above, an internally funded effort has been directed towards an assessment of materials and coatings behavior in Syngas Environments.

High Temperature Bond Coats

Results and Discussion

NiCoCrAlY material bond coats are being evaluated in this program as high temperature oxidation and corrosion resistant bond coats and rare earth elements modifications to the coating powders are being investigated. Studies reported in the literature have shown that the rare earth elements additions could have a positive influence on the improvement of the isothermal and cyclic oxidation resistance of several alumina and chromia forming alloys. The four elements selected for this study are hafnium (Hf), cerium (Ce), neodymium (Nd) and rhenium (Re). The processing technique is the same as the one currently employed for applying bond coats on substrates, i.e. a high velocity oxy-fuel (HVOF) spraying. The status of the program is given below:

- Specimens of the substrate IN939 that were coated with four types of powders of NiCoCrAlY each modified with of a different rare earth element were investigated in the as-coated state. Scanning Electron Microscope micrographs are shown below for the four types of specimens (see Figure 24 to Figure 27).

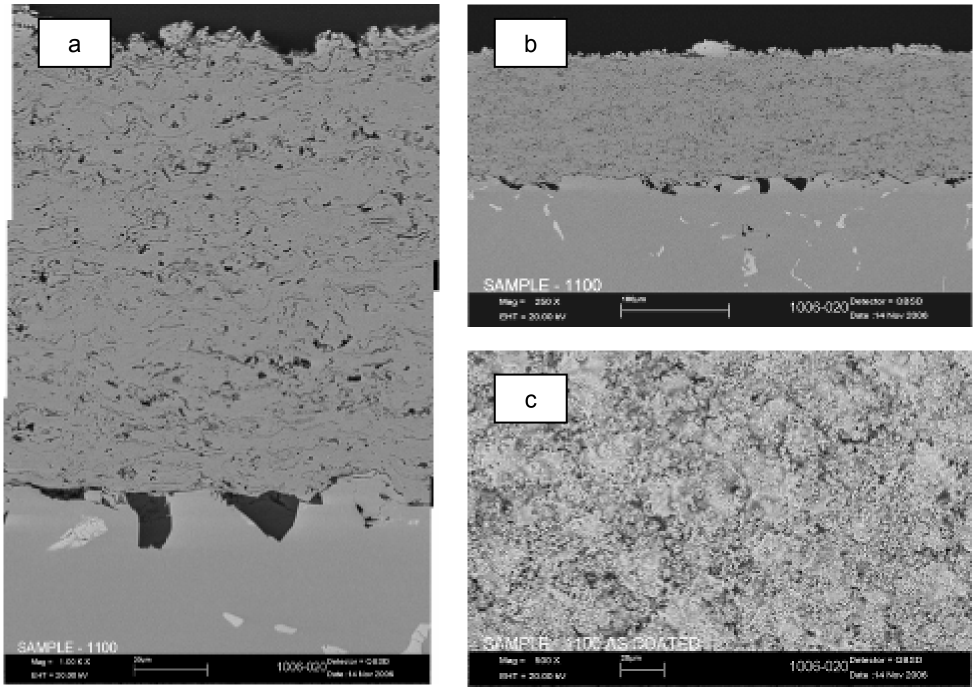


Figure 24. Cross-Section of As-Coated NiCoCrAlY + Ce Bond Coat on IN939 Substrate (a,b – cross-section, c – top view)

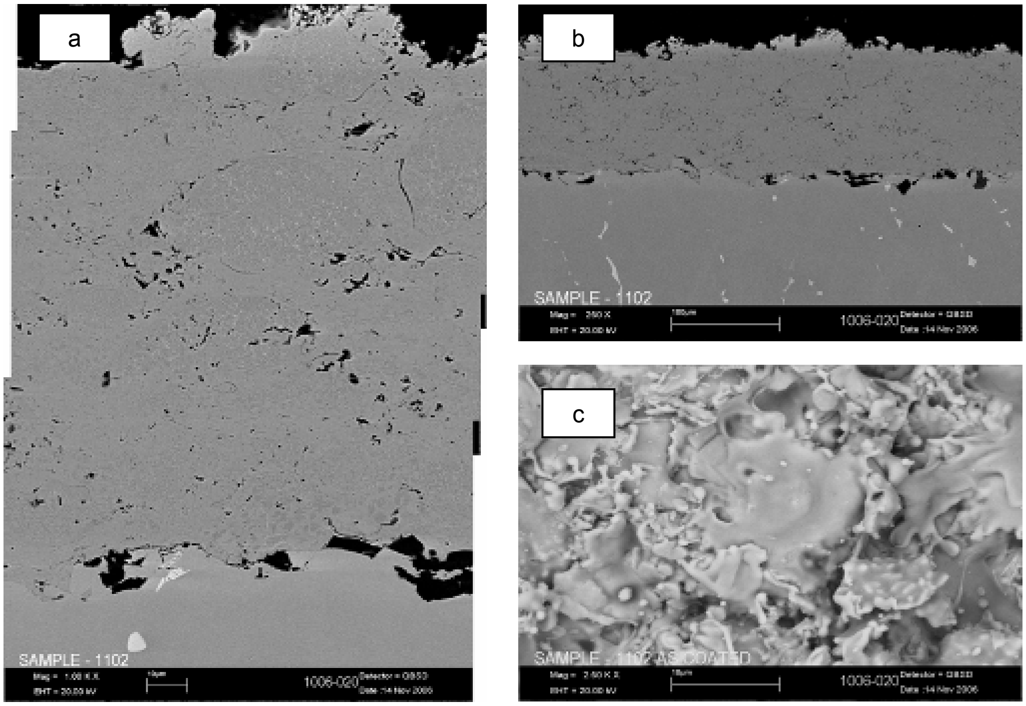


Figure 25. As-Coated NiCoCrAlY + Hf Bond Coat on IN939 Substrate (a,b – cross-section, c – top view)

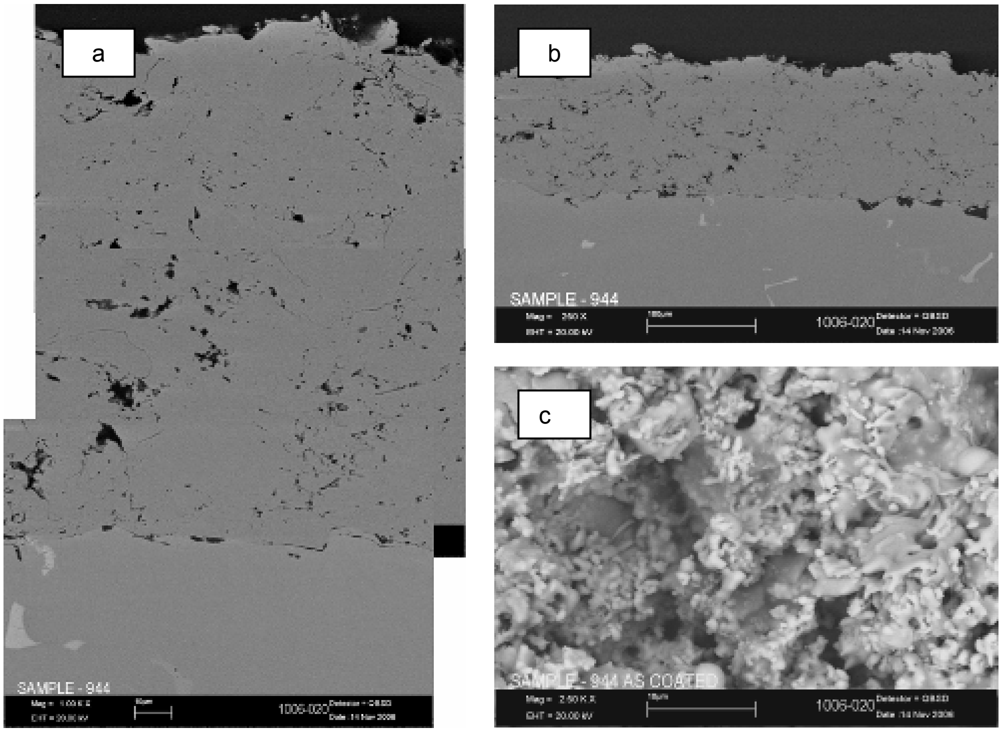


Figure 26. As-Coated NiCoCrAlY + Re Bond Coat on IN939 Substrate (a, b – cross section; c – top view)

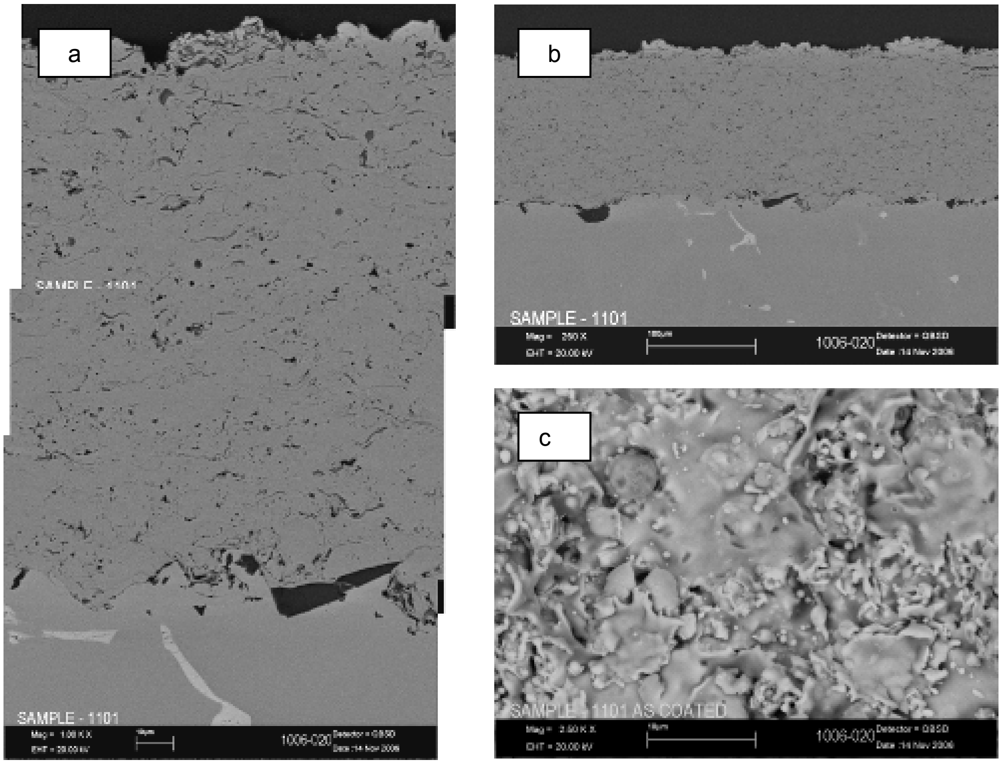


Figure 27. As-Coated NiCoCrAlY+ Nd Bond Coat on IN939 Substrate (a, b – cross section; c – top view)

From the as-sprayed cross-sections of the four bond coats, the Ce-modified bond coat, Figure 24, appears as the most porous, possibly due to a higher deposition velocity and/or different melting properties (lower melting temperature, lower viscosity). The other three bond coats (Hf-, Re- and Nd-modified) present a much denser, more compact morphology in cross-section and the melted splats spread out, covering a larger area (see Figure 25c to Figure 27c compared to Figure 24c).

- Ten coated samples of each of the compositions were TBC coated in each case for spallation studies. The spallation tests are being carried out in static air at three temperatures with 24-hour cycles. For the lowest temperature, the specimens are still in test, whereas for the higher temperatures, the life of the TBC systems is evidently improved for the Nd-modified coating.

Figure 28 shows the time to failure (spallation of top coat) for all the specimens cyclically exposed ”intermediate” and “high” temperatures in laboratory air, where Nd-modified coating specimens have a life increase of about 39% over the Re-modified bond coat

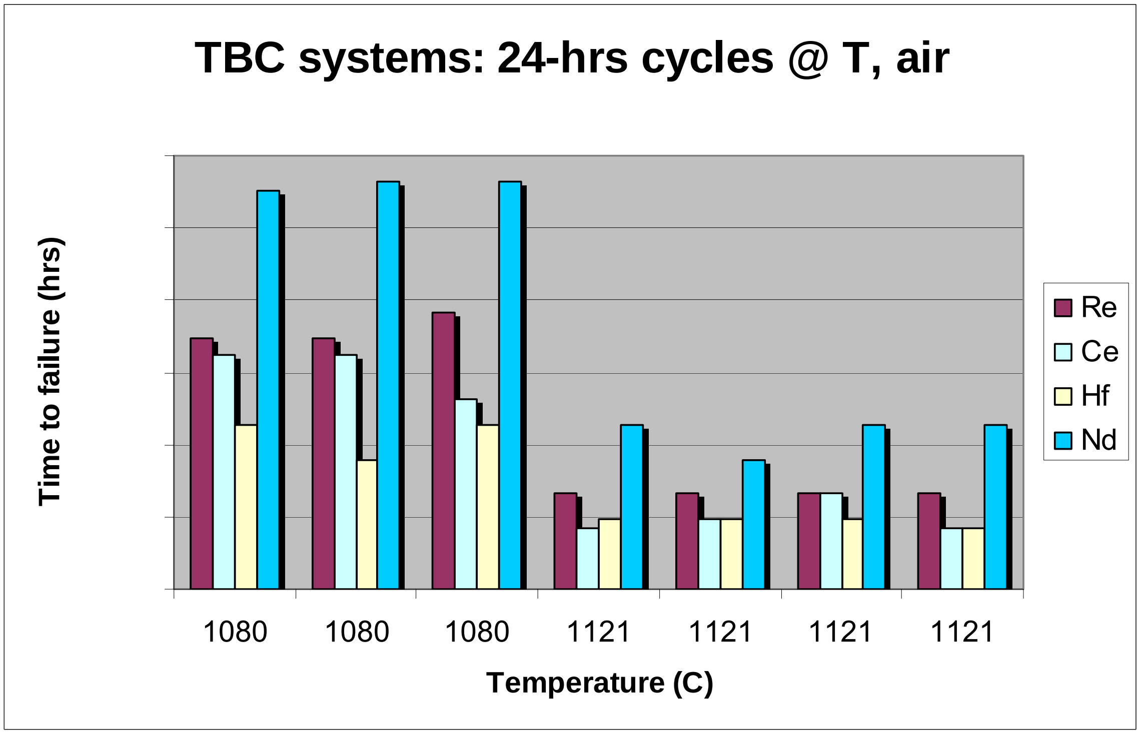


Figure 28. Time to Failure for TBC Systems with Rare Earth Elements Modified Bond Coats at Two Temperatures Cyclically Exposed in Air.

- Oxidation behavior/mass gain studies of the bond coats are currently being performed at 1000°C, cyclically, in an environment containing 10% water vapor in air.

Preliminary results from the first set of specimens point to the fact that, whereas all specimens are having a similar trend in terms of weight change with time, the Nd-containing bond coat shows a better oxidation resistance compared to the other rare earth additions, even in a more aggressive 10% steam in air.

Conclusions

IN939 specimens coated with four types of NiCoCrALY bond coats each modified with different rare earth elements were cyclically tested in static air at three temperatures. Preliminary results showed that all four had similar trend in terms of weight change with time. However, the neodymium containing bond coat showed superior oxidation resistance.

High Temperature Capable TBCs

Results and Discussion

The project focuses on thermal barrier coatings (TBCs) systems that meet the TBC design conditions supplied by the Turbine design group. The goal is to achieve the desired properties with a moderate surface temperature limit for short term goal (2009) and high surface temperature for long term goal (2011). Two potential compositions are being evaluated in this program. The program status is discussed below:

- The two TBC coatings being evaluated have met the room temperature thermal conductivity requirement.
- The phase stability of these TBCs was tested in a high temperature XRD chamber between the temperature range of 1500°C to 1850°C. The TBCs show no phase transformation in this range.
- The thermal conductivity test specimens have been prepared. The samples will be heat treated at temperatures between 700°C and 1400°C to determine the high temperature thermal conductivity properties. The contractual agreements with Oak Ridge National Laboratory (ORNL) are now in place to support this effort.
- Coating spallation studies are currently being carried out to evaluate TBC performance at elevated temperatures.
- Preliminary calculations show the surface temperature capability of one TBC composition could reach satisfactory temperature. This still has to be confirmed by actual testing at this temperature.
- A Peer Review for the high temperature capable TBC was held on 19th December, 2006. The action plan is being formulated and is provided below.
- A new centrifugal pump has been installed for the HADES rig. Preliminary evaluation of the HADES rig is underway and an instrumented metallic specimen has been tested in support of the rig performance evaluation.
- An instrumented TBC specimen was utilized to determine the test rig conditions, and an additional TBC specimen was tested at these conditions. Metallographic studies are planned to evaluate the microstructure and correlate the results back to test rig model.

Milestone

Peer review carried out on the development of high temperature capable TBCs (Thermal Barrier Coating Conceptual Design, DOE Milestone NO. 5) was completed in December, 2006.

To ensure success in advanced coating systems development, a validation plan has been generated (see Figure 29). Various Siemens and external rigs will be utilized in this effort. The testing will involve bond coat temperature limit evaluation, cyclic oxidation testing in steam and contaminated atmospheres, TBC coating system durability testing under thermal gradient and thermal cycling conditions, TBC coating system durability testing under a thermal gradient in simulated combustion atmospheres, coating durability testing under high pressure and velocity conditions in various combustion atmospheres with mechanical loading and, finally, the coating system validation testing in an engine.

Conclusions

Two new TBCs under evaluation met the room temperature thermal conductivity requirement. Phase stability of these TBCs tested at 1500-1850ºC temperature showed no phase transformation.

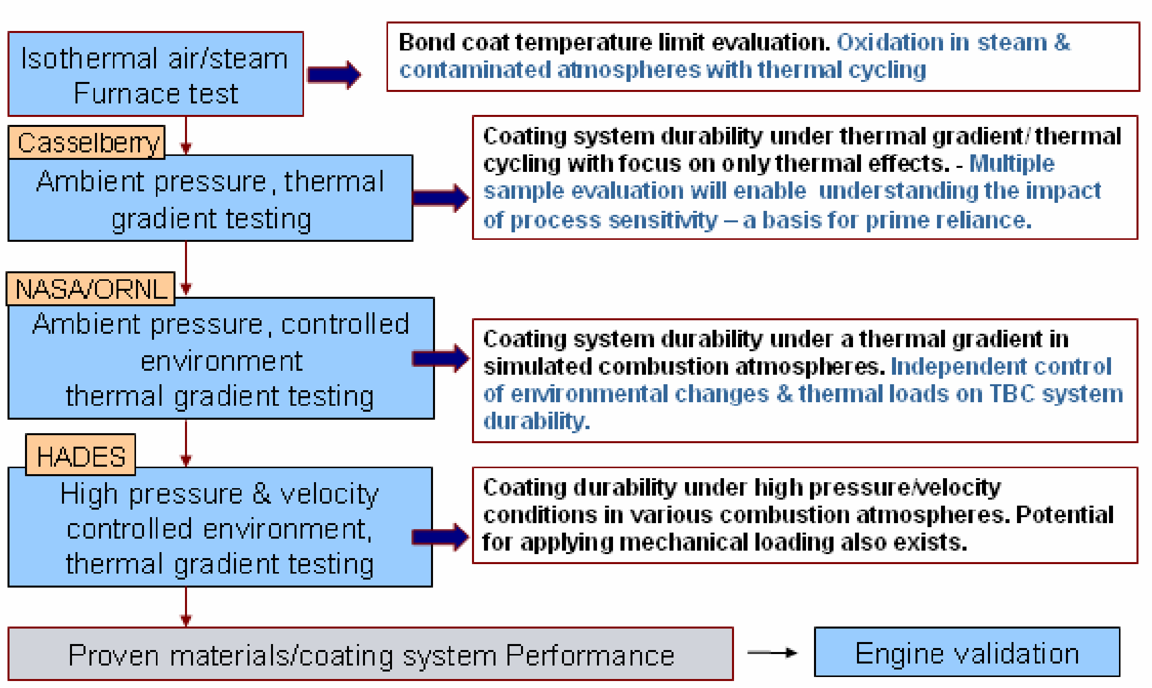


Figure 29 . Advanced Coating System Validation Plan

Rare Earth Alloy Modifications

Results and Discussion

The 180 kg (400 lb) master heat of Alloy (CM)247LC ordered from Howmet Whitehall to support the rare earth modified alloy trials is being manufactured. Test bar molds have been fabricated in preparation for the casting. Howmet have stated that they anticipate approximately 80% retention of the rare earth elements in the alloy during casting. Based on this information, rare earth addition levels have been calculated and the four rare earth elements to support the first iteration of castings have been procured.

Discussions have been held with ORNL concerning the evaluation of the rare earths elements' effect on the oxidation process. ORNL has expressed interest in conducting detailed microstructural analysis to determine the differences in the oxidation mechanisms produced by the four rare earth elements as compared to the baseline control material. This will help in the final optimization of the doping to be carried out on production parts.

Conclusion

Based on information from Howmet Whitehall, rare earth addition levels have been calculated and four selected rare earth elements have been procured to support the first iteration of castings.

Fabricated Airfoils for Near Wall Cooling

Results and Discussion

The Alloy (CM)247LC to Haynes 230 and Alloy (CM)247LC to Haynes 214 coupons diffusion bonded at Integrated Energy Technologies have been sectioned and examined to evaluate bond joint integrity. Metallographic examination revealed that there was incomplete bonding at the edges of the coupons extending inwards along the bond line for approximately 10 mm. The central sections of the bonded coupons appeared to be well bonded with no evidence of cracks or porosity. Optical micrographs showing the microstructure in the bonded regions are shown in Figure 30 to Figure 32.

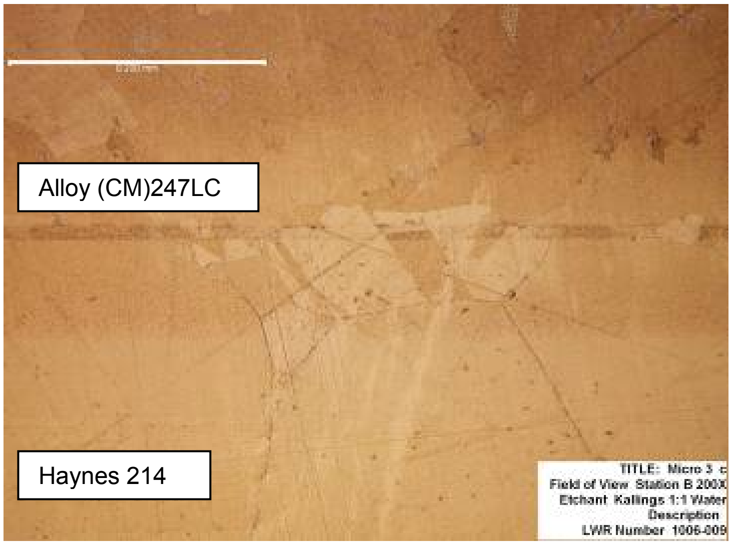


Figure 30. Diffusion Bond Between Alloy (CM)247LC and Haynes 214

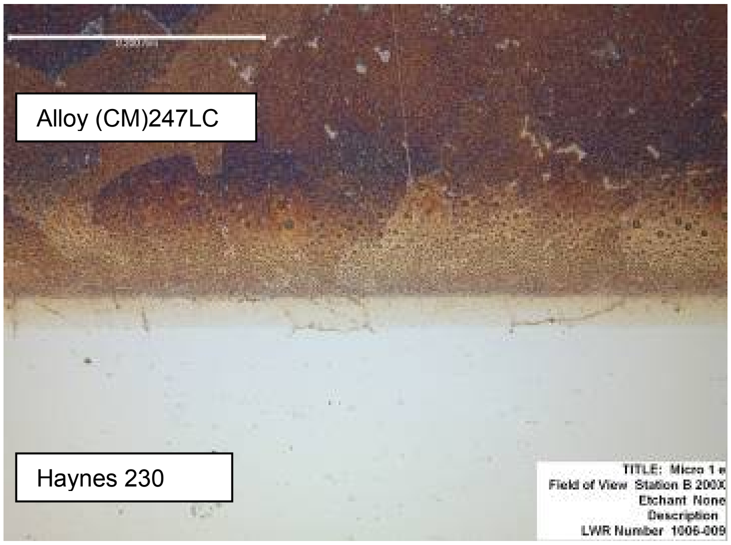


Figure 31. Diffusion Bond Between Alloy (CM)247LC and Haynes 230

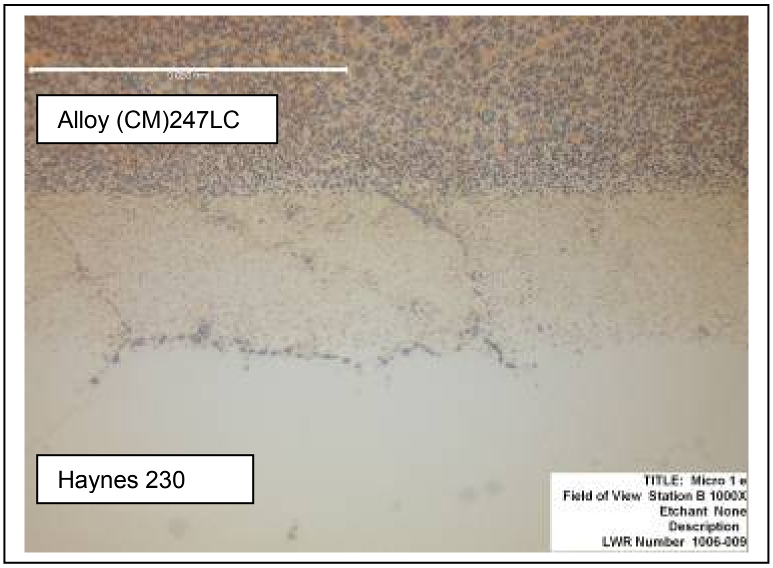


Figure 32. Diffusion Bond Between Alloy(CM)247LC and Haynes 230

Stress rupture and tensile test pieces were machined from the Alloy (CM)247LC to Haynes 230 and Haynes 214 diffusion bonded coupons. The initial tensile tests have been performed at a temperature of 760°C (1400°F). The results of this testing is shown in Table 3.

Identification	0.2% Yield Stress – proportion of wrought base alloy value	UTS– proportion of wrought base alloy value
230-1-4	*	0.4
230-2-1	*	0.62
214-3-1	0.97	0.9
214-4-1	*	0.89

* Testpiece failed prior to yield.

Table 3. Results of Tensile Testing on Diffusion Bonded Alloy (CM)247LC to Haynes 230 and Haynes 214

The ultimate tensile strength and 0.2% yield strength results for the diffusion bonded samples have been plotted against the virgin parent material properties. Figure 33 shows a comparison for Alloy (CM)247LC and Haynes 230 and Figure 34 shows a comparison for Alloy (CM)247LC and Haynes 214.

Stress rupture testing on the diffusion bonded materials has started, but no results are available at the time of writing.

Conclusions

Diffusion bonded (CM)247LC to Haynes 230 and 214 coupons have been sectioned and evaluated for bond integrity. The central sections of the bonded coupons appeared to be well bonded with no cracks or porosity. However, incomplete bonding was observed on the edges. Initial tensile tests that were performed on the bonded test pieces showed promising results.

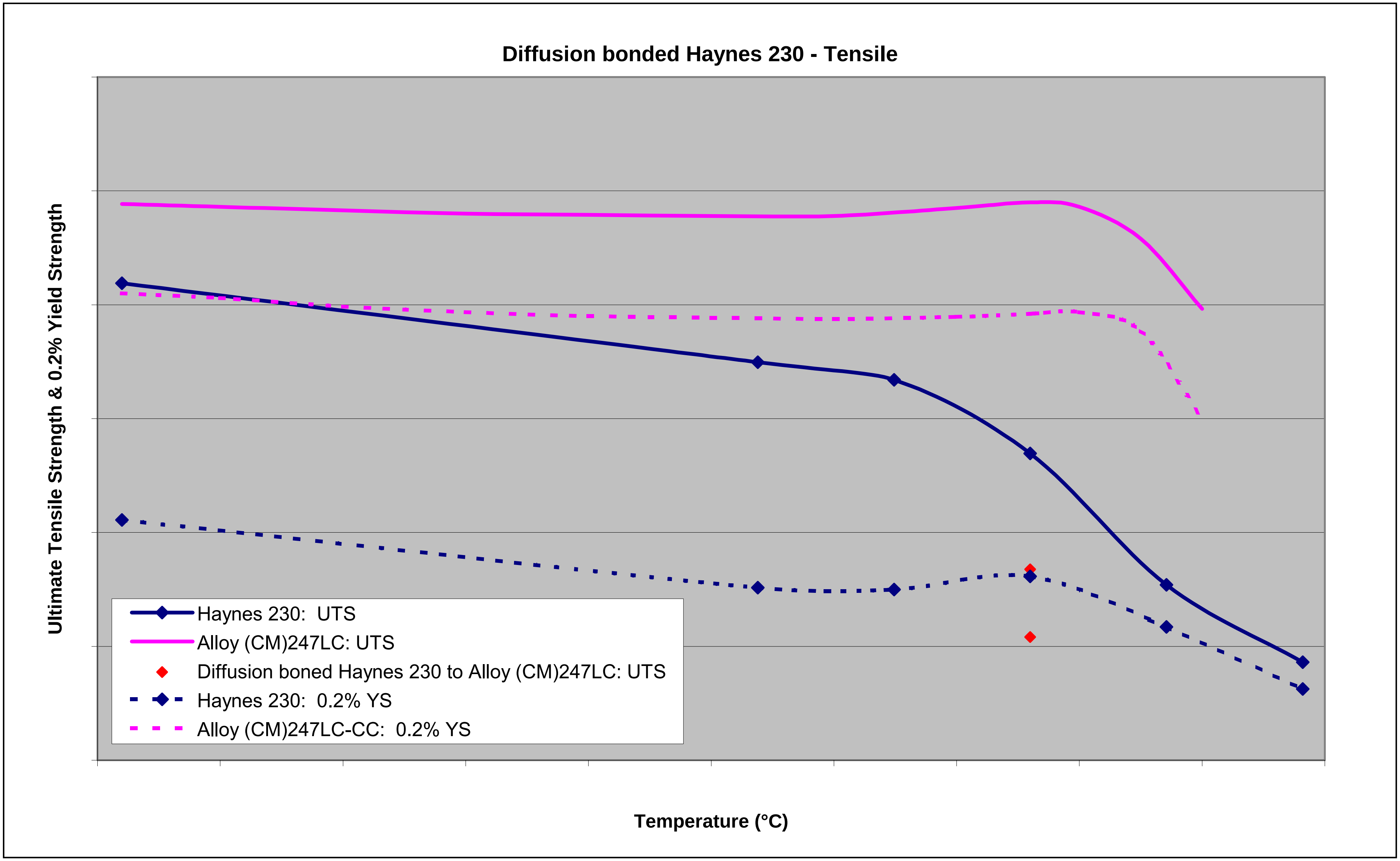


Figure 33. Comparison of Parent Material Tensile Properties with Diffusion Bonded Material Properties (Haynes 230)

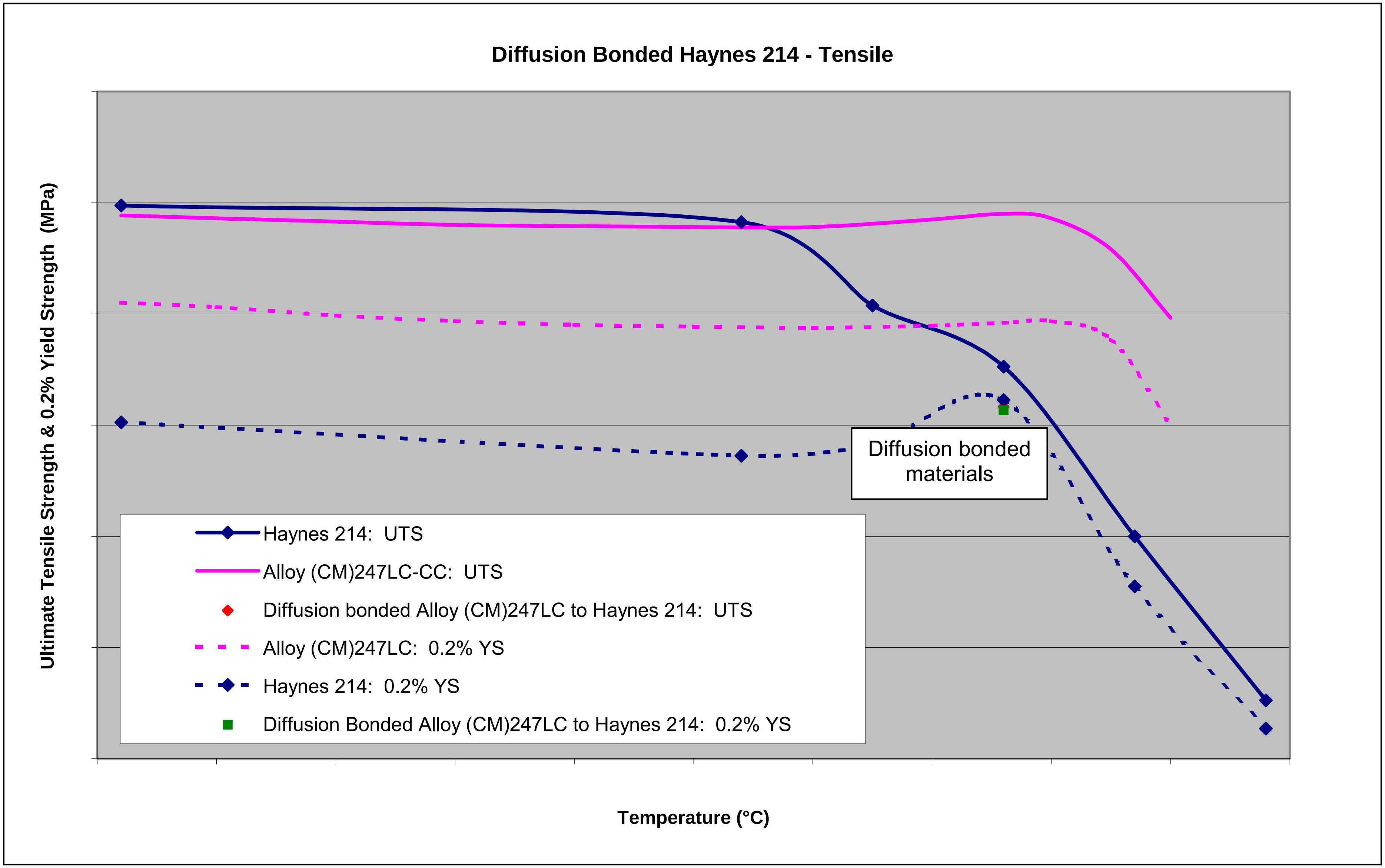


Figure 34. Comparison of Parent Material Tensile Properties with Diffusion Bonded Material Properties (Haynes 214).

Hydrogen Embrittlement

Aspects of Hydrogen Damage in Specific Representative Alloys

Results and Discussion

As reported at the end of the last reporting period, the Materials team have been advised that there would be insufficient funding to support the hydrogen embrittlement testing in FY07. Highlights of the literature review results on hydrogen embrittlement are documented in this report and the full results package is listed in the Appendix section.

The detrimental effects of hydrogen in metals, usually referred to as hydrogen embrittlement, are well known and often-studied. Nonetheless, despite the extensive research conducted over many decades, there is still much confusion over a general definition of hydrogen embrittlement. Usually, an attempt to define hydrogen embrittlement invokes various categories or classifications of the phenomenon. In some other cases, the definitions appear to be somewhat descriptive of the proposed mechanism of embrittlement. The varieties of known forms of damage, combined with the varieties of proposed embrittlement mechanisms, clearly make it difficult to establish a collective definition of hydrogen embrittlement.

Various aspects of hydrogen damage, as available in the literature, are selectively summarized below.

1. Comparison of internal hydrogen embrittlement and hydrogen environment embrittlement of X-750[1]. Much less hydrogen is required on a bulk level to embrittle X-750 in a hydrogen environment as compared to internal hydrogen. The degree of embrittlement of this alloy is controlled by the grain boundary hydrogen concentration irrespective of test temperature and bulk hydrogen concentration.
2. The effect of hydrogen on the fracture of X-750[2]. The fracture mechanism in this alloy is the initiation of voids at grain boundary carbides followed by void growth and coalescence. The hydrogen appears to either decrease the cohesive strength of the grain boundary carbide-matrix interface or create a local hydrogen pressure at the interface, both mechanisms resulting in easier initiation of voids. The diffusion of hydrogen was essential to cause the embrittlement of the material. The critical event apparently was hydrogen diffusion to the high stress region at a dislocation pileup at the grain boundary. The tensile specimens were less embrittled at 175°C and 285°C than at room temperature, showing the need for trapping. Plastic strain was required for fracture.
3. Effect of hydrogen on the mechanical properties of iron base superalloys[3]. Variations in Ti/Al ratio in precipitation strengthened iron base superalloys (15 % Cr + 25 % Ni) showed increased strengths. However, the ductility is strongly affected by thermal exposure to hydrogen, but the effect of the testing environment after charging is small. Losses in RA due to charging range from 40 to 80 %. The extent of RA loss is associated with the accumulation of hydrogen at the interface between the matrix and the hexagonal $Ni_3Ti(\eta)$ precipitates. As the size and morphology of these precipitates changes so does their efficiency in stripping hydrogen from the dislocations. The larger the precipitates and more plate-like they become, the greater the stripping efficiency and greater the RA loss.

4. Internal hydrogen embrittlement at 300°C in Nickel base alloys 690 and 800[4]. The mechanical behavior of the two alloys was studied at a temperature of 300°C with and without hydrogen impregnation. The quantity of hydrogen out gassed under vacuum at 600°C from these alloys is very high (> 100 ppm). No failure was observed on the C-ring specimen of the two alloys when a constant stress lower than the yield stress was applied. In tensile tests, IN690 was embrittled by hydrogen, resulting in about 100% intergranular fracture. The alloy 800 is not embrittled even after 48 hours of hydrogen charging. Interaction between hydrogen atoms and $M_{23}C_6$ precipitated in the grain boundaries promote hydrogen embrittlement.
5. Temperature effects on hydrogen induced cracking in an iron based superalloy[5]. The effects of temperature on hydrogen induced crack growth susceptibility were studied in the iron based superalloy IN903 using hydrogen charged samples. The measured crack growth rates increased by more than two orders of magnitude as temperature increased from 253 to 298°K. Crack growth rates decreased at higher temperatures. Fracture in all samples was initiated by fracture of matrix carbides followed by microvoid formation at slip band intersections and failure of interconnecting slip band segments. Microvoid formation at slip band intersections is the dominant event in the fracture process.
6. NASA-HR-1, A new hydrogen resistant Fe-Ni base superalloy[6]. – NASA-HR-1 is a high strength Fe-Ni base superalloy that was designed to resist high pressure hydrogen environment embrittlement (HEE), oxidation and corrosion. Originally derived from JBK-75, this new alloy has exceptional HEE resistance that can be attributed to an intrinsically HEE resistant γ matrix and η free grain boundaries.
7. NASA-23 for HEE resistant structural applications[7]. NASA 23 was specifically developed as a structural alloy for application in liquid propulsion systems that use hydrogen. It has mechanical properties comparable to Alloy 718 but with a superior resistance to hydrogen induced damage.

Conclusion

A literature review on hydrogen empbrittlement of alloys used in the H2 Turbine was completed.

Materials Experience in Syngas Environment

This section presents the preliminary results of the TBC coated superalloy systems testing in isothermal combusted syngas environments that was funded internally by Siemens. The combusted gas, which in this case was 10.7% O_2, 8.4% CO_2, 5% H_2O, 0.4% Ar, 290 ppm SO_2 and the remainder N_2 , was passed over 25 mm (1”) diameter coated buttons in an isothermal furnace at a temperature of 1000°C. The drawback in this experiment was the much diluted nature of the combustion gas (due to safety concerns in the furnace) and the exposure of superalloy to high temperatures (1000°C).

The coating systems were representative of the hot gas path materials currently employed. These include Standard 250 μm 8YSZ TBC on HVOF rough bond coated Alloy (CM)247LC, IN939 and IN738 (blade and vane materials) and porous 250 μm 8YSZ abradable on HVOF rough bond coated Hastelloy-X (ring segment material) substrates. The results indicate the oxide scale formation to be greater in Alloy (CM)247LC and IN738 as compared to Hast-X and IN939, as shown in Figure 35. These photographs show the back-side (uncoated side) of the coated substrates. Also seen are nitrides in the substrates, owing to high nitrogen dilution in the combustion gas. In addition to the oxide layer, it is also observed that the oxide scale is weakly attached and ready to disintegrate on Alloy (CM)247LC and IN738 as compared to IN939 and Hast-X.

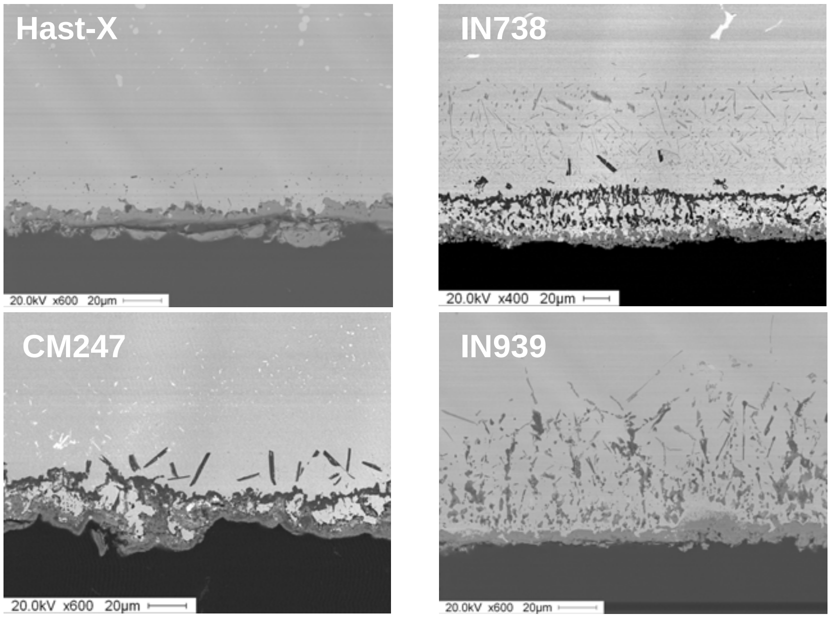


Figure 35. Behavior of Superalloy Substrates in Isothermal Syngas Combusted Environments

While no degradation of TBC coating was observed in the above study in times of up to 500 hours of testing, formation of mixed oxides was observed below the TBC, just above the alumina layer. The characteristic of HVOF bond coat is the formation of an adherent alumina layer, when heat treated in air. Upon total aluminum depletion, Nickel, Cobalt and Chromium in the bondcoat start to oxidize resulting in formation of spinels (mixed oxides) and ultimately spallation of the TBC. In this study, it was observed that the spinel forms beneath the TBC and above the alumina layer, even with aluminum in the bond coat in all four coating systems. This is shown in Figure 36 and can influence the TBC spallation behavior. It should be pointed out that detailed studies need to be performed to comprehend the TBC system integrity.

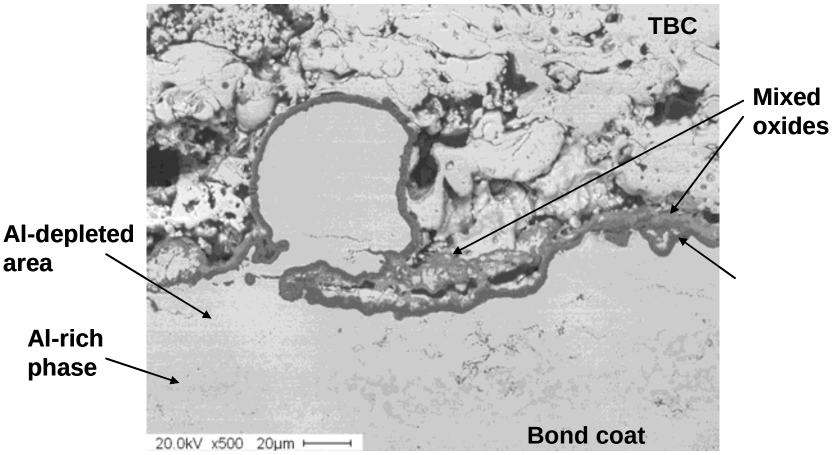


Figure 36. **Bond Coat Behavior in Isothermal Syngas Combusted Environment (Section c – top view)**

Along with the above studies, a furnace cycling test was also carried out on these coated systems in isothermal syngas combusted environment at a temperature of 1100°C. There was no SO_2 gas added in this case. TBC spallation was observed at times of only 400 hours in syngas combusted environment at a temperature of 1100°C. The typical spallation times at this temperature in air are about 1200 hours. This necessitates TBC testing along with development of novel superalloy, bond coat and/or TBC systems.

Figure 37. **TBC Spallation Observed on CM247 at 400 Hours.**

While these results are preliminary, it is necessary to carry out an additional detailed investigation of critical material systems in syngas combusted environments. The mechanism observed in Alloy (CM)247 needs to be characterized in detail to attain more knowledge of the behavior in the combination of oxidative and corrosive environments.

While the furnace environments provide insights into fundamental behavior of the coating-superalloy systems, a burner rig is more representative of the actual conditions in service. A burner rig test is scheduled to be carried out in 2007 with metal surface temperatures in the 750-950°C range and TBC in the 1100–1300°C range.

Technology Transfer Activities

- Discussions were held with representatives from Oak Ridge National Laboratory (Ian Wright and Thomas Gibbons) to determine how ORNL and Siemens could best collaborate in support of the DOE funded programs. Technologies where synergies were identified include:

- Bondcoat development for IGCC applications. ORNL bond coat alloys will be compared with the Siemens bond coat alloys. Siemens will undertake to test both groups of bond coat alloys in the environmental test facilities at either Cranfield University and/or the University of North Dakota Energy and Environmental Research Center.
- Testing in air / water vapor environments. ORNL have offered their facility for the testing of Siemens alloys/coating systems.
- Rare earth modified Superalloys. As described elsewhere in this report, ORNL expressed an interest in conducting detailed microstructural analysis to determine the differences in the oxidation mechanisms produced by the four RE elements as compared to the control material.

To address the concerns on the coating system durability in IGCC plant environments, a comprehensive roadmap was developed for the entire TBC, bond coat and substrate system (see Figure 38). The process includes identifying the materials at risk based on experience in operating IGCC plants, isothermal testing in a burner rig with simulated environment, test results analysis, sample testing at actual gasifier conditions in the North Dakota Energy and Environmental Research Center gasifier, finalizing the alloy / coating test matrix, further isothermal testing in simulated natural gas / syngas / high hydrogen content environments, test result analysis, and finally drawing conclusions and deciding on future steps.

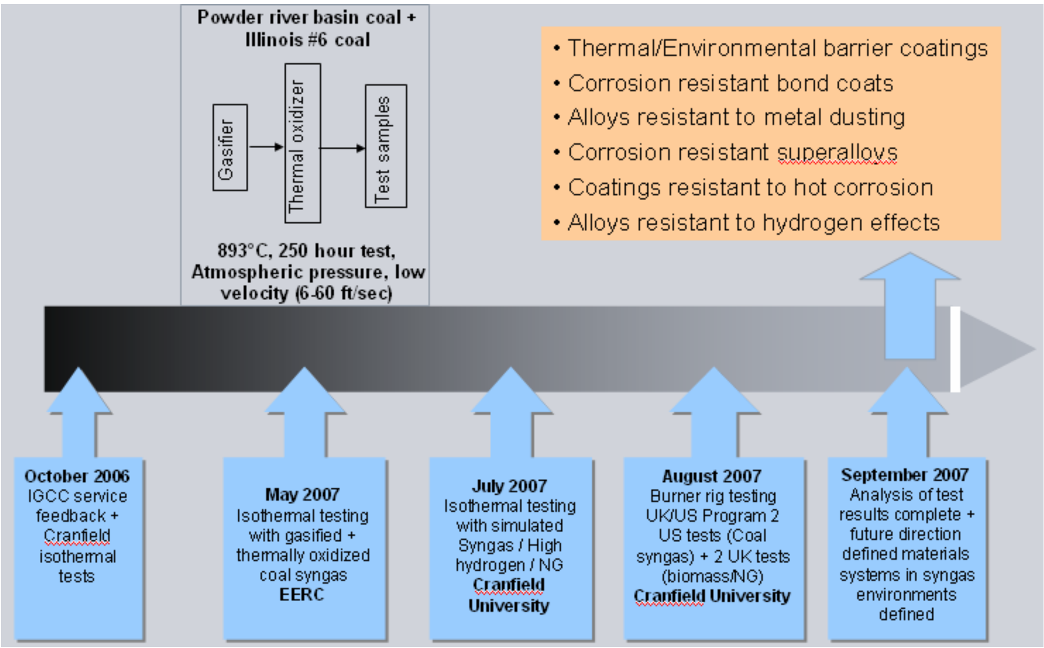


Figure 38. Roadmap for Testing Coating / Materials Systems in IGCC Environments

Conclusion

Preliminary test results were obtained on TBC coated superalloy systems in syngas environments at 1000ºC. While no TBC spallation was observed up to 500 hours of testing, formation of mixed oxides was observed below the TBC just above the alumina layer. A furnace cyclic test carried out at 1100ºC resulted in TBC spallation after 400 hours, compared to 1200 hours in air.

Auxiliaries

Approach

The key Auxiliary Systems were based on the systems identified for the SGT6-5000F frame and the non-IGCC SGT6-6000G frame. These systems include, but are not limited to: Fuel Gas System, Syngas System, Hydrogen Gas System, Steam Injection System, Turbine Cooling Air System, Extraction Air System, Lube Oil System, Control Oil System, Instrument Air System, Nitrogen Systems, Drain Systems, Inlet System, Exhaust System, Piping Systems, Compressor Bleed System, Fire Protection Systems, Electrical Systems, Automation Systems and various smaller systems.

Identification of materials to be reviewed initially was expected to include exotic materials for extremely high temperature and now is limited to those that can support temperature ranges in the 350°C to 400°C. This does not mean that an extended scope could not be opened as necessary in the future.

The approach expected to be utilized on the Risk Assessment will follow the established Six Sigma Risk Assessment program. During this period, alternative design approaches and constraints were identified with relationship to integration and its effect.

The initial approach to cost estimation was to use existing internal databases on different frames and scale up utilizing good engineering practices. Additional factors were added based on initial estimated definitions of boundary conditions.

Results and Discussion

The Key Auxiliary Systems have achieved some level of definition based on boundary conditions presented for the first iteration. Impacts on requirements at Auxiliary boundary conditions and Balance of Plant requirements have been finalized.

Identification of Materials to be Reviewed

The following two documents were reviewed and may play an important part in defining alternative materials, if required: Hydrogen Transportation Pipelines, Reference [8] and Reference [9]. Figure 39 is from the second reference and shows the materials used in the power generation industry and their associated creep strengths.

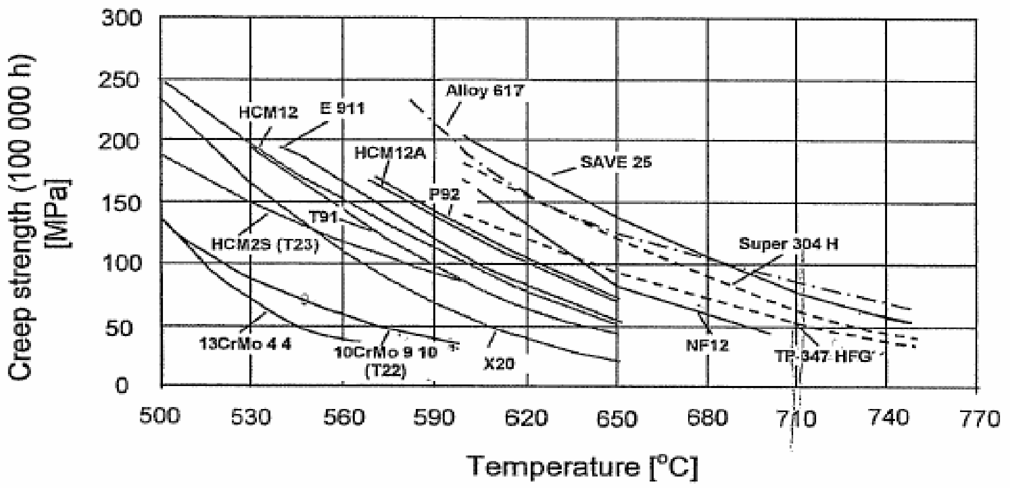


Figure 39. Creep Strength versus Temperature for Materials Used in Power Generation Industry

These steels, such as T/P23, T24, T/P92, E911 and HCM12A, will be reviewed over time and as necessity dictates.

Identification of Alternatives for Risk Assessment

In the conceptual stage, the first decision is the selection of inputs to the Risk Assessment model (see Figure 40). These are mostly external with some internal risks. Fixing the inputs too early could freeze the system analysis and provide something not really needed. This period was used to identify potential design alternatives and constraints associated with each and begin looking at inputs necessary for this analysis.

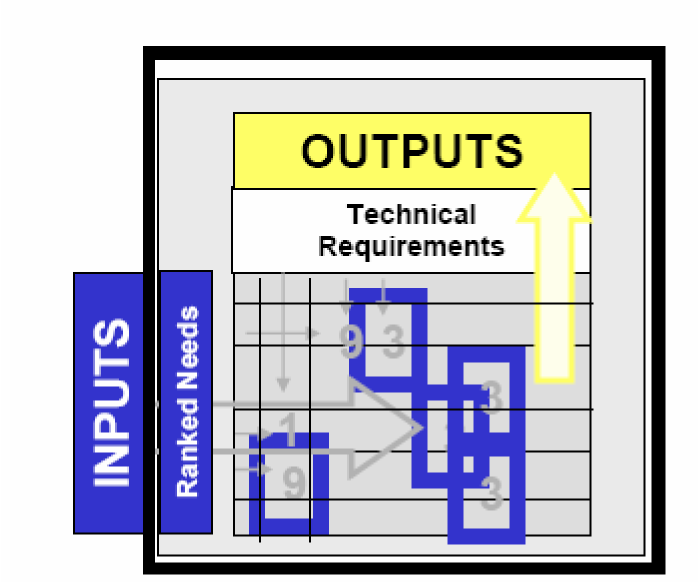


Figure 40. Risk Assessment Model

Identification of Constraints from Gas Turbine that Affect Integration:

Using the basic diagrams shown in Figure 41, which describe the systems operations models, and assigning ranges of operational criteria, work has started to establish the Gas Turbine Econopac boundary conditions for the different fuel requirements.

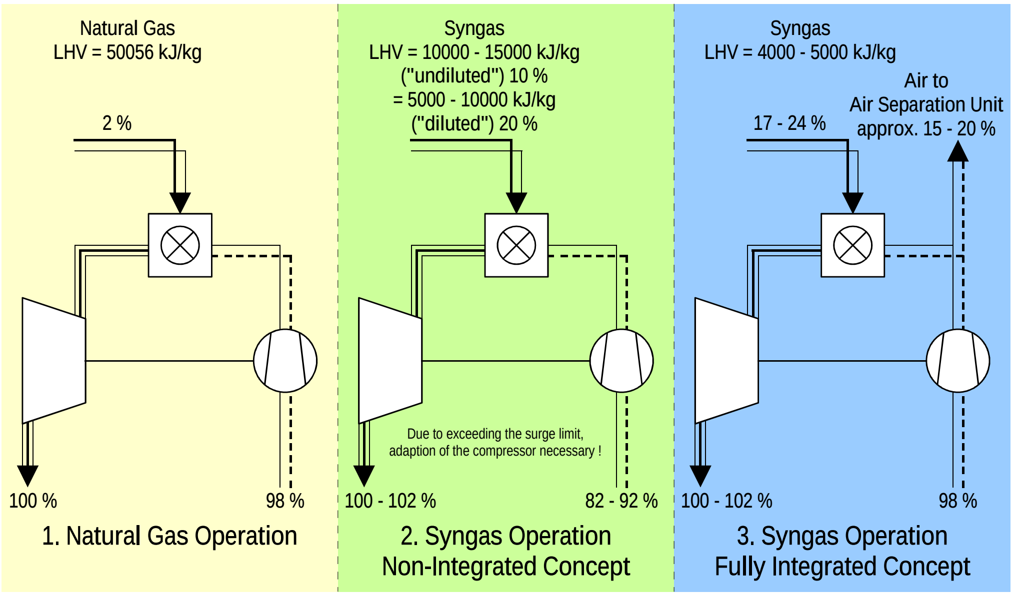


Figure 41. Systems Operations Models

Cost Estimate

Starting with the first cost estimates and updated databases on the SGT6-5000F and comparing the SGT6-6000G deltas, an updated estimate for the Gas Turbine, Compressor, Generator and Auxiliaries was obtained. The cost estimation for the entire plant will be updated on an ongoing basis with continuous refinement. Auxiliaries cost for the SGT6-5000F applied in an IGCC plant was estimated to be 300% higher than in the natural gas fired engine. A similar increase is expected for the SGT-6000G auxiliaries in an IGCC application.

Conclusion

A good start has been made at defining systems, conditions of operation, associated risks and costs at a level that maintains flexibility in Auxiliary Systems design.

Sensors/Controls/Diagnostics Evaluation

No activity in this quarter.

Economic Advantage Evaluations

No activity in this quarter.

Program Management

<u>IGCC Plant Capital Cost</u>

The syngas-fueled advanced Hydrogen Turbine-IGCC plant capital cost is being estimated for the following three cases: 30%, 60% and 90% integration levels. This will be similar to the cost estimation carried out in the third quarter on the hydrogen-fueled advanced GT-IGCC plant incorporating the ITM ASU and provision for CO_2 capture. The plant configuration will consist of two advanced GTs, one steam turbine, ConocoPhillips gasifier, cryogenic ASU, but without CO_2 capture capability. The objective of this study is to evaluate the plant capital cost and the levelized cost of electricity as a function of % integration level. The GT cost estimation has been completed and the Power Block cost estimation is in progress. When this is completed, the overall IGCC plant cost will be estimated. Finally, based on the plant capital cost, the Long Term Program cost and the Operating and Maintenance cost, the Levelized Cost of Electricity for each case will be evaluated.

In conjunction with the above effort, the effect of GT efficiency on the IGCC plant capital cost in $/kW will be estimated. The starting point for this study will be the 30% integration case, mentioned above. It will be assumed that all the plant equipment (and costs) upstream of the GT will remain fixed, i.e. the same coal input, coal handling hardware, gasifier, ASU, % integration, syngas cleanup, syngas flow and syngas HHV. The differences in the GT and the downstream equipment will reflect the following three efficiency levels: (1) advanced H2 Turbine technology, (2) G-technology, and (3) F-technology. The GT cost will be adjusted to reflect lower technology levels for cases (2) and (3). The Power Block cost and then the total IGCC plant capital cost will be estimated for the three cases to provide the sensitivity of the IGCC plant capital cost to GT efficiency.

To provide another data point for comparison, cost estimation was initiated for an IGCC plant based on two syngas-fueled SGT6-6000G GTs. The plant configuration will be similar to that assumed in the above two studies. The GT cost was adjusted from the basic SGT6-6000G model to account for hardware and material changes required for IGCC application. These changes included syngas capable diffusion flame combustion system, improved materials in the compressor rear stages (both airfoils and discs) and thickening of the CCT cylinder to accommodate the higher operating pressure and temperature in the IGCC application.

GT Technology Impact on Coal Consumption

A study was carried out on the effect of advanced GT technology on coal consumption in syngas-fueled IGCC plants. The following three GT technology levels were considered: SOTA F-class, SGT6-6000G and the advanced Hydrogen Turbine. Constant coal HHV, net plant output power and gasifier island equipment were assumed in this study. The results showed that advanced GT technology will have a significant impact on coal consumption and hence emissions. Compared to a SOTA IGCC plant, the SGT6-6000G based plant will result in 10% reduction in coal consumption and the advanced H2 Turbine in 16.5% reduction, respectively (see Table 4. Advanced GT Technology Impact on IGCC Plant Coal Consumption).

GT Class	**Coal Consumption Metric Tonnes / hr**	**Reduction in Coal Consumption, T/hr**	**% Reduction**
SOTA F-class	488	-	-
SGT6-6000G	438.8	49.2	10.0
Advanced H2 Turbine	407.7	80.3	16.5

Assumptions

- Syngas fuel
- Constant HHV = 11,500 BTU/lb (26,731 kJ/kg)
- Constant plant net output power as per 2x1 H2 Turbine case
- Fixed Coal Handling, Gasifier, ASU, GAS Clean-up Equipment

Table 4. Advanced GT Technology Impact on IGCC Plant Coal Consumption

Customer Survey

During the last quarter, the Hydrogen Turbine / IGCC marketing web-survey was launched. Invitations were sent out to 112 target industry experts, IGCC developers, operators and technology managers. 56 responses were received. Among the responses received, over 60% of the respondents indicated their companies are intending to build an IGCC plant within 10 years. Figure 42 shows the distribution of positions being identified in the survey.

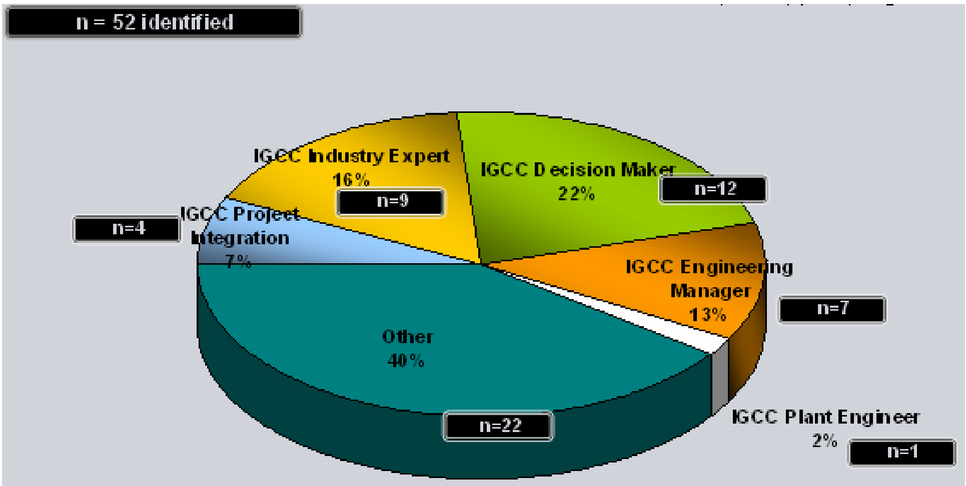


Figure 42. IGCC Industry Respondents Position Distribution

Across the community of respondents that are intending to build IGCC plants, there are significant differences in opinion on plant size, expected efficiency, use of hydrogen as a fuel, and air integration level. This could indicate that agreed upon models for IGCC plants have not emerged in the industry thinking. Thus, while designing a Gas Turbine for IGCC application, flexibility should be one of the key design criteria to ensure applicability to a not completely defined market expectation of the potential technology.

Plant availability, capital cost and technology demonstration was concluded to be the major concern of IGCC developers. Some primary design criteria identified by the customers include baseload operation, pre-combustion CO_2 capture capability, natural gas operation during gasifier down time, adequate plant efficiency to minimize $/kW capital cost and monitoring and diagnostic systems.

Concerning CO_2 sequestration performance penalty, over 60% of the IGCC intent target group indicated an expectation of over 10% on the plant efficiency impact. This reflects a consistency between the current market expectation and the existing technology capability (see Figure 43).

Entire package of survey results & analysis is available to DOE officials upon request.

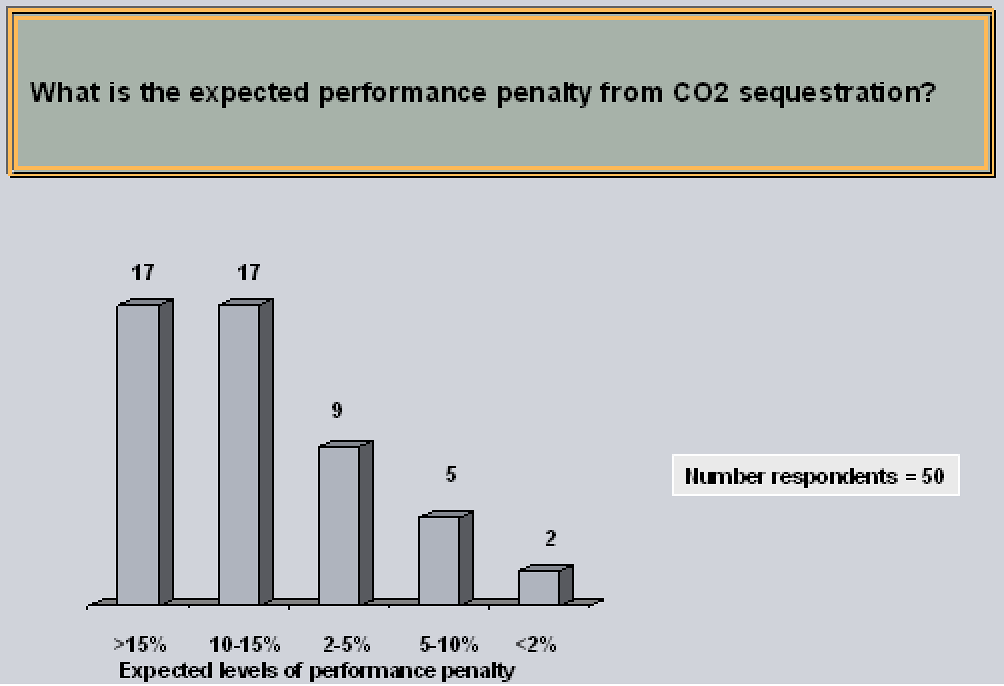


Figure 43. Performance Penalty Expectation for CO_2 Sequestration.

Customer Advisory Board Meeting

As a follow-up to the first Meeting at Electric Power Conference in Atlanta in May, 2006, a second Customer Advisory Board meeting was held on November 27, 2006, with a selected group of customers at the Orange County Convention Center in Orlando. The purpose of this meeting was to gain market feedback on future gas turbines and Integrated Gasification Combined Cycle (IGCC) power plants to support Siemens Power Generation (SPG) product offerings and the DOE Hydrogen Turbine R&D program. The format encouraged dialog and feedback from the selected participants and included sharing the results of the above customer survey, sharing the progress of our Hydrogen Turbine R&D program and an update on our IGCC product offering.

DOE / Siemens Executive Meeting

Also in November, an executive meeting was held in the SPG Orlando campus. Representatives from the DOE’s fossil energy research upper management team visited SPG and met with gas and steam turbine design teams as well as attending a strategy review session with SPG’s CEO Mr. Randy Zwirn. The executives were from DOE NETL's Strategic Center for Coal in Morgantown and Pittsburgh. They met with Dr. Kiesow, GT Engineering Director, and his design team to discuss the H2 Turbine program status and Siemens Gasification technology and its future direction.

COST STATUS

As reported in the last quarterly review, the Earned Value Analysis (EVA) tool will be utilized to track program cost and schedule performance starting in FY07. The data types and formulas used in this powerful technical and financial management tool are listed below.

Planned Value (PV) – The original budgeted cost associated with the scheduled work performed.
Actual Cost (AC) – The actual dollar value spent during the period.
Earned Value (EV) – The value of the work actually completed.
Cost Performance Index (CPI) = EV / AC – The sum of all individual EV budgets divided by the sum of all individual ACs is known as the cumulative CPI. It is generally used to forecast the cost to complete a project.

Schedule Performance Index (SPI) = EV / PV – This is often used with the CPI to forecast overall project completion estimates. The results for FY07 first quarter are given below:

Overall Program CPI: 0.76
Overall Program SPI: 0.59

As of end of December 2006, the total actual spending billed to DOE was $3,894,609. Due to the holidays at the end of the calendar year and some delay in hardware delivery to the scheduled combustion rig test, a few of the major planned activities in December 2006 were delayed until January 2007. Since combustion rig tests involve a relatively large portion of the planned budget, these incidents have a negative impact on the CPI and SPI listed above. As test schedule accelerates in the up-coming quarter, both the CPI and SPI are expected to improve. Figure 44 shows the program Earned Value Analysis results for FY07 first quarter.

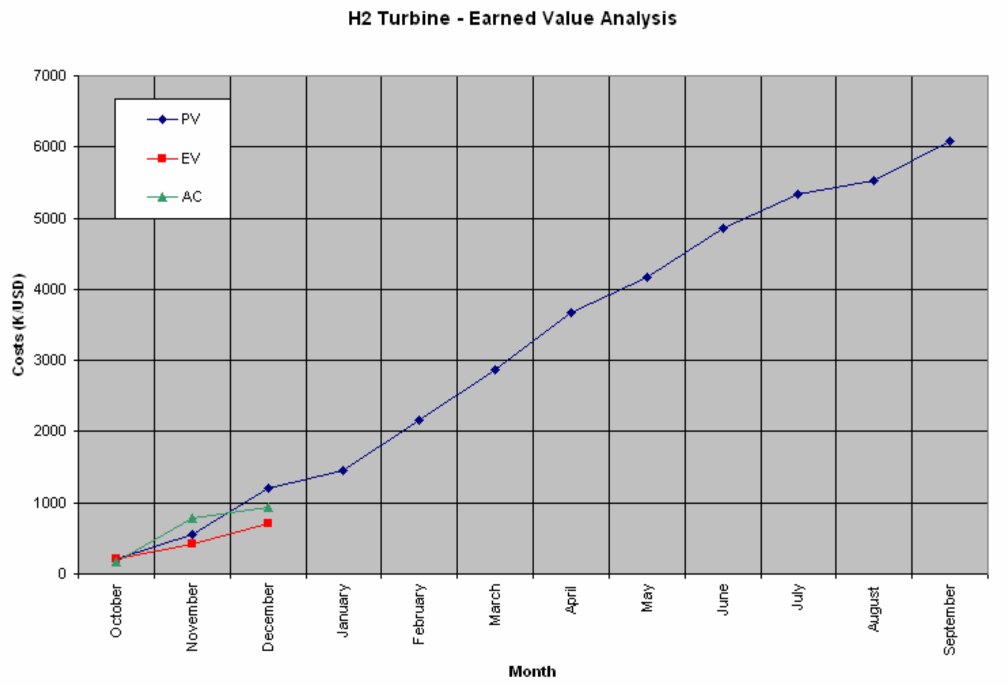


Figure 44. Overall Program Earned Value Analysis Chart for FY07

SCHEDULE STATUS

DOE Milestone No. 5 was met with the completion of Thermal Barrier Coating Conceptual Design. Based on the preliminary requirement defined by the Turbine team, the Materials / Coatings team has performed some fundamental studies and isolation of elements. Several preliminary lab tests were conducted and have identified the most promising TBC conceptual design path to proceed.

Detail on Milestone No. 5 is included under the Material section of this report.

Phase I	Quarterly Milestones	Completion Date
Jan-06	Baseline IGCC Thermal Model Development	12/10/2005
Apr-06	RDI Plan Submission	3/31/2006
Jul-06	1st Iteration of Plant Cost	6/30/2006
Oct-06	Prioritization of Internal Turbine Cooling Passage Concept	9/30/2006
Jan-07	Thermal Barrier Coating Conceptual Design	12/30/2006
Apr-07	Baseline Combustor Test Completion	
Jul-07	IGCC Plant Conceptual Design	
Oct-07	Engine Conceptual Design	

Table 5. Phase I Quarterly Progress Indicators

CONCLUSIONS

Plant thermal performance calculations were completed for different engine technology development levels and a range of air integration levels on syngas and high hydrogen content fuels.

Thermodynamic performance results were obtained for various ASU integration levels. These results, in conjunction with baseline calculations for hydrogen and natural gas fuels, last row turbine blade optimization studies and plant economics, will yield the desirable air integration level range for the advanced H2 Turbine – IGCC plant. Technology integration studies are in progress to determine the optimum combination of advanced technologies to be incorporated into the advanced gas turbine.

Preliminary selection compressor air delivery stages are adequate for providing the required turbine cooling air pressures and temperatures. The feasibility, from the secondary air systems standpoint, was established for cooling the compressor rear stages and utilizing steel discs.

Preliminary test data was obtained on ignition delay and flame speed for high hydrogen content fuels. Full scale basket testing of the axially staged combustion concept has begun. Design and hardware preparations are in progress for high pressure rig tests in 2007. The fuel flexible Rich Catalytic Lean combustor design has been developed through the scale model testing phase. The primary, tube based, catalytic combustor design tested on natural gas resulted in 2 ppm NOx emission at F-Class firing temperature and about 5 ppm on syngas. The fuel injection system for this combustor will be redesigned to improve the fuel/air mixing pattern and increase the margin for flashback.

Significant progress was achieved regarding the overall advanced transition conceptual design configuration, support and exit seal conceptual designs, manufacturing feasibility and preferred fabrication approaches and identification of potential aerodynamics risks and mitigations. CMC was selected as the prime approach for the advanced transition design.

Turbine aerodynamic meanline design was updated and a 2-D throughflow analysis was completed. Preliminary airfoil definition, midspan CFD analyses and cooling concept development was carried out. A feasibility study on increased AN^2 row 4 blade was initiated. A team was formed to review the manufacturability of turbine component conceptual designs. Cooling experiments definition was finalized and testing will start early in the next quarter.

Cost, performance and mechanical integrity has dictated that an “air cooled” compressor disc configuration will be designed where conventional steel rotor material will be utilized if possible. Nickel based materials (IN706 & IN718) have been eliminated from consideration.

Cyclic tests at three temperatures in static air carried out on four types of NiCoCrAlY bond coats, modified with different rare earth elements, indicated that the neodymium modified bond coat had superior oxidation resistance. Two new TBCs met thermal conductivity target and showed no phase transformation at 1500 - 1850ºC. Rare earth addition levels have been calculated and four rare earth elements were procured for alloy casting trials. Diffusion bonded (CM)247LC, to Haynes 230 and 214 test coupons evaluation indicated that the central sections were well bonded. Tensile tests on the bonded test specimens showed promising results. Literature review on hydrogen embrittlement was completed. Preliminary results were obtained on TBC coated superalloy systems tested in isothermal furnace and cycle tests at elevated temperatures to assess the effect on the TBC integrity from syngas.

A baseline 2-D longitudinal for the engine casings has been created, incorporating several down selected concepts. Several limiting constraints, such as spacing of transition portals and rotor cooling air pipes and shipping envelope, have been identified and are being resolved.

A good start has been made at defining systems, conditions of operation, associated risks and costs at a level that maintains flexibility in Auxiliary Systems design.

Plant capital cost estimations are in progress for several cases of syngas-fueled gas turbine-IGCC plants and for the SGT6-6000G-IGCC plant. Advanced GT technology incorporated in IGCC plants will result in reduced coal consumption. It was estimated that compared to the SOTA F-class plant, the coal consumption will decrease by 10% for SGT6-6000G based plant and by 16.5% for the H2 Turbine based plant. The Hydrogen Turbine-IGCC marketing web-survey was completed and results analyzed. The second Customer Advisory Board meeting was held on November 27, 2006, during the Power-Gen Conference in Orlando. The DOE/Siemens executive meeting was held on November 21, 2006, in Orlando.

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