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CERAMIC STATIONARY GAS TURBINE DEVELOPMENT

Final Report - Phase I

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ACRONYMS AND ABBREVIATIONS

ABAQUS	Computer Software Used for Mechanical Analysis of Materials
ABB	ASEA Brown Boveri
AGT	Automotive Gas Turbine
Al_2O_3	Alumina
Al_2O_3/Al_2O_3	Alumina Fiber-Reinforced Alumina
ANL	Argonne National Laboratory
ANSYS	Computer Software Used for Finite Element Analysis
AQCB	Air Quality Control Board
ARCO	Atlantic Richfield Company Oil & Gas
ASCC	AlliedSignal Ceramic Components
ASEA	Swedish Company that Developed the Glass HIP Encapsulation Process
ATS	Advanced Turbine Systems
ATTAP	Advanced Turbine Technology Applications Project
B&W	Babcock and Wilcox
BCF	Billion Cubic Feet (of Natural Gas)
Btu	British Thermal Unit
Btu/ft^2-hr-°F	British Thermal Units Per Square Foot Per Hour Per Degree Fahrenheit
Btu/kW_e-hr	British Thermal Unit per Kilowatt (electrical) Per Hour
CAD	Computer Aided Design
CARES	Ceramics Analysis and Reliability Evaluation of Structures
CARES/LIFE	Uprated Version of CARES
CATE	Ceramics for Advanced Turbine Engines
CAT TC	Caterpillar Technical Center
CC	Abbreviation for ASCC
C-CARES	CARES Computer Code for Continuous Fiber-Reinforced Ceramic Matrix Composites
CEM	Continuous Emissions Monitoring
Centaur 'H'	Solar Centaur Model 'H' Gas Turbine
Centaur 50	Solar Centaur Model 50 Gas Turbine
CF	Centrifugal Force
CFCC	Continuous Fiber-Reinforced Ceramic Matrix Composite
CIS	Commonwealth of Independent States
CNC	Computerized Numerical Control
CO_2	Carbon Monoxide
CO	Carbon Dioxide
CSGT	Ceramic Stationary Gas Turbine
CSU	Cleveland State University
CVD	Chemical Vapor Deposition
CVI	Chemical Vapor Infiltration
DARPA	Defense Advanced Research Projects Agency
DCF	Discount Factor
DCS	Distributed Control System
DLC	DuPont Lanxide Composites
DOD	Department of Defense

ACRONYMS AND ABBREVIATIONS

DOE	Department of Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ER	Average Electric Rate ($/kwh)
ERC	Energy Research Corporation
E/T	Ratio of Electrical to Thermal Output in Cogeneration Mode
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model
FOD	Foreign Object Damage
FP	Average Fuel Price ($/$10^6$ Btu)
FPI	Fluorescent Penetrant Inspection
G&A	General and Administrative
GAPD	Garrett Auxiliary Power Division
GCC	Garrett Ceramic Components
GN-10	Silicon Nitride Manufactured by GCC
GP	Gas Producer
"H"	A Class of Industrial Gas Turbine Manufactured by Solar Turbines Incorporated with 3000-5000 kW Output
H_20	Water
HIP	Hot Isostatic Pressing
Hexoloy®SA SiC	Alpha Sintered Silicon Carbide Manufactured by Carborundum
HiPHES	High Pressure Heat Exchanger Systems
HP	Horsepower
hr	Hour
HR	Net System Heat Rate (Btu/kWh)
HRSG	Heat Recovery Steam Generator
HSCT	High Speed Civil Transport
HT	Heat Transfer
HTC's	Heat Transfer Coefficients
hz	Hertz
IC	System Installed Cost ($/$kW_e$)
I.D.	Inside Diameter
IDR	Inspection Dimension Report (DuPont)
IFC	International Fuel Cell
ISO	International Standards Organization
KICC	Kyocera Industrial Ceramics Corporation
kg/s	Kilograms Per Second
ksi	Thousands of Pounds Per Square Inch
kW	Kilowatt
kW_e	Electrical Output in Kilowatts
kW_eh	Electrical Output in Kilowatt Hours
kWh	Kilowatt Hours

ACRONYMS AND ABBREVIATIONS

lb_f	$Pounds_{(force)}$
LHV	Lower Heating Value
Mars 100	Solar Mars 100 Model Engine
MC	Average Maintenance Cost ($/kWh)
MCFC	Molten Carbonate Fuel Cell
MCP	Molten Carbonate Power
METC	Morgantown Energy Technology Center
mm	Millimeter
MMBtu	Million Btu
MOR	Modulus of Rupture
MPa	Mega Pascal
MPS	Maximum Principal Stress
Msi	Millions of Psi
MW	Megawatts
MWh	Megawatt Hour
NAC	Norton Advanced Ceramics
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NGK	NGK Insulators, Limited
NIC	Newly Industrialized Countries
NIST	National Institute for Standards and Technology
NOx	Oxides of Nitrogen
NPV	Net Present Value
NT154	Silicon Nitride Manufactured by NAC
NT164	Silicon Nitride Manufactured by NAC
NT230	Reaction Bonded Siliconized Silicon Carbide Manufactured by NAC
O.D.	Outside Diameter
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
ODS	Oxide Dispersion Strengthened (alloys)
PAFC	Phosphoric Acid Fuel Cells
POS	Probability of Survival or Success
ppmv	Parts Per Million by Volume
psi	Pounds Per Square Inch
QA	Quality Assurance
R&D	Research and Development
RAM	Reliability, Availability, and Maintainability
RFP	Request for Proposal
SCG	Slow Crack Growth
SCR	Selective Catalytic Reduction
SEP	Société Europėene de Propulsion
SHP	Shaft Horsepower

ACRONYMS AND ABBREVIATIONS

SiC	Silicon Carbide
Si-SiC	Siliconized Silicon Carbide
SiC-SiC	Silicon Carbide Fiber-Reinforced Silicon Carbide
Si_3N_4	Silicon Nitride
SN-84	Silicon Nitride manufactured by NGK
SN-88	Silicon Nitride manufactured by NGK
SN-252	Silicon Nitride manufactured by KICC
SN-253	Silicon Nitride manufactured by KICC
SnO_2	Tin Oxide
SOFC	Solid Oxide Fuel Cell
Solar	Solar Turbines Incorporated
SOx	Oxides of Sulfur
SoLoNOx	Solar Low NOx Combustor
SOW	Statement of Work
SPS	Sundstrand Power Systems
SPSLIFE	Sundstrand Power Systems Life Assessment Computer Code
T5501	Model of Solar Centaur 50 Engine Series
T5701	Model of Solar Centaur 50 Engine Series
T6501	Model of Solar Taurus Engine Series
T6502	Model of Solar Taurus Engine Series
TI 4000	Model of Solar Mars Engine Series
T_{max}	$Temperature_{(maximum)}$
T_{min}	$Temperature_{(minimum)}$
T_{avg}	$Temperature_{(average)}$
T_{inlet}	$Temperature_{(combustor\ inlet)}$
TBO	Time Between Overhaul
TE	Trailing Edge
TIT	Turbine Inlet Temperature
TRIT	Turbine Rotor Inlet Temperature
UDRI	University of Dayton Research Institute
UTIL	Annual System Utilization (hours/year)
VIGV	Variable Inlet Guide Vanes
VPI	Virginia Polytechnic Institute
WBS	Work Breakdown Structure
$W/m^2\text{-}°C$	Watts Per Square Meter Per Degree Centigrade
ZrO_2	Zirconia
2-D	2-Dimensional
3-D	3-Dimensional
ΔP	Differential (change in) Pressure
°C	Degrees Centigrade (Celsius)
°F	Degrees Fahrenheit

1.0

SUMMARY

This report summarizes the work performed by Solar Turbines Incorporated (Solar), a wholly owned subsidiary of Caterpillar Inc., and its subcontractors, during the period September 25, 1992 through April 30, 1993, under Phase I of the DOE Ceramic Stationary Gas Turbine (CSGT) Development program. The objective of the program is to improve the performance of stationary gas turbines in cogeneration through the implementation of selected ceramic components. The work was performed for the Department of Energy (DOE) Office of Industrial Technologies under Contract No. DE-AC02-92CE40960. The program is administered by the DOE Chicago Operations Office, Chicago, Illinois. Mr. Steve Waslo of the DOE Chicago Operations Office is the Technical Manager for the DOE CSGT program.

Solar is leading a team consisting of major suppliers of monolithic and composite ceramic components: AlliedSignal Ceramic Components (CC), Norton Advanced Ceramics (NAC), Carborundum, Kyocera Industrial Ceramics Corporation (KICC), DuPont Lanxide Composites (DLC), Babcock & Wilcox (B&W), and NGK Insulators, Ltd (NGK). Also supporting the team efforts is Sundstrand Power Systems (SPS) in the areas of ceramic engine design, materials properties evaluation, and life prediction, Argonne National Laboratory (ANL), and the Caterpillar Technical Center (CAT TC) in the area of nondestructive evaluation, and the University of Dayton Research Institute (UDRI) with long term testing of ceramics. Key consultants provide support in design, fabrication and testing of ceramic materials. The team is completed with an end user of cogeneration gas turbine equipment, ARCO Oil & Gas (ARCO).

The global goals of the program are to achieve national energy savings and reduced emissions of environmental contaminants through improved gas turbine performance resulting from the incorporation of ceramics. It is also anticipated that the development of high performance ceramic stationary gas turbine technology will be incorporated into advanced gas turbine designs that will provide a quantum jump in performance improvement over existing state-of-the-art gas turbine designs.

The Phase I performance period focused on turbine and component preliminary design, materials selection, technical and economic evaluation, and planning for future phases of the program.

1.1 TASK 1 - GAS TURBINE DESIGN

The Solar Centaur 50 engine was selected as the industrial engine for ceramic component insertion. This engine meets the program requirements of the sponsor. Aerothermal analysis provided performance goals for the program: an increase in turbine rotor inlet temperature (TRIT) from 1010°C (1850°F) to 1121°C (2050°F), an increase in output power of 25.9%, and an efficiency increase of about 5.6% in simple cycle operation. A NO_x emission level of 25 ppmv will be demonstrated, with a stretch goal to achieve 10 ppmv or better.

A conservative design approach was used for this program. This strategy aims to reduce the risks of introducing ceramics by reducing the number of ceramic components, minimizing component stress and temperature levels, using established materials that can meet the design requirements for the components, and by testing the components in the engine through gradual increases in the firing temperature.

The first stage turbine rotor blade and nozzle, and the combustor liner were selected as the primary parts for ceramic insertion. The Centaur 50 engine with the components targeted for ceramic replacement is shown in Figure 1-1. Concept designs for all three components were developed.

The ceramic blade design concepts have the airfoil configuration of the first stage blade of the current all-metal Centaur 50 engine. Three different root attachment concepts were explored, a traditional "dovetail" configuration with compliant layer, a "pinned root" design, and a "ceramic insert" design. The nozzle design concept was also derived from the current Centaur 50 engine nozzle design. For fabrication ease the current metallic two-airfoil nozzle was replaced by two ceramic single-airfoil nozzles, and the current integral tipshoe was decoupled from the nozzle component. Various attachment configurations of the nozzle were evaluated. The detailed attachment design will start with a concept in which the nozzle is cantilevered from the outer metallic support structure and the nozzle airfoil is decoupled from the inner shroud to reduce the stress level in the airfoil. In this concept the nozzle is attached to the outer metallic support structure through an integral or segmented ceramic ring. The combustor design philosophy selected was based on a common combustion system envelope for the ceramic liner regardless of the type of structural ceramic material, monolithic or continuous fiber-reinforced ceramic matrix composite (CFCC). The *primary* concept designs are monolithic ceramic tiles or rings, and integral CFCC liners. These liner concepts will be adapted to the current SoLoNOx™ low emissions combustor design.

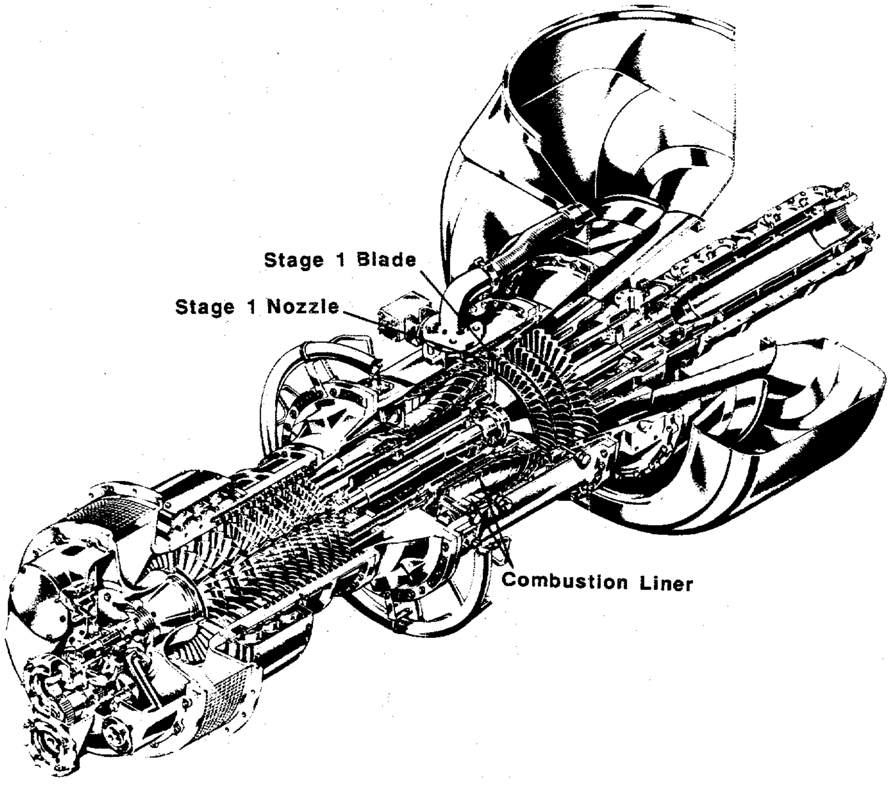


Figure 1-1. Centaur 50 Gas Turbine. Components for ceramic insertion have been indicated.

Preliminary materials selection was based on supplier capabilities, geometric shapes, estimated stress/temperature levels in the parts, known materials properties, and service life requirements. Three silicon nitrides were selected for the blades, GN-10 (CC), NT154 (NAC), and SN-252 (KICC). Two silicon nitrides, NT154 (NAC) and SN-88 (NGK), and one silicon carbide (Hexoloy® SA, Carborundum) were selected for the nozzle. Hexoloy® SA (Carborundum) was also chosen for the combustor liner monolithic design, while two materials, Nicalon/SiC (DuPont) and alumina/alumina (B&W) were selected for the integral CFCC liners. The initial materials selection was reviewed and modified during Task 2 and Task 3 work.

Preliminary parametric stress studies for this task were performed assuming the radial profile of the all-metal Centaur 50, a pattern factor of 0.20 for the combustor liner, and available materials properties for the candidate ceramics.

1.2 TASK 2 - PRELIMINARY DESIGN OF KEY COMPONENTS

Extensive iterative 3-D finite element analysis (FEA) was performed in conjunction with life prediction for the concept designs developed in Task 1. Crucial in all these analyses was the combustor radial profile which was significantly different from the scaled up radial profile of the baseline Centaur 50 engine used in the Task 1 conceptual design studies. The new radial profile was designed to optimize the low emissions characteristics and provide optimal cooling flows to reduce stresses on the secondary metallic hot section components. While the latter objective was successfully met, the selected radial profile resulted in significant increases in the stress levels at critical locations in the blade and nozzle airfoils of the primary ceramic components. Modification of the radial profile to lower the stresses at the critical airfoil locations will be a major focus of the detailed design effort in Phase II.

Blade designs with the "dovetail" and "pinned root" attachments were evaluated in the preliminary design effort. A localized mean principal stress (MPS) of 176.6 MPa (25.6 ksi) at a steady state temperature of about 1093°C (2000°F) was observed in the trailing edge of the blade airfoil at a radial position of 20% of the airfoil chord of both blade designs. This stress/temperature condition is believed to be limiting with respect to slow crack growth (SCG) life of the blade as determined by life prediction analysis using Sundstrand's SPSLIFE and NASA CARES/LIFE codes. Probability of survival (POS) in the 98.0-99.0% were estimated for 30,000 hr blade service life for NT154 silicon nitride. The "pinned root" attachment design showed a maximum stress of 227 MPa (33 ksi) along the inside walls of the pin hole. The stress analyses will be further refined with the detail design analysis in Phase II.

Using the new combustor radial profile preliminary design for the nozzle stresses of 276 MPa (40 ksi) and 262 MPa (38 ksi) were estimated by 3-D FEA for SiC (Hexoloy® SA) and Si_3N (NT154) nozzles, respectively, at the "hot spot" trailing edge locations. These stresses are higher than desirable and efforts during the detail design in Phase II will be directed towards reduction of these stresses.

Preliminary designs for both combustor tiles and continuous ring segments in steady state and start up/shutdown transients were performed using Hexoloy® SA SiC as the structural material. Maximum stresses of 193 MPa (28 ksi) were calculated by 3-D FEA for axial tiles and 78 MPa (11.3 ksi) for continuous ring segments. Both designs will be carried forward for detailing in Phase II. An integral CFCC liner design will also be evaluated in Phase II.

An in-depth study of secondary component design requirements was performed under Task 2. Focus was on boundary conditions and cooling flows for disks, nozzle case and shrouds, diaphragms, and tip clearance management.

1.3 TASK 3 - MATERIALS SELECTION

The materials selection for the ceramic blade, nozzle and combustor liner components was closely integrated with Task 1 (Turbine Design) and Task 2 (Preliminary Design of Key Components) since materials property data are essential for both design/analysis and life prediction.

Part of the work under this task involved an assessment of the capabilities of potential ceramic component suppliers. This assessment was based on the following criteria: (1) low probability of failure of the supplier's material under engine conditions defined by preliminary design, (2) fabrication experience with similar component configurations and ability to deliver components in a timely fashion, and (3) potential for establishing volume manufacturing. This assessment was conducted through examination of suppliers' reports, weekly telephone discussions, and visits to the suppliers' manufacturing facilities.

The assessment included a review of the extensive compilations of the properties of the candidate materials submitted by the ceramic suppliers. The materials property data have been evaluated and gaps in the data base have been identified. Critical data for design/analysis and life prediction will be generated under the Phase II program. Long term property data for creep will be an important element in extending the data base.

Based on the assessment the preliminary selection of the design materials for the program components was reevaluated. The higher than expected stress levels in the blade and nozzle airfoils led to several changes in materials selected under Task 1. Because of its improved creep and fatigue resistance at elevated temperatures the decision was made to select NT164 rather than NT154 silicon nitride from NAC. The higher strength properties in fast fracture and slow crack growth resulted in the selection of KICC's SN-253 over SN-252. And NAC's NT230 silicon carbide material was added as a candidate for the monolithic combustor liner design using integral rings.

The Phase I ceramic suppliers have provided detailed plans for fabrication, quality assurance, and delivery of test specimens, simulated components, and prototype components with delivery schedules. The fabrication plans contained flow charts of each supplier's process, extensive descriptions of existing quality assurance practices, as well as indications of commitments to future certification to recognized quality standards such as ISO 9000/1.

The primary silicon nitrides selected under the program are likely to survive 30,000 hrs of operating life, but machining of some airfoil parts may be necessary. It is recommended that the peak nozzle stresses be lowered to 138-172 MPa (20-25 ksi) to enhance creep and slow crack growth life. There is concern about the 193 MPa (28 ksi) peak stress on the combustor tiles while the size of the large outer combustor rings (diameter: ≈ 75 cm/30 inches) may decrease the average strength of the ring material. Long term materials property data and life assessment data to be generated under Phase II of the program will be used to iterate the design to achieve maximum allowable peak stresses and temperatures.

The status of nondestructive evaluation (NDE) of the ceramic components was reviewed from two perspectives: (1) use of NDE to detect defects in ceramic hardware as part of accept-reject criteria and (2) potential use of NDE to monitor the growth of defects during service to provide a means to predict remaining service life of the component. A methodology plan for NDE in Phase II was developed.

Materials needs were assessed for non-ceramic components associated with the incorporation of the ceramic components and the existing turbine components. Materials changes were recommended for the first and second stage disks, the second stage blade, the second and third stage blade and nozzle, the second stage diaphragm, and the nozzle support housing.

1.4 TASK 4 - TECHNICAL AND ECONOMIC JUSTIFICATION, MARKET POTENTIAL

The effect of the ceramic components on the performance and economics has been determined for the ceramic stationary gas turbine in simple cycle and cogeneration applications. The data have been compared with those for baseline all-metal engines. Based on the predicted performance gains a market penetration scenario has been proposed and the routes to commercialization of the technology have been described.

The presence of a strong suppliers base for ceramic components is a critical element for the commercialization of the ceramic stationary gas turbine. The Phase I manufacturers on the program who will form the nucleus for a future domestic gas turbine component supplier network provided cost projections for commercial quantities of their parts based on the conceptual ceramic component designs. Prices for the highest projected volumes of uncooled silicon nitride rotor blades were under $200, and for silicon carbide and silicon nitride nozzles prices in the $200-350 range were projected by the Phase I suppliers. These prices are competitive with current prices of cooled advanced superalloy components. Projected costs for combustor liners ranged from about $10,000-$30,000, somewhat higher than those of current metal components. All estimates are in 1993 dollars.

Net Present Value (NPV) and Return on Investment (ROI) calculations were performed for several ceramic engine designs derived from existing all-metal engines based on performance estimates from aerothermal cycle data for various combinations of fuel and electricity prices. The NPV is arrived at by comparing revenue to the end user of the gas turbine equipment with the costs of purchasing, installing, and operating this equipment. The ceramic gas turbine showed a significantly positive NPV delta for electricity at $0.08/kWh at fuel prices ranging from $2-4/MMBTU, and for electricity at $ 0.06/kWh and fuel at $2/MMBTU. An examination of incremental costs for uprating the Solar Centaur 50 engine with ceramics indicated significant residual NPV delta's depending on the actual application (simple cycle base load or cogeneration) and energy scenario.

A case study was also conducted to evaluate the market penetration of the ceramic Centaur 50. Scenarios of full market penetration ranged from four to five years after initial production release depending on the success of the engine field tests and general economic conditions. Market penetration could start in 2000 and be substantial in the 2005-2010 time frame.

An examination of competing technologies which may affect the successful introduction and market penetration indicated potential challenges from alternative materials technologies utilizing thermal barrier coatings (TBC's) and advanced cooled superalloy technologies, from existing (but very expensive) methods for emissions reduction such as Selected Catalytic Reduction (SCR), and from potentially high performance power generation devices such as fuel cells.

The main elements of a commercialization plan for the ceramic gas turbine have been defined. These include: demonstration of technical feasibility through successful field testing, establishment of a reliable ceramic component supplier base, trained sales and technical personnel, a warranty program, and a product support infrastructure.

The end users of the ceramic turbine technology employ largely economic criteria in their evaluation. There should be no erosion of equipment reliability, availability, maintainability, and durability (RAMD), and operating costs must be predictable and low.

1.5 TASK 5 - CONCEPT ASSESSMENT

The results of Tasks 1-4 were used to evaluate the fit of the ceramic stationary gas turbine into the equipment manufacturers product line. The current Centaur 50 market for new and for retrofit engines would be the first opportunity for commercialization of the ceramic turbine technology. As the technology matures it will be increasingly integrated into second generation gas turbine products derived from existing engine models with optimized ceramic hot sections and greater output power and efficiency gains. Eventually third generation gas turbine products will be developed incorporating ceramic components in advanced cycles. It is in these advanced turbine system that the full benefits of the ceramic hot section technology will be realized.

The main benefits of the ceramic gas turbine technology, increased output power and improved thermal efficiency, reduced emissions, and higher electrical power to heat (E/T) ratio will appeal to various market segments in different ways. Emissions reduction will be generally attractive to all market segments. For end users in the mechanical drive sector of the power generation market the significant increase in output power achievable with ceramic engines compared to current all-metal models will initially be of greater interest than the improvement in fuel efficiency because of current modest fuel prices for this application. A combination of lowered installation and life cycle costs, combined with reduced emissions of NO_x and CO and a higher value of output power, will be a strong incentive to utilize cogeneration with ceramic industrial gas turbines in distributed power generation strategies composed as a substitution for conventional large scale power. This application could account for a substantial fraction of future power generation output traditionally served by larger utility engines. While the ceramic gas turbine technology is being developed for the industrial gas turbine the technologies with some modifications will also be applicable to utility and aeroderivative gas turbine designs.

A benefit-risk analysis has been conducted taking into account national, end user, and gas turbine equipment manufacturer viewpoints. In addition to reduced emissions, increased output power and fuel efficiency, and improved electrical-to-thermal ratios, enhanced competitiveness of the U.S. turbomachinery industry is perceived as a benefit. Slow customer acceptance of the technology, unknown component reliability, the absence of an established supplier network, and the lack of a reliable data base for long term materials properties were perceived as detriments.

Critical activities for key technical and economic factors associated with the development and eventual commercialization of the ceramic turbine technology have been identified. The major factors relate to engine and component design, materials data base and component life prediction, component fabrication and handling, engine assembly and testing, and customer services and aftermarket support. Design and data base issues are perhaps the most critical for the technical success of the ceramic stationary gas turbine. Critical design issues requiring resolution are stress/temperature control in blade and nozzle airfoils for creep/slow crack growth resistance, interfacing of ceramic components and adjacent metal parts, achieving the target emission levels, and adequate blade tip clearance control. The critical activities which form an integral element of the Phase II work must generate the solutions which will result in a low risk design that maximizes the potential for success for the Phase III field test and subsequent commercialization of the ceramic turbine technology.

Design of the low emissions combustor with ceramics will require special attention in Phase II. While the program requires demonstrating 25 ppmv NO_x levels, to be truly successful NO_x levels of 10 ppmv or better will be required from ceramic "hot wall" combustors. This CSGT NOx goal of <10 ppmv at 15% O_2 is beyond Solar's current capabilities and represents a stretch "high risk" position. Solar believes that additional program efforts would be desirable to address optional promising technologies in an off-line can configuration as Solar's traditional full in-line annular combustion

1.6 TASK 6 - FUTURE PROGRAM PLAN

A program plan was furnished for Phases II and III that covers development and test needs for the successful completion of the 4000 hour performance test for the "ceramic stationary gas turbine". The Task 6 section is a summary of the work detailed in the Management Plan for Phases II and III for the program.

1.7 TASK 16 - MANAGEMENT AND REPORTING

The project management and reporting functions for Solar and the subcontractors on the program contract and subcontract administration, design reviews, and conference presentations for the program are included in this task.

1.8 RECOMMENDATIONS

Component Design

1. **Nozzle.** A radial combustor profile has been conceived that provides sufficient cooling to keep temperatures and stresses low on the secondary metallic components in the hot section. However, this same profile results in stress/temperature combinations at critical locations on the nozzle airfoils that are life limiting for the engine in service. Design strategies must be developed in Phase II to lower these high stresses. Potential approaches include:

   a. Modifying the combustor radial profile to give lower temperature gradients
   b. Incorporating airfoil trailing edge cutbacks to reduce stress levels
   c. Modifying the airfoil geometry to lower the stresses within the limits of the retrofit goal of the CSGT program
   d. Segmentation of the nozzle to reduce stress levels
   e. Modifying (increase and or redirection) of secondary cooling flows on inner and outer flowpath components and support structures
   f. Uprate secondary components (e.g. disks, diaphragm) to enable higher temperatures in the airfoil to lower stresses

2. **Blade.** The blade design with the "dovetail" attachment will require a compliant layer material to prevent the ceramic component loads to react directly with the interfacing blade disk, and resulting in possible failure during transient operation. The selection and evaluation of compliant layer materials that will meet the long (30,000 hours) engine service requirement will be a critical activity in Phase II.

3. **Combustor.** The combustor design has been unified to include the same component envelope for monolithic and continuous fiber-reinforced ceramic matrix composite (CFCC) liners. Within this envelope several preliminary design geometries are being evaluated for testing in Phase II. Each of these designs has challenges that will require solutions.

   a. Monolithic tiles have the potential problem of "sticking" at high (≈1371°C, 2500°F) liner temperatures. The use of coatings should be explored to prevent "sticking".
   b. The segmented monolithic liner designs also provide the potential for leaking between the segments and strategies to minimize leakage need to be addressed.
   c. Various monolithic liner designs (axial tiles, continuous rings) have different stress levels and different stressed volumes. A trade-off study should be conducted to select an optimal combination of component geometry, low stress and minimum stressed volume.

Life assessment studies using the SPSLIFE and NASA CARES computer codes will be essential elements in this evaluation.

The combustor development task needs to be broadened to explore alternate ways of meeting the CSGT system NO_x goal of <10 ppmv. Combustor designs incorporating off-line can type geometries offer a potential route to achieving this NO_x emissions goal.

Data Base and Life Assessment

4. Slow crack growth (SCG) and creep have been identified as life limiting failure modes for the ceramics from SPSLIFE assessment studies on the basis of a limited data base. The development of a long term materials property data base to enable life assessment of the key ceramic components will be an important subtask in Phase II. The initial designs may have to be modified for improved SCG and creep resistance as new long term property data becomes available. Long term data for oxidation also needs to be generated. For the purposes of the CSGT program 10,000 hr test data will be required. For commercialization of the CSGT technology 30,000 hr test data will be needed to assess component life between typical overhaul intervals.

5. Design of the integral CFCC combustor liners is limited by the absence of a comprehensive effective component reliability/life assessment code for CFCC materials/components which addresses all relevant failure modes. In the absence of such a code design for CFCC components will have to rely on finite element analysis supplemented by the extrapolation of specimen and subscale component testing to gain confidence in designing with composites. There is a need for the development of a user friendly computer code to assist the designer of CFCC components. Development and verification of such a code is outside the scope of this program.

6. Nondestructive evaluation (NDE) to (1) detect defects in ceramic hardware as part of accept-reject criteria, and (2) monitor the growth of defects during service and as a means to predict the remaining service life of the component needs to be an integral subtask of the Phase II/III work.

Ceramic Processing Issues

7. Components fabricated by processes that utilize HIP-densification with a glass encapsulant show significantly lower strength in the as processed state compared to the machined state and are consequently limited in SCG resistance. Localized surface finishing in critically stressed area may need to be explored to improve SCG resistance and enhance the life of components fabricated using this process.

Commercialization

8. An economic analysis has been presented that correlates predicted engine performance with fuel and electricity prices and with extrapolation of historical trends in the gas turbine industry. The economic scenario is generally favorable for the commercialization and market penetration of the ceramic stationary gas turbine. The scenario presented here envisions introduction and market penetration in the 2000-2010 time frame. The scenarios need to be revisited at critical stages of the program to assess the effect of changes in economic conditions such as fuel and electricity prices. It is vital for the commercial viability of the ceramic gas turbine technology that a supplier system be in place to ensure fabrication of quality parts at prices and delivery schedules that are competitive with those of alternate technologies.

2.0

INTRODUCTION

This Technical Progress Report is the Phase I Final Report for the "Ceramic Stationary Gas Turbine (CSGT) Development Program performed under DOE Contract No. DE-AC02-92CE40960. The work reported covers the period September 25, 1992, through April 30, 1993. The project is sponsored by the DOE Office of Industrial Technologies and administered by the DOE Chicago Operations Office, Chicago, Illinois. Mr. Steve Waslo of the DOE Chicago Operations Office is the Technical Manager for the DOE CSGT program. The objective of the program is to improve the performance of stationary gas turbines in cogeneration through the implementation of selected ceramic components.

The "Ceramic Stationary Gas Turbine Development" program is being performed by a team headed by Solar Turbines Incorporated (Solar), of San Diego, California, a wholly owned subsidiary of Caterpillar Inc. Solar is a U.S. manufacturer of industrial gas turbine equipment in the 500-25,000 HP range, with a strong position in the domestic and international markets in power generation and cogeneration, and mechanical drive applications. Supporting Solar on this program are the leading U.S. and offshore manufacturers of monolithic and composite ceramic components, AlliedSignal Ceramic Components, Norton Advanced Ceramics, Carborundum, Kyocera Industrial Ceramics Corporation, DuPont Lanxide Composites, Babcock & Wilcox, and NGK Insulators, Ltd. Also supporting the team efforts are Sundstrand Power Systems in the areas of ceramic engine design, materials properties evaluation and life prediction, Argonne National Laboratory, and the Caterpillar Technical Center in the area of nondestructive evaluation, and the University of Dayton Research Institute with long term testing of ceramics. Key consultants provide support in design, fabrication and testing of ceramic materials. The team is completed with an end user of cogeneration gas turbine equipment, ARCO Oil & Gas.

For the program contract a domestic natural gas fired turbo engine model is selected that falls within the following specifications:

- air flow of 10 - 40 kg/s
- rated for continuous duty
- capable of a turbine rotor inlet temperature over 1000°C when fitted with ceramic components
- pressure ratio that is less than 20:1
- an axial flow turbine geometry

The engine selected for the program is the Solar Centaur 50. Under the program design modifications will be undertaken in the engine:

1. To accept and fasten the ceramic parts to the interfacing metallic structures;

2. To ensure structural integrity, mechanical, and vibrational stability, and safety;

3. To endure a minimum of 25 start-ups without rebuild of parts other than maintenance or rebuild caused by ceramics;

4. To demonstrate a potential for performance improvements in a non-optimized engine configuration;

5. As a minimum to conform to the environmental and safety standards of the all-metal engine;

6. And to demonstrate reliability under conditions of enhanced performance.

The Centaur 50 model selected for the program, formerly known as the Centaur 'H', is nominally a 5880 HP engine, operating at a turbine rotor inlet temperature (TRIT) of 1010°C (1850°F), with a shaft thermal efficiency of 29.63%. The ceramic Centaur 50 engine to be developed under the program from the baseline engine has a shaft output target of about 7400 HP, a TRIT of 1121°C (2050°F), and a thermal efficiency goal of 31.29%. These goals are envisioned to be achieved by replacing key components, the first stage turbine rotor blade and nozzle, and critical segments of the combustor liner with ceramic parts. A further goal of the program is to demonstrate emissions of NOx of 25 ppmv, with a stretch goal to achieve NO_x levels of 10 ppmv or better.

Ceramic turbine technology is a key factor in advancing turbine equipment capabilities, and development and implementation of this technology will be critical for ensuring a continued favorable share of domestic and international markets for the U.S. gas turbine industry. The program can achieve these goals if it accelerates the development of the ceramic turbine technology and demonstrate its effectiveness in improving engine performance in a manner that is convincing to the end user of turbomachinery equipment. A 4000 hour field test at an end user cogeneration site is planned to provide an opportunity to prove performance improvement potential under conditions that will be the ultimate test of ceramic hardware durability. It has been Solar's experience that a field test of this duration is a necessary first step to introduce a new product to the market place. The market study included in this report presents a clear time frame for commercialization of the new ceramic turbine technology.

The DOE Ceramic Stationary Gas Turbine Development Program is structured in three phases. Phase I involves turbine and component preliminary design. The work under this phase includes the initial engineering that addresses the potential impact of ceramic components on Solar's products, the technical and economic benefits, and a detailed program plan. Phase II, Final Design, Material and Component Testing, focuses on completing the detailed design of the ceramic gas turbine and its components, the procurement and testing of ceramic parts, and the gathering of long term test data to ensure the ceramics will provide adequate performance in an engine in service. The program plan for the field test will be refined. Phase III is directed to conducting a 4000 hour field test of the ceramic stationary gas turbine at a cogeneration test site. In preparation for the field test engine hardware is procured and pre-tested. A full evaluation of the engine and its components following the field testing will be conducted.

This report focuses on the work conducted for Phase I of the program, performed at Solar Turbines and its subcontractors. The work planned for Phases II and III is described in Section 8.0, Program Plan for Phases II and III. Figure 2-1 gives the Timeline schedule for the seven Major Tasks in Phase I. The Phase I Statement of Work has organized the work under these tasks according to the Work Breakdown Structure (WBS) shown in Figure 2-2. The work presented in this Phase I Progress Report follows closely the logical sequence of the WBS. The overall work scope for the Major Tasks is summarized below.

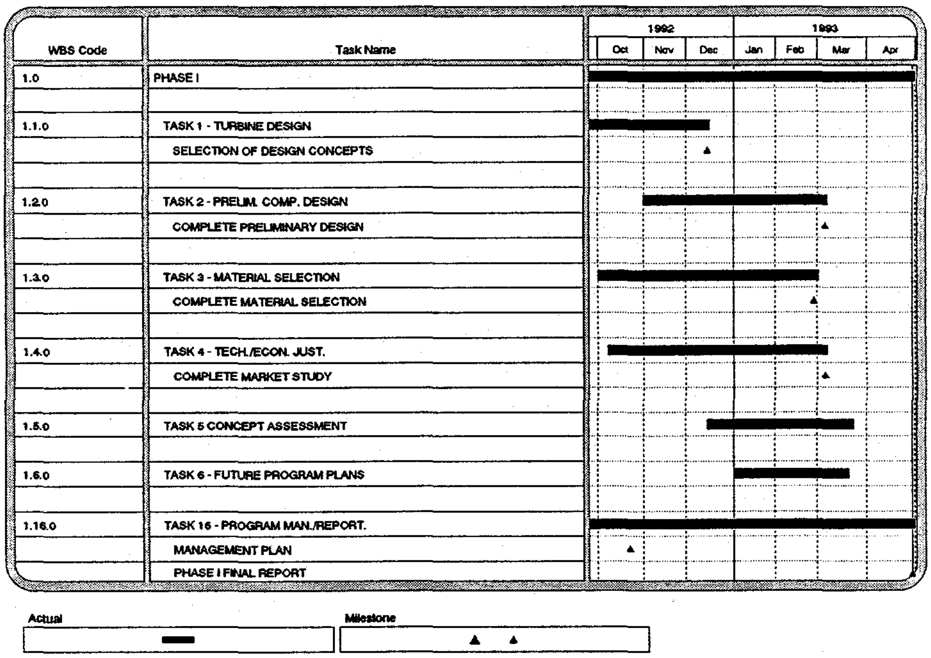


Figure 2-1. Timeline Schedule for Phase I

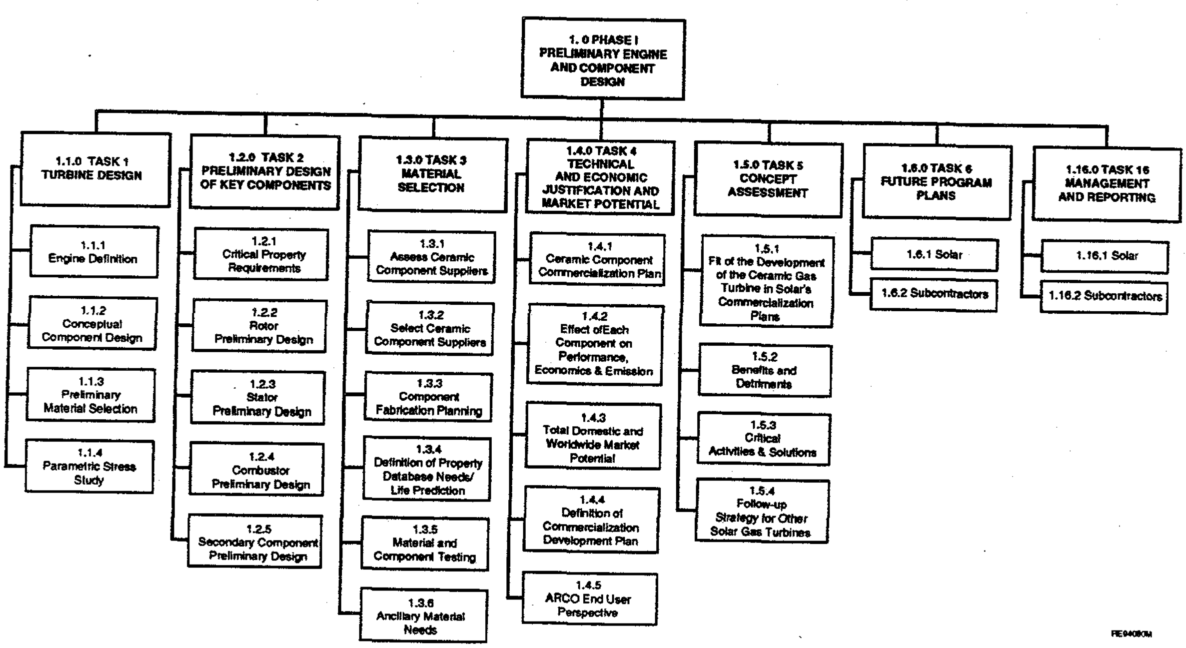


Figure 2-2. Major Tasks and Subtasks in the Work Breakdown Structure - Phase I

2.1 TASK 1 - TURBINE DESIGN

A preliminary design for the ceramic stationary gas turbine engine is produced using existing available background knowledge of ceramics and existing techniques for engine design. The engine with its performance goals is defined. The performance of the current metallic engine is compared with that of the ceramic engine through aerothermal cycle analysis for simple and cogeneration cycles. Results are extrapolated for other Solar engines. Conceptual designs are evaluated for the first stage ceramic turbine blade and nozzle, and for the combustor liner. Preliminary materials selection is reviewed from the known materials data base. Preliminary stress/temperature estimates for the ceramic components are made. The conceptual designs generated for the key components are accommodated within the current flowpath and aerodynamics of the engine. The metallic support structure is modified to accept the ceramics components.

2.2 TASK 2 - PRELIMINARY DESIGN OF KEY COMPONENTS

Preliminary design is conducted for the key ceramic components identified in Task 1 that will be characterized and tested in Phase II, and ultimately in the 4000 hour performance test in Phase III. Critical property requirements for the ceramic components are identified. Preliminary design of the key components includes the generation of solid models, 3D finite element models, and stress and temperature profiles, in steady state and transient operation. Reliability calculations for fast fracture are made as well as comprehensive life prediction analyses. Suppliers are requested to review the Solar designs and comment on fabrication feasibility and anticipated component durability with respect to materials properties. Secondary metallic component materials selection and design are reviewed for the operating conditions and acceptance of metallic components in the Ceramic Stationary Gas Turbine.

2.3 TASK 3 - MATERIALS SELECTION

Based on the performance to date and material properties, the best structural ceramic materials are selected for the design to meet critical requirements for the key ceramic components identified under Task 2. Suppliers of ceramic components are requested to furnish an up to date data base for the materials and fabrication processes under consideration. Supplier selection is then reviewed and fabrication planning by the suppliers is performed. Data from stress/temperature analysis and life prediction at Solar and Sundstrand are analyzed to identify gaps in the materials property data base and recommendations are made for generation of essential data. Recommendations for materials and components testing are also be made. Ancillary materials needs are reviewed.

2.4 TASK 4 - TECHNICAL AND ECONOMIC JUSTIFICATION, MARKET POTENTIAL

For the ceramic stationary gas turbine, the additive effect of each component on performance, economics, and emissions is determined for two cases comprising in the first case a simple cycle engine and, in the second case, a cogeneration system. The results are compared with those for an existing metallic engine. The total domestic and worldwide market potential for the ceramic gas turbine is estimated, commercialization issues for ceramic materials and derivative parts are projected, and a development plan for commercialization is defined.

2.5 TASK 5 - CONCEPT ASSESSMENT

The fit of the development engine in the equipment manufacturer's commercialization plans is examined. The projected benefits and possible detriments resulting from the development plan of Task 4 are ranked in order of importance. Critical activities and solutions are identified to overcome technical and economic barriers to technology demonstration and commercialization. A follow-up strategy for other Solar engines is formulated.

2.6 TASK 6 - FUTURE PROGRAM PLAN

Based on the findings of Tasks 1-5 a program plan is furnished for the follow-up phases that covers development and test needs for the successful completion of the 4000 hour performance test for the "ceramic stationary gas turbine". Design and procurement of engine hardware, procurement and modification of testing equipment, test plans, component fabrication plans and procurement, and materials property data requirements and testing are all reviewed.

2.7 TASK 16 - MANAGEMENT AND REPORTING

The project management and reporting functions for Solar and the subcontractors on the program contract and subcontract administration, as well as the travel to design reviews, and conferences for the program are included in this task.

The organization for the program is summarized in Figure 2-3. The program organization is structured following a team approach in which the Solar engineering, technical, and administrative staff conducts the work following a concurrent engineering strategy. The concurrent engineering approach is the official Solar strategy for new product development. This strategy integrates all aspects of the product development cycle including engine and component design, materials and testing support, manufacturing, customer services, purchasing, marketing, and finance from the conception of the design to the commercialization of the finished product. The subcontractors on the program are integrated to a high degree in the concurrent engineering approach. Work is conducted through teams with broad focus on design, materials, testing, new product development, and subcontract management and administration.

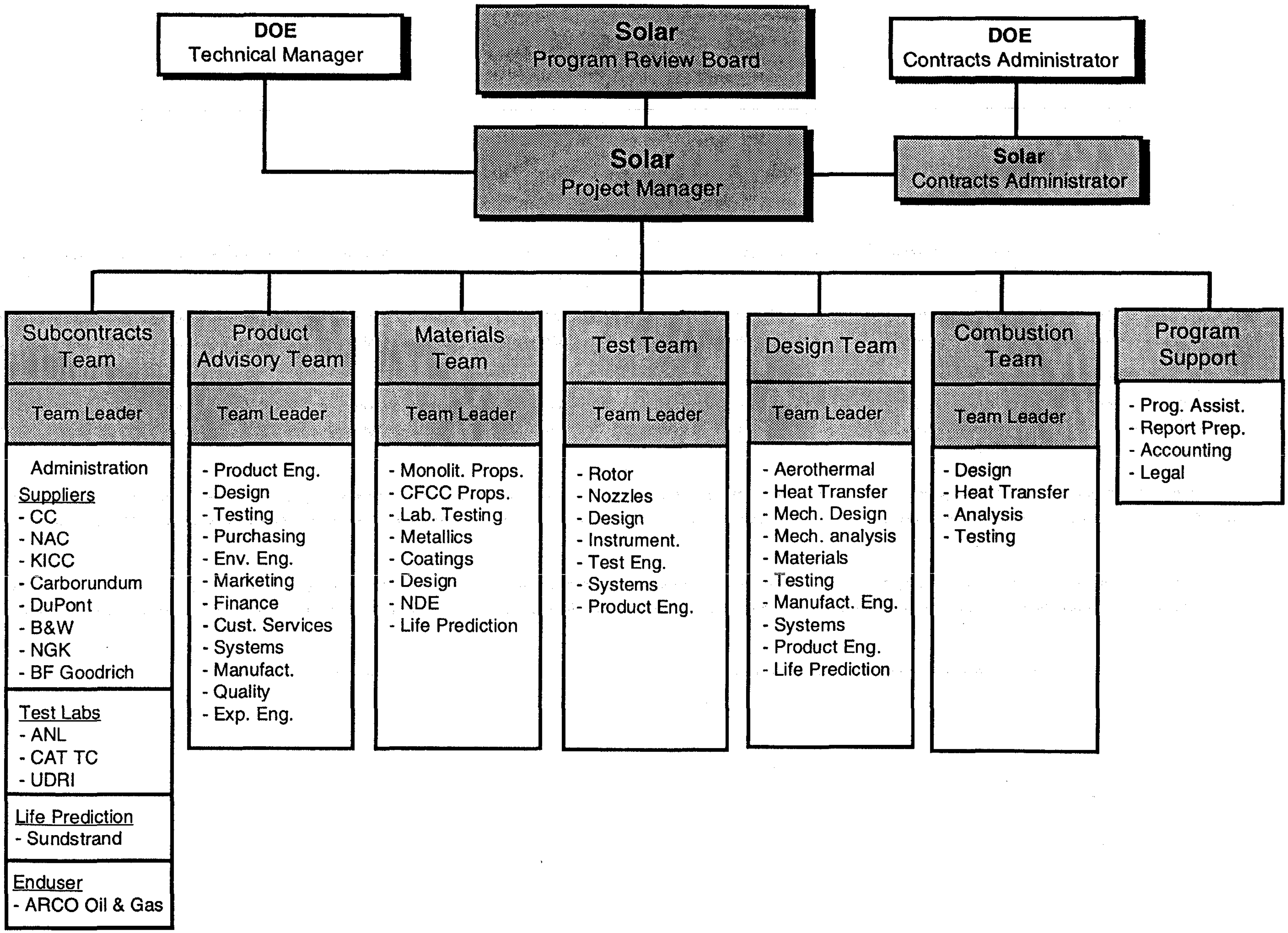


Figure 2-3. CSGT Program Organization

3.0

TASK 1 - TURBINE DESIGN

3.1 INTRODUCTION

The objective of Task 1 was to produce a preliminary design for the ceramic stationary gas turbine using available background knowledge of ceramics and existing techniques for engine design. Specifically, the engine with its performance goals was defined. Operating conditions for the ceramic stationary gas turbine including temperatures, pressures, fuel flow, air flow, thermal and electrical efficiencies, and output power, and other relevant parameters were estimated. Aerothermal cycle analysis was used to compare the performance of the ceramic engine in simple cycle and cogeneration with that of the current metallic engine baseline.

Conceptual designs were developed for the first stage ceramic turbine blade, the first stage nozzle, and for the combustor liner. Preliminary materials selection was reviewed with reference to the known materials data base. Preliminary stress and temperature estimates for component designs were made. Where appropriate, alternative concept designs were generated for the key components accommodating them within the current flowpath and aerodynamics. Modifications to the existing metallic support structure were made to adapt the ceramic components.

The engine selection requirements of the Statement-of-Work included:

- Air flow of 10-40 kg/s
- Rated for continuous duty
- Capable of operation at Rotor Inlet Temperature over 1000°C (1832°F) when fitted with ceramic components
- Pressure ratio that is less than 20:1, and an axial flow turbine geometry

The program engine selected is the Centaur 50, formerly known as the Centaur 'H'. The engine was introduced into the Solar fleet in 1985 and a significant data base exists for its performance, emissions and maintenance. The program philosophy involved a modification of this engine to incorporate a limited number of ceramic parts that are substituted for existing metal parts.

In addition to the incorporation of ceramic parts design modifications were envisioned to integrate the ceramic parts with the metal support structure ensuring structural integrity, mechanical and vibrational stability, and safety. Additional program goals include a design life that is compatible with a minimum of 25 start-ups without rebuild of parts other than maintenance or rebuild caused by ceramics.

In some cases existing design techniques were not adequate and preliminary design solutions were adopted. These preliminary solutions will be further evaluated in Phase II of the program through detailed engine and component design, and testing of prototype hardware. An iterative strategy based on materials selection, component design, component fabrication and component testing will be employed to demonstrate design solutions that will ultimately be incorporated in the ceramic gas turbine to be field tested in Phase III of the program.

3.2 ENGINE DEFINITION

The engine selection requirements described in 3.1 have been addressed with the selection of the Centaur 50. The ceramic modification of the Centaur 50 engine is referred to as the Centaur 50 CSGT engine or CSGT engine in the body of this report. A schematic of Centaur 50 engine is shown in Figure 3-1.

General Engine Description

The Centaur 50 gas turbine selected for this program is a single-shaft axial geometry engine. The engine variant selected for the program will have a $SoLoNO_x$ low emissions combustor capable of 42 ppmv NOx or lower on natural gas fuel. The engine will be fitted with selected ceramic hot section components (e.g., combustor liner, stage 1 turbine blades and stage 1 turbine nozzles) so as to enable continuous duty operation at a turbine rotor inlet temperature (TRIT) of 1010°C (1850°F) to 1121°C (2050°F). The CSGT engine may also incorporate certain revisions to and redesign of existing metallic components as may be required to properly fix and support the prototype ceramic components, and to survive the duration of the specified field test, or to maximize performance gains realized from the increased firing temperature.

The CSGT engine will operate in a cogeneration field test planned for Phase III of the program in continuous duty mode using natural gas as the fuel. The CSGT design is not limited to cogeneration operation as it will also be capable of natural gas based power generation and mechanical drive applications.

The CSGT field test engine is to demonstrate 4000 hours of continuous duty cogeneration operation while firing at 1121°C (2050°F) TRIT. The objective is to demonstrate the maximum possible enhancement of the output power and the thermal efficiency of the CSGT power plant through the use of ceramic hot section components. Actual field operation at such enhanced levels of engine performance may be limited by such site factors as generator and switchgear capacity, etc. The specified firing temperature of 1121°C (2050°F) must, however, be maintained.

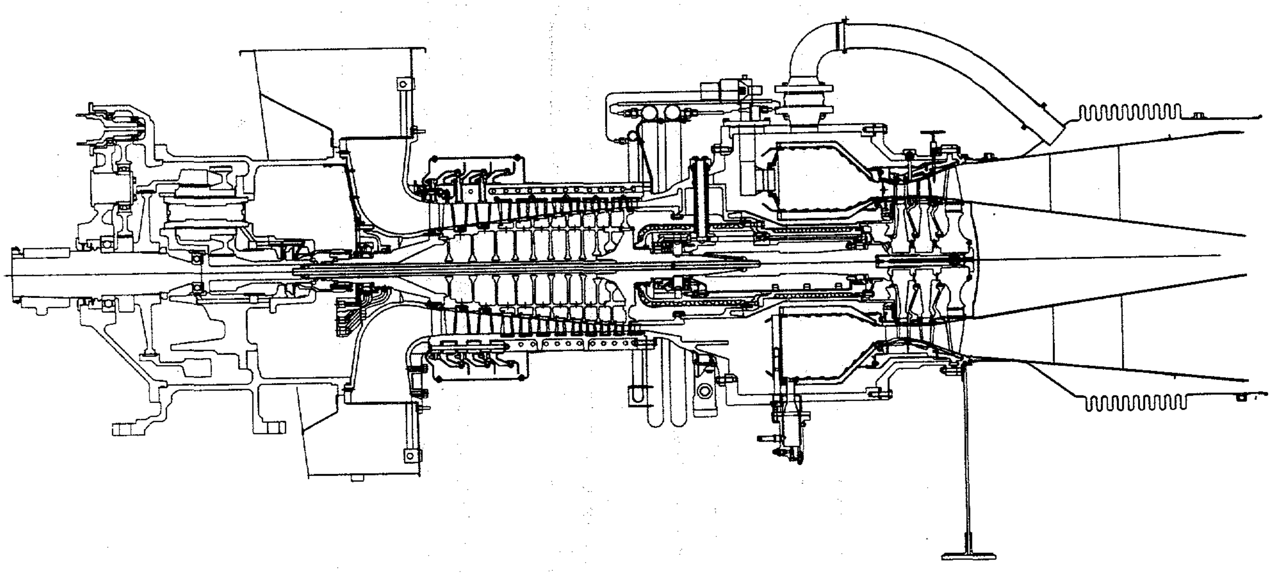


Figure 3-1. Centaur 50 Gas Turbine

Centaur 50 Engine Performance Improvements

Analytically predicted engine performance analyses indicate engine performance improvements can be achieved due to the following changes:

a) reduction in secondary cooling flow requirements to the stage 1 blades and nozzles with the introduction of ceramic components in these locations

b) increased TRIT

c) replace power turbine to better match increased flow/area with increased TRIT

Item (c) above was included in an attempt to recover a portion of the engine performance which was predicted to be lost due to the increased engine volume flow in the turbine section resulting from the increase in firing temperature. A production Taurus 60 engine power turbine effectively opens the stage 3 turbine rotor throat area sufficiently to achieve enhanced output power and stage efficiency. Performance data are listed in Table 3-1.

Nominal performance of the CSGT powered continuous duty, 60 hz generator set is specified to be as listed in Table 3-2.

Table 3-1. Predicted Performance of Solar Centaur 50 Demonstration Engine (Single Shaft Engine, Simple cycle Operation, ISO Conditions)

Description	All Metal Centaur 50 (1)	Centaur 50 with Ceramics (2)	Centaur 50 with Ceramics and Taurus 60 Third Stage (3)	Percent Change (3 - 1)
TRIT °C	1010	1121	1121	
Electrical Output (kW)	4144	4937	5217	+ 25.9
Electrical Thermal Efficiency (%)	28.01	28.15	29.58	+ 5.6

Table 3-2. CSGT Field Test Conditions*

Engine Parameter	
Fuel	Natural Gas
Output (kW_e)	4785
Heat Rate (Btu/kWh)	11,847
Thermal Efficiency (@ Terminals)	28.8%
TRIT °C (°F)	1121 (2050)
***NOTE:** Field test conditions were assumed to be: [15°C (59°F), 60% rel. humidity, 850 ft. elevation (ARCO test site), and, Installation losses of: 3" H_2O inlet, 8" H_2O exhaust].	

Centaur 50 Combustor Emissions Goals

In 1992 Solar introduced its SoLoNOx™ combustion system which reduces NOx emissions without the need for water injection. Current NOx and CO guarantee levels provided by SoLoNOx are 42/50 ppmv at 15% O_2, respectively. By late 1995, these guarantees will drop to NOx and CO levels of 25/50 ppmv.

Solar continues to explore combustion technologies that can further reduce emissions. Ceramics may play a key role in further NOx/CO reductions.

Ceramics, which can operate at elevated temperatures compared to metals, can be used advantageously in the combustor liner to reduce emissions. The hotter combustor walls minimize quenching of the reaction zone that tends to produce elevated levels of CO and augments combustor stability, thus allowing reduced reaction zone temperatures and NOx production levels.

For the purposes of this program, NOx/CO levels will be maintained below 25/50 ppmv for the full scale ceramic combustor.

Service Life Objectives

Initial minimum useful life objectives consistent with continuous duty operation on natural gas were defined as follows:

- All monolithic ceramic components: 30,000 hrs, i.e., one Time Between Overhaul (TBO) interval. Continuous Fiber Reinforced Ceramic Composites (CFCC) components: a minimum useful life target of 10,000 hrs.

- All existing standard metallic components whose normal life may be shortened in conjunction with operation of the engine at 1121°C (2050°F): 10,000 hrs, i.e., 2.5.times the planned field test duration. These items may include, but are not limited to:

  - Turbine rotor disks
  - 2nd & 3rd stage turbine nozzles and blades
  - Turbine rotor rim seals
  - Exhaust system components
  - Turbine nozzle support case

The stated component life goals will be reviewed during Phase II based on the results of life prediction studies. Depending on the life assessment data trade-offs may be required between acceptable component life to meet the field test conditions and duration and, complexity and cost of component designs.

The engine data supplied in this section form part of the product specification for the CSGT engine.

3.3 CONCEPTUAL COMPONENT DESIGN

The CSGT program has recognized the paramount importance of a sound conceptual design for each of the selected ceramic components and their interfaces with the metallic support structures. Background is based on:

1. Available literature from other ceramic engine programs both domestic and from abroad (eg: Japanese 100 kW, 300 KW, and 20 MW programs, U.S. and ATTAP programs).

2. Direct component and engine design experience from DOE and DARPA funded programs (eg: AGT-101 [DOE Contract # DEN 3-167], ATTAP [DOE Contract# DEN 3-335], [Ceramic Gas Turbine Engine Demonstration Program DARPA/Navy Contract # N00024-76-C-5352]).

3. Direct component and engine design experience from both internal and government funded programs at the Sundstrand Corporation.

The conceptual design criteria derived from the stated resources are discussed later in this section and along with cursory analysis have formed the basis for the concepts discussed. Each concept is designed to draw on the available ceramic component iterative design development achievements of the listed programs to help ensure early program success.

The CSGT program incorporates ceramic components in the combustor, stage 1 nozzles, and stage 1 turbine blades. Figure 3-2 shows the conceptual design criteria for ceramic components which have evolved through over a decade of experience from DOE funded ceramic automotive turbine engine (AGT, ATTAP) programs. These criteria were considered in the CSGT engine design in which the ceramic components are supported on or by metallic structures versus ceramic structures as in the automotive engine programs. Special consideration was required for the expansion mismatch of ceramics to metallics and the large thermal growth of metallic engine structural components for this size engine versus the (relative) size requirements of the automotive (duty cycle) engine .

- Simple Shapes/Loosely Supported
- Single-Load Path Mounting
- Low Thermal Stress Features
- Vibration Tolerant
- No Turbine Tip Rub - Stable Mounting Platforms
- Line Contact Interfaces (Ceramic/Ceramic)

Figure 3-2. Conceptual Component Design Criteria From Prior Programs

Further criteria used in the design of the critical ceramic components have been in the assumptions for thermal transient conditions which are typically the most severe conditions for ceramic components. In this regard, engine start, and "trip" shutdown transient philosophies have been reviewed in detail and engine digital electronic control logic changes recommended to mitigate the deleterious effects of these conditions on the ceramic components. Specifically, recommendations to modify the control logic are as follows:

Lightoff:

- Reduce "purge" cranking speed from 25% to 15% $N_{GasProducer(GP)}$ for smoother lightoffs
- Increase the fuel schedule ramp rate from 7 seconds to 15 seconds
- IGV's closed during startup to ~ 90% N_{GP}
- Bleed valve "open" during startup to loaded condition at 100% N_{GP} (design)

Trip Shutdown:

- Install 3 additional bleed valves on compressor discharge flow (~20% bleed/valve)

- Independently driven valves for redundancy simultaneously with engine fuel shutdown
- Close IGV's simultaneously with fuel shutoff

These recommended changes to the control logic will dramatically reduce the thermal transient induced temperature/stress distributions in the ceramic components by reducing the heat transfer coefficients (HTC's) along the meridional hot gas flowpath. A more benign temperature distribution correlates with a lower Maximum Principal Stress (MPS) in all the ceramic components and therefore a higher probability of component survival.

The iterative ceramic component design started with the conceptual designs shown in Figure 3-3 for the nozzle, blade attachments, and combustor tiles respectively.

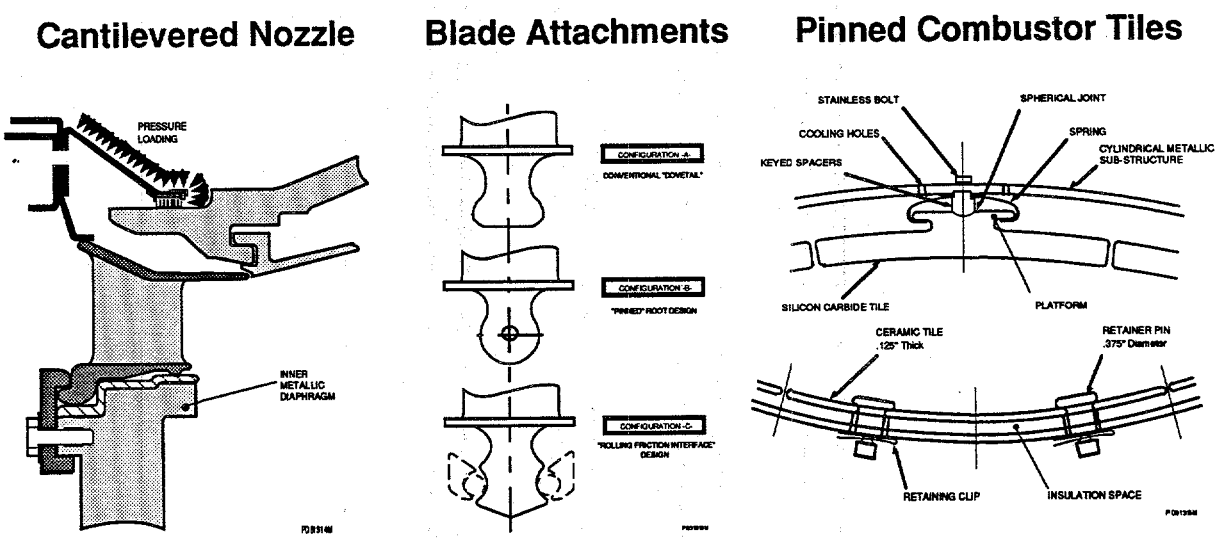
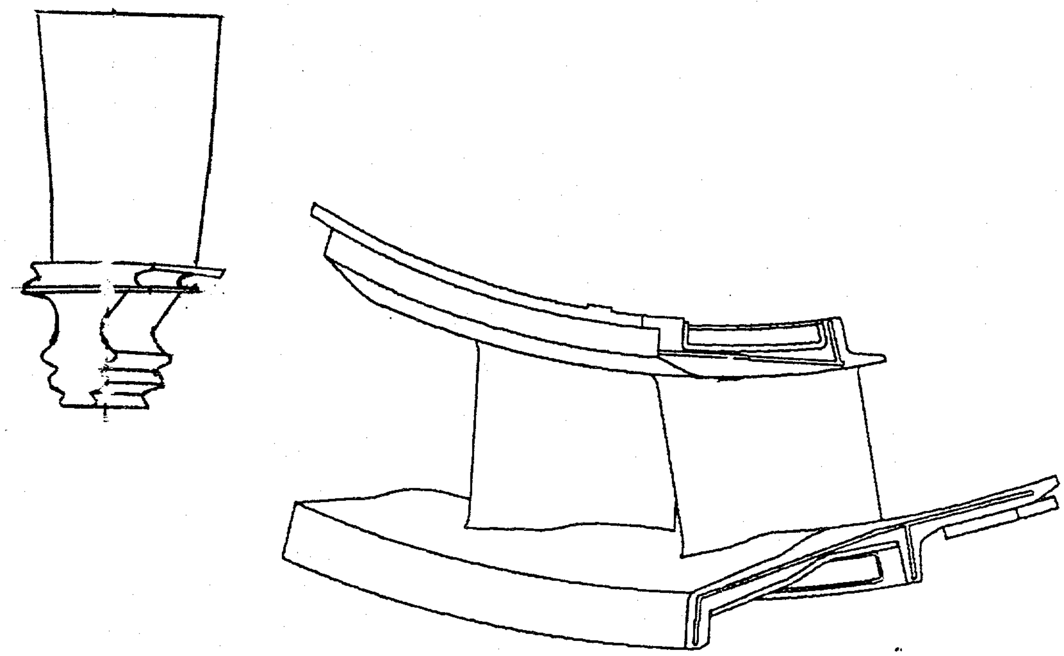


Figure 3-3. CSGT Program (Proposal) Conceptual Designs

Inserted Turbine Blade Design

Conceptual design of the turbine blades on the CSGT program has addressed the critical cycle dependent issues related to the blade root attachment to the metallic disk. The current Centaur 50 engine incorporates cooled stage 1 turbine blades with a firtree root attachment (Figure 3-4A). There are a total of 62 stage 1 turbine blades. The blade material is (cooled) MAR-M247 (equiaxed). This attachment is less suitable for a ceramic blade because high stresses between the surrounding metal disk and the ceramic blade root. An alternate design that has been universally used in ceramic turbine design in the U.S. and abroad consists of an airfoil mounted on a platform and a "dovetail" root. The dovetail attachment is critical for component life, since the highest stresses are typically found in the neck region below the platform. Most experience with this design has been gained on programs where the engine life target was less than 10,000 hours, such as in prior U.S. Government funded ceramic engine programs. This contrasts with the 30,000 hour TBO life requirement in the CSGT program for industrial turbine applications. On the other hand, the dovetail design is also the major blade attachment configuration in several Japanese engine programs, which are targeted for service lifetimes similar to those of the CSGT program.

(A)



(B)

Figure 3-4. Centaur 50 Stage 1 Turbine Blade (A) and Nozzle (B).

The dovetail design depends on the ability of a metallic compliant layer material to redistribute the blade loads over a planar interface. This planar interface, through which the blade loads are reacted, can assume various load distribution scenarios depending on the angle of the platform which in turn is constrained by space limitations imposed by a specific turbine disk geometry. For the CSGT both the 60° and the 45° platform angles were evaluated as both angles respond to: (1) attachment geometry space limitations; (2) disk rim stiffness; and (3) blade/disk stresses, and (4) the potential for metallic to ceramic interference in the disk rim during cool down. The centrifugally induced blade loads are transmitted to the metallic disk through the (approximately 5200 lb_f load) angular planar interfaces which must respond (without ceramic surface damage) to the relative interfacial motion associated with a mismatch in material expansion during engine start transients. A compliant layer is therefore required in the angular interface between the ceramic blade root and the metallic disk. This compliant layer must have sufficient plasticity at the desired temperatures to provide adequate cycle life.

The compliant layer material selection must ensure that the material does not wear through and allow the blade loads to react directly between the ceramic attachment and the metallic disk. Prior programs (1,2) have successfully demonstrated ceramic "dovetail" attachments and compliant layer materials for relatively short periods of time. However, these programs have clearly shown linkage between compliant layer wear-through and blade root failure via tests conducted without the use of a compliant layer material (re: ceramic blade in direct contact with the metallic disk material). Ceramic blade failure in the direct contact case has been attributed to the generation of critical surface flaws in the ceramic material with the absence of the strain relief properties of the compliant material as interfacial sliding friction occurs in thermal transients. Life prediction for the "dovetail" attachment configuration is made more difficult as a result of interfacial sliding friction contact stresses that can occur between the ceramic and metallic materials upon the loss of critical interfacial compliancy. The selection and evaluation of a compliant layer material that will meet the long (30,000 hours) engine overhaul interval requirement will be a critical activity under Phase II of the program.

In addition to the "dovetail" blade design several other root attachment configurations were conceived under the CSGT program. All blade conceptual designs under consideration are shown in Figure 3-3. Solar refers to these designs as the baseline "dovetail", "pinned root", and "ceramic insert" configurations. Each of the latter two concepts directly addresses the planar contact/relative motion, potential flaw-generating mechanisms of the "dovetail" (in cyclic operation) by eliminating tangential sliding friction in the heavily loaded and highly stressed interface region of the blade root. Further, since these concepts do not require the use of a life limited compliant layer material the cycle life behavior should improve over the conventional "dovetail" attachment scheme.

Nozzle Design

The Centaur 50 stage 2 nozzle consists of outer and inner shrouds and two airfoils. Fifteen of these two-airfoil nozzles make up the stage 1 turbine nozzle section. The nozzle material is (cooled) FS-414 (Figure 3-4B). To simplify fabrication, the baseline adapted for the ceramic nozzle was a single-airfoil concept. A complete nozzle section would consist of 30 individual nozzle segments.

Conceptual nozzle design was initiated through a thorough evaluation of prior axial-flow ceramic nozzle designs in the areas of; mechanical load path, the need for near isothermal operation for low component stresses, vibratory response due to mounting schemes, etc. With these considerations in mind, the initial nozzle concept for the CSGT program involved a nozzle configuration which was cantilevered from the inner shroud metallic support structure and incorporated an insulative material (castable-partially stabilized ZrO_2) which performed the dual functions of load bearing and insulator (thermal dam) material. This configuration had the following features:

- Single load path
- Simple geometry - single airfoil segments
- Near isothermal (steady state) operation
- Vibration tolerant
- Line contact interfaces

In addressing the sealing issues of compressor discharge air and nozzle hot gas bypass leakage on the outer nozzle shroud area, several seal concepts were investigated in which the seals were required to physically touch the ceramic nozzle outer shroud. Additionally, the seals required secondary cooling air to maintain material integrity with the deleterious effect of cooling the outer shroud of the nozzle segment. This cooling of the outer shroud prompted use of the existing 3-D FEA of the nozzle to determine the sensitivity of the nozzle Maximum Principal Stress (MPS) to an increased radial thermal gradient between the airfoil and the shrouds. The radial gradient of the baseline analysis was based on a standard Centaur 50 (average) radial temperature distribution for a SoLoNOx combustor scaled up to a TRIT of 1121°C (2050°F). The results of this analysis (discussed under 3.5 "Parametric Stress Study") indicated the potential for nozzle operation below the suspected material slow crack growth (SCG) regime if one of the two nozzle shrouds was physically separated from the airfoil. The inner nozzle shroud was selected for separation from the nozzle airfoil since the inner shroud line, from airfoil leading edge to trailing edge, is parallel to the engine centerline and can therefore accommodate the relatively large axial thermal growth differential between the inner and outer shroud meridional flowpaths. With the inner shroud separated from the airfoil the nozzle support had to be shifted to the outer shroud from which the nozzle is cantilevered[1]. Since no SCG data has been generated for a 30,000 hour engine operating

[1] This separated shroud configuration is referred to as the de-coupled and/or cantilevered nozzle configuration.

interval, it was determined that a nozzle configuration modified in this way would be required to address the reduction in trailing edge (TE) steady state stress.

One nozzle concept from the Phase I "Conceptual" and Preliminary Design" tasks is shown in Figure 3-5 in which the nozzle segments are cantilevered from the outer shroud on Si_3N_4 ceramic pins which engage an integral monolithic ceramic anti-rotation support ring or ring segments. A potential monolithic structural ceramic for an integral ring is NT230, a siliconized silicon carbide (Si-SiC) fabricated by Norton Advanced Ceramics (NAC). Large rings of this material have been fabricated by NAC for other applications. Both SiC and Si_3N_4 are candidate monolithic ceramics for a segmented ring configuration and will undergo extensive analysis as part of the Phase II Detail Design activity. The integral/segmented support ring is attached to the existing metallic nozzle case via 3 (equally spaced) lugs and grooves which contact the metallic nozzle housing through a ceramic/ceramic rolling friction interface. The nozzle inner shroud flowpath is formed by a simplified integral ring which has a steady state thermal expansion matching that of the nozzle support/anti-rotation ring. The matching thermal expansion of these two structures is critical to providing close tolerance control (minimal hot gas leakage[2]) between the nozzle airfoil (inner shroud) tip and the inner shroud O.D.

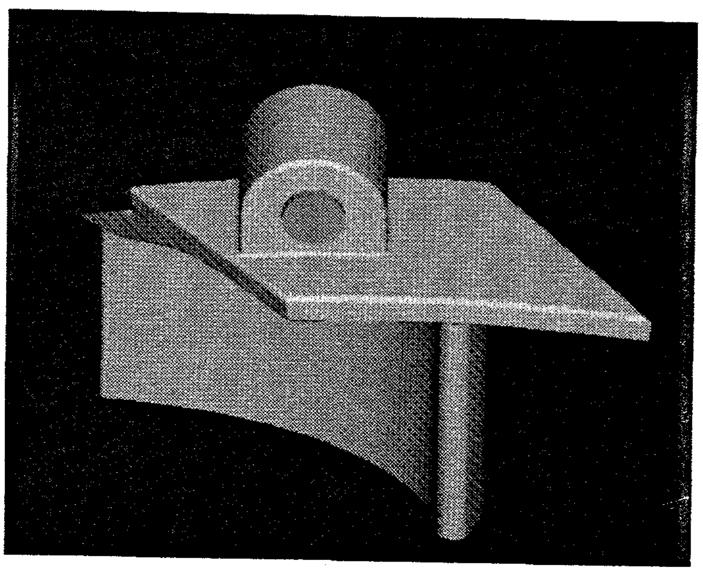


Figure 3-5. "Pinned" Ceramic Nozzle Configuration

This configuration responds to all the conceptual component design criteria shown in Figure 3-2 while also providing a low risk means of sealing the nozzle airfoil inner shroud - hot gas flowpath. The relatively low stress decoupled airfoil design must also be vibration tolerant, so a 2-D finite element analysis (FEA) of the airfoil was completed to determine the vibratory response of the airfoil to periodic aerodynamic loads generated in normal combustor operation. An empirical test was conducted to determine the sensitivity of the cantilevered airfoil to engine order frequencies by modifying a production Centaur 50 metallic nozzle to a cantilevered airfoil configuration. The results of this test were inconclusive in that it was learned that the nozzle frequency response in the

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[2] Hot gas leakage in this region equates to a performance decrement and must therefore be closely controlled in steady state engine operation.

cantilevered airfoil configuration is dependent on the method of attachment between the outer shroud and the support structure. A rigidly constrained outer shroud created a low frequency response signature (300 - 400 hz. range), while a loosely supported outer shroud tended to respond in the 3000 - 4000 hz. range. Since the primary nozzle support configuration for this program utilizes a "loose" ceramic "pinned" nozzle approach, it is unclear what affect this will have on the nozzle frequency response until a more representative nozzle geometry can be fabricated and tested.

Combustor Design

Combustors for Industrial Gas Turbines

The combustion system, a key component of the gas turbine engine produces thermal energy from the chemical energy of fuel at high temperatures and pressures. To generate this thermal energy the combustor utilizes compressor supplied air in three different ways. Firstly, reaction air is required to oxidize the fuel. Secondly, dilution air is required to both reduce the overall temperature of the gases entering the turbine section and to tailor the temperature distribution of those gases for optimum turbine design. Thirdly, a significant amount of air is utilized to cool the combustor liner. A schematic of a typical conventional combustor is shown in Figure 3-6.

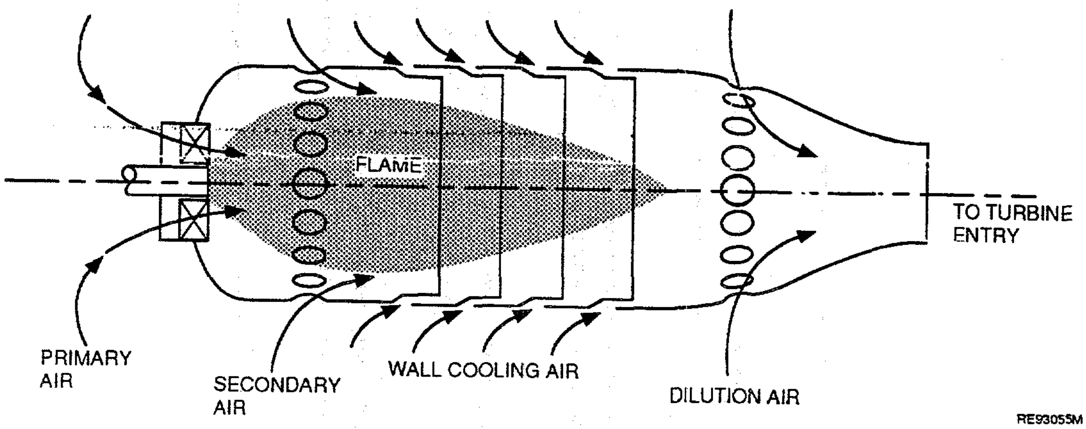

Figure 3-6. Schematic of a Typical Combustor

With conventional sheet metal combustors, up to 50% of the compressor supplied air is directed toward the combustor liner walls in order to maintain structural integrity and ensure component life. A significant increase in turbine inlet temperature complicates the cooling process using standard wall materials. More air is necessary in the reaction zone leaving less air for cooling and dilution. Materials with improved durability (compared to metals) could advantageously be used in the combustion liner to reduce the need for cooling air at elevated turbine firing temperatures. The reduction in the cooling air requirement would increase the supply of air available for dilution and exit gas temperature profile trimming.

These factors point to several benefits of the application of ceramics in Solar's combustors:

a. Ceramic materials can replace metals in current combustor liners that are limited in service life because of oxidation and creep rupture.

b. Ceramic materials will reduce the need for cooling air which will assist in reducing CO and NOx emissions and increase the amount of dilution air.

c. The increased availability of dilution air is expected to improve the pattern factor of the combustor. This will lessen the occurrence of hot spots in the first stage nozzle area of the gas producer turbine, improve nozzle durability and/or allow increased firing temperatures.

To fully eliminate the film cooling requirement, the wall material must operate in an oxidizing environment with temperatures of potentially up to 1371°C (2500°F), a substantial increase compared to 871°C (1600°F) which is approximately the maximum temperature of current metallic combustor liners in Solar's engines. An intermediate goal could be to design a liner for a temperature well above the current wall temperature but below 1371°C (2500°F) while possibly retaining some supplemental film cooling. The material requirements are the ability to fabricate the geometries needed for an efficient energy conversion device and thermo-mechanical compatibility with the adjoining engine components.

SoLoNOx™ Combustor Emissions Reduction

The ceramic combustor conceptual design for the CSGT engine is based on the SoLoNOx™ low emissions combustor design of Solar's engines. The SoLoNOx™ combustor is a Lean Premix Combustor (LPM) in which the conversion of atmospheric nitrogen to NOx within a gas turbine combustor is reduced by lowering the combustor flame temperature. As NOx formation rates are exponentially dependent on temperature, lowering the flame temperature is extremely effective in reducing NOx emissions. The reduction in flame temperature is accomplished in two ways. First, the combustor primary zone is operated at a lower average temperature (lower average fuel/air ratio) than is typical. Lean primary zone operation is achieved through an increase in the primary zone air flow and a corresponding decrease in the dilution zone flow (Figure 3-7). Total combustor air flow and combustor exit temperature remain unchanged, thus no change in gas turbine output or heat rate occurs. Second, lean-premixed combustion limits NOx formation by preventing high, near-stoichiometric flame temperatures from occurring locally within the primary zone. Any high temperature regions can contribute disproportionately to overall NOx emissions. High temperatures can occur locally (despite a low average temperature) if high fuel/air mixture ratios exist locally within the flame zone. This is typical in a conventional combustor where fuel is injected directly into the primary zone and the fuel/air mixing and combustion processes occur simultaneously.

In lean-premixed combustion, the mixing and combustion processes are uncoupled. The fuel and primary zone air are mixed upstream of the combustion zone. Premixing produces a more uniform flame temperature and prevents high NOx production locally within the combustor. The NOx reduction capabilities of lean-premixed combustion are well documented (3).

Lean-premixed burners have a relatively narrow operating range over which both low NOx and CO are obtained (Figure 3-8). This low emissions range occurs near the combustor lean limit. A lean-premixed gas turbine combustor designed for low emissions at full load will eventually produce high CO emissions as load is reduced. To broaden the combustor operating range, combinations of fuel staging (multiple sets of fuel injectors), variable geometry (active control of the combustor air flow distribution), and combustion staging (multiple combustion zones) are required to apply lean-premixed combustion to the gas turbine.

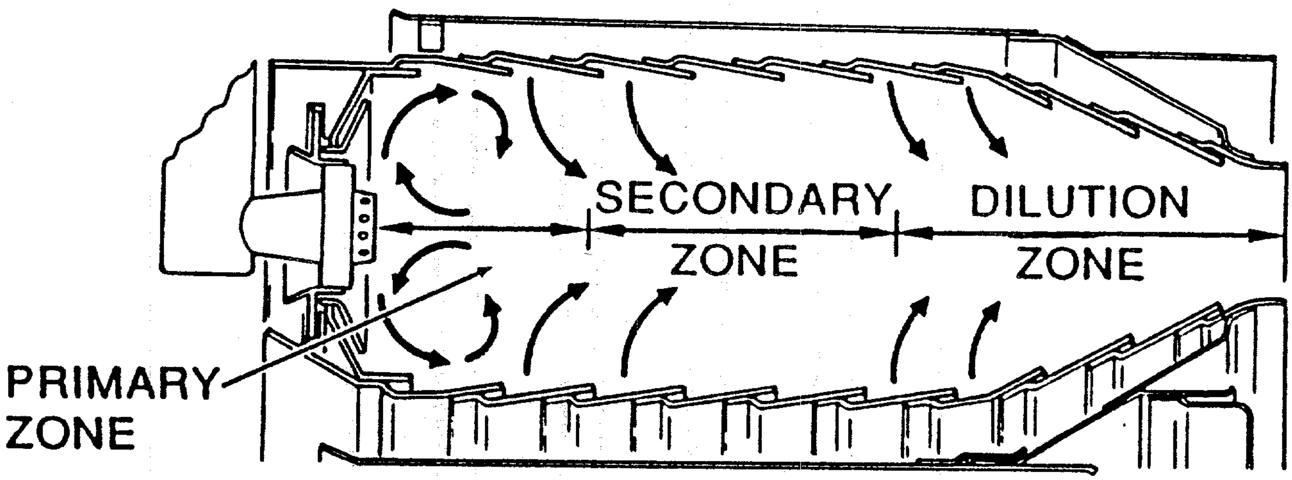

Figure 3-7. Lean-Premixed Combustor Concept 52-003

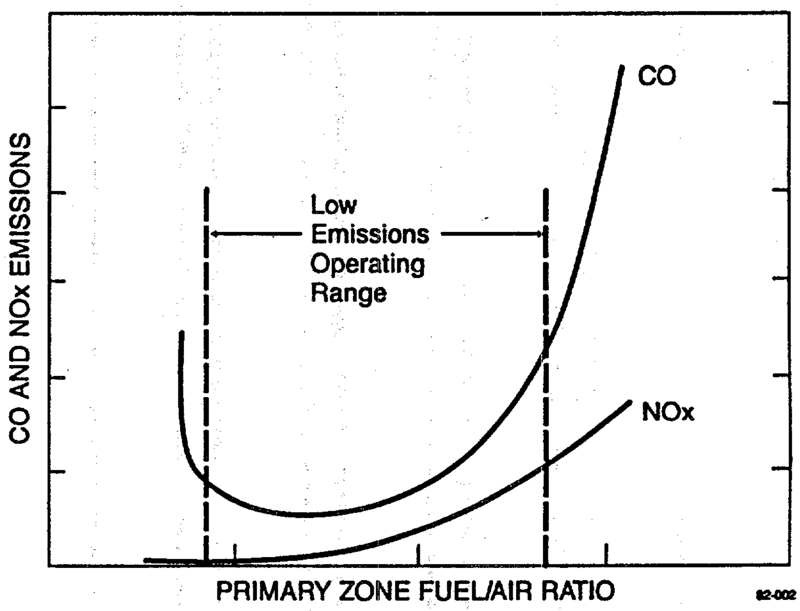

Figure 3-8. Typical Lean-Premixed Combustor Emissions

The annular SoLoNOx combustor development started with initial rig testing with cylindrical can combustors employing single fuel injectors. The can combustors employed the same basic swirl-stabilized, lean-premixed combustion process eventually used in the annular SoLoNOx combustors. The can combustor tests established low emissions capabilities and key design parameters. Subsequently, a sector representative of a one-quarter section of the annular Centaur 50 SoLoNO$_x$ combustor was evaluated. The sector utilized three fuel injector/air swirler modules. Finally, in the full scale combustors used in Solar's Centaur, Taurus, and Mars engine a fuel complement of injectors (12 for the Centaur 50) is used. A noticeable difference between a full scale SoLoNOx combustor and a conventional annular combustor is the increased combustor volume. A Centaur 50 SoLoNOx combustor is shown in Figure 3-9. The larger volume ensures complete combustion (low CO emissions) at the lower, lean-premixed flame temperature. Since combustor length is constrained to minimize gas turbine redesign, the increased volume is achieved by an increased combustor outer diameter.

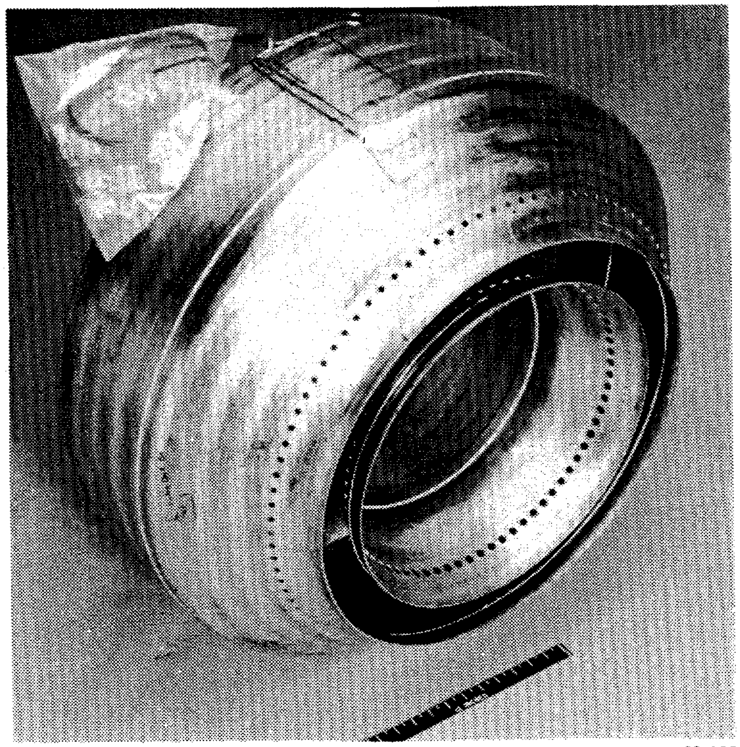

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Figure 3-9. Centaur Type 50 SoLoNOx Combustor Liner

The key elements of the SoLoNOx technology are the larger liner for low CO emissions and a fuel injector design that allows fuel/air premixing prior to combustion.

Current SoLoNOx units are being offered with NOx guarantee levels of 42 ppmv over the 50 to 100 percent load range and -18°C to 38°C (0°F to 100°F) ambient temperature range. Technical developments indicate that units shipped for startup in 1995 will be at NOx levels below 25 ppmv at 15% O_2. This decrease in NOx level will result from injector/premixer modifications already developed. The liner design will also emit lower CO levels.

CSGT Combustor Design

The initial combustor design proposed for the CSGT program utilized ceramic (SiC) tiles that were to be attached to the existing metallic SoLoNOx combustor liner as illustrated in Figure 3-10. The attachment was to be made via ceramic clevis pins through holes (minimum of 3/tile) in the ceramic tiles and retained through the use of a metallic spring clip. This configuration, would have required the development in the areas of:

- A compliant layer material that would not blow out due to liner ΔP and which may require operation at temperatures as high as ~1370°C (2500°F)
- An insulation material that would not degrade at temperatures as high as ~1370°C (2500°F)
- Ceramic clevis pins that would not react with SiC at temperatures as high as ~1370°C (2500°F), and would retain their initial mechanical integrity
- Tile vibration damping
- Producing holes in the SiC tiles in a complex thermally induced transient stress field

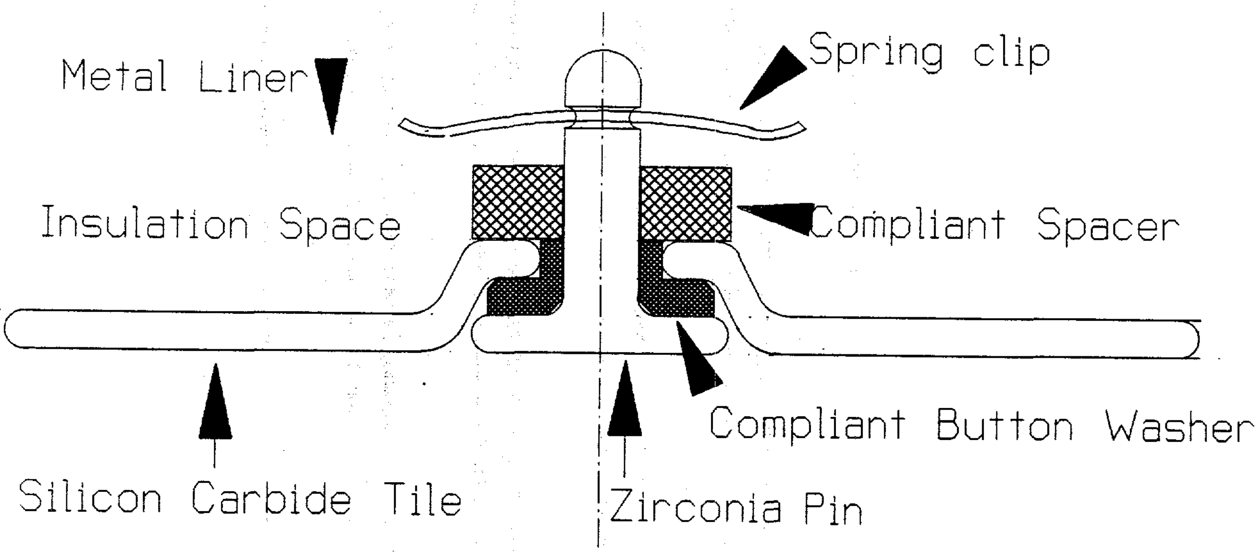

Figure 3-10. Ceramic Tile Attachment

The requirement to develop these technologies provided the driver to iterate the design away from these potential technology "barriers" into a configuration that could be backed mechanistically from prior program experience. This rationale led to the combustor configuration illustrated in Figure 3-11 in which the entire combustor was to be fabricated from ceramic ring segments clamped together in close tolerance planar interfaces. This design concept was subsequently simplified by electing to incorporate ceramics only at the cylindrical portions of the combustor walls. It was decided that at the relatively modest TRIT goal of 1121°C (2050°F) of the program significant benefits could be realized from lining the cylindrical portions with ceramic while retaining metallic structures in the dome and transition liner areas.

One ceramic combustor assembly design is illustrated in Figure 3-12. This design incorporates the use of tiles in both the inner and outer cylindrical portions of the SoLoNOx annular combustor. The tiles are retained via I-beam shaped ceramic segments. An additional monolithic ceramic material design involves the use of continuous ring segments for both the inner and outer cylindrical portions of the combustor. The ceramic rings are stacked against each other (axially) to fill the cylindrical portions of the combustor liner.

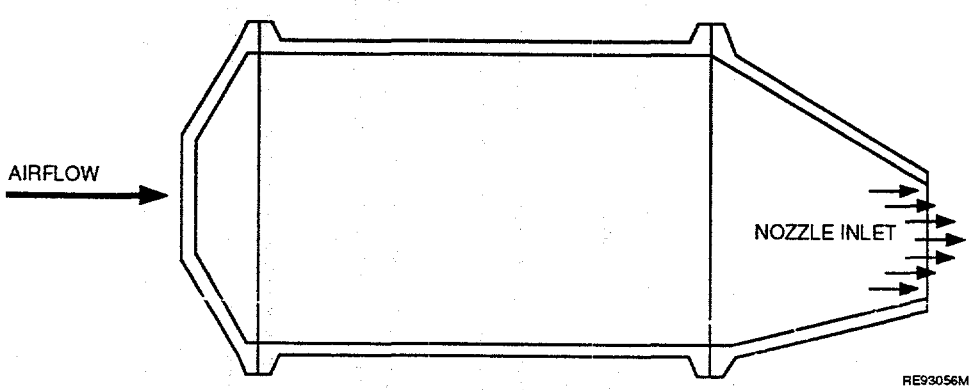

Figure 3-11. Ceramic Tile/CFCC Combustor Design

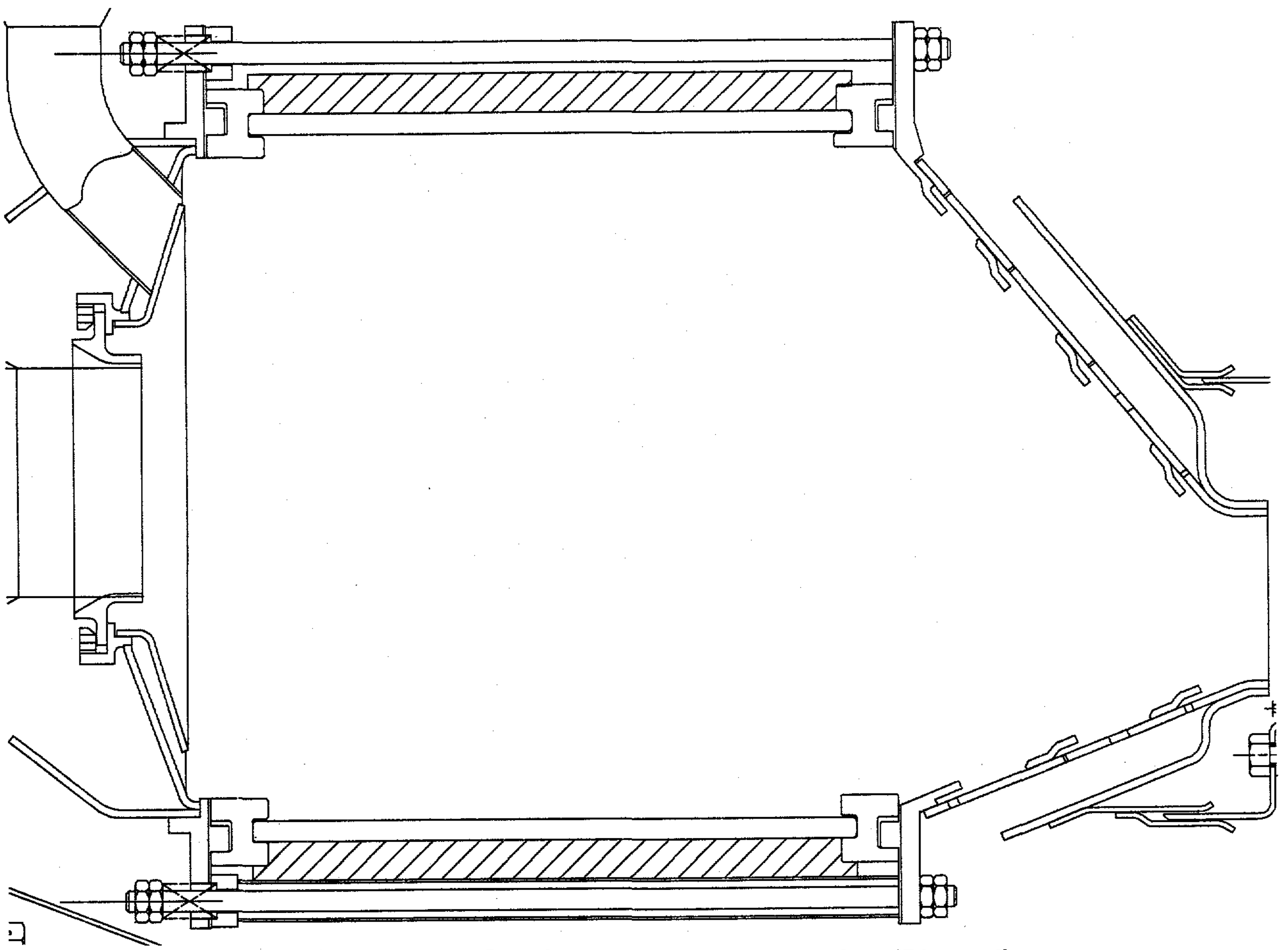

Figure 3-12. Combustor Assembly Design (Phase I)

The same ceramic envelope lends itself also to application of continuous fiber-reinforced ceramic matrix composite materials (CFCCs). Like the monolithics the CFCC combustor liners have been designed to occupy the cylindrical portions of the combustor and are interchangeable with the monolithic tiles. The advantage of the CFCC material is the opportunity to incorporate integral liners into the combustor simplifying the requirements for attachment to the metallic support structure and eliminating the concerns about sticking and leaking which must be addressed with monolithic tiles or rings.

All of the ceramic combustor liner concepts are to be piloted/retained by existing metallic dome and discharge section annular conical rings which are retained axially by a cylindrical metallic spring diaphragm. The tiles are "shingled" (along the axial interfaces) with adjacent tiles in an effort to control inter-tile leakage paths while the ceramic rings are simply sealed via planar interfaces. Preliminary analyses of each of the concepts indicates the need for an insulation blanket around the periphery of the ceramic assemblies to minimize convective and radiation heat losses which would limit tile (steady state) temperatures to approximately 870°C (1600°F).

3.4 PRELIMINARY MATERIALS SELECTION

Candidate advanced ceramic materials have been selected for the combustor, stage 1 blades, and stage 1 nozzles based on the estimated temperatures, stresses, geometric shapes, supplier capabilities, and life requirements identified at the start of Phase I. The monolithic ceramic materials listed in Table 3-3 have been identified for the component specific applications shown.

Table 3-3. Candidate Monolithic Ceramic Materials for the CSGT Program

Component	GN-10 (Si_3N_4)	NT154 (Si_3N_4)	SN-252 (Si_3N_4)	SN-88 (Si_3N_4)	Hexoloy®S A (SiC)	NT230 (SiC)
Blades	Yes	Yes	Yes	----	----	----
Nozzles	----	Yes	----	Yes	Yes	----
Combustor	----	----	----	----	Yes	Yes

Selection of materials for the blades, the nozzles and the combustor liner tiles were made on the basis of the following criteria:

a. Experience of the supplier with fabrication of components having a similar degree of complexity to Solar's preliminary drawings
b. Design and analysis database
c. Estimation of projected life of these materials used as components in Solar's preliminary design.
d. Cost of the components
e. Adequate design life

Predicted primary critical modes of failure for the components are identified below:

- Blades	Slow crack growth
- Nozzles	Creep and oxidation
- Combustor Tiles	Creep and oxidation, thermal shock resistance

Blades - The blade has stress induced from 3 sources: (1) aerodynamic loading, (2) thermal loading, (3) centrifugal force (CF) loading, and (4) vibration loading. Thermal loads are most prevalent in the airfoil section of the blade where the material temperature is highest, while CF loads are predominantly located in the relatively "cold" blade root attachment region. Analytical predictions indicate that the blade is likely to see material temperature in the 649-1093°C (1200-2000°F) range between the blade root and the airfoil. In this range silicon nitride materials generally have a noticeably higher fast fracture strength than silicon carbide. Also silicon nitrides have better thermal shock resistance than silicon carbide. Based on the slow crack growth parameters A and n (Derived from the Charles equation $V=A^*K_I^n$, where V is the velocity of SCG and K_I is the stress intensity factor) of two of the three silicon nitrides chosen for the blade (NAC's NT154 and Kyocera's SN-252), preliminary life assessment indicated that these materials are life limited due to slow crack growth but will readily meet the 4,000 hour field test engine life requirement. GN-10 data were not available during the Phase II performance period but will be investigated extensively in Phase II prior to any long duration gasifier rig and/or engine testing.

Nozzle - This application could use both silicon carbides and silicon nitrides, since the component is stationary and does not have the CF load of the blades. The analytically predicted "worst case" nozzle steady state stresses are 276 MPa (40 ksi) in SiC, and 262 MPa (38 ksi) in Si_3N_4 material. (see Task 2 "Nozzle Preliminary Design" for a detailed discussion on the "worst case" nozzle location). Hexoloy® SA has no known strength degradation as a function of time or cross-head speed over the temperature range of interest, indicating that it does not undergo noticeable creep or slow crack growth at this temperature. NAC's NT154 is a well characterized material which has a creep life that exceeds the 4,000 hour engine field test requirement at this temperature and at a stress level of 262 MPa (38 ksi). NT154 nozzles, albeit smaller, have been successfully demonstrated in prior programs such as the Advanced Turbine Technology Applications Project (ATTAP). NGK's SN-88 silicon nitride is gas pressure sintered and does not have the glass based encapsulant reaction layer (common to GN-10 and NT154) formed during hot isostatic pressing (HIP). This reaction layer degrades the "as-fabricated" surface strength of the HIP'ed materials and as a result the SN-88 material has superior "as-fabricated" surface strength. The creep behavior of SN-88 is comparable to that of NT154.

Combustor Liner - Materials were selected on the basis of known high temperature resistance and good oxidation, creep, and thermal shock behavior. The tile concept has one candidate material, Carborundum's Hexoloy® SA. This SiC material has good oxidation resistance at the hot wall maximum design temperature of 1370°C (2500°F), and also exhibits very little creep behavior. NT230 SiC was slected for a ring configuration. This material can be fabricated near net shape and the supplier, NAC, has experience with fabricating large ring-shaped components. Silicon nitrides degrade noticeably at this temperature and were not considered for this application. Continuous Fiber- Reinforced Ceramic Composites (CFCC's) were included in the material selection process because of: improved material toughness over monolithic materials, and the potential to fabricate large integral liners, but CFCCs are limited to a maximum use temperature of ~1200°C (2912°F). The two CFCC materials selected under this program are alumina/alumina (Al_2O_3/Al_2O_3) from Babcock & Wilcox and a silicon carbide/silicon carbide (SiC/SiC) CFCC from DuPont Lanxide Composites. Solar is involved in several CFCC programs with combustor liner applications, concurrent with this program, and it is expected the developing CFCC technologies may benefit this program.

There is also a need to select ceramic materials for the nozzle ring support. NC230 silicon carbide which can be fabricated in large integral shapes is being considered for these applications.

Three material suppliers were selected for the blade and nozzle and four for the combustor liner component to provide an optimum pathway to technology demonstration and eventual commercialization.

3.5 PARAMETRIC STRESS STUDY

A parametric stress study was performed on the stage 1 nozzle utilizing the existing 3-D model and scaled up Centaur 50 SoLoNOx™ combustor radial profile to determine the sensitivity of the airfoil trailing edge (TE) stress to increases in the radial thermal gradient. The outer shroud temperature was reduced in 139°C (250°F) increments to a maximum differential shroud to airfoil temperature of 556°C (1000°F) and the resulting increase in TE stress was approximately 34.5 MPa (5 ksi) per 139°C (250°F) increment. This increase in the TE stress was at a material temperature of 1245°C (2273°F) which, when combined with the increased TE stress state, was driving the material in the direction of the SCG regime.

Another finite element analysis (FEA) was conducted to determine if the root cause of the increased TE stress was attributable to the interaction of the 2 integral shrouds with the airfoil *vis a vis* the radial thermal gradient. Prior DOE funded ceramic automotive gas turbine engine programs (AGT-101/ATTAP) came to the conclusion that, during the rapid start transients, the high TE stress resulted directly from a substantial radial temperature gradient between the 2 integral shrouds and the airfoil. Several design modifications to the nozzle segments in these programs were implemented to lower the TE stress such as a simple (radius) cut-back in the TE. This technique mitigates the TE transient stress as follows:

- The TE stress acts over a curved surface versus a straight line.

- The throat area is increased which, via lower local heat transfer coefficients, reduces the transient radial temperature gradient
- It increases the thin TE section modulus by an increase in the material cross section from 0.5 mm (0.02") to approximately 1.0 mm (0.04") in the midspan of the TE

In the case of the AGT-100, the ceramic nozzle design utilized individual airfoils without shrouds that fit into recesses in two appropriately spaced (B-width) concentric ceramic rings.

These prior program designs for lowering the TE stress in transients were used in the CSGT by eliminating the mechanical coupling of the 2 integral shrouds to the airfoil by removing (de-coupling) the inner shroud.

The FEA referred to above was based on the following assumptions:

- Current Centaur 50 metallic nozzle geometry with single airfoil segments
- Combustor "average" radial profile of Centaur 50 SoLoNOx™ combustor scaled to a TRIT of 1121°C (2050°F)
- Nozzle/shroud secondary cooling flows reduced to "0"
- Material: NT154 silicon nitride
- Inner shroud de-coupled from the airfoil

The results of this analysis showed a reduction in the TE stress to approximately 34.5 MPa (5 ksi) which is well below the suspected SCG regime in candidate materials operating at a material temperature of 1245°C (2273°F). An additional analysis was then conducted to determine the TE stress sensitivity to a decrease in the outer shroud temperature in 139°C (250°F) increments to a maximum differential temperature of 556°C (1000°F) the same as in the integral 2nd shroud configuration. This analysis indicated the TE stress was essentially unaffected by the decrease in outer shroud temperature with the assumed combustor discharge radial profile.

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4.0

TASK 2 - PRELIMINARY COMPONENT DESIGN

4.1 INTRODUCTION

Task 2 focused specifically on the preliminary design of the key ceramic components for which design concepts were proposed in Task 1. Critical material property requirements were identified and stress/temperature profiles were run for the selected ceramic components and adjacent metallic support structures using 3-D finite element analysis. Interfacing of the ceramic components with the metallic support structures was given considerable attention. Matching of the coefficients of thermal expansion, and compatible design solutions for the ceramic components and their adjacent metallic support structures were the primary factors in the preliminary design. Designs were modified to iower stresses and reduce temperature differentials where appropriate. Design adaptation and materials selection for secondary components were incorporated in the Task 2 efforts.

Figure 3-2 of Section 3.3 (Conceptual Component Design) indicates that ceramic to ceramic line contact (Hertzian) interfaces are always preferred over planar load bearing surfaces. Line contact interfaces react loads along a well defined line contact zone which has (in monolithic materials) the capability of surviving hertzian compressive stresses in excess of 1725 MPa (250 ksi). The concept of ceramic/ceramic line contact loading was therefore adopted for use in both the blade root attachment and the nozzle mounting and support structure locations. A clear understanding of the actual contact zone stresses typically requires the aid of "zoom" modeling (3-D FEM) in the contact interface area to more closely evaluate the stress conditions. Further, any tangential sliding friction that occurs in this interface loading scheme generally results in damage to one or both of the ceramic surfaces. This can result in primary failure of the components. The following paragraphs address the mechanics of a ceramic/ceramic line contact interface.

Contact Stress at Interfaces - Accurate assessment of ceramic/ceramic or ceramic/metal interface stresses is extremely important in the design of the ceramic turbine blade, and to a somewhat lesser extent, for the static structural interfaces. Analytical modeling of these frictional interfaces using finite element methods is very complex, usually requiring a high degree of element refinement in the vicinity of the contact area. Moreover, conventional finite element methods have employed only 2-D models to investigate these effects due to the considerable computing power required.

All finite element models used to predict component reliability in the CSGT program must be 3-dimensional. Therefore, if conventional methods of contact stress analysis were used for these models, the task would be prohibitive with respect to modeling time and computational resource.

These deficiencies can be overcome by acknowledging that the significant (life limiting) stress component at a frictional interface is a tangential force component which introduces a tensile stress component over the contact region, and testing has shown that this tensile component is largely responsible for the degradation of component reliability. If this tensile stress can be accurately estimated, it is, in principle, possible to adjust a finite element results file to reflect this additional component without having to formulate complex modeling techniques. As it happens, this stress component can be readily evaluated using a mixture of standard Hertzian-type relationships and finite element analysis with unrefined FE meshes.

The closed form equations used for the purpose of estimating the surface contact length are adaptations from Timoshenko and Goodier (1) by Juvinall (2). For the case of a cylindrical pin radius R_p length L within a hole of radius R_h, the normal pressure distribution is given by:

(Local normal contact) pressure distribution at any point $P = P_0 \times (1-y^2/b^2)^{1/2}$

Where: b is the length of the elliptical contact zone (perpendicular to the pin axis) and y is the distance from the center of pressure

Also: $P_0 = 2 \times W / (\pi \times L \times b)$ (max contact pressure)
W = Total load
$b = 1.13\ (W \times \delta / [L\ (1/R_p - 1/R_h)])^{1/2}$
$\delta = (1-\mu_1{}^2)/E_1 + (1-v_2{}^2)/E_2$
v = Poisson's Ratio
μ = Coefficient of Friction

The solution to the frictional[1] sliding situation is a superposition of the stress state due to the normal loading case (without friction), and the tangential (frictional) stress state. Assuming that the frictional forces are distributed in the same elliptical pattern as the normal forces, when sliding occurs, the maximum tangential stress q_0 is given by:

$$q_0 = \mu \times P_0$$

With superposition, as with the normal load case, the maximum shear stress occurs below the surface. However, unlike metals, reliability of ceramic materials depends more on maximum principal stress than on shear stress. The maximum principal stress for this system occurs at the surfaces (as distinct from internal), and is a strong function of coefficient of friction. For example, if $v = 0.3$ and $\mu = 0.33$ the magnitude of the maximum tensile stress component (superposition of normal and tangential) is $0.65\ P_0$.

Note: (*) Tangential tensile stress occurs in the ceramic surface even before relative motion (sliding) occurs at the interface and can therefore still damage the surface without the presence of the coefficient of friction component.

It should be clear from the above discussion that the tensile stress components, (which results from the hertzian frictional force component) can be extracted by consideration of the finite element (normal load) solution of P_0 and the above equation relating P_0 to q_0. This can be accomplished even with a mesh of 'modest' refinement.

This approach has not been adopted in the Phase I studies due to time constraints, and the preliminary nature of the investigations. However, the Phase II strategy for interface stress assessment will be as follows:

a) Calculate contact length 'b' by hand calculations using above equations to estimate the degree of mesh refinement required and the extent (spread) over which the gap elements should be placed on the surface elements

---

[1] Tangential tensile stress occurs in the ceramic surface even before relative motion (sliding) occurs at the interface and can therefore still damage the surface without the presence of the coefficient of friction component.

b) Run the finite element model for normal loading (P_0) case only

c) Obtain the elastic normal stress distribution from P_0 and calculate the surface tangential stress component distributions

d) Incorporate the tangential stress components (X and Y) by superposition for the affected elements into the ANSYS FEA results file

e) Carry out reliability analysis on modified ANSYS FEA results file

The validity of using finite element meshes of modest refinement for interface analysis has been verified by using a 2-D finite element model representing a round bar against a flat, infinitely stiff plate. The results shown in Figure 4-1 indicate that for an element length of approximately 2% of a pin radius (i.e. the type of mesh that will be used frequently on the CSGT program for 3-D models), both the maximum compressive stress P_0 and the contact length 'b' are in agreement with the closed form equations to within 5%. In other words, surface deformation and normal (compressive) stress analysis can be adequately represented by this type of model, leaving only the tangential stresses to be superposed onto this distribution.

4.2 CRITICAL PROPERTY REQUIREMENTS

The material property requirements have been subdivided into two categories: Design /analysis requirements and Life Prediction requirements. Table 4-1 lists the critical properties for design and life prediction, indicating the components for which these properties are critical. This list may be expanded as the design becomes more detailed.

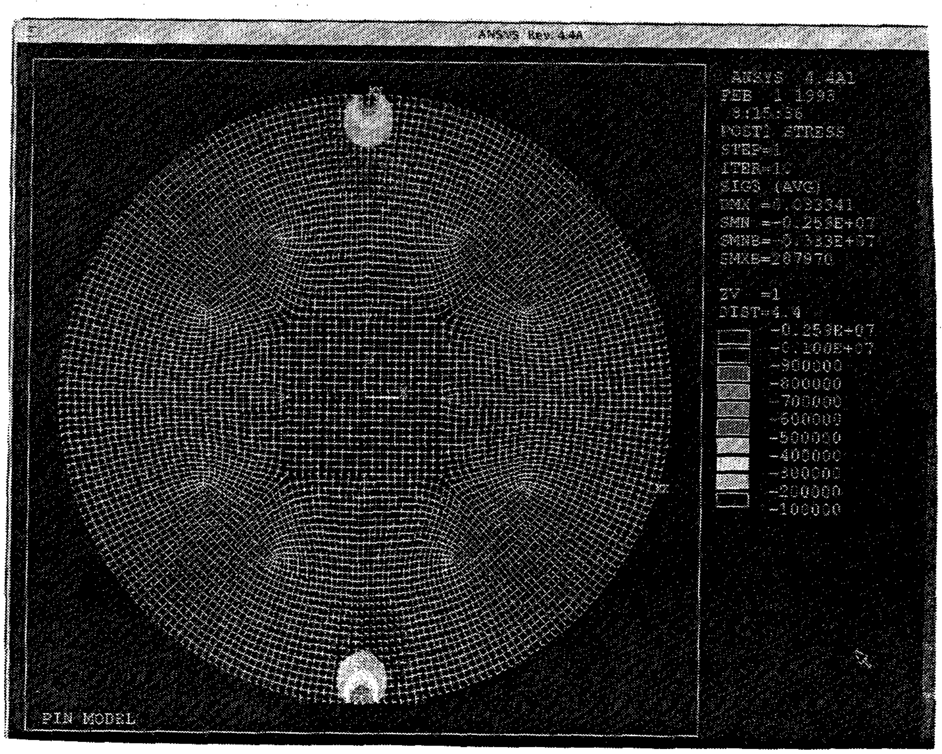

Figure 4-1. 2-D FEM of Contact Stresses at Interface of Round Pin and Flat Plates

Table 4-1. Critical Component-Specific Material Properties

Property	Components
Design and Analysis Requirements	
Elastic Modulus vs. Temperature	Blade, Nozzle, and Combustor
Poisson's Ratio vs. Temperature	Blade, Nozzle, and Combustor
Coefficient of Thermal Expansion vs. Temperature	Blade, Nozzle, and Combustor
Thermal Conductivity vs. Temperature	Blade, Nozzle, and Combustor
Density vs. Temperature	Blade, Nozzle, and Combustor
Specific Heat vs. Temperature	Blade, Nozzle, and Combustor
Thermal Shock Resistance	Blade, Nozzle, and Combustor
Strength (As-Fabricated and As-Machined)	Blade, Nozzle, and Combustor
Weibull Modulus	Blade, Nozzle, and Combustor
Life Prediction Needs	
Fracture Strength vs. Temperature • As-Fabricated Surface • As-Machined Surface • Volume	Blades, Nozzles, and Combustors
Fracture Toughness vs. Temperature	Blades, Nozzles, and Combustors
Slow Crack Growth Parameters A and n, vs. Temperature	Blade and Nozzle
Monkman Grant Creep Parameters	Nozzle and Combustor
Activation Energy For Creep	Nozzle and Combustor
Oxidation Activation Energy	Nozzle and Combustor
Thickness of Oxide Layer and Weight Change With Time At Constant Temperature	Nozzle and Combustor
Others	
Coefficient Of Friction Between Silicon Nitride and Superalloys vs Temperature and Time	Blade
Sticking Between Silicon Based Ceramics with Temperature	Nozzle and Combustor
Damping Coefficients	Blades, Nozzles, and Combustors

4.3 ROTOR BLADE PRELIMINARY DESIGN

Blade Root Attachment Design

Three candidate ceramic blade root attachment conceptual designs were discussed in Section 3.3 (Conceptual Component Design). These were the conventional "dovetail", the "pinned", and the "ceramic insert" design concepts. Preliminary analysis narrowed these candidates down to the "dovetail", and the "pinned" attachment configurations. Packaging of the "ceramic insert" configuration in the limited metallic disk rim geometry has eliminated this concept from further analysis in this phase of the program, but it may be revisited during the Phase II Detail Design.

Dovetail Root Attachment Design

The conventional "dovetail" attachment has been analyzed using 3-D FEA methods to determine the complete nature of the aerodynamic, centrifugal, and thermally induced loads on the blade and the root attachment as part of the Phase I - Preliminary Design, while blade airfoil vibratory analysis will be performed as part of the Phase II -Detail Analysis. Prior DOE funded ceramic engine programs have shown the vibratory blade stresses to be of reduced emphasis in the overall blade/attachment design as candidate ceramic materials and processes have significantly improved over the course of the last decade. The analysis for the candidate turbine blade configurations has made the following assumptions:

- Material NT154 silicon nitride
- Steady state operation
- Sensitivity of thermal conductivity (SN-252 vs NT154)

The airfoil and attachment regions of all candidate blades are subject to relatively benign resultant aerodynamic loads of less than 39 lb_f in the axial direction and less than 41 lb_f normal to the axial direction, while centrifugally induced loads due to disk rotation are higher by a factor of 100. The interface geometry through which these loads are reacted both in steady state (thermal equilibrium) and most importantly, transient relative thermal growth conditions, is of paramount importance in the probability of blade survival analysis. Thermally induced stresses are consistent in both blade configurations since the airfoil geometries are identical, with the only significant difference being the conduction heat transfer path through the attachments.

The analytically predicted blade stress distribution, which is in part a function of the aerodynamic loads, creates a resultant load of 56 lb_f which acts on the blade at an angle of 46° from the engine centerline axis. A maximum principal stress (MPS) of 42.8 MPa (6.2 ksi) is seen at the base of the blade leading edge with lower stresses in the attachment at the blade trailing edge region. The centrifugally-induced stress distribution has a MPS of 151.8 MPa (22 ksi) located in the necked down section of the attachment region. The compressive stress field in the 60° planar[2] contact region of the attachment surface has a magnitude of 18.6 MPa (2.7 ksi).

The tangential stresses in this interface region have been sufficient (in prior ceramic inserted blade engine programs) to degrade the surface of the ceramic material through the introduction of critical surface flaws which propagate to failure in the surrounding tensile stress field. A relatively soft metallic compliant layer has demonstrated varying degrees of success in this location through the redistribution of locally high tangential tensile stresses via plastic deformation in the compliant layer material. The useful life of the compliant layer material can be engineered by careful materials selection to accommodate a number of engine cycles in a specific operating temperature regime, and is therefore one of the stated goals of this program.

Figure 4-2 shows the analytically predicted temperature distribution in the blades as a result of the rotor inlet temperature profile illustrated in Figure 4-3. This profile represents the maximum (design average) radial temperatures based on a 0.2 combustor pattern factor. The resulting airfoil temperatures reflect the circumferential temperature mixing that occurs as each blade rotates through a complete revolution. The relatively low temperature 649°C (1200°F) attachment region results from the 704°C (1300°F) aerodynamic streamlines closest to the blade shroud which have been designed to aid in the task of stage 1 disk cooling at a TRIT of 1121°C (2050°F).

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[2] The planar stress field is the region through which the aerodynamic and centrifugal blade loads are reacted, and along which the relative thermal growth occurs between the metallic disk rim and the ceramic blade root. This is the region where contact stress must be addressed.

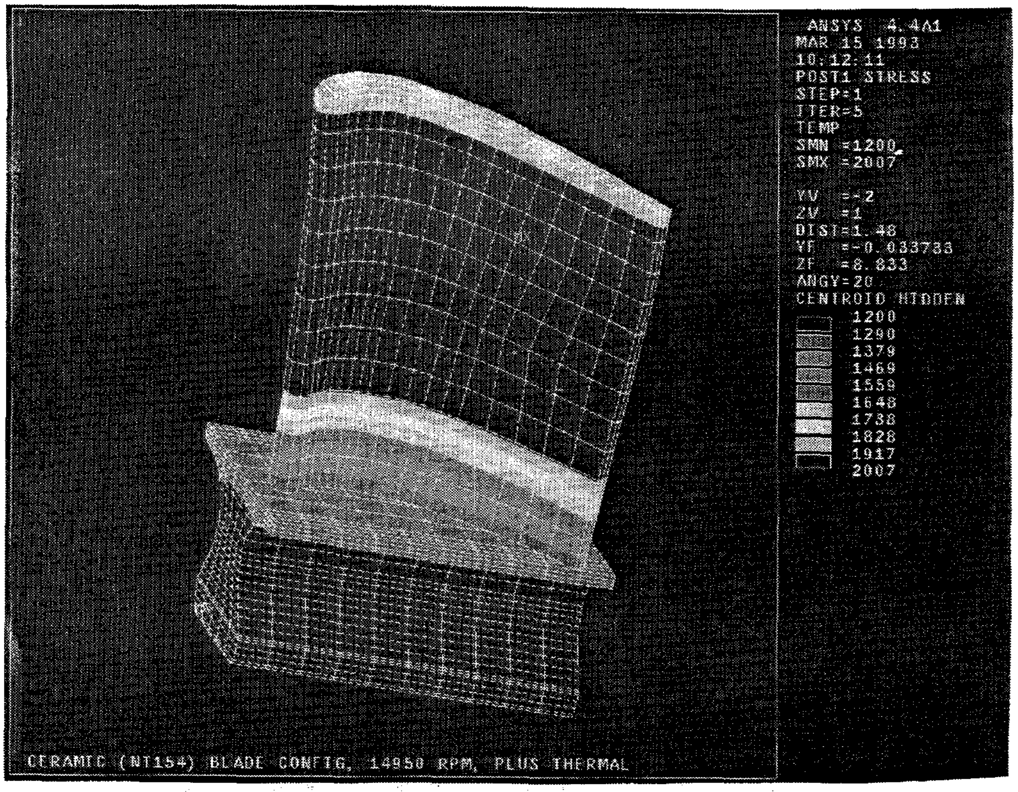

Figure 4-2. Analytically Predicted Temperature Distribution in "Dovetail" Blade

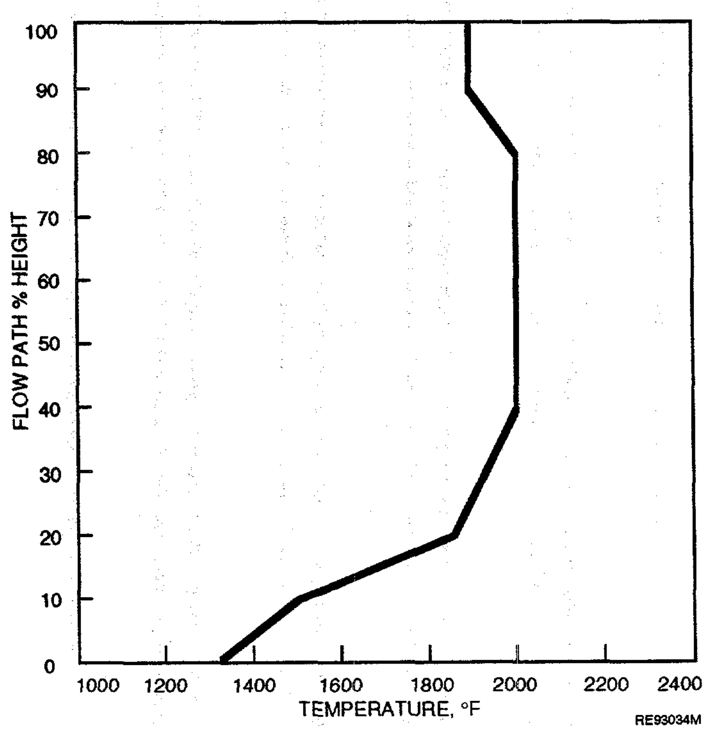

Figure 4-3. Stage 1 Rotor Inlet Temperature Profile Assumption

Figure 4-4 illustrates the combined stresses resulting from the aerodynamic, thermal, and centrifugally induced loads. The MPS of 176.6 MPa (25.6 ksi) is located in the necked down portion of the blade root primarily due to the predominant centrifugally induced (rotational) loads. An additional area of tensile stress on the order of 173 MPa (25 ksi) is seen in the trailing edge of the airfoil at a radial position of approximately 20% of the airfoil chord. The material temperature at this location is approximately 1093°C (2000°F) and is therefore an area of concern with regard to the Slow Crack Growth (SCG) life of the blade. This region of the airfoil will be modeled in greater detail during the Phase II detail design to determine how localized this stress is, and if there is a means of minimizing and/or shifting the location to a cooler portion of the airfoil where the deleterious effects of SCG would be mitigated.

"Pinned" Root Attachment Design

The "pinned" root attachment configuration utilizes a ceramic pin 8.9 mm (0.35") in diameter as a fastener to retain the ceramic blade in the metallic disk. This simplified approach to blade mounting reacts the centrifugal (CF) and aerodynamic blade loads through a (hertzian bearing load) ceramic/ceramic line contact interface. The material selected for the ceramic pin is a silicon nitride capable of reacting the blade loads while limiting the conductive heat flux into the metallic disk.

Figure 4-5 shows the temperature distribution in the blade in which the maximum material temperature is 1093°C (2000°F) over approximately 75% of the airfoil. The minimum material temperature is 649°C (1200°F) in the root area[3] which is based on nodal temperature assignment in this region for the preliminary analysis. The 2-D[4] combined stress model including aerodynamic and CF loads is shown in Figure 4-6. The MPS is located along the inside walls of the pin hole (90° to the load axis) at a magnitude of 227 MPa (33 ksi). The ceramic pin MPS is of the same order as the MPS of the pin hole in the blade. Additional stress reduction techniques will be investigated for the "pinned" root attachment as part of the Phase II detail design.

Blade Life Prediction

The CSGT Phase I "dovetail" blade design was analyzed using the SPSLIFE life assessment code developed at the Sundstrand Corporation. SPSLIFE is a Sundstrand proprietary, user-friendly, interactive computer program for the evaluation of ceramic turbine engine components. The program is used for materials selection, design optimization and life assessment. The program links structural analysis files and materials data files with life assessment modules for different life-limiting modes to provide quantitative estimates of component life and survival probability. Life assessment maps are produced depicting stress and temperature distributions for the components together with limit curves for fast fracture, slow crack growth, creep, and oxidation. Nodal points depicting stress temperature conditions at selected locations (nodes) are shown as dots. Surface and volume nodes are being distinguished. SPSLIFE output can be prepared either as color or black and white maps. The fast fracture survival probability predicted by the NASA CARES program[(3)] and the slow crack growth (static fatigue) survival probability predicted by the NASA CARES/LIFE program[(4)] are shown in the top right hand corner of the map.

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[3] The actual material temperature in the root attachment region will be adjusted after the instrumentation data has been reduced from the initial gasifier rig run. Actual heat transfer coefficients will be back-calculated from measured material temperatures for boundary condition verification.

[4] A 2-D model was used for the "pinned" root attachment to assist in the resolution of blade constraint issues associated with blade load reaction (line contact interface) in only one plane.

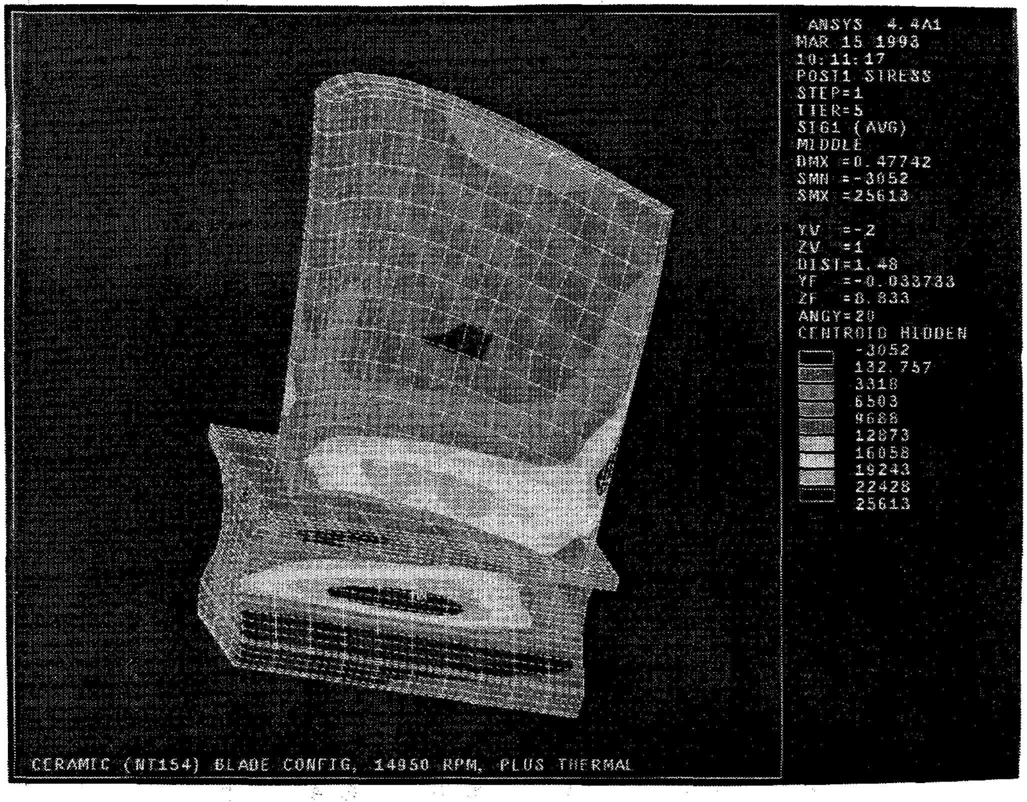


Figure 4-4. Analytically Predicted Aerodynamic, Thermal, and Centrifugally Induced Stresses in the "Dovetail" Blade

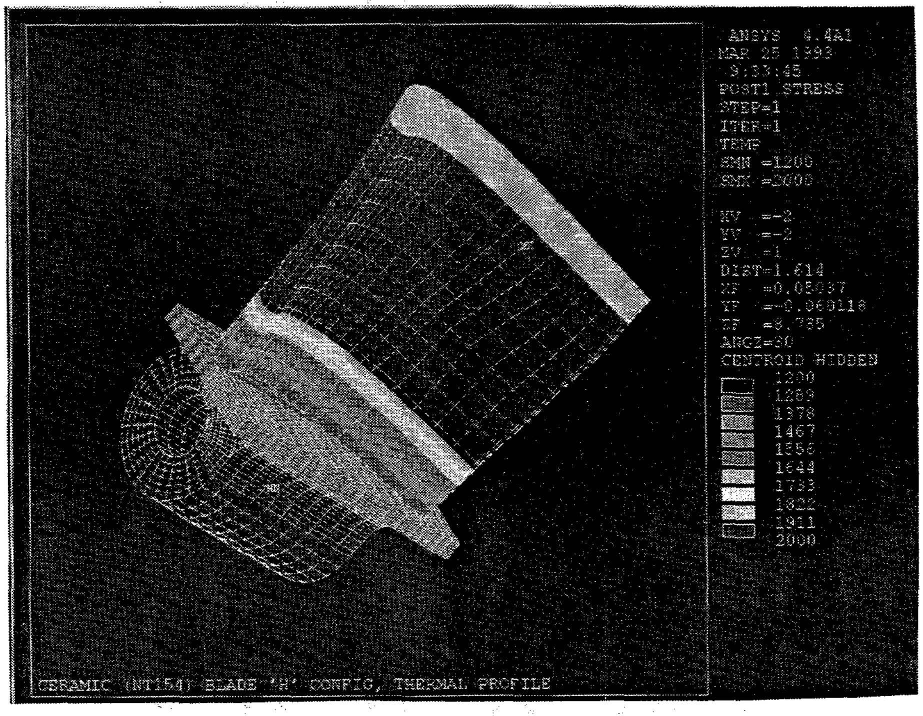


Figure 4-5. Analytically Predicted Temperature Distribution in "Pinned" Blade

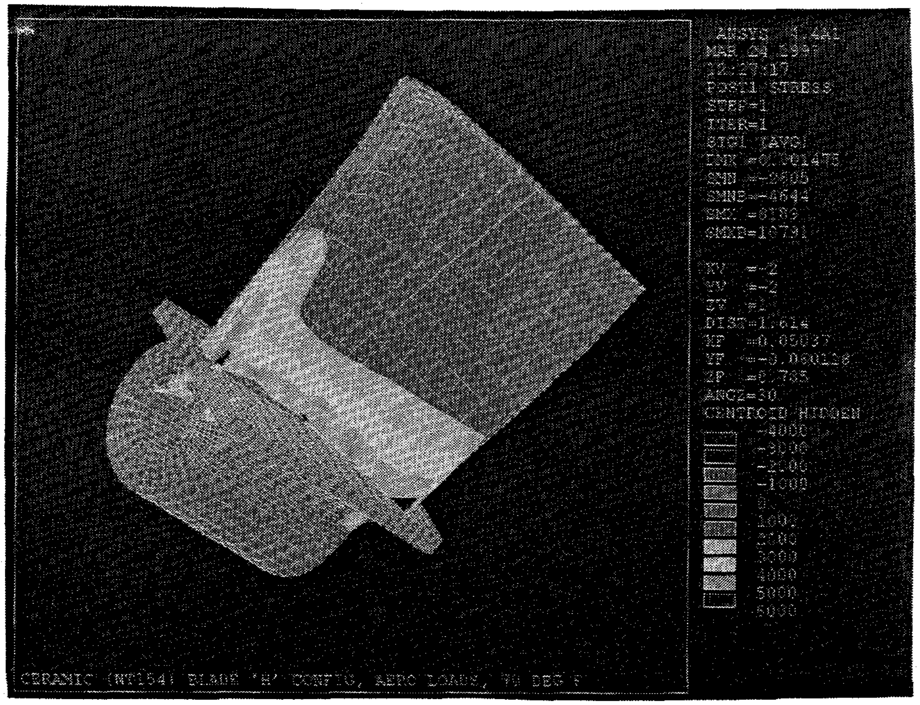


Figure 4-6. Aerodynamic and CF Loads on "Pinned" Blade (2-D Model)

The life assessment map for the "dovetail" blade is shown in Figure 4-7. The data is for a NT154 blade machined in the root attachment area which is common for a dovetail configuration while the remainder of the component is in the as-processed condition. The map was prepared based on the ANSYS finite element analysis output data files provided by Solar for SPSLIFE assessment. The map is plotted for a design life of 30,000 hours, and assumes that the blade is made of NT154 silicon nitride (Norton Advanced Ceramics). Based upon the ANSYS output files, the maximum surface stress is 172 MPa (25 ksi), and the maximum internal stress is 186 MPa (27 ksi). These results are for steady state operation with the blade temperatures ranging from approximately 649°C (1200°F) in the root area to slightly above 1093°C (2000°F) in the airfoil.

Creep Life

The life assessment map of Figure 4-7 shows the boundary for a 30,000 hour creep life. Since all the nodes are to the left of and below this line, the component is assessed to be safe in the creep mode. Creep life for the component is assessed to be greater than 1 x 10^9 hours. The creep life numbers are based on NIST creep data for NT154.

Oxidation Life

Also represented is the boundary for a 30,000 hour oxidation life. Since all the nodal points are to the left of and below this line, the component is assessed to be safe in the oxidation mode. Oxidation life for the component is assessed to be greater than 1 x 10^9 hours. However, it should be noted that the oxidation life numbers are based on NGK silicon nitride data as suitable oxidation data for NT154 was not available at the time of report preparation.

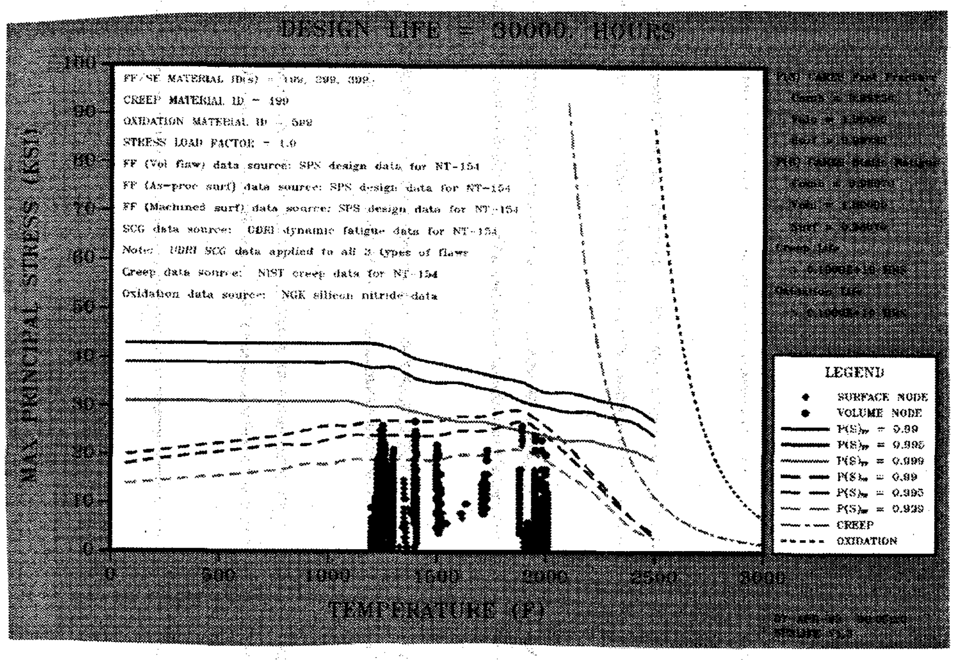


Figure 4-7. CSGT Dovetail Blade Life Assessment Map

Fast Fracture Survival Probabilities

The solid continuous lines correspond to SPSLIFE cumulative fast fracture survival probabilities of 99.0%, 99.5% and 99.9%, respectively, for each blade. The SPSLIFE estimate for the fast fracture survival probability of each blade is 99.8%. The fast fracture survival probability predicted by the NASA CARES program for each blade is 99.73%. It is recommended that the NASA CARES results be used for quantitative work. A conservative value of 0.8 was used for the Shetty constant in the CARES analysis.

Slow Crack Growth Survival Probabilities

The dashed lines correspond to SPSLIFE cumulative slow crack growth survival probabilities of 99.0%, 99.5% and 99.9% respectively for each blade. The SPSLIFE estimate for the slow crack growth survival probability is 99.0%. The slow crack growth survival (static fatigue) probability predicted by the NASA CARES/LIFE program for each blade is 98.07%. It is recommended that the NASA CARES results be used for quantitative work. Note that for both SPSLIFE and CARES analyses, the assumption was made that the UDRI (University of Dayton) slow crack growth parameters obtained with MOR bars also apply to internal flaws. It is also assumed that the slow crack growth parameters are the same for cracks initiating at machined and at as-process surfaces. The eventual effect of engine environment on slow crack growth parameters is not represented by the materials data.

CSGT Fully Machined Dovetail Blade Life Assessment Map

Figure 4-8 represents a "What-If" analysis showing the effect of fully machining the dovetail blade. This run assumes that all as-processed surfaces from the blade of Figure 4-7 have been machined to obtain typical "as-machined" properties. The run represents the upper bound survival probabilities achievable for abrasive flow machining. SPSLIFE survival probabilities for each blade are greater than 99.99% in fast fracture and in slow crack growth. The CARES survival probability increases to 100% in fast fracture and to 99.99% in slow crack growth.

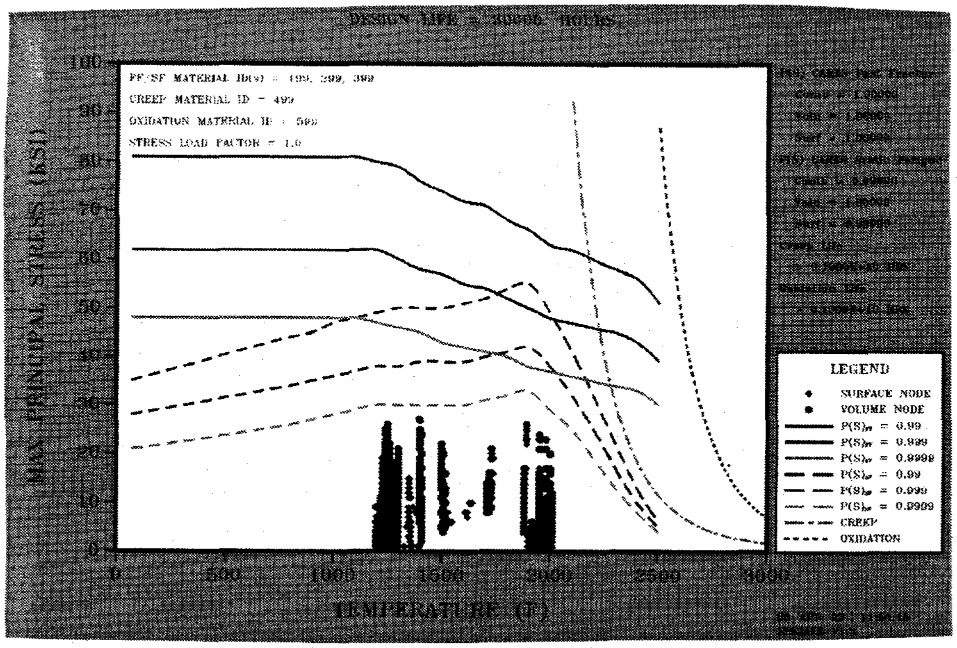


Figure 4-8. CSGT Fully Machined Dovetail Blade

The improvement of the probability of survival in Figure 4-8 compared to Figure 4-7 is attributed to the increase in strength of the as-processed areas of the blade following machining.

<u>Supplier Review of Blade Designs</u>

As part of the Task 2 work the candidate suppliers were requested to comment on the design of the component for which they had been selected. In this section the comments of the candidate suppliers for blade fabrication, AlliedSignal Ceramic Components (CC), Norton Advanced Ceramics (NAC), and Kyocera Industrial Ceramics Corporation (KICC) have been compiled.

AlliedSignal Ceramic Components

AlliedSignal Ceramic Components addressed the datuming procedure, machining parameters, edge configuration, the beneficial effect of surface layer removal on component life under the prevailing stresses, and cost of fabrication. The CC blade material is GN-10 silicon nitride. The component will be fabricated by pre-sinter machining of slip cast stock material followed by HIP densification. The blade root will be machined for the "dovetail" configuration. The external and hole surface and the retaining pin will be machined for the "pinned" attachment design.

<u>Datuming Structure</u>

CC has experience with fabricating blade components with the dovetail configuration. These components were fabricated using a process very different from the process proposed for this project. To accurately machine and inspect the dovetail root, a well designed datum structure must be employed. CC had recommended a datum structure in which the blade layout be based on the leading and trailing edge rather than on the blade contour. This will facilitate locating the blade so that the dovetail attachment location can be easily determined.

Contour and Edge Machining

One of CC's concerns was the effect of uneven tool wear during machining of the dovetail configuration. Accurate machining can be accomplished by frequently truing up the grinding wheel. CC recommended the use of a continuous arc rather than a radius transitioning from 0.60 inch to 0.75 inch as proposed by Solar. The latter radius would be difficult to machine because of differential tool wear occurring during CNC machining. For production quantities, this could be avoided by creep feed grinding with a form wheel. However, for smaller quantities, creep feed grinding would not be cost effective. The continuous arc radius provides a solution in this respect.

The type of radius break that Solar would require for the edge where the contoured shape intersects with the front face, Figure 4-9, will significantly impact the cost of the dovetail design. If an edge break of 0.003"/0.005" was required, an inexpensive procedure could be used to generate that type of break. However, if an edge break of > 0.050" was required, then the edge would have to be CNC machined. This requirement would cost at least four times as much as the aforementioned break. Similar comments were made by CC for the "pinned" blade design (Figure 4-10) although the cost impact here will not be as great as in the "dovetail" design, but the cost factor will still be between three to four times as much as for the aforementioned break.

Hole Machining

From a machining point of view, the "pinned" root design is much simpler to machine than the dovetail design. The critical factors in this design are the hole's length-to diameter ratio, hole tolerances and the datum structure associated with the hole's position. In order to be able to machine the hole, the ratio of the hole's length-to-diameter must be less than or equal to 5. For the current design, the ratio is less than 3; therefore, the L:D ratio is not a concern.

Solar has indicated that they would require a true position call out of 0.002" to 0.003" on the hole. CC expressed that a call out of 0.010" could be achieved if the hole position was directly related to an as-processed surface datum. However, if the hole position was related via a datum structure to a fully machined surface, then a call out of 0.002" could be achieved. This type of reference structure would also greatly enhance machining/inspection reproducibility and repeatability.

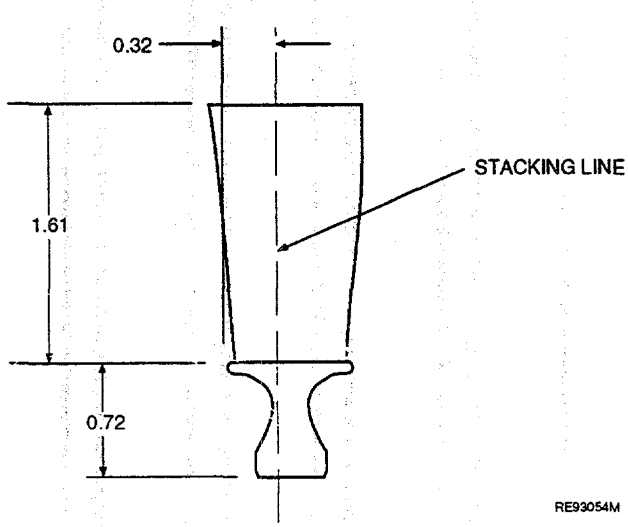


Figure 4-9. "Dovetail" Blade Attachment

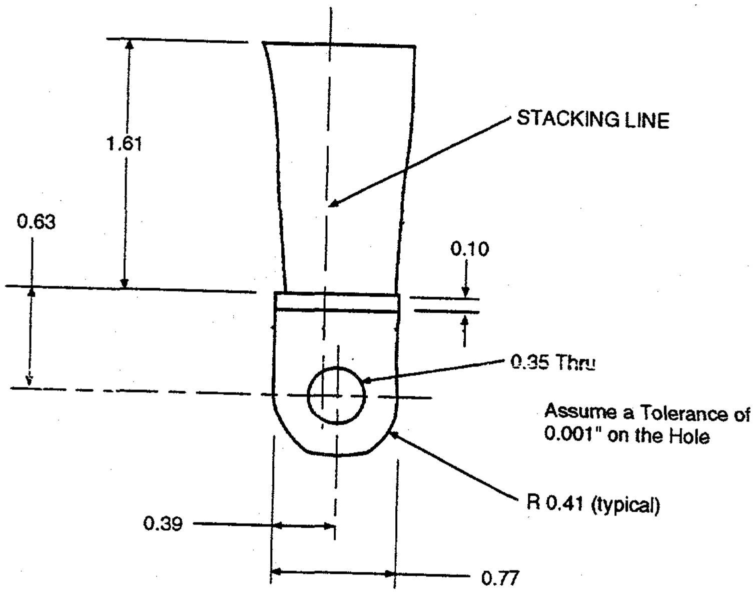


Figure 4-10. "Pinned" Blade Attachment

Component Stress Levels

The steady state stresses in the root section of the "dovetail" design are estimated at ≈ 180 Mpa (26 ksi) at temperatures between about 649°C and 760°C (1200°F and 1400°F). Fully machined GN-10 will perform very well under these conditions. Steady state stresses in the blade airfoil are estimated at 187 Mpa (27 ksi) at temperatures around 1093°C (2000°F). The data on as-processed GN-10 surfaces indicates that if the blade surfaces were left as-processed, that is to say that they were formed net-shaped after densification, the material should be marginal for this application. Adding a machining step to remove the as-processed layer will have to be evaluated and will increase cost and reduce dimensional control. The benefits of removing the layer are that the blade surface now has bulk properties resulting in a greater safety factor.

The steady state stresses in the "pinned" root design are estimated at 228 Mpa (33 ksi) at 649°C (1200°F). MIL-STD-1942(MR)(B) flexural stress rupture data for fully machined GN-10 indicates that this material would be able to meet the performance criteria under these stress conditions, but redesigning of the configuration is recommended so that steady state stresses are comparable to those of the dovetail configuration.

Cost

CC estimated that rough order of magnitude (ROM) prices for the "pinned" configuration would be 160% of the "dovetail" configuration for production quantities. Prototypes would cost 120% more. The relative cost increase is attributed to the hole in the root section. The wheels necessary to create the root section would wear rapidly, remove stock slowly and might introduce dimensional variances during machining. A hole tolerance of 0.001" was assumed and datuming to an as-processed surface. Cost could be reduced to the level of that of the "dovetail" if the hole was datumed to machined surfaces.

Kyocera Industrial Ceramics Corporation

KICC supplied comments on machining, preferred edge shapes, component stress levels, and cost of fabrication. KICC will fabricate the blade component from its SN-253 silicon nitride material using its Hybrid Molding Process. The forming process is a semi-automatic net, and near-net shape forming process used to fabricate many developmental gas turbine parts as well as production quantities of ceramic turbocharger rotors for automotive application. Forming will be followed by sintering, final machining, and heat treatment.

<u>Contour and Edge Machining</u>

KICC recommended chamfers as the preferred approach for the platform edges. Chamfers can also be hand finished to remove edges. The possibility of a conflict between the fillet radius and platform edge radius could exist at the point where the platform meets the leading and trailing edge of the airfoil. This conflict would only occur if the leading or trailing edge is located at a distance less than the sum of the fillet and edge radii.

<u>Dovetail and Hole Machining</u>

The two contact surfaces at the neck of the "dovetail" will be machined with a formed grinding wheel. The two surfaces are machined in separate set-ups. Maintaining positional tolerance is considered one of the manufacturing challenges. The hole in the "pinned" root will be green machined and final machined after densification. Making an oval hole is considered eight times more difficult than a round hole. Hole final grinding is performed in one set-up, and positioning issues are not the same as for the "dovetail" design. However, the hole requires an additional green machining step.

<u>Component Stress Levels</u>

High stressed areas in the attachment were identified as an area of concern. Surface finish alone is not believed to be sufficient to achieve maximum strength. Areas where maximum strength is required should be noted on the print. Appropriate processing can then be utilized to achieve the desired surface finish and strength.

<u>Cost</u>

Although not as technically difficult KICC estimated that the cost of the "pinned" design would be approximately 5 to 10% higher than that of the dovetail, the additional cost being due to the additional green machining step.

Norton Advanced Ceramics

NAC's comments addressed forming, machining, dimensional control, and cost factors. NAC will use the pressure casting process to fabricate the blade from its NT164 silicon nitride.

<u>Forming</u>

Using current pressure casting technology, NAC believes that all candidate blade designs can be formed at high yields regardless of attachment area geometry. On a relative basis, NAC believes the casting yields for the "dovetail" will be highest (> 80%) and lowest (~ 60%) for the "pinned" root configuration due to the hole in the attachment area. The complexity of the casting tool necessary to cast this hole near net shape is expected to result in lower yields.

Machining

In the opinion of the machining vendors, the "dovetail" design will be easiest to fabricate and the "pinned" root attachment will be the most difficult solely due to the hole. Given a constant hole diameter tolerance, increasing the depth will increase the difficulty of machining as a small diameter diamond wheel would have to be mounted on an increasingly longer and smaller diameter drive spindle, making uniform hole tolerancing more difficult.

Dimensional Control

NAC plans to net shape form the blade surfaces and fully machine the attachment areas. Tolerancing experience on smaller ceramic components has been successfully demonstrated for other NAC customers. NAC's process is currently capable of meeting these tolerances with minimal rejection.

Cost

NAC indicated that relative machining cost for the "pinned" attachment compared to the "dovetail" would be 25-42% more depending on lot size for prototype quantities of components. The relative cost of production quantities of each of the two designs was not supplied.

4.4 NOZZLE PRELIMINARY DESIGN

Prior to committing this revised geometry model to analysis, a revised set of boundary condition estimates were completed based on the secondary (metallic) component analysis discussed in Section 4.6 (Secondary Component Preliminary Design). This analysis indicated that in order to achieve acceptable stage 1 and 2 metallic disk rim temperatures the combustor discharge radial temperature profile had to be modified from the previously scaled up Centaur 50 profile to provide an inner nozzle shroud streamline gas temperature of approximately 788°C (1450°F). In addition, since the stage 1 turbine tip shoe was added to the existing metallic nozzle support housing, the maximum temperature allowable on the outer shroud was 954°C (1750°F). This thermal boundary condition scenario was imposed on the new ceramic nozzle model along with the following assumptions:

- Combustor "worst case circumferential" radial temperature profile for the ceramic SoLoNOx combustor operating at an average TRIT of 1121°C (2050°F) with a 0.2 pattern factor
- Heat transfer coefficient on outer shroud O.D. reduced (on a first estimate basis) to "0" (assumes an insulated outer shroud wall)
- Material: Hexoloy® SA (SiC) - selected nozzle material
- Material: NT164 (Si_3N_4) - selected nozzle material

The combustor radial temperature profiles are shown in Figure 4-11. The three profiles represent the average, maximum and minimum circumferential temperature distributions, respectively, of the exiting combustor air experienced by the nozzles. The worst case temperature distribution ("hot spot" profile) is represented by the maximum radial profile. In the engine typically two or three out of a total of 30 nozzles are expected to be subjected to this temperature gradient associated with the "hot spot" profile while the vast majority of the nozzles (about 90%) experience a profile close to the "average". The flat portion of this maximum profile which constitutes approximately 50% of the nozzle throat area is operating at a gas temperature of 1297°C (2366°F) which is calculated in accordance with a 0.2 pattern factor via the relationship:

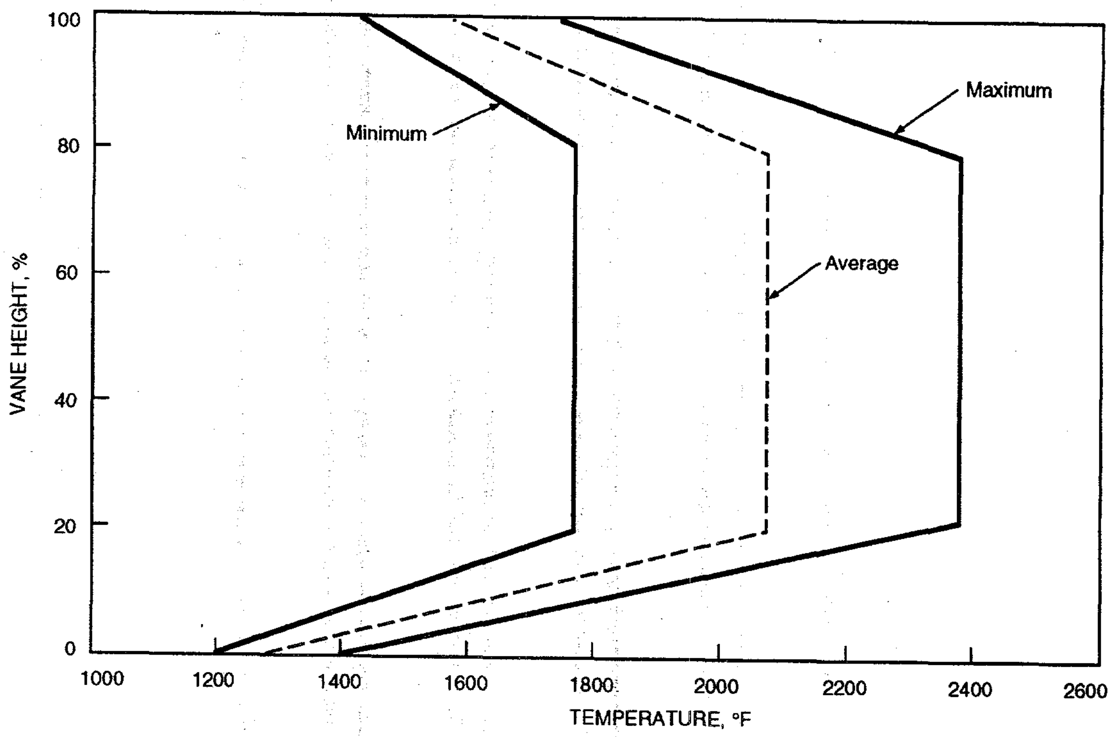


Figure 4-11. "Revised" Combustor Discharge Radial Temperature Profile

$$\textit{Pattern Factor} = 0.2 = \frac{T_{max} - T_{avg}}{T_{avg} - T_{inlet}}$$

Where: T_{max} is unknown
T_{avg} = 1138°C (2080°F)
T_{inlet} = 347°C (657°F)

The hot gas streamlines adjacent to the outer shroud wall have a maximum (downstream metallic component) temperature limit (based on secondary component analysis) of approximately 954°C (1750°F), but the latter temperature can potentially be as low as 816°C (1500°F) along a portion (15° arc length) of the outer shroud circumference under normal combustor operation. The inner shroud wall streamlines have a maximum temperature limit of approximately 788°C (1450°F) due to the stage 1 and 2 metallic disk rim temperature requirements based on secondary component analysis. Since the CSGT engine does not incorporate cooled stage 1 blades, in addition to the relatively cool inner shroud gas path streamline, the stage 1 disk requires a material change from V-57 to Waspalloy[5] or U-720.

The nozzle temperature distribution maps, based on the maximum ("hot spot") temperature profile presented in Figure 4-11, are shown in Figures 4-12 and 4-13 for Hexoloy®SA SiC and NT 154 Si_3N_4, respectively. Maximum and minimum temperatures have been tabulated in Table 4-2. The nozzle temperature distribution maps for SiC and Si_3N_4 for the "average[6]" temperature profile are shown in Figures 4-14 and 4-15, respectively. The maximum and minimum material temperatures for this portion of the circumferential profile are also tabulated in Table 4-2.

[5] Higher temperature disk materials (ie: Waspaloy, Inconel 718) are currently used in the production Solar Mars engines.

[6] The "revised average" temperature profile affects 90% of the nozzle segments (approximately 27 of the 30 nozzle segments).

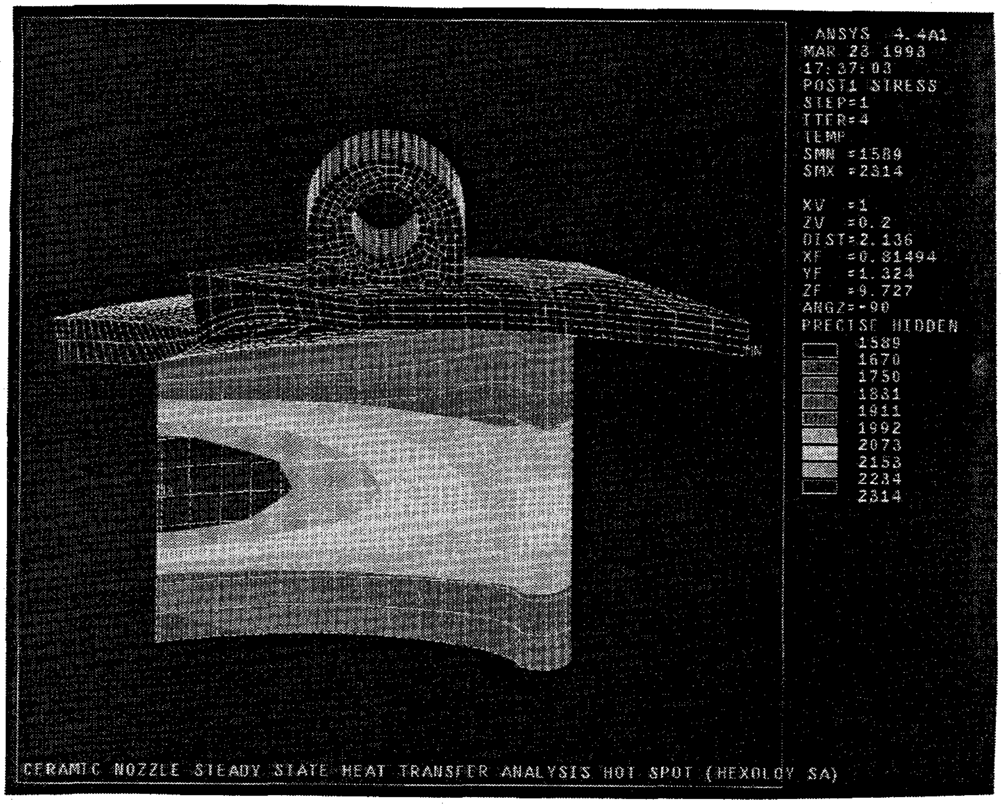


Figure 4-12. Analytically Predicted Temperature Distribution in SiC Nozzle - "Hot Spot" Radial Profile

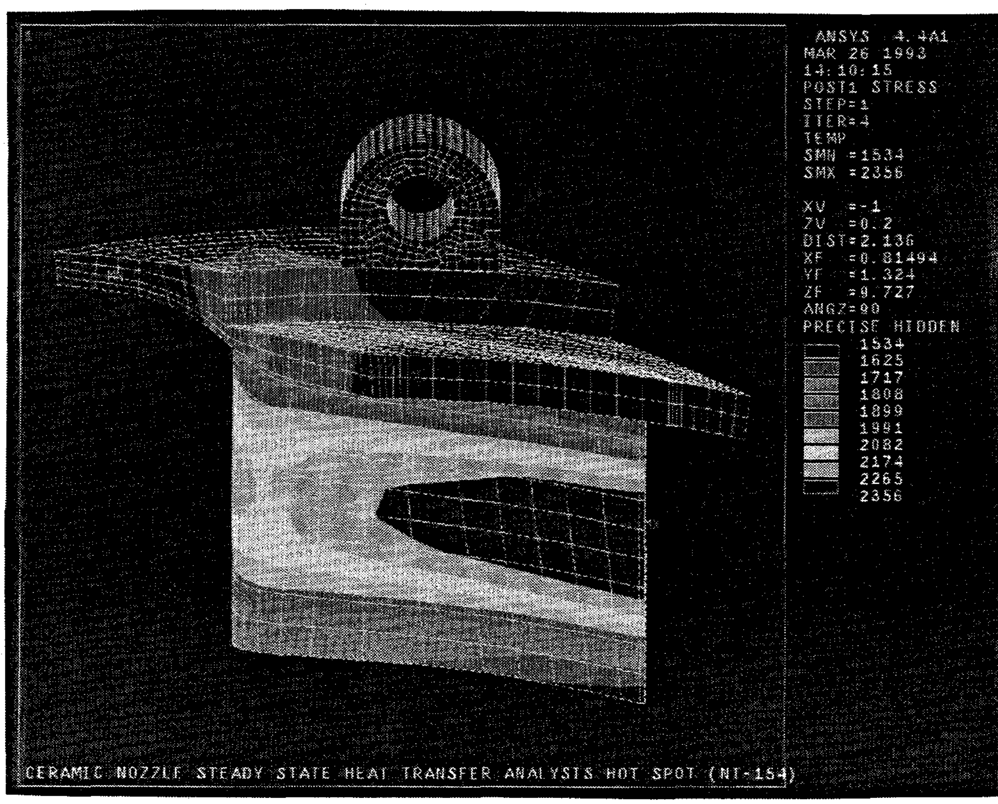


Figure 4-13. Analytically Predicted Temperature Distribution Si_3N_4 Nozzle - "Hot Spot" Radial Profile

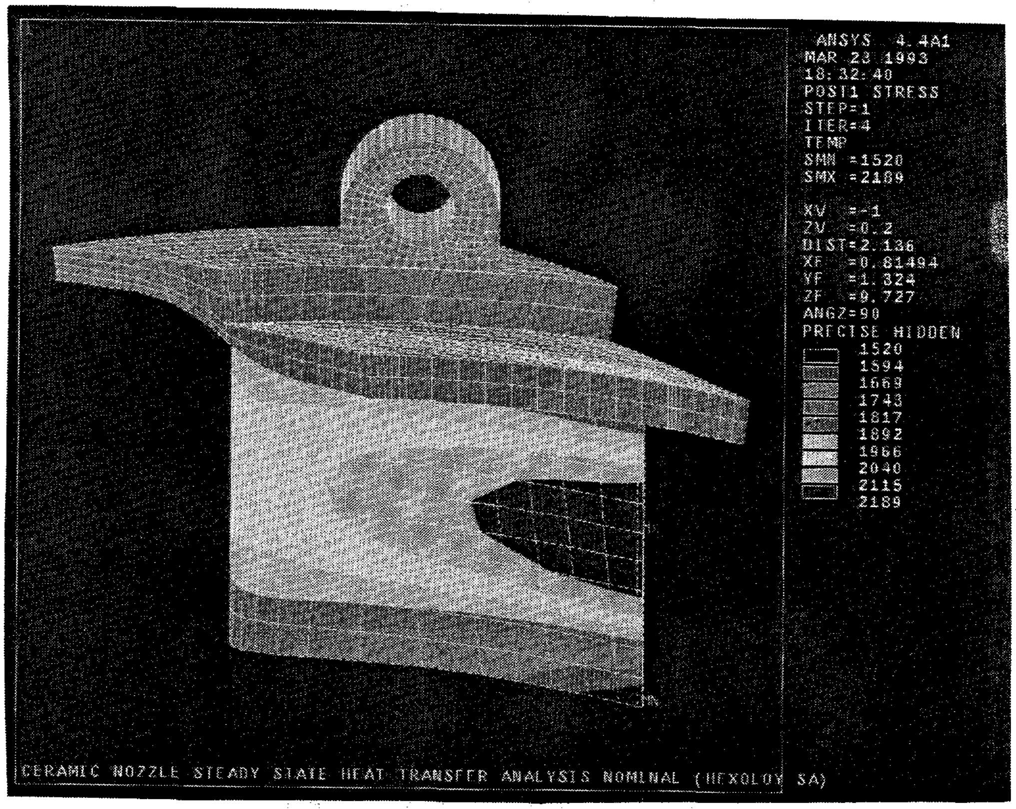


Figure 4-14. Analytically Predicted Temperature Distribution in SiC Nozzle - "Average" Radial Profile

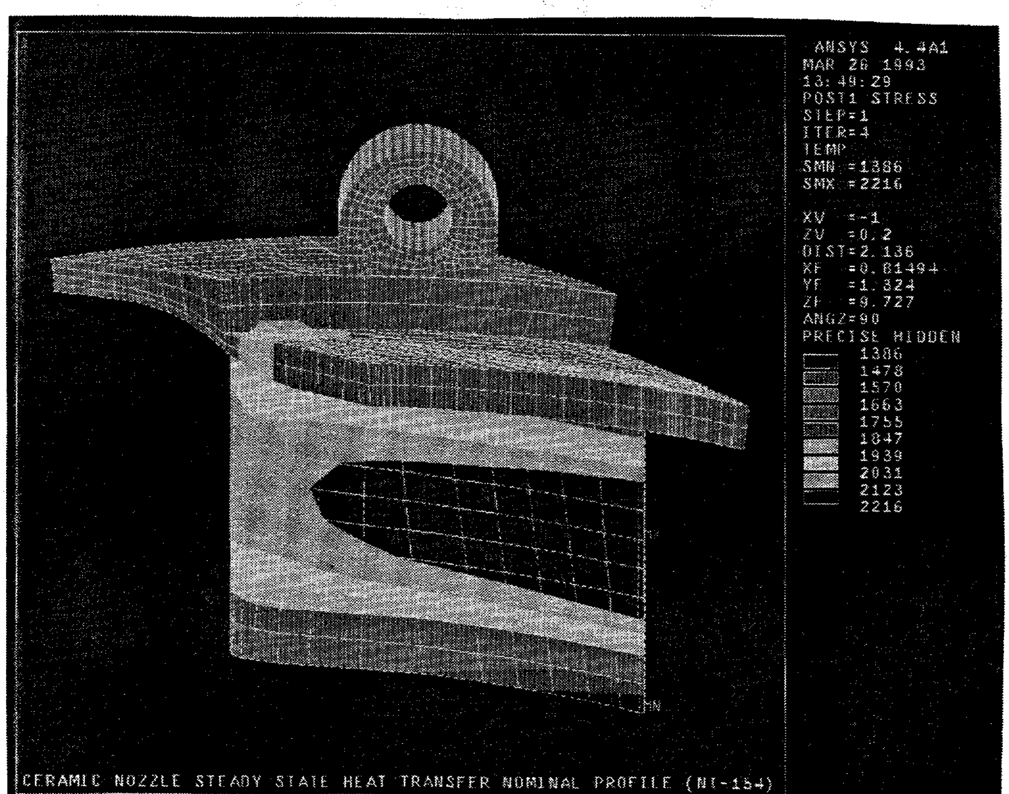


Figure 4-15. Analytically Predicted Temperature Distribution in Si_3N_4 Nozzle - "Average" Radial Profile

Table 4-2. Nozzle Temperature and MPS versus Material, Revised Radial Profile and Geometry
(n/a: not analyzed)

Geometry	Profile	Material	T_{max} °C(°F)	T_{min} °C(°F)	MPS MPa (ksi)	1st CB* MPS MPa (ksi)	2nd CB* MPS MPa (ksi)
1 Shroud	"Hot Spot"	Hexoloy® SA SiC	1268 (2314)	865 (1589)	276 (40)	241 (35)	220 (32)
1 Shroud	"Hot Spot"	NT154 Si_3N_4	1291 (2356)	834 (1534)	262 (38)	n/a	241 (35)
1 Shroud	"Average"	Hexoloy® SA SiC	1198 (2189)	827 (1520)	207 (30)	n/a	172 (25)
1 Shroud	"Average"	NT154 Si_3N_4	1213 (2216)	752 (1386)	193 (28)	n/a	186 (27)
2 Shrouds	"Hot Spot"	Hexoloy® SA SiC	1267 (2313)	864 (1587)	482 (70)	n/a	n/a

* CB: Cut Back

A ≈50% increase in the radial thermal gradient on the nozzle has resulted from the revision of the combustor radial temperature profile from the scaled up Centaur 50 profile described in Section 3.3 (CONCEPTUAL COMPONENT DESIGN) because of the secondary component inner and outer flowpath streamline cooling requirements. The increased gradient (which has shifted inward towards the airfoil midspan) is acting on both the airfoil and the inner and outer shrouds. The maximum principal stress (MPS) which occurs in the airfoil trailing edge (TE) is driven by elements of both the radial gradient in the airfoil, and the added increase in section modulus and heat sink affected by each shroud.

The nozzle stresses are tabulated with the temperatures in Table 4-2. Figures 4-16 and 4-17 show the stress distribution in the SiC and Si_3N_4 nozzle respectively resulting from the revised radial profile under "hot spot" conditions. The MPS is localized at approximately midspan on the airfoil TE of the SiC and Si_3N_4 nozzles. Figures 4-18 and 4-19 show the stress distributions in the SiC and Si_3N_4 nozzle, respectively, resulting from the "average" temperature profile. Again, the nozzles subject to the "average" radial profile constitute an estimated 90% of the nozzle segments (~ 27 nozzle segments).

Figures 4-20 and 4-21 show the temperature and stress distributions, respectively in a SiC nozzle model modified to include both shrouds. The maximum and minimum temperatures are within a few degrees of the decoupled case discussed earlier, while the MPS has increased by about 75% compared to the decoupled case. This analysis clearly indicates the advantage of a decoupled shroud for the SiC nozzle configuration and the trend parallels the results of the nozzle FE analysis given previously (Section 3.5, PARAMETRIC STRESS STUDY) which used the scaled up Centaur 50 radial temperature profile.

In a preliminary attempt to reduce the MPS in the nozzles subjected to the "worst case" temperature profile, the technique of "cutting back the trailing edge" was modeled by removing 1 (1^{st} iteration) then 2 (2^{nd} iteration) rows of elements from the airfoil FEM trailing edge (TE) to simulate a full radius TE cutback. Figures 4-22 and 4-23 illustrate the reduction in the nozzle MPS in the SiC nozzle segments due to the two TE cutback iterations, and Figure 4-24 illustrates the 2^{nd} iteration cutback in the Si_3N_4 nozzle segment. The stresses from the cutback TE analyses are included in Table 4-2.

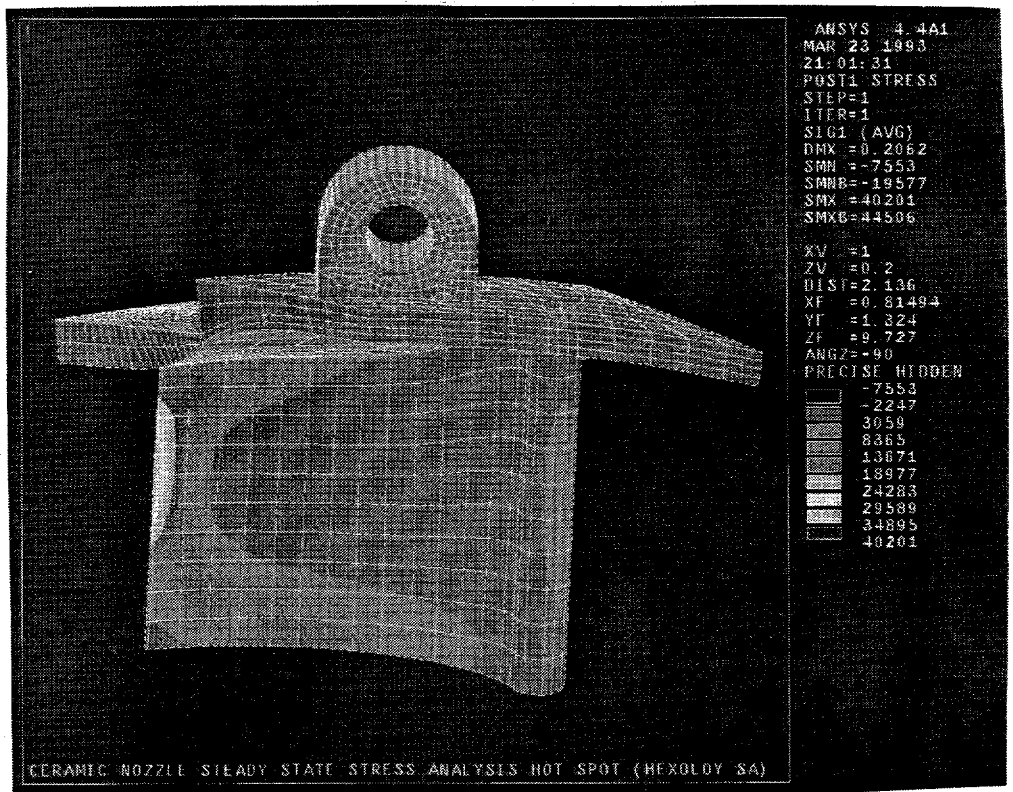


Figure 4-16. Analytically Predicted Stress Distribution in SiC Nozzle - "Hot Spot" Radial Profile

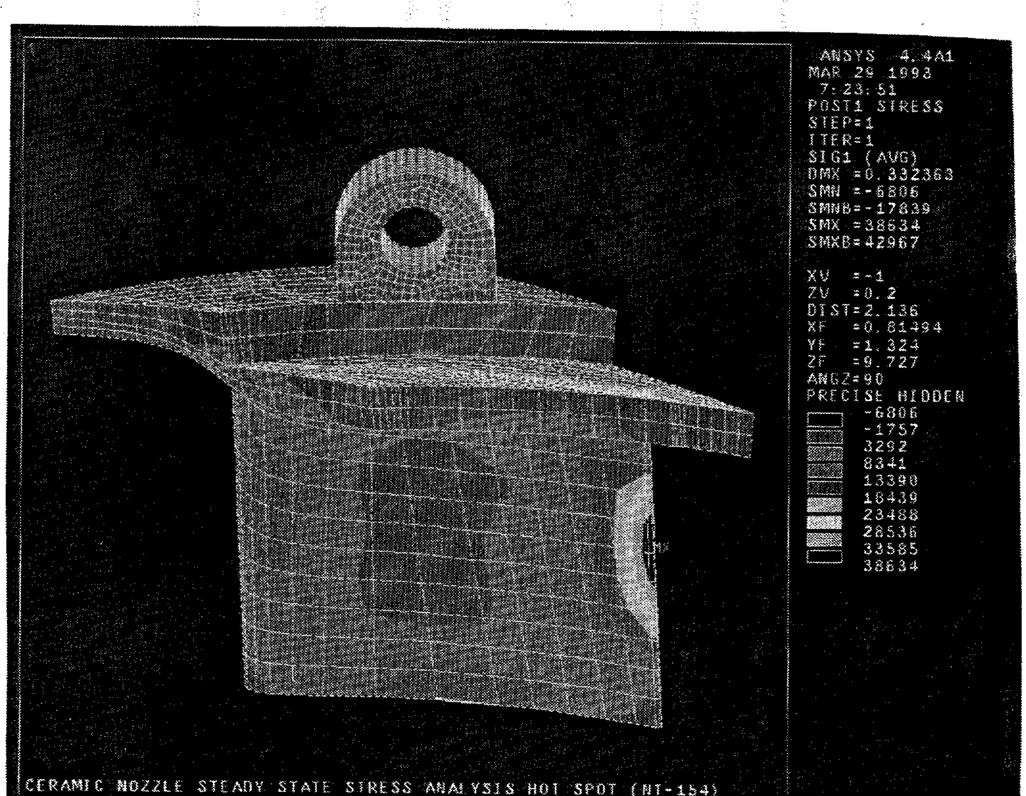


Figure 4-17. Analytically Predicted Stress Distribution in Si_3N_4 Nozzle - "Hot Spot" Radial Profile

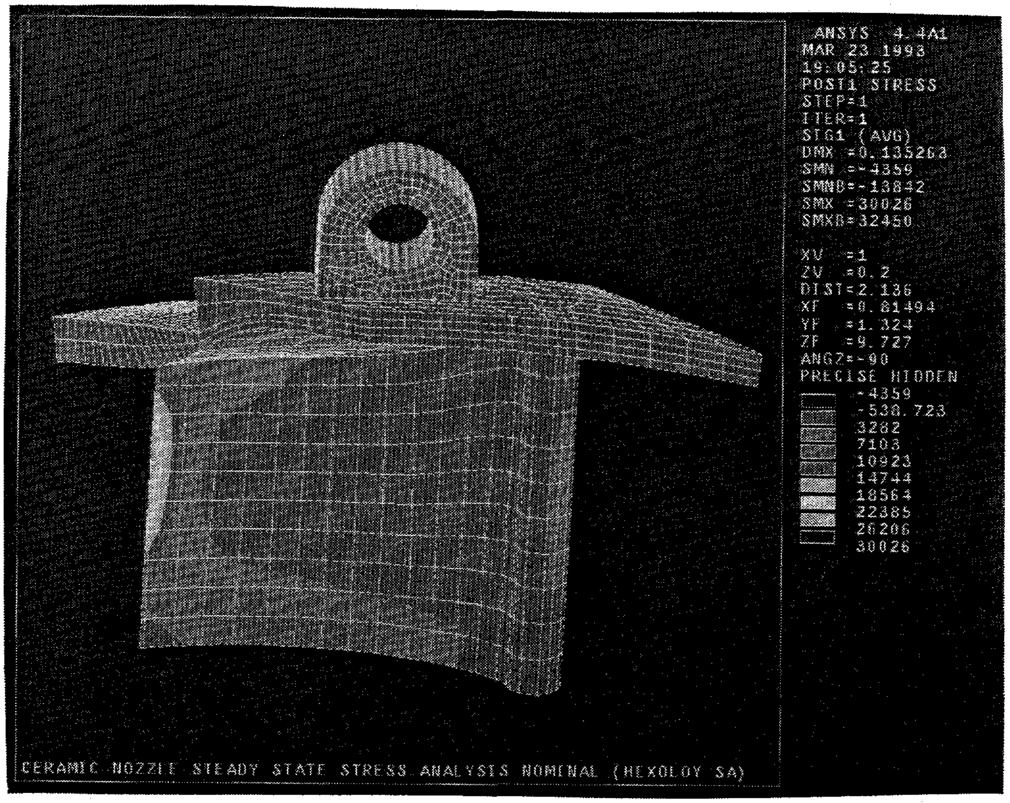


Figure 4-18. Analytically Predicted Stress Distribution in SiC Nozzle - "Average" Radial Profile

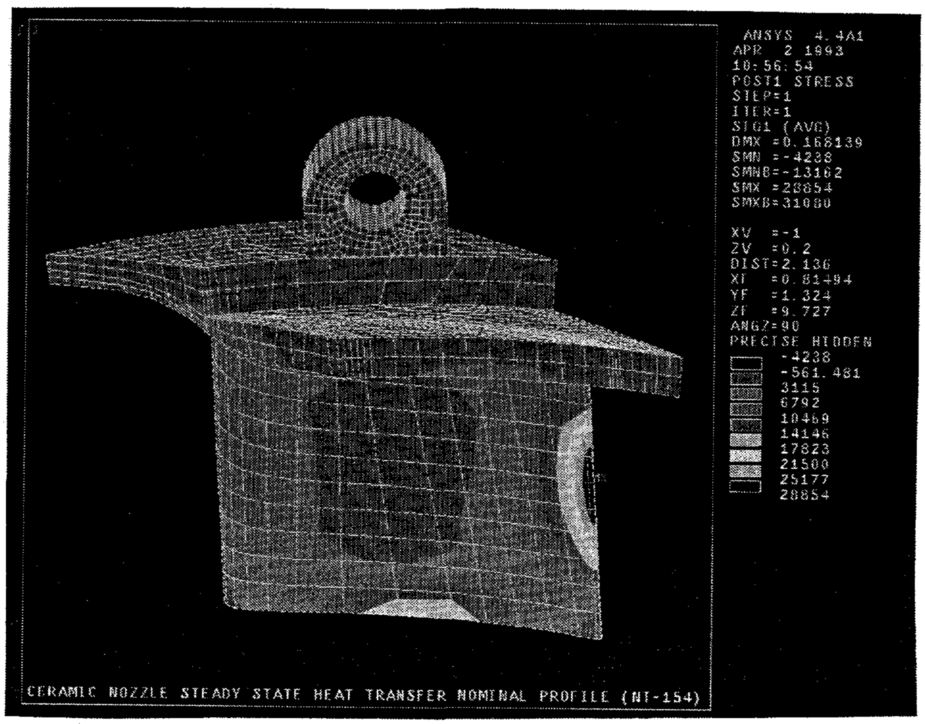


Figure 4-19. Analytically Predicted Stress Distribution in Si_3N_4 Nozzle - "Average" Radial Profile

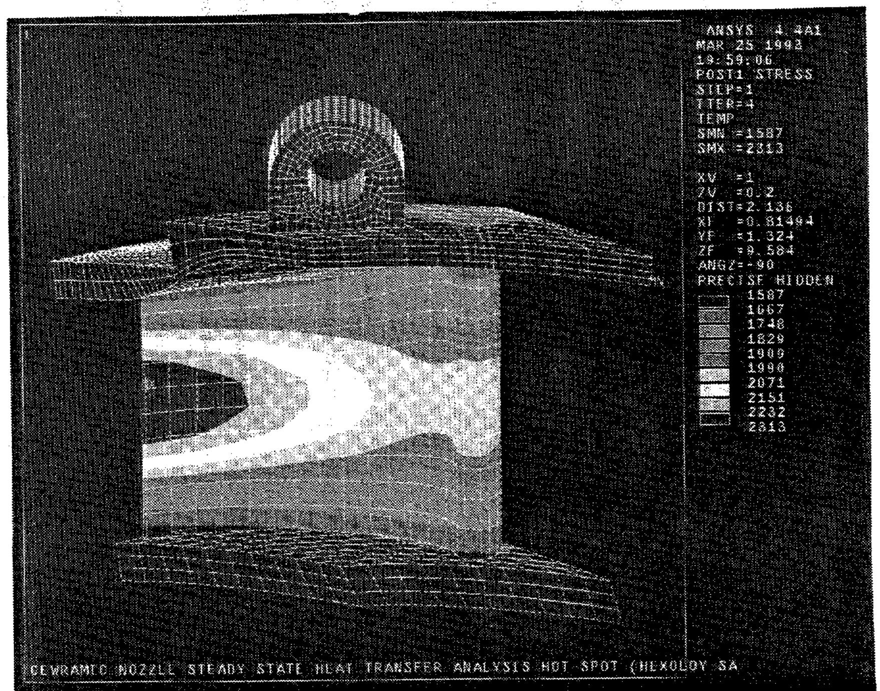


Figure 4-20. Analytically Predicted Temperature Distribution in 2-Shroud Integral SiC Nozzle - "Hot Spot" Radial Profile

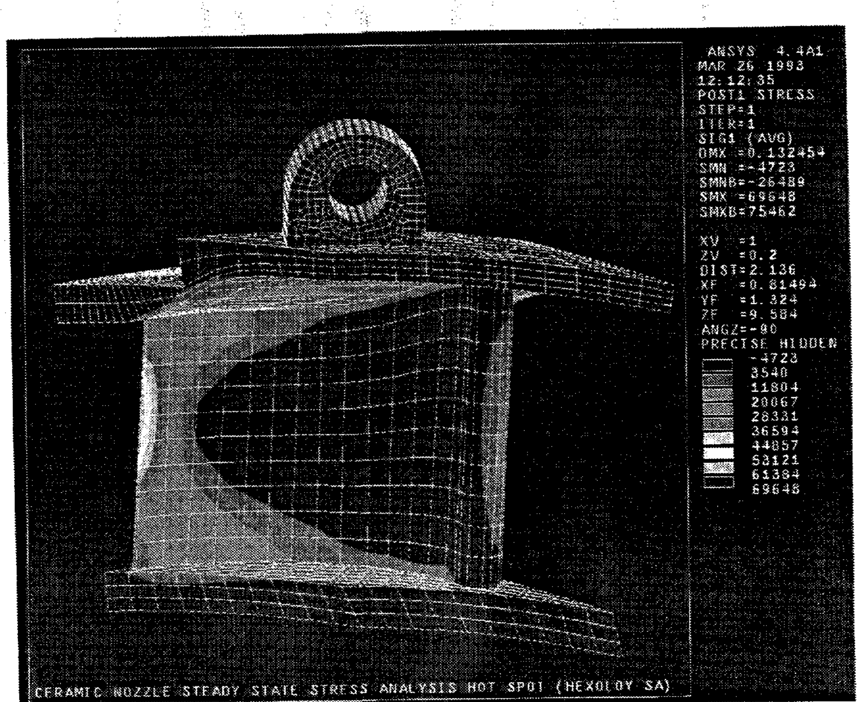


Figure 4-21. Analytically Predicted Stress Distribution in 2-Shroud Integral SiC Nozzle - "Hot Spot" Radial Profile

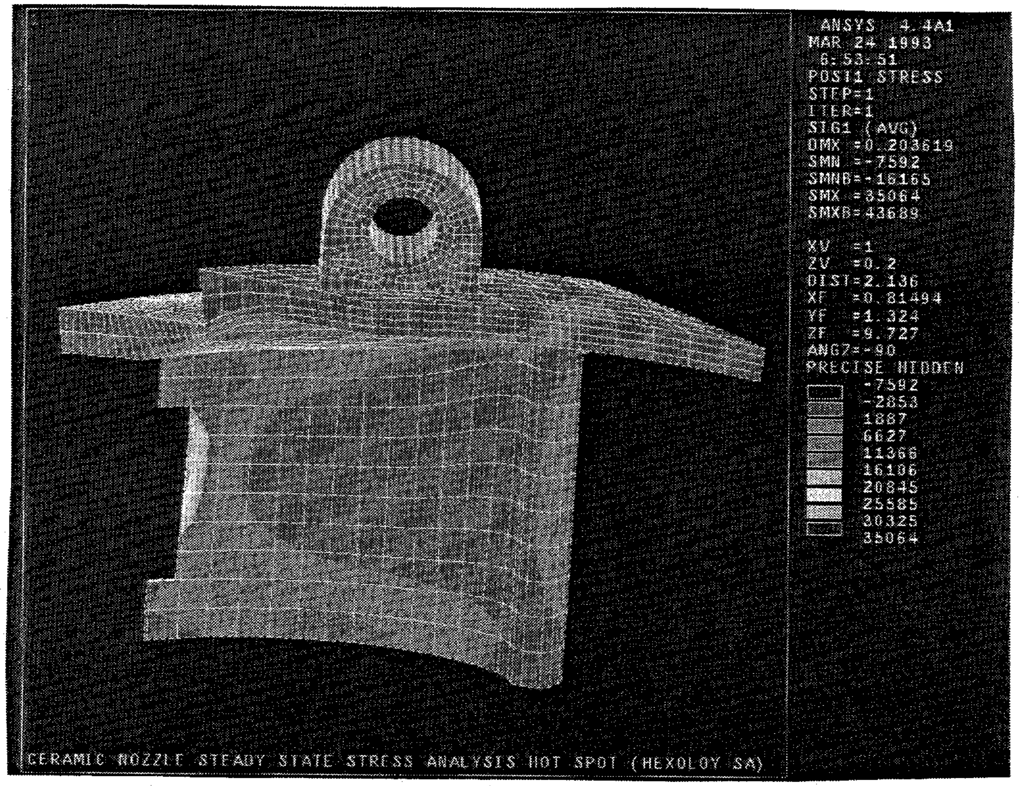


Figure 4-22. Analytically Predicted Stress Distribution in SiC Nozzle - "Hot Spot" Radial Profile; 1st Iteration TE Cutback

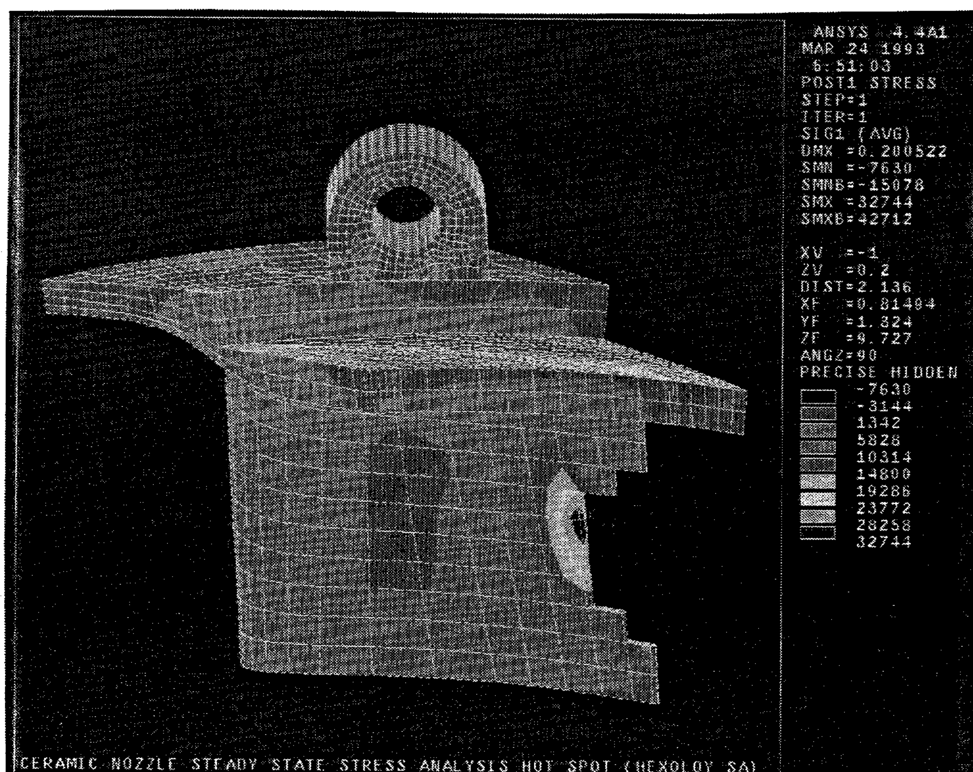


Figure 4-23. Analytically Predicted Stress Distribution in SiC Nozzle - "Hot Spot" Radial Profile; 2nd Iteration TE Cutback

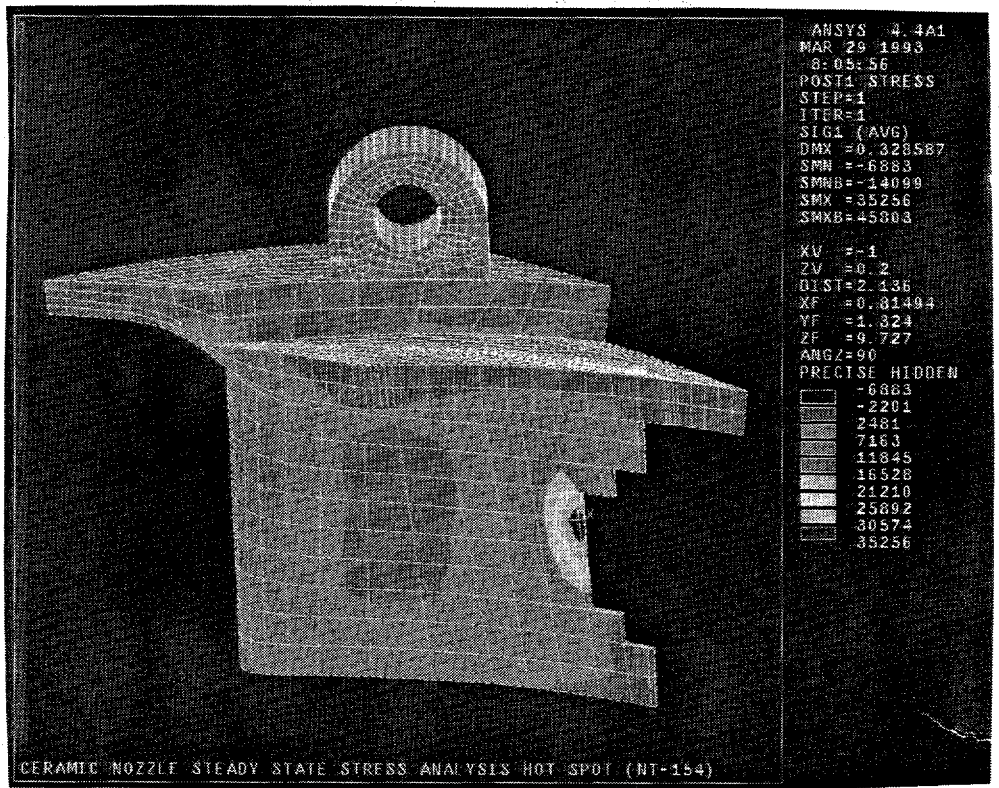


Figure 4-24. Analytically Predicted Stress Distribution in Si_3N_4 Nozzle - "Hot Spot" Radial Profile; 2nd Iteration TE Cutback

It is assumed from the analytical results to date that the cutback TE method of stress reduction will reduce the MPS by a maximum of 30% in SiC. However, the tradeoff is an increase in the nozzle throat area which may (for aerodynamic reasons) require a re-staggering of the stage 1 nozzles (increase in the nozzle count, e.g. from 30 segments to 32 segments). Further aerodynamic and stress analysis will be required to determine if nozzle re-staggering is required, and if the answer is affirmative, what the new nozzle count would be. This will be done via a tradeoff study in the detailed design during Phase II of the program. A more direct approach to nozzle stress reduction would be to mitigate the root cause of the stress by increasing the temperature of the relatively cool streamlines at the inner and outer nozzle shrouds to generate a less severe radial temperature (gradient) profile.

Under consideration are the following:

1. Methods to modify (increase and/or redirect) secondary cooling flows on both inner and outer flowpath components and support structures.

2. Extending the blade neck region so that the disk rim can be physically reduced in size (reduction in rim O.D.) away from the hot gas flowpath and then redirect secondary cooling flow on the extended blade neck region to reduce the heat flux into the metallic disk rim.

These methods of nozzle stress reduction for the "hot spot" circumferential temperature locations which affects approximately 2-3 nozzle segments may enable a steady state stress reduction of 20 to 30% without a TE cutback and nozzle restaggering. Many tradeoffs will have to be made in a retrofit engine application, until such time as a substantial improvement in metallic disk temperature/stress capability is achieved.

Life assessment for the nozzles based on the number of nozzles exposed to the "hot spot" and "average" radial gradient for both candidate materials was initiated in Phase I and will be continued in Phase II. The Probability Of Survival (POS) will be estimated for SiC and Si_3N_4 with respect to fast fracture, slow crack growth, creep, oxidation, and fatigue.

Conservative engine thermal transient conditions have been imposed on the cantilevered airfoil nozzle design. The engine start transient assumes a "standard" Centaur 50 start profile, and the shutdown is a "standard" trip shutdown profile. Neither of these transient cases takes into account the control modifications under "lightoff" and "trip shutdown" discussed in Section 3.3 CONCEPTUAL COMPONENT DESIGN . In the case of a modified electronic controller coupled with the hardware changes discussed the transient conditions will be more benign due to the significant reduction in engine mass flow (throttled flow) and the attendant reduction in the transient heat transfer coefficients (HTC's) along the hot gas flowpath. Results of this analysis confirm the worst case stress state on the nozzle segments is in the steady state mode, "hot spot" temperature location on the radial combustor discharge profile, in SiC material.

Supplier Review of Nozzle Design

As for the ceramic blade the candidate suppliers for the stage 1 ceramic nozzle were requested to comment on design of the component for which they had been selected. In this section the comments of the suppliers for nozzle fabrication, Norton Advanced Ceramics (NAC) and Carborundum are being discussed. The third nozzle supplier, NGK Insulators Inc., a part supplier on the program, is less intimately involved in the design development and was not included in the design review. The suppliers reviewed various design options. This section will focus on a nozzle concept which consists of a single airfoil attached to either one shroud (outer) or an integral design with two shrouds. In both designs the attachment is via a boss and pin to the outer nozzle case.

Norton Advanced Ceramics

NAC noted in its review of the single airfoil nozzle preliminary design that this concept has substantial similarities to the design of the "pinned" blade. NAC addressed forming, machining, and dimensional, and cost factors. As for the blade NAC will use pressure casting technology to form the nozzle which will be fabricated from NT164 silicon nitride.

Forming

NAC noted the simplification in forming a single shrouded nozzle versus a two-shroud design. The current nozzle design with the hole in the attachment would be fabricated by casting it with ≈ 0.050" overstock for machining. The complexity of the casting tool necessary to cast the hole near net shape is expected to lower part yields. NAC recommended that an alternative attachment configuration replace the hole in the outer shroud. A hole-less design would be simpler to fabricate. Such a design could include a simple post, a dovetail, dual pinning, etc.

Machining

NAC solicited input from machining vendors for the nozzle. The assumptions were that airfoil and shroud would be net shape, with 0.050" overstock for machining at the edge surfaces and airfoil end, and tolerances similar to those done for other NAC customers. The hole diameter tolerance was specified as 0.0005".

Dimensional Control

NAC plans to net shape from the airfoil, inner, and outer surfaces (for a two-shroud design). The platform edges (including slash angles), attachment lobe ends, and hole ID will be formed with ≈ 0.050" dense overstock for machining. NAC expressed that the print tolerances were within the capability of NAC's process with minimal rejection.

Cost

NAC's comments on cost addressed specifically the cost of machining the single shrouded nozzle which was less than that of a two-shroud design as expected.

Carborundum

Carborundum will use injection molding of Hexoloy® SA silicon carbide to fabricate the nozzle. Carborundum's review of Solar's designs addressed injection molding tool design, molding, fixturing during sintering, and machining. For either a single shroud or two-shroud design the process is net shape. Carborundum's review was less directed to the Solar design than the presentation of options for fabrication. The summary here will predominantly address the requirements for forming.

Forming

Carborundum recommended different forming strategies for a single shroud or two-shroud design. The outer shroud platform surface was considered rather complex. In Carborundum's opinion using conventional graphite fixturing it would be difficult to keep the airfoil/platform geometric relationship intact with this design.

For a single shroud design a fabrication process was recommended (one-platform approach) for the nozzle design in which the injection molding tool would comprise a relatively simple two-piece mold. With no airfoil twist, a simple knockout could be used to eject the part. The presence of the boss with the hole would add substantial complexity to the design. The probability of platform maintenance during fabrication was estimated to be fairly good. Some development work was expected to be required to eliminate possible airfoil distortion and adhesion during sintering.

For a two-shroud design several (two-platform) forming options were presented. One strategy was based on a one-piece mold comprising the airfoil with two attached platforms. This approach could also be used to fabricate a single shroud nozzle. The airfoil would be elongated to create extra stock and the inner platform would be cut off after sintering. This approach would minimize distortion more effectively. The advantage of this approach is reduced need for close tolerance grinding and fixturing during grinding.

In an alternative approach the airfoil and both shrouds would be molded in separate cavities within one mold. This approach would allow for a relatively simple, inexpensive tool and minimum requirements for sintering fixtures to control distortion. To facilitate alignment between the platforms and the airfoil, the airfoil would have generous radii on either end leading into narrow pseudo-platforms. From a ceramic fabrication point of view this approach was deemed most desirable. However, Carborundum expressed that extensive grinding and fixturing would be required to obtain a tightly controlled nozzle.

The two-platform forming processes are based on past injection molding experience and require a lengthy empirical approach in the sintering fixture development area. This approach has been successfully demonstrated in producing a component on a scale 30% of this size and required the use of a complex reusable graphite fixture.

4.5 COMBUSTOR PRELIMINARY DESIGN

The preliminary designs of the ceramic combustor tiles and the continuous ring segments were analyzed for thermal and stress performance in both the steady state rated power and the start-up/shut down transient conditions. Solar FE analyses have concentrated on the SiC tiles and ring segments while Babcock & Wilcox has completed an analysis on the their CFCC liner which has been summarized in this section.

Solar Designs

The internal bulk gas axial temperature profile for a SoloNOx combustor was used as primary input to the thermal analysis (Figure 4-25). The estimated circumferential heat flux variation to the combustor walls was taken from Centaur 50 SoloNOx liner thermal paint data available from recent tests. An insulation layer of Nextel on the back side of the tiles allows the steady state temperatures to approach design levels of 1316°C (2400°F). The Nextel also limits the heat flux through the tiles which effects more isothermal operating conditions. All analytical data for monolithic combustor designs in this section were generated using Hexoloy® SA silicon carbide materials property data.

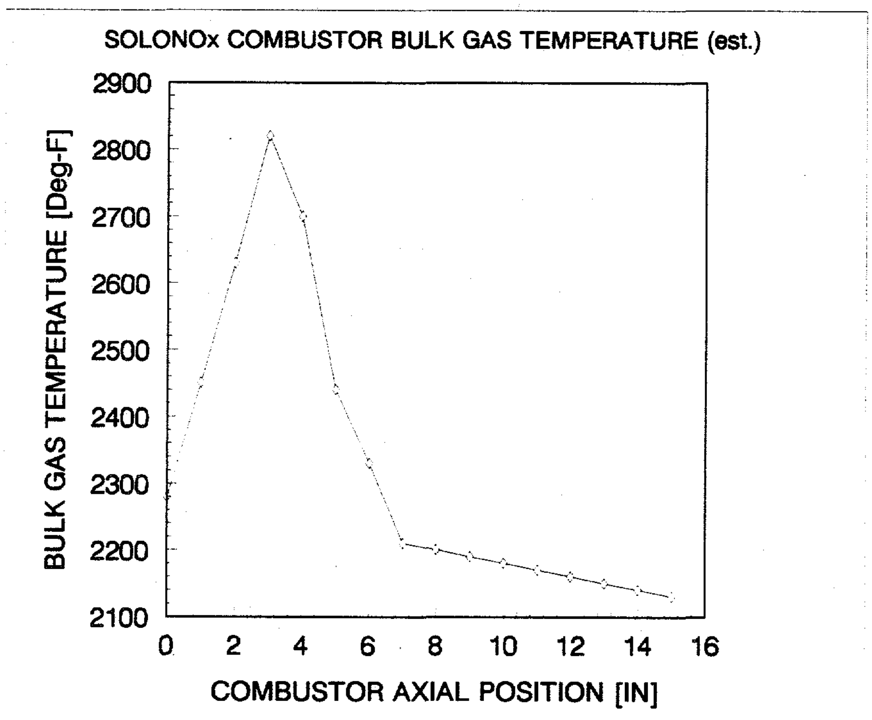


Figure 4-25. SoLoNOx Combustor Internal Bulk Gas Axial Temperature Profile (Measured)

The steady state temperature profile on the tiles was calculated and plotted in Figure 4-26. A sensitivity analysis first assumes that a hot spot is centrally located aft on the tile while iterations will investigate the peak temperature occurring in other regions. The through-wall temperature gradient is plotted in Figure 4-27. The associated stress on the tile at steady state is plotted on the hot side in Figure 4-28. Tensile stress concentrations are observed along the edges of the tiles which approach 193 MPa (28 ksi). Further design refinement will focus on geometric changes to reduce the MPS. The strategy is to bring the maximum principal stress (MPS) level under 103.5 MPa (20 ksi). Earlier ceramic engine programs indicated this to be a desirable design stress maximum.

A transient analysis was performed which predicted the temperature gradients on the tiles for both a start up and a trip shutdown. Figure 4-29 displays the temperature difference in the tile (inner surface temperature minus outer surface temperature) for both the startup, steady state and shutdown conditions. The maximum tile delta of 25°C (45°F) occurs at steady state.

An FE analysis has been completed on the continuous monolithic ceramic ring segments which utilized identical boundary conditions (axial temperature profile) that were imposed on the tiles with the axial temperature distribution occurring along a segment length of 50.8 mm (2"). The shorter axial length of 50.8 mm (2") in the ring segments versus 178 mm (7") in the tiles effectively lowers the maximum axial thermal gradient on the ring segments, thus making the circumferential gradient the primary stress driver in the rings. Figure 4-30 shows that the MPS in the ring segments is about 78 MPa (≈ 11 ksi), a reduction of 60% over the tiles. A sensitivity analysis of intertile/ring segment leakage must be completed as part of the Phase II detailed design activity to determine the most "robust" combustor design for the monolithic materials.

The continuous fiber ceramic composite (CFCC) combustor configuration will be interchangeable with the monolithic tiles. Two candidate CFCC material systems are being considered, a Nicalon/SiC (SiC/SiC) system from DuPont Lanxide Composites and an alumina/alumina system from Babcock & Wilcox. No extensive analysis was performed but, due to the relatively low Young's Modulus of the SiC/SiC material (approximately 70 GPa/~10 Msi), the liner stresses are expected to be lower than in the monolithic tile materials.

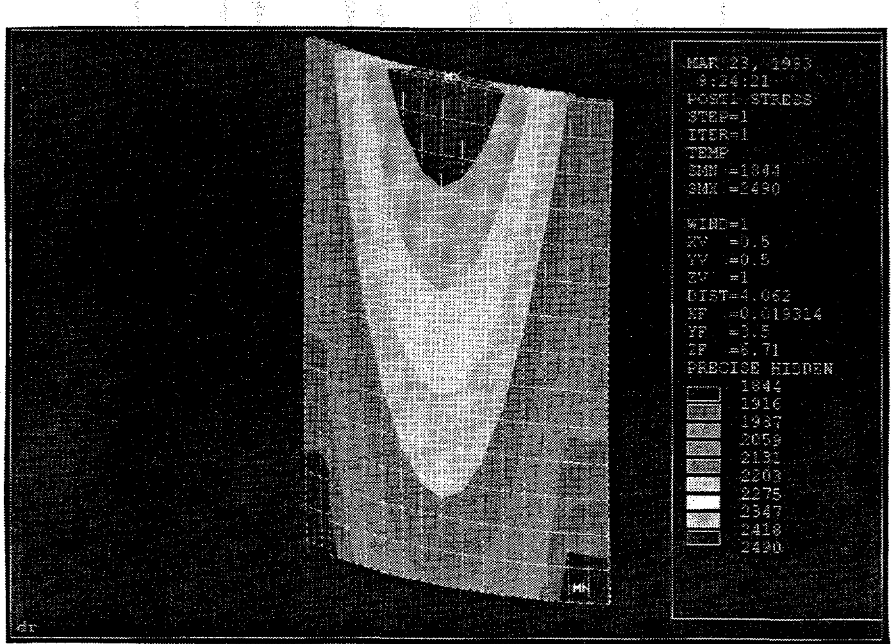


Figure 4-26. Ceramic Tile - Analytically Predicted Steady State Temperature Profile

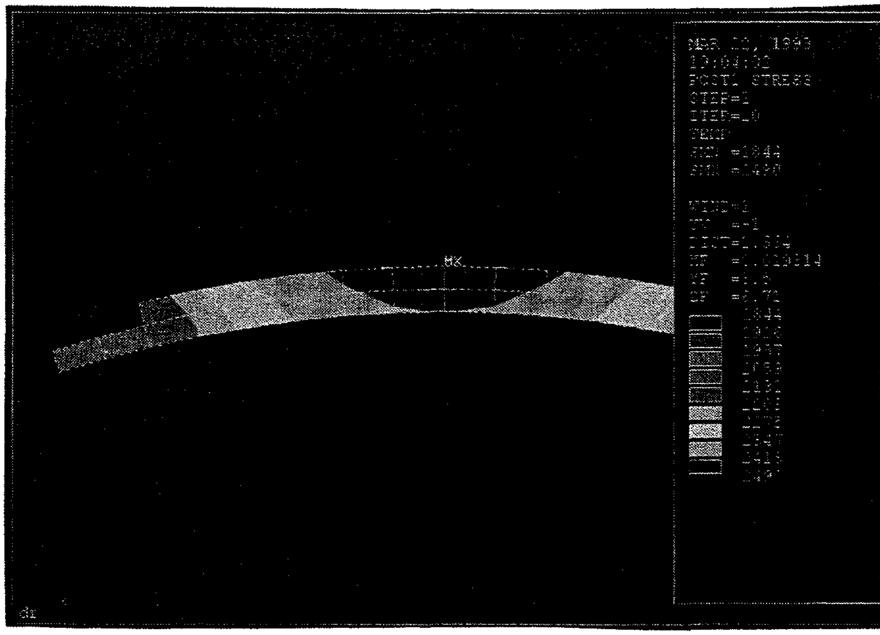


Figure 4-27. Ceramic Tile - Analytically Predicted Through-Wall Temperature Gradient

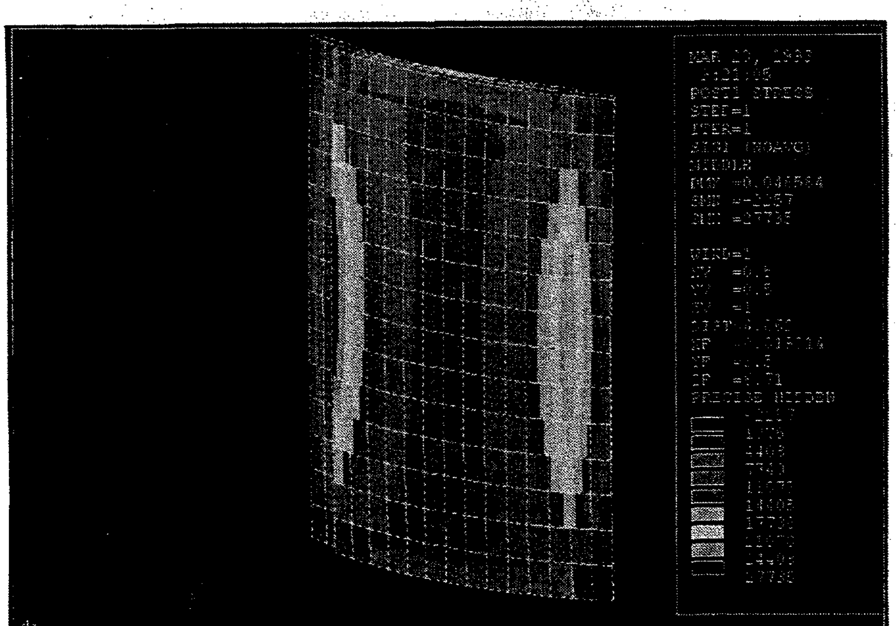


Figure 4-28. Analytically Predicted Steady State SiC Combustor Tile Stresses

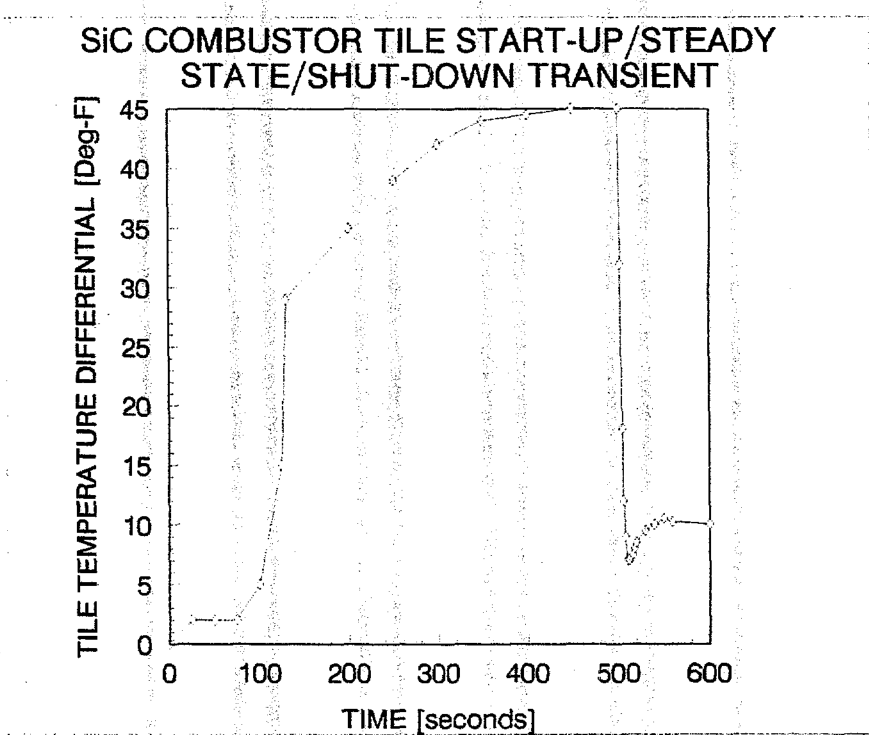


Figure 4-29. Analytically Predicted Through-Wall Temperature Distribution in SiC Combustor Tile

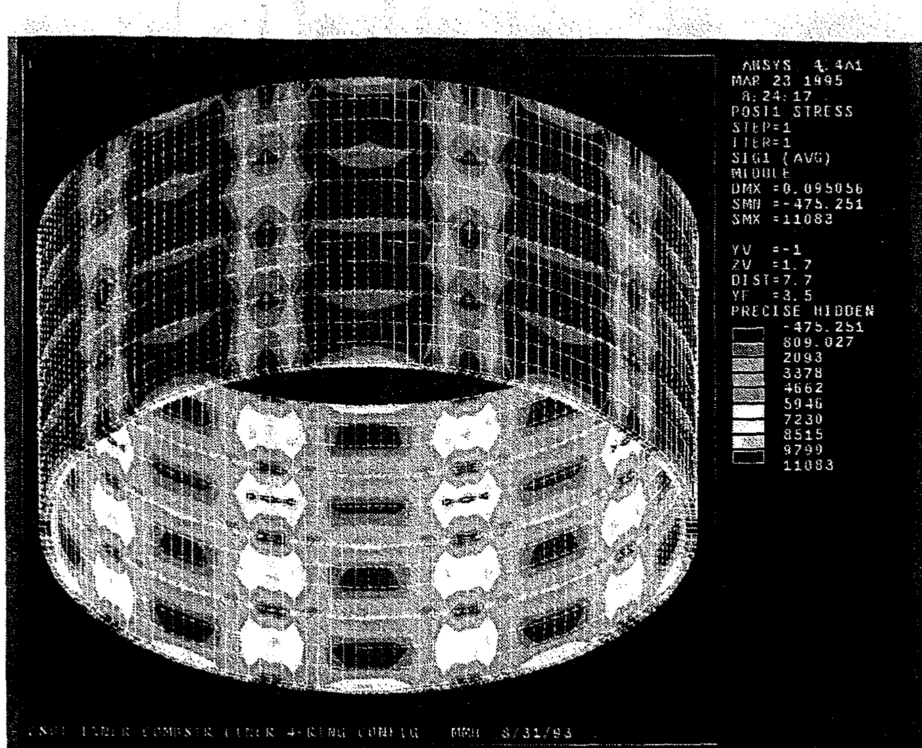


Figure 4-30. Analytically Predicted Stress Distribution in Continuous Monolithic Ring Segments

Combustor Technical Challenges/Solutions - Several technical challenges are envisioned for the development of the ceramic combustor. These challenges and potential solutions are listed below in Table 4-3.

Table 4-3. Technical Challenges for the Combustor Development

	Challenges		Potential Solutions
a)	Interfacial material "sticking" between tiles at 1371°C (2500°F) material temperature	a)	Reduce the material temperature in the tiles/ring segments to 1204°C (2200°F) - Investigate coatings to eliminate sticking
b)	Intertile leakage	b)	Pursue lowest (potential) leakage design - Evaluate insulation sealing capability
c)	Fabrication capabilities of the candidate SiC materials	c)	Work closely with suppliers
d)	Accurate determination of combustor boundary conditions for ceramic component FEA	d)	Predict boundary conditions through the use of a 3-D viscous flow model code - Instrumentation of full scale atmospheric rig early in test program.
e)	Lowest stress (most "robust") configuration	e)	Detailed FE analyses of all candidate concepts complete with sensitivity analyses.

These technical challenges have been planned for the Phase II "Detail Design" and have been integrated into all sub-scale and full size combustor testing prior to the gasifier rig tests. Each test directly feeds into the iterative design process to: (1) learn the weaknesses of the design; and, (2) improve the design.

Supplier Review of Combustor Designs

As for the blade and nozzle components suppliers were asked to review the Phase I designs. The summaries presented here include comments from Carborundum on Solar's monolithic tile design, and from DuPont Lanxide Composites and Babcock & Wilcox for their CFCC designs. The monolithic combustor ring design was conceived late during the Phase I performance period and time constraints precluded a design review by the selected supplier for the combustor rings, Norton Advanced Ceramics.

Carborundum

Carborundum received two tile designs from Solar for supplier review, each having the same basic geometry and dimensions. The designs both require an overlap between tiles along the axial length of the tile for sealing purposes. Carborundum will fabricate the tiles using isopressing and green machining. This method has wider applicability than the slipcast technique which is limited to tiles with thicknesses up to 6.4 mm (0.25").

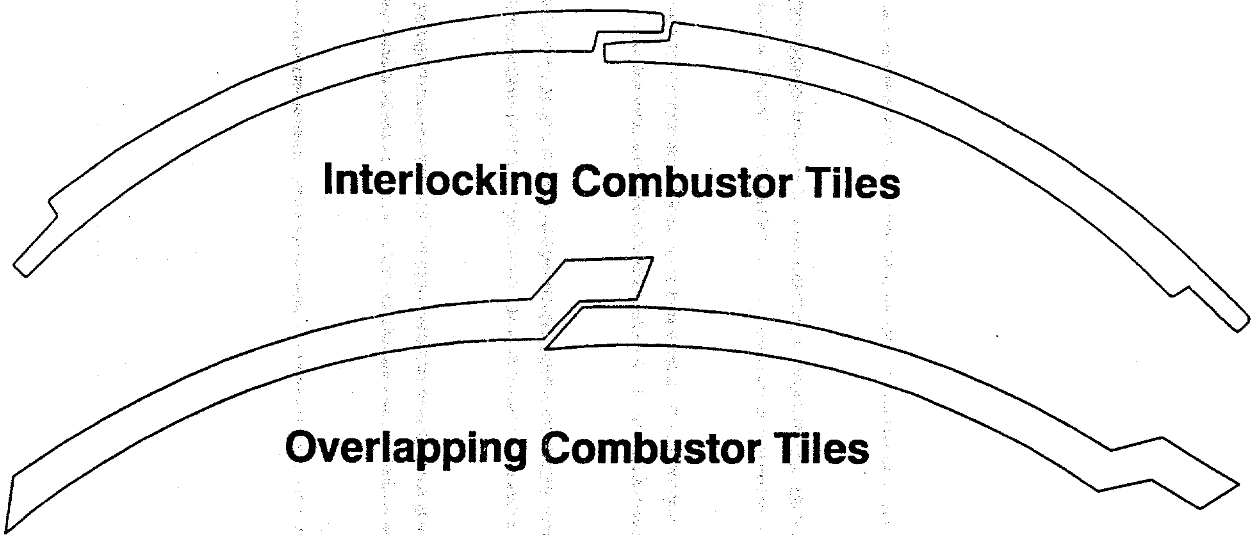


Figure 4-31. SiC Combustor Tile Interlock Concepts

<u>Forming</u>

The two combustor tile concepts being considered to date are schematically shown in Figure 4-31. The first design consists of notched tiles to provide a ship-lap joint to form a continuous thickness ring. The other design under consideration is based on a similar idea but the constant thickness tiles overlap to form a ring with double wall thickness in the overlap regions. It is assumed that both tiles have the same general dimensions: 6.35 mm (0.250") thick, 203 mm (8.00") high, 163 mm (6.42") inside arc radius for the inner combustor ring, and a 387 mm (15.2") inside arc radius for the outer ring. For the thickness under consideration the proposed method of fabrication would be near net-shape isopressing. Based solely on the ability to iso-press, neither tile design offers any significant advantage over the other or poses any major obstacles in forming. Both designs are believed to be within the forming capabilities of the iso-press process.

<u>Machining</u>

Carborundum recommends chamfering or radiusing of all of the edges and inside corners of the tiles in order to eliminate stress risers that result from sharp corners and edges. On machined surfaces, a typical fillet on an inside corner would have at least 0.38 mm (0.015") to 1.0 mm (0.040") radius and be tangent to the inside surface. Edges should be chamfered at 45° extending at least 0.15 mm (0.006") from the edge. Larger radii and chamfers are recommended for larger surfaces. Green machining contributes to fabrication cost. To eliminate the green machining step would require to round off the edges where the tiles are notched. Both designs require a small amount of dense grinding to ensure a tight fit at the mating surfaces. Neither design is believed to present barriers to the final grinding of the tile.

DuPont Lanxide Composites

DuPont Lanxide Composites (DLC) will fabricate the combustor liners (inner and outer) using its chemical vapor infiltration (CVI) process. The DLC material is a continuous fiber-reinforced composite based on a 2-D Nicalon layup with SiC CVI matrix. DLC's supplier review addresses dimensional and shape aspects, and fabrication cost.

Dimensional and Shape Considerations

Simple cylinders with outer liner dimensions of 762 mm (30.0") O.D., and inner liner dimensions of 305 mm (12.0") O.D., both with an axial length of approximately 216 mm (8.5") and wall thickness of 3.18 mm (0.125") pose no fabrication problems for the DLC CVI process although the thin-walled outer liner is larger than any DLC has fabricated to date. Changes to diameter and/or wall thickness (within limitations) should be no problem. Wall thicknesses in excess of 6.4 mm (0.25") will become difficult to thoroughly infiltrate, although DLC has successfully infiltrated components over 12.7 mm (0.50") thick. A wall thickness < 1.5 mm (0.060") is not recommended because the component would lack sufficient strength for fabrication and installation. Design features such as conical rather than cylindrical shapes, tapered wall thicknesses, collars, ribs, holes, and others can be accommodated in the DLC process.

Cost

Cost considerations figure prominently in the DLC review. Since the furnace volume is a critical factor in the CVI fabrication process DLC recommends consideration be given to design changes that would allow nesting of components thereby reducing fabrication costs. For volume quantities of parts fabrication as "barrel stave" pieces that would be assembled into the combustor liner is recommended.

Babcock & Wilcox

Babcock & Wilcox (B&W) has proposed that filament winding be used for the fabrication of its alumina/alumina CFCC combustor liner. B&W has performed a preliminary stress analysis on the combustor liner using its material as part of its design review. A summary or the data is presented here.

Stress Analysis

B&W has performed an analysis of the current integral combustor liner design. As shown in Figure 4-32, two concentric liners surround the combustion zone, the dimensions and fiber architecture used in the design analysis are briefly described in the figure.

The hot wall temperature for both the inner and outer liner will be kept at 1149°C (2100°F) through the use of insulation in the rigs and engine. Previous calculations performed by Solar Turbines to estimate the hot wall and cold wall temperature of a combustor can (8" in diameter with a 0.125" wall thickness) used for a combustion rig test indicated a temperature difference of 227°C (409°F) at a gas temperature of 1371°C (2500°F) and a hot wall temperature of 1229°C (2216°F). A temperature differential across the walls of the inner and outer liner of the integral combustor design was estimated to be 111°C (200°F) based on the surface area ratio between the integral liner and the combustion can used in the rig test. This is a very rough estimate. Empirical data will be available in Phase II to provide more accurate temperature estimates.

Table 4-4 lists the material properties used in the stress analysis of the CFCC combustor liner performed with the ABAQUS finite element program. The source for the data were B&W, Virginia Polytechnical Institute (VSI), and Cleveland State University (CSU).

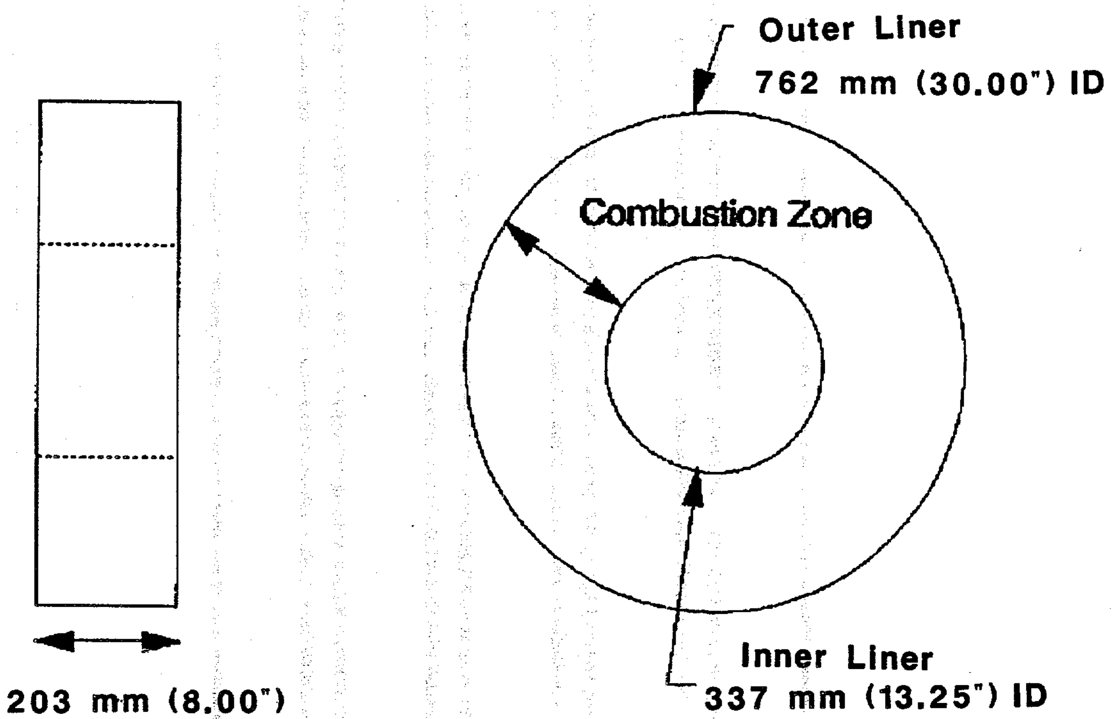


Figure 4-32. Integral Combustor Liner Design Analyzed by B&W - Both liners have a wall thickness of 0.125" (5 closures) and a +/- 30 fiber orientation.

Table 4-4. Material Properties for B&W's Stress Analysis

Property	Value	Source	Property	Value	Source
Coefficient of Thermal Expansion	8.41×10^{-6} °C^{-1} 4.67×10^{-6} °F^{-1}	B&W	Modulus: E_1 E_2 G_{12}, G_{13}, G_{23}	 138 GPa (20.0 Msi) 66 GPa (9.6 Msi) 48 GPa (7.0 Msi)	 VPI VPI VPI
Poisson's Ratio	0.26	VPI*	Strength: S_1 (Nonlinearity) S_2 S_{12}, S_{13}, S_{23}	 305 MPa (44.3 ksi) <7 MPa (<1 ksi) 9.4MPa (1.4 ksi)	CSU CSU CSU

* Virginia Polytechnical Insititute
* Cleveland State University

Forty-six shell elements (S8R5) were used to model the CFCC outer combustor liner geometry. The hot and cold wall temperatures were assumed to be uniform (i.e. no end effects). A linear temperature gradient through the liner wall was assumed. The results of the stress analysis are presented as plots of stress versus axial location along the liner. Surfaces containing tensile stresses for S_1 and S_2 were examined since ceramics are generally weaker in tension than in compression. The assumptions made in this analysis cause the stresses at a given axial location to be constant around the circumference of the liner. The maximum tensile stress in the fiber direction (S_1) which is located on the outer diameter of the liner is 78.5 MPa (11.4 ksi). A maximum in-plane transverse tensile stress (S_2) of 43.7 MPa (6.34 ksi) is predicted. Shear stresses were higher on the hot wall than the cold wall. A maximum shear stress (S_{12}) of 25.4 MPa (3.69 ksi) is predicted at the end of the liner.

Similar stress levels were obtained for the inner combustor liner. The maximum value for the longitudinal stress (S_1) is 76.3 MPa (11.1 ksi). The transverse stress (S_2) has a maximum predicted value of 43.5 MPa (6.31 ksi). The in-plane shear stress (S_{12}) is predicted to be -33.3 MPa (-4.84 ksi). The stress analysis performed by B&W under this task shows that in-plane longitudinal stresses in both the inner and outer liner exhibit a fairly high safety margin. The in-plane transverse tension strength is greatly exceeded. B&W questioned the accuracy of the of the transverse tensile modulus (E2 = 66 GPa/9.6 Msi) which was determined by VPI from multi-axial filament wound tube tests. CSU has determined an average modulus of only 42 GPa (6.12 Msi) from coupon tests. A lower transverse modulus would decrease the transverse stresses generated within the liners. The shear stresses predicted by the analysis are close to the in-plane shear strength of the material.

B&W pointed out that the failure mechanisms in CFCCs are not well understood at this time, causing uncertainties in the interpretation and implications of the stress analysis results. The high in-plane transverse stresses (S_2) implies that matrix cracking within the first ply of the cold wall of each liner could occur. Load redistribution to the neighboring orthogonal ply should arrest these surface matrix cracks. B&W recommends optimization of the fiber orientation, the use of more accurate modulus data in subsequent stress analysis, the use of high temperature modulus data (room temperature modulus data were used for this analysis), and the use of a new version of ABAQUS which will permit B&W to assess the level of interlaminar shear and tensile stresses.

Notwithstanding the favorable longitudinal and shear stresses the preliminary steady-state thermomechanical analysis indicates high transverse tensile stress levels which potentially compomise the integrity of the CFCC liner during combustion operation. Redesign of the current fiber architecture, obtaining more accurate materials property data, and the gathering of actual temperature gradient data during rig testing will be required to establish whether this material will continue to be a viable candidate for the combustor liner application.

4.6 SECONDARY COMPONENT PRELIMINARY DESIGN

This section addresses the secondary component design issues. All materials issues related to the secondary components will be addressed in Section 5.6 ("ANCILLARY MATERIALS NEEDS").

Secondary Component Boundary Condition Assumptions

Secondary Cooling System

An initial Heat Transfer (HT) feasibility study of the Centaur 50 engine to operate at 1121°C (2050°F) TRIT in the CSGT program has indicated the main areas of concern. The most severe combustor radial profile predicted for nozzles subjected to "hot spot" conditions, is shown in Figure 4-33. An intensive conceptual and preliminary design activity generated a number of structurally and thermally acceptable attachment configurations, particularly around the stage 1 nozzle attachment area.

Compared to the Centaur 50 engine, increased cooling flow for stage 1 and 2 disks will be required to compensate for the uncooled stage 1 blade configuration and for increased gas temperatures[7] around the stage 1 and 2 disk rims. A small increase in cooling flow around the forward face of the nozzle case will be necessary to protect it from the high heat flux induced by the attached stage 1 nozzle shroud.

[7] Stage 2 and 3 disks predicted metal temperature distribution is based upon the extrapolation of previous analytical or experimental data. Calculations of boundary conditions were based on preliminary thermodynamic data published for the selected engine configuration.

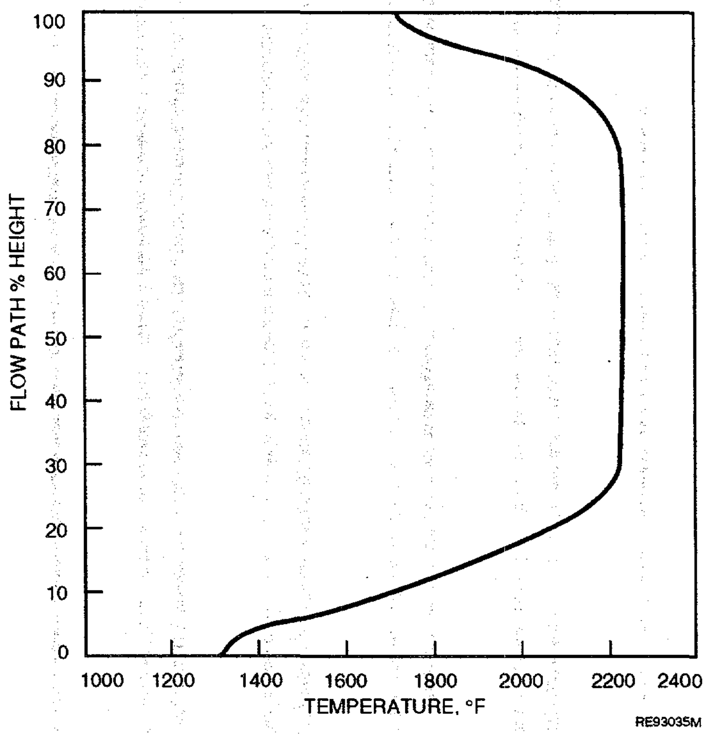


Figure 4-33. Most Severe ("Hot Spot") Radial Combustor Discharge Profile

Secondary Components

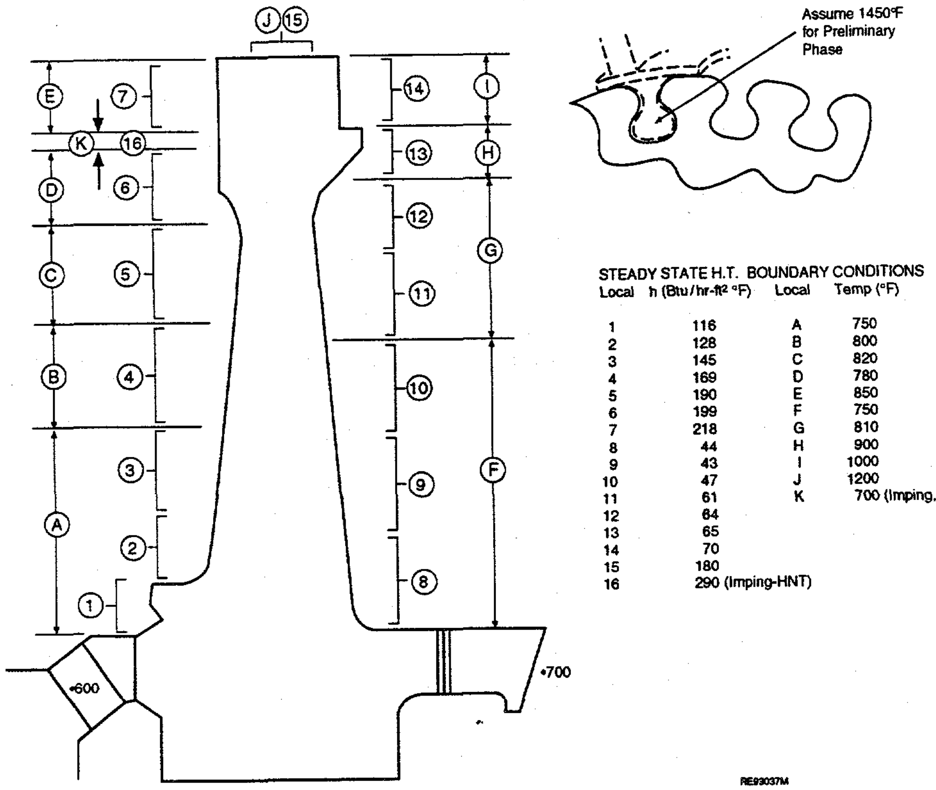
Turbine Disk (Stage 1)

No decision has been made on the final stage 1 ceramic blade attachment design. Therefore, only preliminary boundary conditions could be produced for stage 1 disk faces as illustrated in Figure 4-34. To avoid a large radial temperature gradient through the blade shank, the disk impingement cooling is positioned at a slightly smaller diameter than the bottom of the blade root shown in area K-16 of Figure 4-34. For the first iteration of the stage 1 blade structural analysis, it is recommended that a blade root neck temperature of 788°C (1450°F) can be assumed. Current stage 1 disk material for the Centaur 50 will not have sufficient creep strength at the higher firing temperature. Therefore, a change in disk material is planned. Disk finger temperatures will be investigated in Phase II.

Details of the thermal conduction path through the axial pins attaching the nozzles will be provided after the detail design is complete. Local gas temperature along a tip shoe can reach 1177°C (2150°F) (notice that the value is even higher than the maximum temperature specified for the nozzle shroud due to span-wise temperature mixing). Provision for a minimal conduction surface between the stage 1 tip shoe hooks and the nozzle support case is critical for the nozzle case temperature management. The same philosophy applies to the stage 1 nozzle outer shroud.

Turbine Disk (Stage 2)

Disk rim steady state temperature is expected to increase by about 83°C (150°F). Most likely this will require a disk material upgrade. Figure 4-35 presents stage 2 disk steady state and critical transient (max radial Δ T) metal temperature distributions which were extrapolated from measured Centaur 50 engine data.



STEADY STATE H.T. BOUNDARY CONDITIONS

Local	h (Btu/hr-ft² °F)	Local	Temp (°F)
1	116	A	750
2	128	B	800
3	145	C	820
4	169	D	780
5	190	E	850
6	199	F	750
7	218	G	810
8	44	H	900
9	43	I	1000
10	47	J	1200
11	61	K	700 (Imping. Zone)
12	64		
13	65		
14	70		
15	180		
16	290 (Imping-HNT)		

Figure 4-34. Preliminary Stage 1 Disk Boundary Conditions

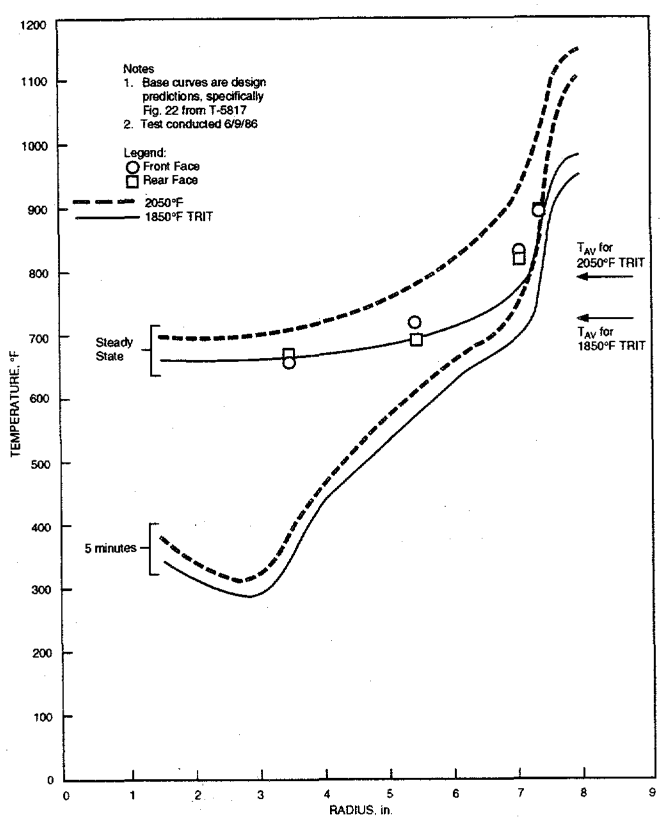


Figure 4-35. Stage 2 Disk Steady State and Critical Transient (Maximum Radial ΔT) Metal Temperature Distributions

Turbine Disk (Stage 3)

Disk metal temperatures are not expected to change significantly relative to the Centaur 50 engine as shown in Figure 4-36.

Turbine Nozzle (Stage 1)

For a conservative structural steady state analysis of the ceramic airfoil, a peak gas temperature of 1297°C (2366°F) has to be applied with a lowest expected outer shroud temperature of 816°C (1500°F). The thermal model of the stage 1 nozzle should include radiation between the shrouds and surrounding metallic structure (no forced convective cooling is anticipated for the outer shroud). Structural analysis of the inner shroud should assume a worst case circumferential temperature gradient of about 222°C (400°F) along a 15° angular arc. A sheet metal shielding of the support structure with backside convective cooling is essential for this design.

Ceramic airfoils, which are sensitive to thermal shock, require accurate prediction of the thermal transient boundary conditions, particularly during cold starts and emergency shutdowns. For a given geometry of the airfoils and known temperature dependent properties (thermal conduction, density and specific heat) of the materials, transient temperatures become a function of the local gas temperature and the heat transfer coefficient at every moment during transient operation. Variation of mainstream mass flow during a transient has a strong impact on local heat transfer coefficients.

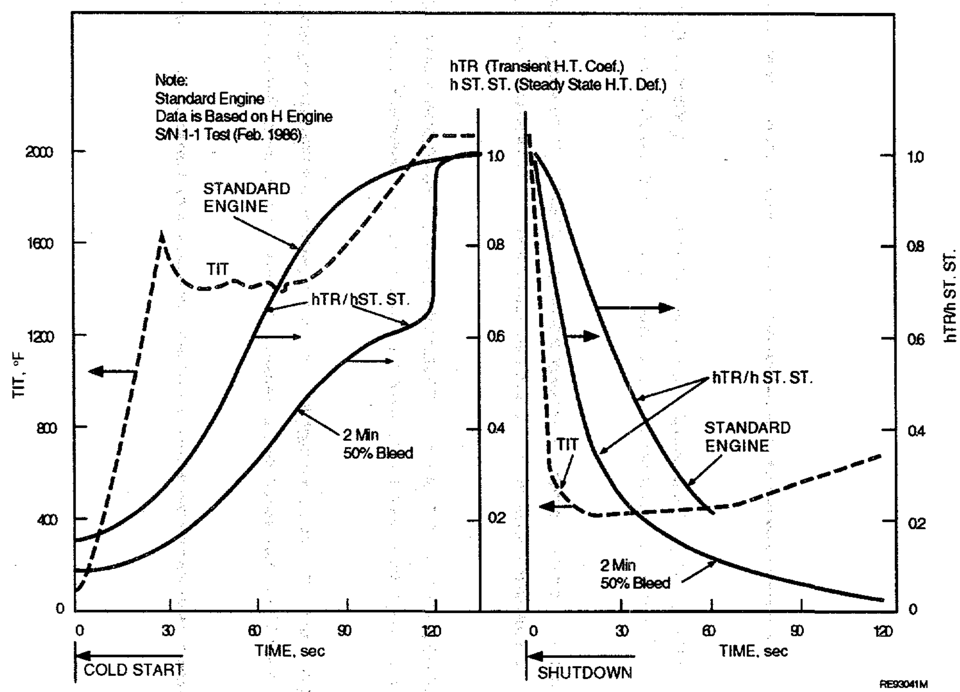


Figure 4-36. Stage 3 Disk Temperatures at 1121°C (2050°F) TRIT vs 1010°C (1850°F)

Transient Boundary Conditions[8]

Figure 4-37 presents realistic transient characteristics of start and shutdown cycles affecting both stage 1 nozzle and blade. Different flows of combustion products controlled by Variable Inlet Guide Vanes (VIGV) and/or bleed valve opening will lead to corresponding changes in heat transfer values. The ratio of HT coefficients relative to steady state operation are included in Figure 4-37 for the standard engine configuration and for the proposed 50% transient bleed flow.

Nozzle case and nozzle shrouds, shaft, disks and diaphragms have much larger thermal capacity (time constant) than airfoils. For this reason, their cold start transient thermal boundary conditions can be replaced with instantaneous application of steady state boundaries, with little error.

Similarly, boundary conditions during and after fast shutdown should be based on gas temperature variation immediately after shutdown. T5 transient recording provides a good reference for the gas path temperatures after shutdown. HT coefficients for shutdown transients can be reduced to the level of natural convection 0.86-8.68 $W.m^{-2}{}^{\circ}C^{-1}$ (0.5 - 5 $Btu.ft^{-2}.hr^{-1}.{}^{\circ}F^{-1}$). The most powerful factor for the rotor transient after shutdown is a heat sink into the bearings with oil temperature around 93°C (200°F) and oil convective HT coefficients on the order of 3470 $W.m^{-2}.{}^{\circ}C^{-1}$ (2000 $Btu.ft^{-2}.hr^{-1}.{}^{\circ}F^{-1}$).

Some additional information for turbine structure transient temperatures can be extrapolated from existing Centaur 50 engine data. Figure 4-38 presents transient metal temperature response for stationary components including the main heat load for the nozzle case. This data must be compiled with the thermal boundary conditions to the nozzle case and shroud plenums.

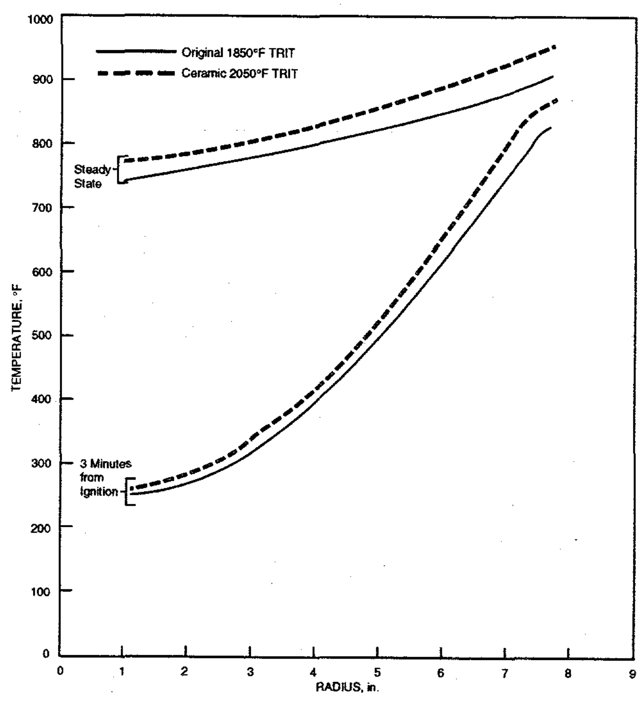


Figure 4-37. Thermal and Aerodynamic Transient Characteristics affecting Stage 1 Nozzle and Stage 1 Blade

[8] For the preliminary phase of the program standard transient boundary conditions were applied to perform a conservative stress analysis.

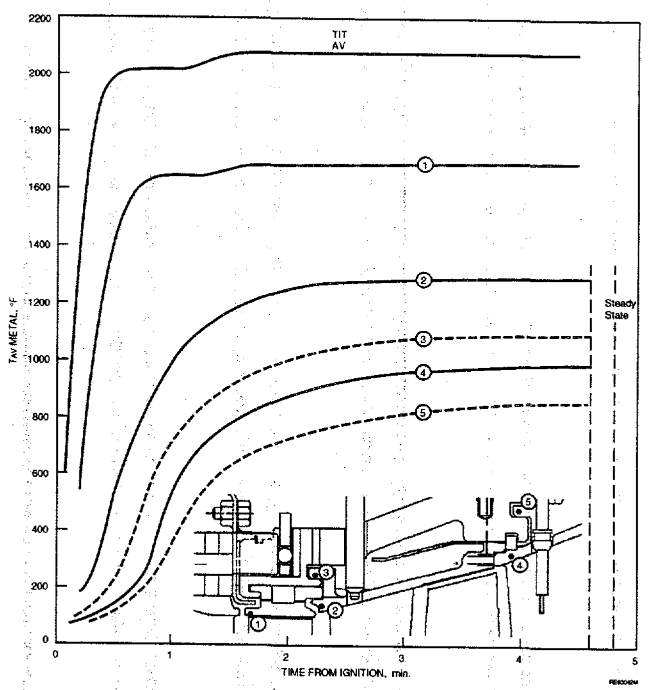


Figure 4-38. Transient Structural Metallic Temperature Response

Tip Clearance Management

The criticality of blade tip clearance management for the success of the CSGT program was recognized from the beginning. Some difficulties of applying the Centaur 50 stage 1 nozzle support concept for the ceramic program led to a separate nozzle and tip shoe supported directly from the nozzle case. Known limitations of such a method will require an increase in tip clearance from 0.5 mm (0.02") [Centaur 50] to 0.89 mm (0.035") [CSGT] to avoid the possibility of blade rub.

Although the CSGT program is not currently designing the stage 1 blade to rub the tip shroud for clearance control considerations, development of a suitable abradable tip shoe coating which could potentially allow a ceramic blade rub is under consideration at Solar. A turbine stage design capable of a blade to tip shroud rub would have a favorable effect on minimum tip clearance and thus improve the potential for performance enhancement.

The general trend in tip clearance variation will be similar to the trend for the transient data collected for the Centaur 50 engine. Definition of cold build clearances through all 3 stages will require completion of transient thermal and displacement analyses for all components affecting tip clearance. Table 4-5 presents a summary of the data required to accomplish this task.

Centaur 50-CSGT Turbine Section (Rotor Disk Analysis)

The CSGT will be operated at an increased TRIT of 1121°C (2050°F) versus the production Centaur 50 TRIT of 1010°C (1850°F) which means that the hot section static and rotating components will be subjected to higher operating temperatures. Increased temperature on these components will cause increased displacements (changes in established turbine tip clearances), reduced stress rupture margin on turbine disks, etc. A preliminary analysis of the turbine disks has been conducted with respect to revised temperature distributions, displacements, and stresses in response to the 111°C (200°F) increase in the steady state TRIT.

Table 4-5. Data Summary of Required Transient and Steady State Clearances to Accurately Define Cold Build Clearances

Tip Clearance Change	1st Stage		2nd Stage		3rd Stage	
	St.St.	Hot Restart	St.St.	Hot Restart	St.St.	Hot Restart
C1. Clearance Reducing Factors:						
- Disk thermal Growth	TBD	TBD	TBD	TBD	TBD	TBD
- Disk Centrifugal Growth	TBD	TBD	TBD		TBD	TBD
- Blade Growth Total	TBD	TBD	TBD		TBD	TBD
- Nozzle Shoe Bowing	.002	.002	.002	.003	.003	.004
- Axial Rotor-Stator Displacement Converted to Radial One			.022	.008	.024	.009
- Bearing Housing Droop	.002	.006	.002	.006	.003	.007
- Bearing Clearance	.001	.001	.001	.001	.002	.002
Total	TBD	TBD	TBD	TBD	TBD	TBD
C2. Clearance Increasing Factor:						
- TNC (Including Axial Growth Effect for ST.2 & 3)	TBD	TBD	TBD	TBD	.049	.025
C3. Other Unpredictable Factors:						
- Circumferential Temperature	.002	.003	.002	.002	.001	.002
- Manufacturing Tolerance	.003	.004	.005	.008	.005	.008
Total Additional	.005	.007	.007	.010	.006	.010
C4. Actual Running Clearance	.035 + .007		.030 + .007		.035 + .007	
C5. Cold (Build) Clearance	TBD		TBD		TBD	

Figure 4-39 shows the revised temperature distribution in the 3 turbine disks and the main rotor shaft. The peak temperature in the stage 1 and 2 disk rims is 581°C (1078°F) with the local temperature in the disk finger (area between blade attachments) approaching 677°C (1250°F). Close observation of the stage 2 disk rim shows a larger area of material operating at the peak temperature than on the stage 1 disk. This is due to the probable impingement cooling applied to the stage 1 disk rim for adequate disk finger cooling.

Figure 4-40 illustrates the tensile stress distribution in the disks at a maximum level of 814.2 MPa (118 ksi) in the bore holes of the stage 2 and 3 disks. The disk finger area of the stage 1 disk adjacent to the inserted ceramic turbine blades is of critical importance in the disk analysis as indicated in the above sections on Boundary Condition Assumptions and Ancillary Component Material Needs. At a material temperature of approximately 677°C (1250°F) and stress levels approaching 172-207 MPa (25-30 ksi) the stress rupture life of the selected material is of paramount importance.

Figures 4-41 and 4-42 show the radial and axial rotor displacements, respectively, due to thermal growth under steady state conditions. Both interstage sealing and rotor blade tip clearances are critical in this analysis. All 3 rotor stages expand as much as 3.05 mm (0.120") in the radial direction and as much as 3.6 mm (0.140") in the axial direction. Knowledge of the magnitude of these thermally induced dimensional changes must be fully understood when setting the engine cold build clearances in order to ensure there will be no stage 1 ceramic blade rub on the metallic tip shoe under "hot" steady state operating conditions.

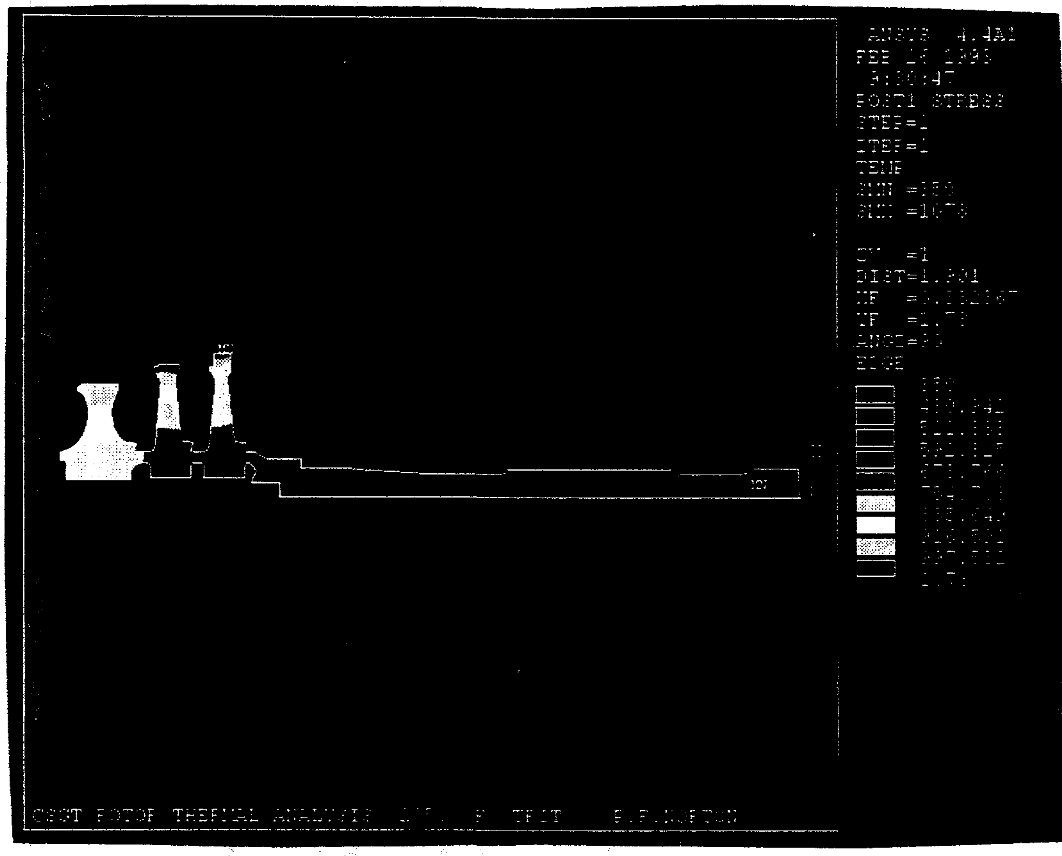


Figure 4-39. Predicted Temperature Distribution in Turbine Disks/Shaft for 1121°C (2050°F) TRIT

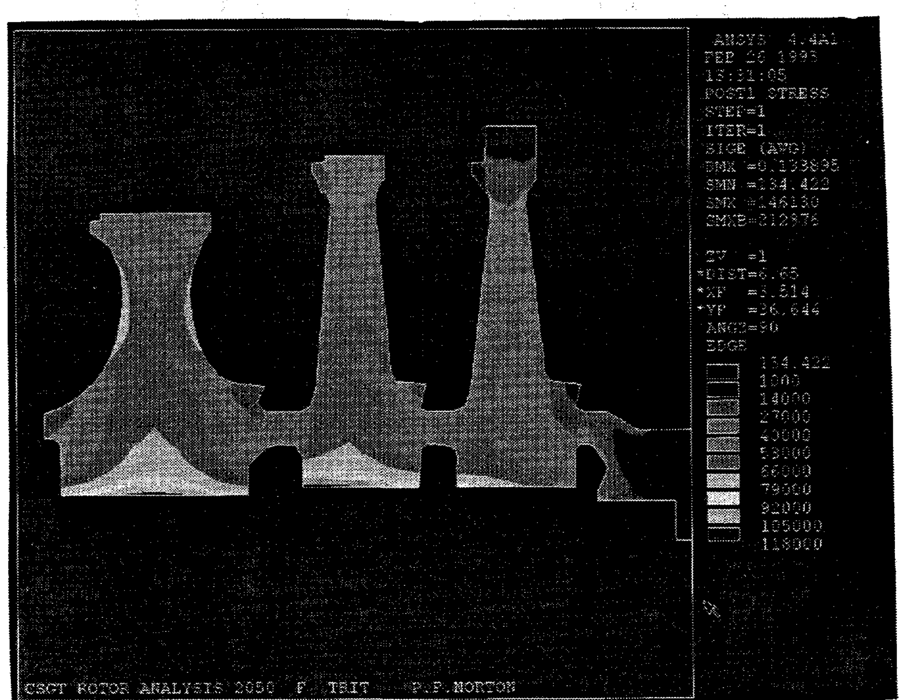


Figure 4-40. Stress Distribution in CSGT Metallic Disks at 1121°C (2050°F) TRIT

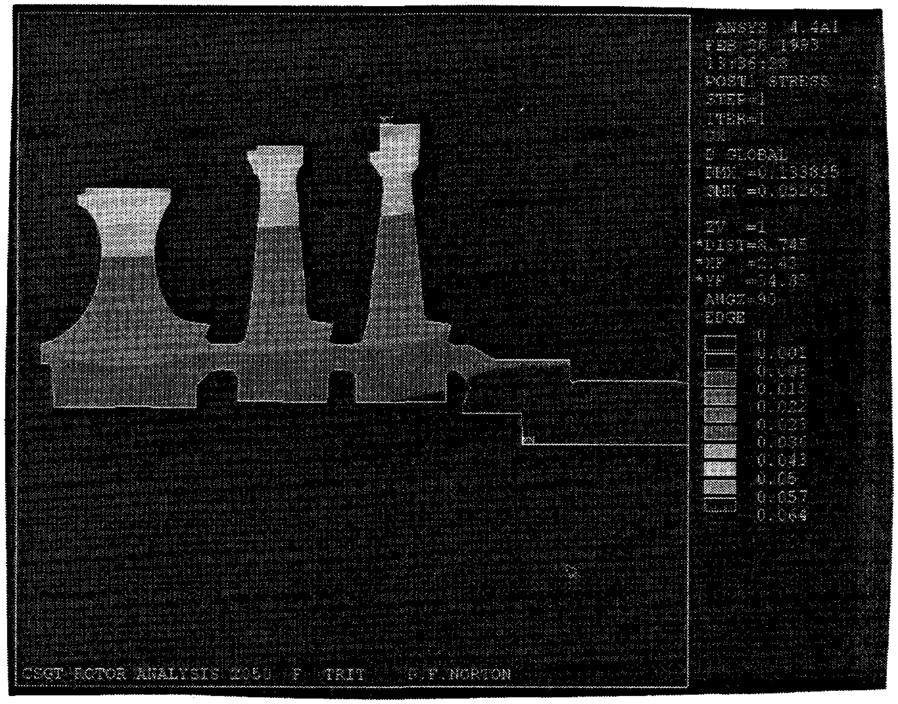


Figure 4-41. Radial CSGT Turbine Disk Displacements at 1121°C (2050°F) TRIT

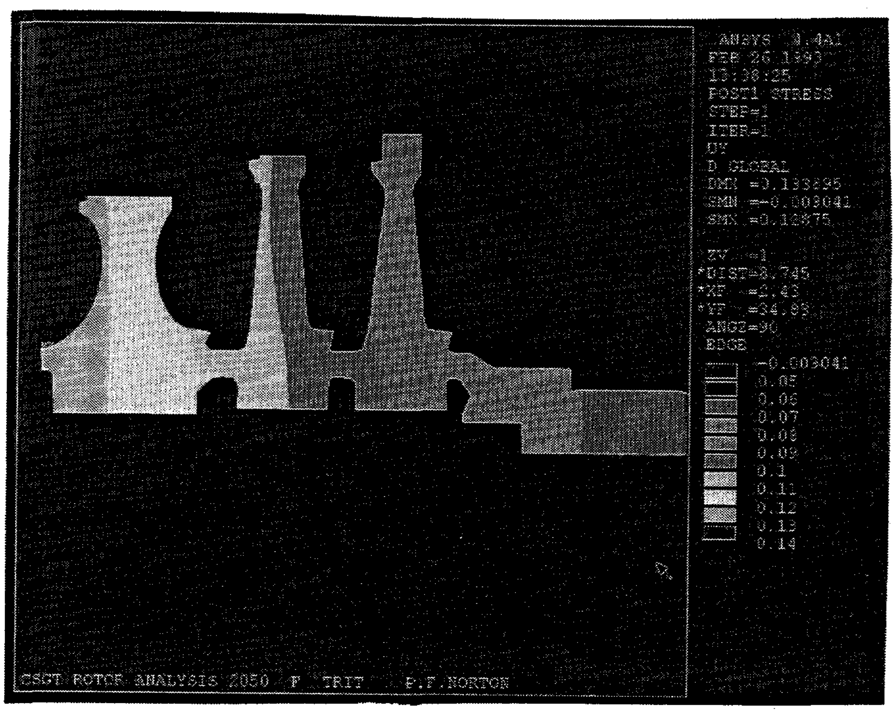


Figure 4-42. Axial CSGT Turbine Disks Displacement at 1121°C (2050°F) TRIT

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3. Nemeth, N.N., Mandersheid, J.M., and Geykenyesi, J.P., 1989, "Ceramics Analysis and Reliability Evaluation of Structures (CARES)", NASA Technical Paper 2916.

4. Nemeth, N.N., et al, 1993, "Time-Dependent Reliability Analysis of Monolithic Ceramic Components Using the CARES/LIFE Integrated Design Program," ASTM Symposium on Life Prediction Methodologies for Ceramic Materials In Advanced Applications - A Basis for Standards, Cocoa Beach, Florida.

5.0

TASK 3 - MATERIALS SELECTION

5.1 INTRODUCTION

The results from the work performed under Task 1 (Turbine Design) and Task 2 (Preliminary Design of Key Components) have been incorporated into the material selection for the Ceramic Stationary Gas Turbine. Engine performance data, ceramic component finite element analysis and life assessment, together with the material property data form the basis for the selection of the ceramic materials. The ceramic suppliers have submitted fabrication plans for the components that they have been selected to fabricate. Solar has developed for each material a recommended testing sequence that will ensure materials and component integrity and reliability. All relevant material property needs, including long term material property requirements such as oxidation and creep, have been defined.

The Task 3 work involved:

- Supplier Assessments
- Materials Properties Data Base Compilation
- Correlation of Materials Properties and Engine Requirements
- Materials Selection for Component Development in Phase II
- Evaluation of Fabrication Process and Quality Assurance Methodology Evaluations
- Database/Life Prediction Methodology
- Component Testing Methodology Review
- NDE Development Evaluation Planning
- Ancillary Materials Needs

5.2 CERAMIC COMPONENT SUPPLIER ASSESSMENT

Important efforts during Phase I were for Solar to assess the capabilities of each potential ceramic component supplier and establish a close working relationship with each supplier. Assessment was based on the following criteria:

- Low probability of failure of their recommended material under engine conditions defined by preliminary design
- Credibility based on prior experience to fabricate and deliver in a timely fashion similar component configurations
- Credibility to later establish volume manufacturing

The Phase I assessment was conducted through a combination of activities including reports, weekly telephone discussions and visits to facilities of the potential suppliers.

Ceramic Supplier Assessment Summary

Silicon nitride was selected as the blade material. Three suppliers were assessed: AlliedSignal Ceramic Components (CC), Kyocera Industrial Ceramics Corporation (KICC), and Norton Advanced Ceramics (NAC). Silicon nitride and silicon carbide were selected as the nozzle materials. Candidate silicon nitride nozzle suppliers were NAC and NGK Insulators, Ltd. (NGK). The candidate silicon carbide supplier selected for assessment was Carborundum. Three candidate combustor liner suppliers were selected for assessment. Carborundum for segmented liners of monolithic silicon carbide, DuPont Lanxide Composites (DLC) for cylindrical inner and outer liners of a SiC/SiC continuous fiber-reinforced ceramic matrix composite (CFCC) material and Babcock & Wilcox (B&W) for cylindrical inner and outer liners of an alumina/alumina CFCC. A limited assessment was also made of NAC as a supplier of rings for combustor liners and nozzle support rings. This section summarizes the conclusions reached by Solar for each supplier.

AlliedSignal Ceramic Components

1. The CC GN-10 silicon nitride material database indicates that the revision 17 grade of this material is acceptable for the CSGT blade if the high stress region of the attachment is machined and oxidation heat treated (resulting in a flexure strength of about 896 MPa/130 ksi). The as-fabricated (hot isostatically pressed) surface with a strength of only about 545 MPa/79 ksi is not acceptable for the attachment, but is anticipated to be acceptable for the platform and airfoil after localized surface finishing.

2. CC has presently not established volume manufacturing of their GN-10 and has not implemented a production quality system. However, efforts are in progress to achieve these goals. The projected timing appears compatible with CSGT needs. CC is scheduled to be ISO 9000 certified in December 1994.

Kyocera Industrial Ceramics Corporation

1. The SN-252 and SN-253 silicon nitride grades have been reviewed as candidates for the CSGT blades. SN-253 has been selected by Solar for Phase II blade fabrication development based on its higher machined (724 MPa/105 ksi) and as-fabricated (586 MPa/85 ksi) strength compared to SN-252. The machined surface with a suitable oxidation heat treatment is specified for the high stress region of the blade attachment. The as-processed surface is acceptable for the platform and airfoil. SN-253 will be considered as a backup material for the nozzle.

2. KICC's parent company, Kyocera Corporation, has demonstrated production capability (up to 30,000 turbocharger rotors per month) with one grade of silicon nitride using the fabrication process that will be used for CSGT blades.

3. KICC presently has a quality system in place that meets the CSGT requirements. KICC is planning to be ISO 9002 certified by April 1995.

Norton Advanced Ceramics

1. The NT154 and NT164 silicon nitride materials have been reviewed as candidates for the CSGT blades. Either is acceptable in the machined and oxidation heat treated condition for the high stress region of the blade attachment. As-processed material is not acceptable for the attachment, but is acceptable for the platform and airfoil after localized surface finishing.

2. NAC has gained extensive experience in fabrication of test bars and prototype components and has demonstrated good reproducibility over many batches. NAC has not yet demonstrated volume production for NT154 or NT164. However, efforts towards this goal are in progress.

3. NAC has established a quality assurance system that is acceptable for the CSGT program and subsequent production. NAC is planning ISO 9000 certification in early 1996.

4. NT154 and NT164 have also been considered for the CSGT nozzle. Both materials have adequate fast fracture strength at room temperature and engine operation temperature. Creep resistance and stress rupture life also appear adequate if the peak stress is below 138 MPa/20 ksi at the maximum temperature of about ~1300°C/2370°F. However, if the temperature and/or stress are much higher, an adequate database is not available for reliable life prediction. For the lower temperature or stress scenario, NT154 would be acceptable. For a higher temperature or stress scenario, NT164 is recommended.

5. NT230 is being considered as a candidate material for combustor liner rings. A ring design lowers the stress level of the combustor considerably. Presently NT230 is the only high temperature SiC that can be made into parts with a diameter of 76.2 cm (30 inches, outer diameter of the combustor).

Carborundum

1. Hexoloy® SA SiC has been assessed for the nozzle and segmented combustor liner tiles. The big advantage of the SiC is resistance at high temperature to creep and slow crack growth. Concerns are the relatively low tensile strength (approx. 276 MPa/40 ksi), fracture toughness and Weibull modulus compared to the silicon nitride materials. Hexoloy® SA should be acceptable up to at least 1371°C (2500°F) for stresses up to about 138 MPa/20 ksi, although life prediction analysis will be necessary for verification. For stresses greater than that level life prediction analysis will definitely be necessary.

2. The nozzles will be fabricated by injection molding. Carborundum has fabricated prior turbine components of shape and complexity equivalent to the CSGT nozzle, but has not demonstrated production capability with this process. The Hexoloy® SA material is in production for simpler shapes (seals) fabricated by uniaxial pressing.

3. The fabrication technique for combustor tiles will be isopressing followed by green machining. This technique is preferred for tiles under the program which will have thicknesses in excess of 6.4 mm (0.25").

4. Carborundum has a quality system in place that meets CSGT requirements.

NGK Insulators, Ltd.

1. Because NGK's SN-88 material has shown acceptable properties it is considered a candidate for the nozzle.

2. NGK has shown that it can make production quantity ceramics (e.g. turbocharger rotors) in a very reproducible manner.

DuPont Lanxide Composites

1. The DuPont Lanxide SiC/SiC composite fabricated by chemical vapor infiltration (CVI) has been assessed for the inner and outer combustor liners as integral cylinders rather than segments. The material was considered based on its high fracture toughness and excellent resistance to thermal shock. Initial testing at Solar of a subsize cylinder in a combustor test

rig has been encouraging. Testing under load at 2200°F in an oxidizing atmosphere at DuPont has also been encouraging; a test coupon survived over 4400 hours at 80 MPa (11.6) ksi stress before the test was terminated.

2. DuPont Lanxide Composites has fabricated parts of size comparable to the inner combustor liner, but not the outer liner. The production facilities (furnaces, etc.) are large enough to fabricate the program components. Fabrication at production levels has not been demonstrated. Dupont Lanxide Composites has recommended fabricating the combustor in segments to reduce cost. DuPont Lanxide Composites QA plan conforms to military specifications.

3. The major concerns with the DuPont Lanxide Composites SiC/SiC CFCC are (1) long term retention of properties under an oxidizing atmosphere and (2) cost.

4. DuPont Lanxide Composites is working to become compliant to ISO 9002 requirements by 1996.

Babcock & Wilcox

1. The Babcock & Wilcox alumina/alumina CFCC fabricated by sol-gel infiltration has been assessed for the inner and outer combustor liners. This material was selected for evaluation largely because an all oxide material should be stable in an oxidizing atmosphere. However, no data are available to verify this.

2. B&W has not fabricated oxide-oxide composite parts as large as the CSGT combustor liners. B&W also has not demonstrated production capability.

3. The major concerns with the B&W material are lack of data, lack of component test experience, lack of long term high temperature exposure data. The material is at an early stage of development.

4. B&W has an extensive quality control system that meets CSGT requirements.

<u>Key Supplier Issues</u>

Allied Signal Ceramic Components (CC)

CC's silicon nitride material (GN-10) is a candidate material for the blades. CC utilizes pressure slipcasting to compact the silicon nitride powder, machining of presintered material to the component shape and hot isostatic pressing (HIP) to densify the components.

The assessment of GN-10 silicon nitride for CSGT blades addressed several key issues:

1. Material properties versus engine requirements
2. Maturity of the fabrication process recommended by CC for blades
3. Which material grade or revision to use
4. Strength of machined versus as-fabricated surfaces

Items 1 and 2 are discussed in subsequent sections on fabrication (Section 5.3) and database (Section 5.4). Items 3 and 4 are discussed in the following paragraphs.

Selection of GN-10 Material Grade

CC has conducted extensive process development to achieve a viable fabrication process which yields reproducible GN-10. The present process is referred to as Revision 17, which was adopted in the first quarter of 1992. Figure 5-1 which compares the flexural strength as a function of test temperature for samples cut from AGT 101 rotors made by revisions 17 and 15 illustrates the improvements that have been made. Further refinements are still in progress, such as improvement in Weibull modulus, yield and shape forming capability.

Machined Versus As-Fabricated Surfaces

Solar's current blade design has a machined root and an as-HIPed airfoil. Table 5-1 compares the flexural strength of GN-10 in various machined and unmachined states. The blade root will be machined in a manner that makes the residual stresses similar to those of a transversely machined component. Based on the data available, it appears that transversely machined GN-10 with a post-machining oxidation treatment is acceptable to provide high probability of survival of the blade attachment region. Further analysis will be necessary to assess airfoil life, with emphasis on time dependent material behavior at engine temperatures and stresses. Based on the latest design stresses it may become necessary to machine parts of the blade airfoil.

Kyocera Industrial Ceramics Corporation (KICC)

The assessment of KICC's silicon nitride materials for the CSGT blades addressed key issues similar to those discussed for CC:

1. Material properties versus engine requirements
2. Component fabrication experience
3. Selection of SN-252 or SN-253
4. Effect of surface condition on properties
5. Resistance to long term creep and slow crack growth

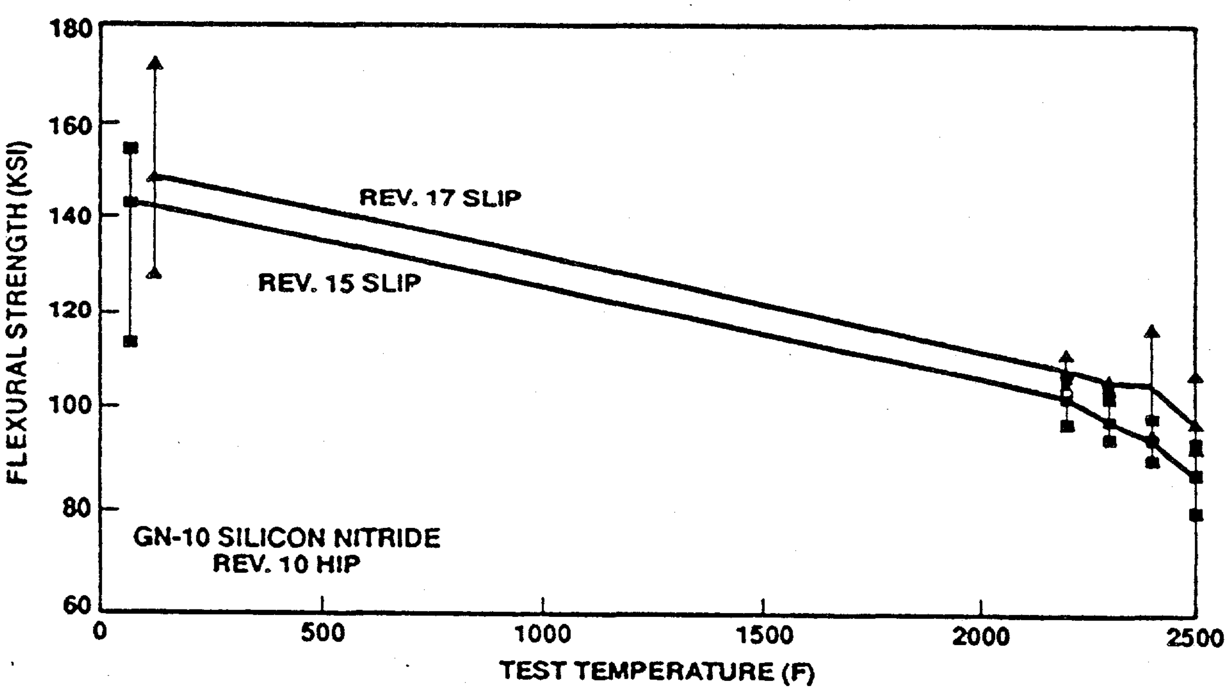

Figure 5-1. Flexural Strength as a Function of Temperature for GN-10 Components Made by REV 15 and REV 17[1]

Table 5-1. Effect of Surface Condition on Strength of GN-10[1]

Machined State	Oxidized	RT Flexural Strength in MPa (ksi)	Machined State	Oxidized	RT Flexural Strength in MPa (ksi)
Regular Machined	No	916 (132.9)	Transverse Machined	Yes	896 (130)
Regular Machined	Yes	883 (128.2)	As-HIPed	No	541 (78.5)
Transverse Machined	No	462 (67)	As-HIPed	Yes	537 (77.9)

SN-252 versus SN-253

SN-253 is a relatively new improved Si_3N_4 material which KICC recommends as a candidate for both blade and nozzle applications. SN-253 has a higher strength than SN-252 in both the machined and the as-processed condition, but can be processed from the same tooling as SN-252. SN-253 is presently being evaluated at the University of Dayton Research Institute (UDRI) as part of a DOE/ORNL funded evaluation.

A factor of importance in comparing SN-252 and SN-253 is the difference in the Weibull modulus of the two materials at elevated temperatures. SN-253 appears to have an m value of 20-28 in the 1000 to 1400°C (1832 to 2552°F) range, reportedly an improvement over the SN-252. Component evaluations performed in Japan confirm the improved characteristics. A major advantage of the SN-253 material is the improvement in strength properties in the as-fired condition. At elevated temperatures the as-fired strength approaches the machined strength. Figure 5-2 shows that SN-253 has better stress rupture properties in the machined condition than SN-252. The only disadvantage of SN-253 is that an adequate database is currently still limited.

In final selection SN-253 was the material of choice for the blade, because of the higher strength properties in both fast fracture and slow crack growth. The physical and the thermal properties of the two materials are very similar. A key task will be the subsequent life prediction analysis.

Effect Of Surface Condition on Properties

SN-252 has longitudinal machined average strength of 615 MPa (89.3 ksi) and as-fabricated average strength of 470 MPa (68.1 ksi). SN-253 has longitudinal machined average strength of 724 MPa (105.2 ksi) and as-fabricated average strength of 583 MPa (84.6 ksi). Even though the materials were not HIPed, they still exhibit a substantial difference in strength between machined and as-fabricated surfaces. Data for transverse ground and oxidized samples are being gathered by KICC and will be available soon. Based on the data supplied so far, the SN-253 material appears superior to the older SN-252 material.

Time Dependent Property Degradation

Stress rupture flexural test results have been promising for both KICC materials. As-machined samples have survived over 100 hours at 1200°C (2192°F) for SN-253 at over 482 MPa (70 ksi) and for SN-252 at about 445 MPa (65 ksi). As-fabricated SN-253 has also survived over 100 hours at 1200°C (2192°F) and over 482 MPa (70 ksi) in the slow crack growth regime. This should provide substantial margin for the rotor blades. Creep rates and oxidation rates also appear to be acceptable. The high temperature stability suggests that SN-252 and SN-253 are also viable alternate materials for the nozzle.

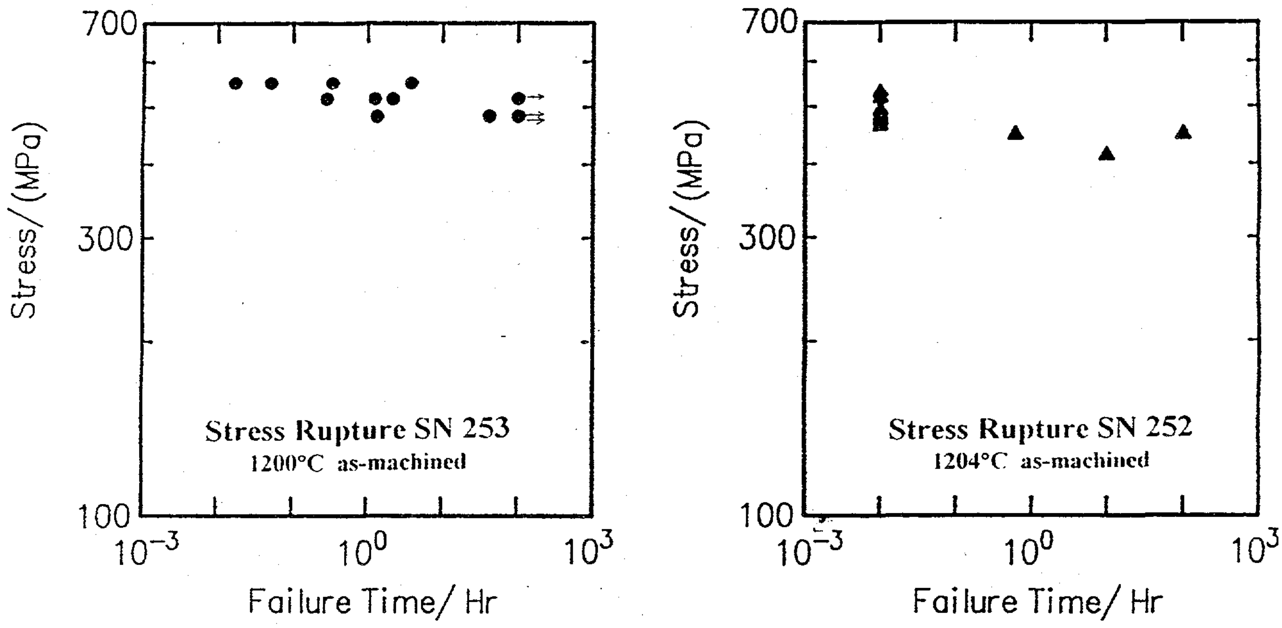

Figure 5-2. Comparative Stress Rupture Properties of SN-252 and SN-253 Silicon Nitrides[2]

Norton Advanced Ceramics (NAC)

NAC's NT154 and NT164 grades of silicon nitride are candidates for the rotor blades and the nozzles. These materials were selected because of their combination of physical, thermal and mechanical properties which limit thermal stresses and resist mechanical stresses. Specifically, these favorable properties include low density ($\approx$3.2 g/cm^3), low coefficient of thermal expansion ($\approx$3.92x10^{-6}/°C; 2.18x10^{-6}/°F), moderate elastic modulus (315 GPa, 45 Msi), high room temperature tensile strength (> 700 MPa; >100 ksi), moderate high temperature tensile strength (up to 574 MPa; over 80 ksi at 1200°C/~2200°F), high fracture toughness compared to other monolithic ceramics (5.4 MPa.m$^{0.5}$;$\approx$5.0 ksi.in$^{0.5}$) and moderately high thermal conductivity (37.6 W/mK at room temperature). A second criterion for selection of NT154/NT164 was fabrication capability. NAC has demonstrated that high quality gas turbine engine components can be fabricated to near-net-shape from both NT154 and NT164.

Several key issues have been identified during the assessment of the NAC silicon nitride materials:

1. Which grade and revision should be specified for the CSGT program based on properties and fabrication process maturity?

2. What are the differences in strength for as-fabricated versus machined material and how should this be handled for analytical life prediction?

3. What potential property degradation might occur over time, and what are the key temperatures and stresses that might activate this degradation in NT154 and NT164?

These issues are discussed in subsequent paragraphs.

Selection of a Preferred NAC Silicon Nitride Grade

The candidate NAC silicon nitride materials are fabricated to the complex turbine component shape by pressure slip casting and densified by hot isostatic pressing (HIP). The fabrication process has evolved over recent years to achieve improvements in properties and reliability of shaped components.

A comparison of properties between NT154 and NT164 shows similarities in the thermo-physical properties. However, while NT154 has higher room temperature tensile strength than NT164, the latter shows better creep and fatigue resistance at elevated temperatures. Figures 5-3 and 5-4 compare time to failure as a function of total strain and applied stress at 1370°C (2498°F) for NT154 and NT164, respectively. For example, at a stress level of 100 MPa (14.5 ksi) NT154 failed in 1216 hours, while NT164 at the same stress level failed after 4800 hours of testing time. Figure 5-5 compares the static fatigue life of NT154 and NT164, showing a definite advantage for NT164 in the creep controlled regime.

NT154 and NT164 both appear acceptable for the rotor blade. NT164 appears superior for the nozzle, especially at the high stresses currently projected by analysis. Questions still exist whether NT164 can be fabricated as reliably as NT154. However, considering the nozzle requirements, NT164 was the material of choice in the final selection.

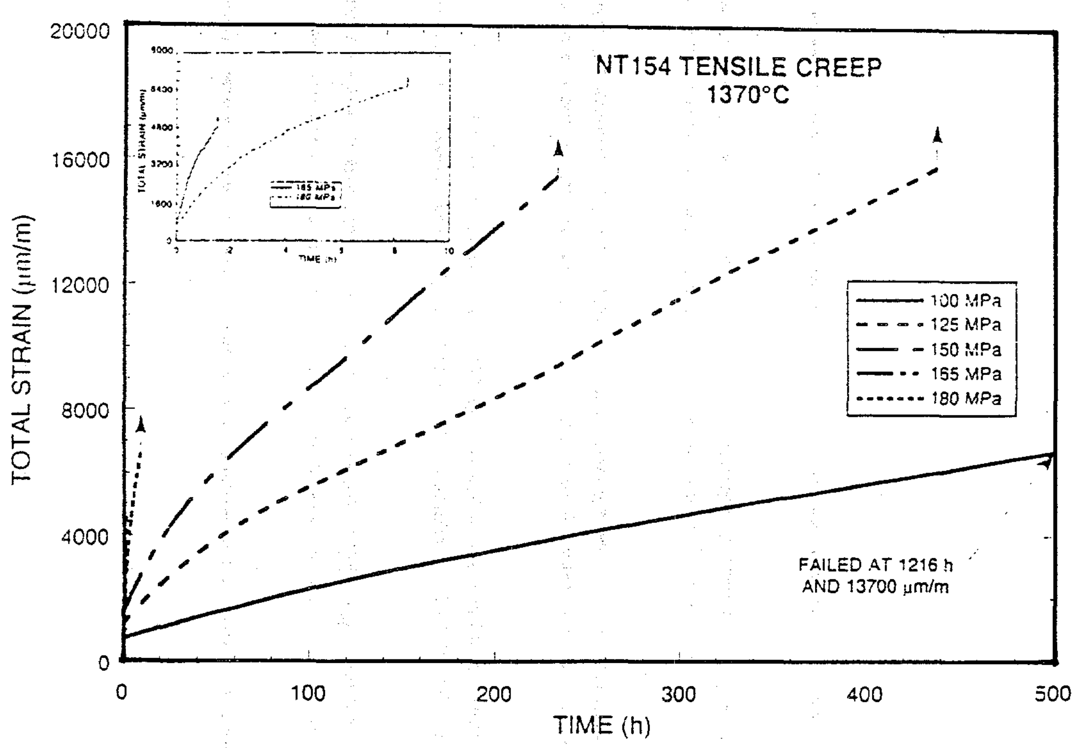

Figure 5-3. Total Strain as a Function of Time and Applied Stress at 1370°C for NT154[3]

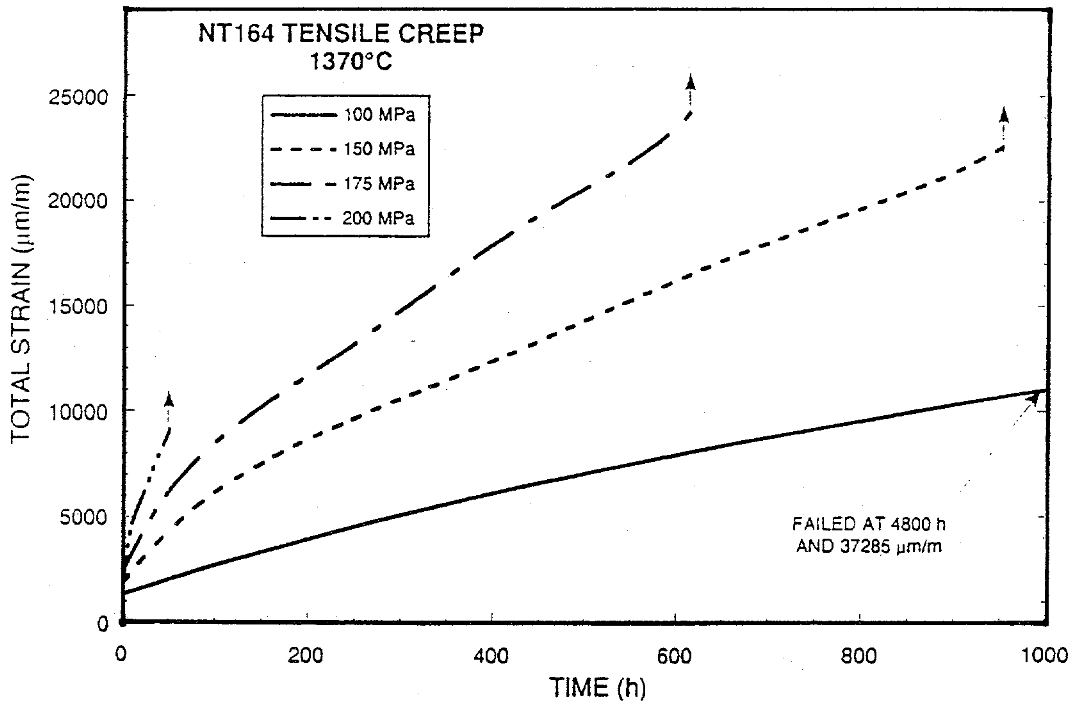

Figure 5-4. Total Strain as a Function of Time and Applied Stress at 1370°C for NT164[3].

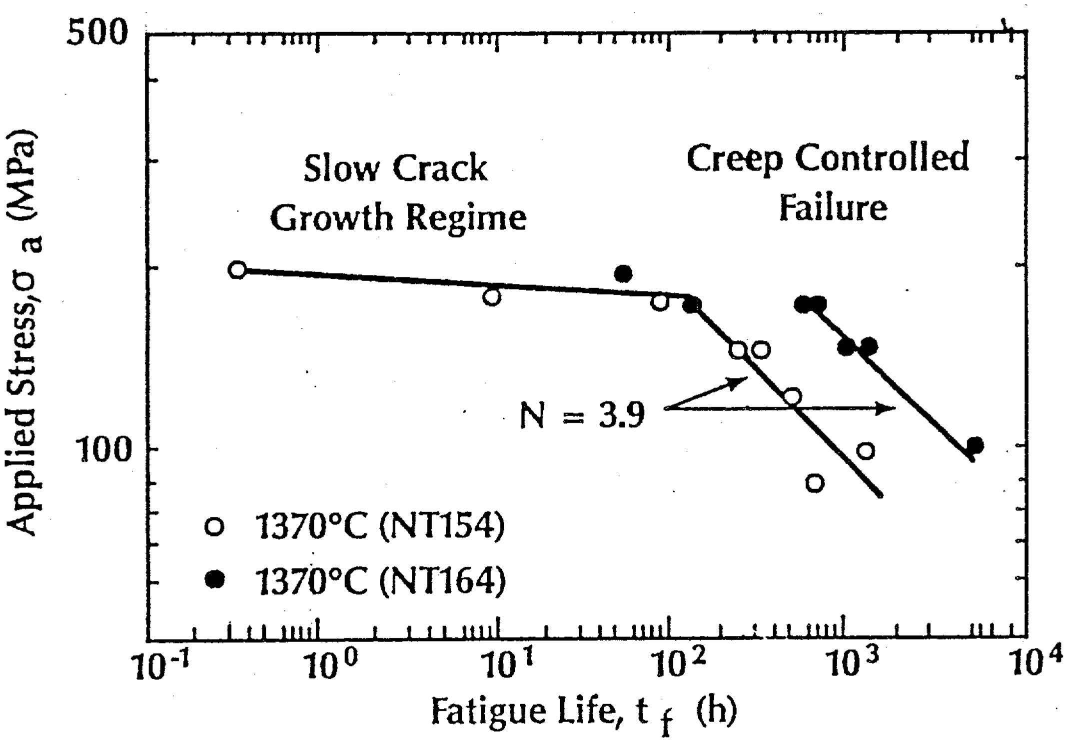

Figure 5-5. Fatigue Life Comparison Between NT154 and NT164 in the Slow Crack Growth and Creep Regimes[4].

Longitudinal Versus Transverse Machining

Most published strength data are for test samples which have been surface ground in the lengthwise direction (longitudinal) with diamond tooling, followed by a high temperature oxidation heat treatment. This procedure results in strengths that are higher than occur for as-fabricated NT154/NT164 material or for specimens ground perpendicular (transverse) to the long axis. A rotor blade will have transverse ground surfaces (relative to the stress during engine operation) in the attachment and as-fabricated surfaces in the airfoil. Similarly, the nozzle airfoil will have as-fabricated surfaces. It is extremely important to conduct life prediction analysis using appropriate strength data for each region of the component.

Table 5-2 compares the typical strength of NT154 and NT164 with different surface conditions. The data are from different lots of material, but still are suitable to illustrate the effects of surface condition. To use the data for NT154 as an example, as-fabricated material has the lowest strength (579 MPa; 84 ksi). This is due to a rough surface and a 0.13 mm (0.005 inch) thick surface layer resulting from interaction between the silicon nitride and glass encapsulant during HIP. The transverse machined material also has a low strength (600 MPa; 87 ksi) due to subsurface cracks resulting from the machining. A post-machining oxidation heat treatment removes or blunts the cracks and increases the strength to 799 MPa (116 ksi). The latter conditions should provide high probability of survival for the blade attachment at engine operation conditions.

Table 5-2. Strength Versus Surface Preparation[5]

Process	NT154 (20°C/68°F)	NT154 (1370°C/2499°F)	NT164 (20°C/68°F)	NT164 (1370°C/2499°F)
As Fabricated (4 PT. Flexure Strengths, MPa/ksi)	579 (84)	-	545 (79)	538 (78)
Transversely Machined (4 PT. Flexure Strength, MPa/ksi)	600 (87)	-	-	-
Transversely Machined & Heat Treated (4 PT. Flexure Strength, MPa/ksi)	799 (116)	-	-	-
Longitudinally Machined (4 PT. Flexure Strength, MPa/ksi)	896 (130)	579 (84)	-	-
Longitudinally Machined & Heat Treated (4 PT. Flexure Strength, MPa, ksi)	937 (136)	641 (93)	876 (127)	634 (92)
Longitudinally Machined & Heat Treated, Tensile Strength (ksi)	723 (105)	344 (50)	-	-

Surface Layer Caused by HIPing

As shown in Table 5-2 and discussed above, the lowest strength condition for NT154 and NT164 is the as-fabricated condition. Property data for this as-fabricated condition will be used for all non-machined surfaces for blades and nozzles during preliminary design and life prediction. Life assessment for the "dovetail" blade using the "SPSLIFE" life prediction analysis system from Sundstrand has been performed with a "dovetail" blade partially machined (in the attachment area) as well as with a completely machined "dovetail" blade (see Section 4.3, Figures 4-7 and 4-8). It was found that static fatigue life was reduced because of the lower strength of the as-processed areas of the blade compared to significantly higher strength in the machined areas. This scenario represents a "worst case" analysis and provides a conservative life prediction. However, there is further concern that the as HIPed surface layer might respond in an accelerated fashion to potential time dependent degradation mechanisms such as slow crack growth and oxidation. The sources of these degradation mechanism concerns are the composition of the surface layer and its increased glassy content compared to the bulk NT154/NT164. NAC and Solar are dealing with this issue in several ways:

1. NAC has a high priority internal development program in progress to remove the surface layer uniformly by an abrasive flow process.

2. Solar is preparing a plan to experimentally assess during Phase II whether as-fabricated surfaces lead to accelerated degradation mechanisms, under simulated engine temperatures and stresses.

3. Solar is attempting by design to reduce stress to provide a larger margin of safety.

Volumetric Versus Surface Failures

Another issue for life prediction is volumetric strength versus surface strength. Solar is working with Sundstrand and the materials suppliers to identify the most valid data to represent surface initiated fractures versus fractures initiating at volumetric material defects. Preliminary SPSLIFE and CARES-LIFE data shows surface flaws to be the predominant contributor.

Time Dependent Property Degradation

Fracture occurs instantaneously in a material when a stress is reached which causes a flaw to propagate from an existing defect (such as a crack, pore or inclusion). Fast fracture properties from flexure and tensile strength tests are suitable for analyzing for instantaneous component failure. However, mechanisms exist for ceramics whereby existing defects can grow and new defects can form during the life of the component. This growth leads to time-dependent failure. Potential modes of time-dependent failure are creep, slow crack growth (static fatigue), oxidation, corrosion, stress corrosion and cyclic fatigue. The database for NT154 and NT164 includes limited creep, stress rupture, and oxidation data up to about 1000 hours, but little if any for longer times. Extrapolation of the data suggests that NT154 and NT164 are acceptable for the rotor for the stresses and temperatures presently defined for the rotor blade.

Key Issues for NT230

During the Phase I preliminary design the potential need has been identified for additional components and materials. These new components are combustor liner rings and a nozzle support ring. NAC's NT230 reaction bonded silicon carbide is a candidate material for these components. The advantage of NT230 over other potential candidate silicon nitride and silicon carbide materials is that NAC has the capability to fabricate large integral shapes because of the availability of large furnaces and the relative low shrinkage factor ($\approx$0.5%) for the processing of this material.

The nozzle support ring acts as an intermediary between the individual nozzles and the nozzle support structure. The combustor ring is part of a 4-ring assembly which forms the liner. Since this is an integral ring, primary issues of concern deal with the reduction of average strength because of the increase in stressed volume. Also, the presence of greater than 10% of silicon in this material could be a concern for long life of the component. NAC has indicated that it can fabricate parts of the desired dimensions.

Carborundum

Carborundum Hexoloy® SA silicon carbide is a candidate material for the nozzle and the combustor tile applications. Hexoloy® SA SiC was selected as a candidate for several reasons: (a) higher temperature capability than silicon nitride; (b) good slow crack growth resistance (c) high resistance to creep and stress rupture failure; (c) good thermal shock resistance (although not as good as silicon nitride); and (d) extensive component fabrication and test experience.

The assessment of Carborundum Hexoloy® SA SiC for CSGT nozzles and combustor liner tiles addressed several key issues:

- Fabrication capability status
- Properties at room temperature and elevated temperature
- Fracture toughness
- As-fabricated versus machined strength

Fabrication Status

Hexoloy® SA has been commercially available since the late 1970's and has gone through many iterations of optimization and refinement. The refinements have reduced flaw size in the interior and at the surface of the parts fabricated by pressing/machining, by injection molding and by slip casting. Addition of a post-sintering HIP step has further reduced flaw size and frequency. Post-HIP annealing has reduced the severity of surface flaws for both machined and as-fired Hexoloy® SA SiC. The processing refinements have resulted in improved strengths and improved reproducibility of strength from batch to batch. However, the strengths between room temperature and 1200°C (≈2200°F) are still substantially below those of the high strength silicon nitride materials.

Another fabrication concern is the high temperature of densification. Unsupported material sags. To avoid distortions, fixturing and careful positioning is necessary, especially for a component like the nozzle with a large overhang of the platform. Control of dimensions and tolerances has been a problem reported for Hexoloy® SA SiC parts on prior programs.

High Temperature Stability

Figure 5-6 shows the strength versus temperature curve for Hexoloy® SA SiC at various strain rates. The curves show that the strength is retained at least to 1400°C (2552°F) even at a low strain rate. Figure 5-7 shows the results of cyclic fatigue testing at 1300°C (2372°F) up to 300 MPa (43.5 ksi). Individual samples survived well over 100,000 cycles.[6]

Fracture Toughness

A significant concern with Hexoloy® SA SiC is low fracture toughness. Depending on the measurement technique, values range from about 2.5-3.0 MPa.m$^{1/2}$, compared to about 5.5-7.0 MPa.m$^{1/2}$ for the candidate silicon nitride materials. The fracture stress (σ_f) and the critical flaw size that results in fracture (c_f) are related to the fracture toughness K_{IC} by the equation:

$$K_{IC} = \sigma_f \, Y \, c_f^{1/2}$$

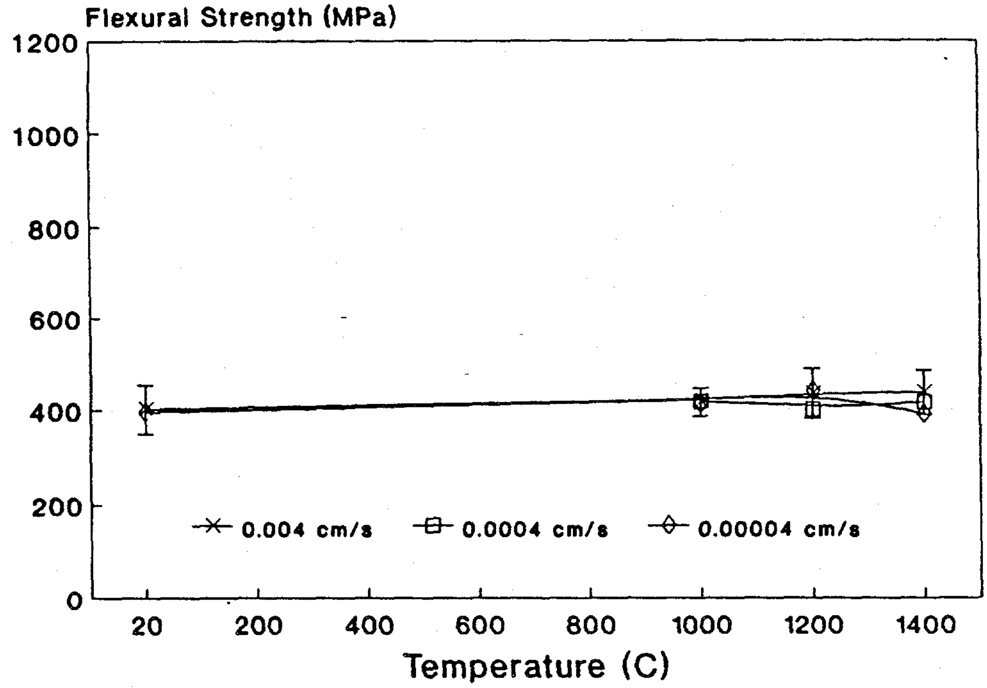

Figure 5-6. Strength Versus Temperature Variation for Hexoloy® SA At Various Strain Rates.

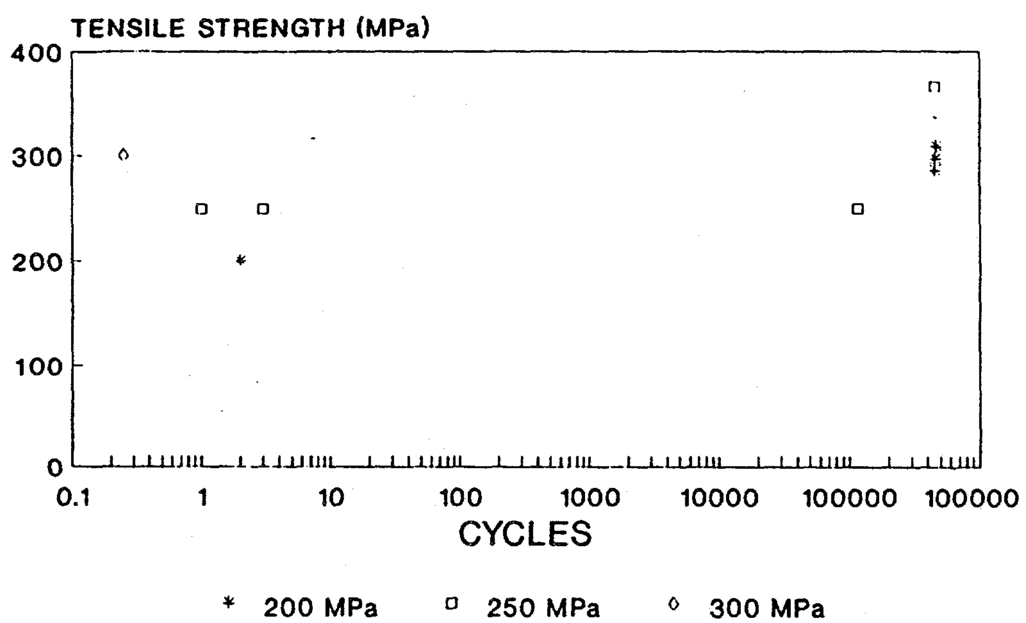

Figure 5-7. Cyclic Fatigue Testing at 1300°C for Hexoloy ® SA up to 300 MPa.

where Y is a dimensionless term determined by the crack configuration and loading geometry. It is apparent by examining the equation that an increase in fracture toughness results in either *increased* stress capability or larger flaw size necessary to cause failure. Specifically, the fracture toughness of the candidate silicon nitride materials is roughly twice that of Hexoloy® SA, so the equation indicates that the fracture stress for silicon nitride should be double that for Hexoloy® SA and the critical flaw size 4 times that for Hexoloy® SA. Efforts during recent years have been directed towards increasing the fracture toughness of SiC. Carborundum has demonstrated a new SiC (Hexoloy SX) with toughness comparable to that of silicon nitride. However, this material has substantial concentrations of yttrium aluminates at the grain triple junctions and limited high temperature stability at T > 1300°C. The Hexoloy SX does not appear at this time to be a viable candidate for nozzles or combustor liner tiles.

As-Fabricated versus Machined Strength

Parts fabricated by injection molding have as-fabricated strength relatively close to the machined strength, i.e. around 480 MPa (≈70 ksi) flexure strength. Slip cast parts typically have substantially lower as fabricated strength on untreated as-molded surfaces. This is illustrated in Table 5-3. The first three rows of Table 5-3 shows the flexure strength of test bars cut from simultaneously processed slip cast test crucibles. The test bars were ground in one of three ways: (a) the surface in contact with the mold was left unmachined (as-fired surface); (b) the inside drain surface was left unmachined; or (c) all sides were machined. The bars were tested after annealing with the unmachined surfaces in tension.

The last line in Table 5-3 shows the strength results from the best surface treatment found in the study. The samples from which the bars were cut underwent a light grit blasting prior to sintering. The grit blasting raised the as-fired strength of the material to 495 Mpa (71.8 ksi) which is essentially the same strength expected of fully-machined Hexoloy® SA. All slip cast components are now grit blasted prior to sintering to provide maximum as-fired material strength.

Table 5-3. Effect of Surface Treatment on the Flexure Strength of Hexoloy® SA[7]

Unground Surface	Nos. Of Tests	Strength, MPa (ksi)	Std. Dev. MPa (ksi)
Mold Surface	10	353 (51.2)	50 (7.2)
Drain Surface	10	461 (66.9)	41 (6.0)
None	8	482 (69.9)	38 (5.5)
Mold Surface (Control)	8	347 (50.3)	50 (7.3)
Treated Mold Surface	11	495 (71.8)	72 (10.4)

Annealing Effects

Carborundum observed in their internal studies, that injection molded Hexoloy® SA components showed a noticeable increase in strength in the annealed state as compared to the unannealed state. A study conducted by Carborundum to corroborate these findings to the slip cast components was carried out in 1989. Unlike injection molded material, there appears to be no significant increase in the flexure strength as a result of annealing at 1250°C (2282°F) for 24 hours. As a consequence of these results, components made via slip casting are not routinely annealed prior to delivery.

NGK Insulators, Ltd. (NGK)

NGK's SN-88 silicon nitride was selected as a candidate nozzle material for several reasons:

- High strength at room temperature and at projected nozzle temperature during engine operation
- High fracture toughness
- Excellent creep and stress rupture resistance
- Reliable performance in prior gas turbine development programs

The database for SN-88 has been obtained primarily from NGK. The NGK policy has been to thoroughly characterize their materials as part of their internal development and commercialization efforts. Data generated at laboratories other than NGK are starting to become available for SN-88. These data correlate well with the NGK data and suggest that the NGK generated data are suitable for use in design and life prediction at Solar. Figure 5-8 shows that SN-88 has similar stress rupture behavior to NT154. The data were obtained by Oak Ridge National Laboratory.

DuPont Lanxide Composites (DLC)

DuPont Lanxide Composites has licensed the Chemical Vapor Infiltration (CVI) technology from the French Company, Société Européene de Propulsion (SEP) for processing of composites. One advantage of this technology is the ability to produce uniform materials throughout the working volume of large commercial CVI furnaces. DLC's Pencader facility furnaces can easily accommodate the 76 mm (30 inch) diameter outer integral combustor liner design.

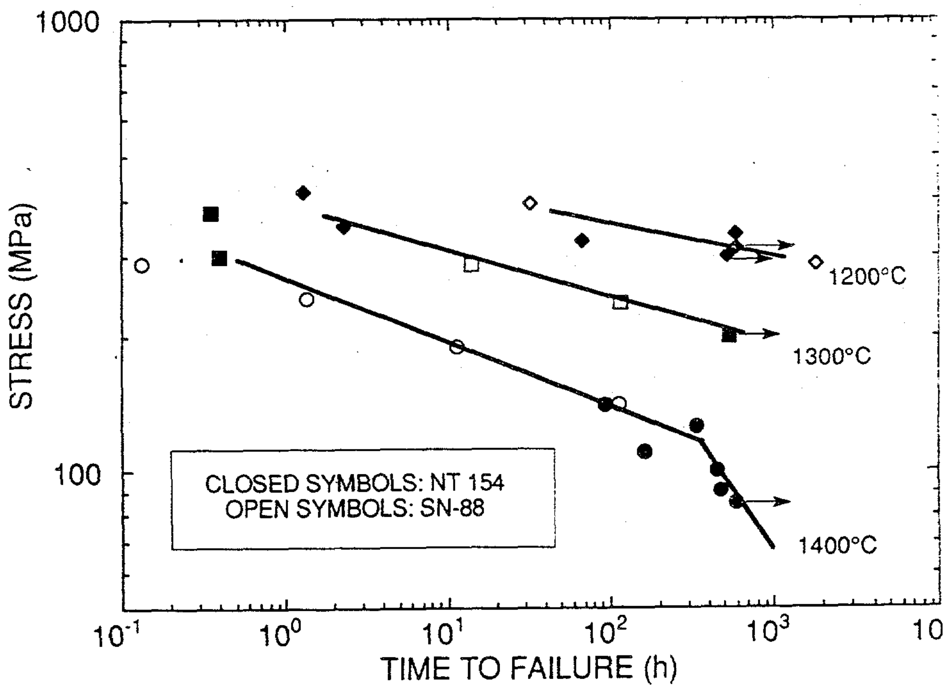

Figure 5-8. Time to Failure Comparisons Between NT154 and NGK SN-88[8]

DLC recommends their continuous fiber-(Nicalon) reinforced modified SiC matrix composite for the combustor liner application. This material has greater oxidation resistance and better mechanical properties retention than their standard SiC/SiC CFCC material. The fiber is in a balanced, plain weave fabric form. To form the combustor liner, plies of fabric are laid up in a 0°\90° orientation on a mandrel to the desired thickness. Thicknesses of 5 mm (0.2 inch) and less are most suitable for the CVI process, but greater thicknesses can also be achieved. The preform is first infiltrated with a coating of carbon. Then it is repeatedly infiltrated with SiC until the composite density is sufficient. The carbon coating keeps the matrix from forming too strong of a bond to the fiber, so that the composite will exhibit "graceful" failure. DLC plans to coat the combustor as a secondary safety against oxidation damage of the composite. The advantage of the modified matrix is that if cracks or chips form in the coating, the exposed composite will have greater oxidation resistance than the standard matrix.

DLC has supplied an extensive database on the standard SiC/SiC material. The properties that have been requested are listed in Tables 5-4 and 5-5. Work is currently being done to provide a similar database for the modified material. DLC will estimate some properties from the standard material values, which they can do with confidence. The key issues for the DLC material are cost and oxidation resistance.

Babcock & Wilcox (B&W)

B&W is recommending an alumina/alumina continuous fiber reinforced ceramic matrix composite (CFCC) for the combustor liner. The composite is fabricated by filament winding a preform, which is infiltrated with the matrix material using a sol-gel technique. To control the fiber/matrix interface properties, an in-situ sol-gel SnO_2 coating is applied to the fiber preform. Desired density levels are usually reached in fifteen infiltration cycles.

The recommended material has a porosity level of 23 percent. This high level of voids was chosen because B&W alumina/alumina composites with lower porosity do not exhibit graceful failure. The 23 percent porosity material has high permeability. Solar's Combustion Engineering Department indicated that this will not be a design concern. However, the effects of permeability should be investigated during the design of the combustor with this composite.

Testing is continuing on the recommended alumina/alumina material. Cleveland State University (CSU) will be generating a Weibull tensile modulus. Other tests that are being run are listed in Table 5-6. Some properties will be determined both from flat coupon tests at B&W and CSU and from ±45° tubes tested at Virginia Polytechnical Institute (VPI). Key issues for the B&W material are lack of property data and uncertainty about long term response to gas turbine conditions.

Ceramic Component Suppliers Selection

Property data and information on component fabrication experience have been gathered for each candidate material from the literature and from discussions with suppliers, test laboratories, and gas turbine engine companies.

Table 5-7 shows the candidate ceramic materials selected for each of the components. Based on the assessment of current status of these materials, it was concluded that these ceramics offer promise for the components identified at the beginning of Phase I. Design iterations have resulted in additional components (like the ring adjacent to the nozzle structure, and the pin going through the nozzle boss). Solar recognizes that the key ceramic materials are going through a stage of refinement and that materials selection discussion (such as which process revision to use for a spec-

Table 5-4. Thermal Properties Required for Combustor Analysis

Property	Temperature	Orientation
Coefficient of Thermal Expansion	RT to 1260°C (2300°F)	Longitudinal
Coefficient of Thermal Expansion	RT to 1260°C (2300°F)	Transverse
Coefficient of Thermal Expansion	RT to 1260°C (2300°F)	Through Thickness
Thermal Conductivity	RT to 1260°C (2300°F)	Longitudinal
Thermal Conductivity	RT to 1260°C (2300°F)	Transverse
Thermal Conductivity	RT to 1260°C (2300°F)	Through Thickness
Specific Heat	RT to 1260°C (2300°F)	

Table 5-5. Mechanical Properties Required for Combustor Analysis

Property	Temperature	Orientation
Matrix Cracking Tensile Strength	RT, 1260°C (2300°F)	Longitudinal
Matrix Cracking Tensile Strength	RT, 1260°C (2300°F)	Transverse
Ultimate Tensile Strength at Two Rates	RT, 1260°C (2300°F)	Longitudinal
Ultimate Tensile Strength at Two Rates	RT, 1260°C (2300°F)	Transverse
Tensile Modulus at Two Rates	RT, 1260°C (2300°F)	Longitudinal
Tensile Modulus at Two Rates	RT, 1260°C (2300°F)	Transverse
Tensile Strain at Failure at Two Rates	RT, 1260°C (2300°F)	Longitudinal
Tensile Strain at Failure at Two Rates	RT, 1260°C (2300°F)	Transverse
Poisson's Ratio	RT, 1260°C (2300°F)	Longitudinal
Poisson's Ratio	RT, 1260°C (2300°F)	Transverse
Across-Ply Tensile Strength	RT	Through Thickness
Interlaminar Shear Strength	RT, 1260°C (2300°F)	Longitudinal
Shear Strength	RT, 1260°C (2300°F)	Longitudinal
Shear Modulus	RT, 1260°C (2300°F)	Longitudinal
Compressive Strength	RT, 1260°C (2300°F)	Longitudinal
Compressive Strength	RT, 1260°C (2300°F)	Transverse
Compressive Modulus	RT, 1260°C (2300°F)	Longitudinal
Compressive Modulus	RT, 1260°C (2300°F)	Transverse
4-Point Flexure Strength	RT, 1260°C (2300°F)	Longitudinal
Oxidation Resistance (Residual Strength)	1260°C (2300°F)	Longitudinal
Thermal Fatigue	1260°C (2300°F)	Longitudinal
Tensile Stress Rupture	1260°C (2300°F)	Longitudinal

ific lot of components) will have to be made throughout the program. This will require a close working relationship between Solar and the ceramic component supplier team members. It will also require a formal protocol for qualifying a material revision for Solar use and a quality assurance methodology acceptable to Solar.

5.3 COMPONENT FABRICATION PLANS

Solar and each selected supplier have met and reviewed the required test samples and prototype configurations, quantities, and delivery schedules. The suppliers have provided to Solar detailed plans for fabrication, QA, and delivery of each item. Details from these plans are excerpted in this section.

Solar Fabrication Planning Review

Solar reviewed with the suppliers the plans for fabrication, delivery of simulated blades for early testing, full blades for cold and hot spin testing, nozzles and simulated nozzles, tiles and rings for combustors, integral CFCC combustor liners and test bars for certification. Flexural bars for oxidation testing and tensile bars for creep studies have also been included in the fabrication plan.

Table 5-6. Test Plan for B&W Oxide/Oxide Material

Property	Orientation	Specimen Geometry
Coefficient of Thermal Expansion	Longitudinal	Flat Coupon
Coefficient of Thermal Expansion	Transverse	Flat Coupon
Thermal Conductivity	Longitudinal	Flat Coupon
Thermal Conductivity	Transverse	Flat Coupon
Emissivity		Flat Coupon
Tensile Modulus (RT)	Longitudinal	Flat Coupon, ±45° Tube
Ultimate Tensile Strength (RT, 1800°F, 2100°F)	Longitudinal	Flat Coupon
Tensile Modulus (RT)	Transverse	Hoop Wound Tube, ±45° Tube
Ultimate Tensile Strength (RT)	Transverse	Hoop Wound Tube
Tensile Modulus (1800°F, 2100°F)	Longitudinal	Hoop Wound Tube, ±45° Tube
Tensile Modulus (1800°F, 2100°F)	Transverse	Hoop Wound Tube, ±45° Tube
Poisson's Ratio (RT)	Longitudinal	±45° Tube
Compressive Modulus (RT)	Longitudinal	Flat Coupon
Ultimate Compressive Strength (RT)	Longitudinal	Flat Coupon
Compressive Modulus (RT)	Transverse	Hoop Wound Tube
Ultimate Compressive Strength (RT)	Transverse	Hoop Wound Tube
Compressive Modulus (1800°F, 2100°F)	Longitudinal	Hoop Wound Tube
Compressive Modulus (1800°F, 2100°F)	Transverse	Hoop Wound Tube
Shear Modulus (RT, 2100°F)	Longitudinal	±45° Tube
Shear Strength (RT, 2100°F)	Longitudinal	±45° Tube
Shear Modulus (RT, 2100°F)	Transverse	Hoop Wound Tube, ±45° Tube
Shear Strength (RT, 2100°F)	Transverse	Hoop Wound Tube, ±45° Tube

Table 5-7. Candidate Ceramic Materials

Supplier	GCC	Carborundum	NAC	KICC	DuPont	B&W	NGK
Blades	GN-10	-	NT164	SN-253	-	-	-
Nozzles	-	Hexoloy® SA	NT164	SN-253 BACKUP	-	-	SN-88
Combustor	-	Hexoloy® SA	NT230		SiC/SiC	Al_2O_3/Al_2O_3	

Test specimens will be produced in a consistent fashion by all the suppliers, meaning that the direction of grinding, the dimensions of the specimen, etc., will be the same from each supplier. The designs of ancillary components made of silicon nitrides and silicon carbides have evolved since the fabrication plans were submitted by the suppliers. Further discussions on including these components in the fabrication planning are currently in progress. These discussions are being pursued as part of the Phase II effort. First generation blade, nozzle and combustor sketches with adequate details were submitted to the suppliers before the fabrication plans were submitted. Although these drawings are close enough to the current design, the evolving nature of these designs may result in alterations in the fabrication plans. The following sections review the fabrication process recommended for each component by each supplier, describe some of the background experience of each supplier (and the degree of confidence in fabrication of CSGT parts), and identify the status of quality assurance systems at each supplier.

AlliedSignal Ceramic Components Blade Fabrication

Figure 5-9 is a flow chart of the process CC will use to fabricate blades for the CSGT program. The forming steps consist of pressure slip casting a rectangular block of silicon nitride of the GN-10 composition, presintering (to achieve enough strength to allow green machining), green machining the airfoil and upper platform, full densification by hot isostatic pressing (HIP), and diamond grinding of the attachment and other reference surfaces to achieve final tolerances.

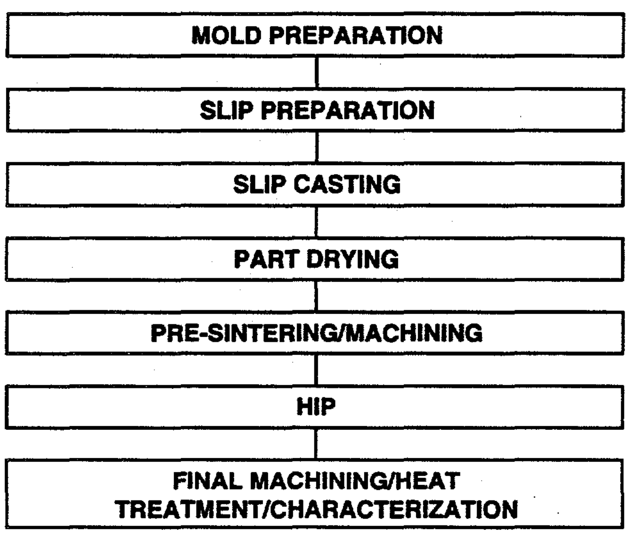

Figure 5-9. CC Blade Fabrication Process For Blade

CC can also achieve the blade shape using cold isostatic pressing to compact the powder into a rectangular block, but has chosen the pressure slip casting approach because: (1) it results in better mechanical properties, (2) it has potential for evolution into near-net-shape capability and low production cost and (3) a more extensive database for slip cast GN-10 exists.

CC has extensive fabrication experience with preparation of tooling for slip casting complex turbine components and with successfully conducting the slip casting, drying and other steps of the process to achieve an acceptable component. This experience dates from the fabrication of radial turbocharger rotors in the late 1970's to AGT radial rotors throughout the 1980's to a variety of advanced design components in the 1990's. This experience has been paralleled with substantial improvements in materials strength both in test bars and in components. For example, early AGT radial rotors failed at less than 50,000 rpm, but later ones survived over 100,000 rpm. From a materials property perspective, early CC materials compositions had oxidation, high temperature strength and stress rupture limitations, whereas the current GN-10 material has improved high temperature strength and stress rupture life and should meet the needs of the CSGT program for the ceramic blade.

Although GN-10 has acceptable properties for the rotor blades, and components have been fabricated which survived as turbine rotors and turbine nozzles in developmental engines, CC is still at an early stage in establishing a production manufacturing capability. CC is at the stage of verifying reproducibility, defining and implementing a quality assurance system and scaling up. The following discussion addresses the current state of quality assurance at CC and describes the quality plan relevant to the CSGT program.

CC is presently controlling their process in an R&D mode, but are transitioning to a production mode. Key variables in each step of the process have been identified and key measurements to monitor these variables have been established. CC has conducted many development iterations to obtain control over these key variables. For example, a reproducible powder supply is always a problem in development of ceramics. GCC has worked closely with suppliers to establish a specification and verify that the suppliers can reproducibly deliver powder within the specification.

CC has a commitment to a formal Quality Assurance System and is in the process of establishing one to meet MIL-I-45208 by the end of May, 1993. They have completed a Quality Manual, are providing training to all their personnel and are implementing production-level QA procedures into their fabrication process. The procedures include a Customer Requirements Data Pack which accompanies each batch of product. It includes a traceability cover sheet, a detailed inspection plan, dimensional/marking instructions and a revision record. The Quality Manual (which is presently being drafted) includes the following: (1) Introduction, (2) Distribution, (3) Change and revision control, (4) Quality control function, (5) Purchasing control, (6) Raw material control, (7) Receiving inspection, (8) In-process inspection, (9) First article inspection, (10) Manual control and description/distribution, (11) Final item inspection control, (12) Inspection stamp control, (13) Corrective action control, (14) Customer furnished material, (15) In-house audit system, and (16) Packaging/handling/shipping control.

In summary, Solar believes that CC has a fabrication process and experience base to success-fully achieve acceptable rotor blades for the CSGT program and is implementing a Quality System that will meet future production standards. CC will have MIL-I-45208 certification by the end of May 1993 and is working toward ISO-9000 certification by December 1994. One present concern is the viability of the selected fabrication process (machining from a presintered block) as a future production process. GCC believes it can be viable, but is conducting parallel development on an alternate process/material. This involves near-net-shape pressure slip casting (to eliminate bisque machining) and gas overpressure sintering (to eliminate the need for encapsulation and HIP). This will eliminate several process steps and reduce the cost of other process steps. Furthermore, the resulting material (designation AS-800) will have higher toughness, better surface finish, and as-processed strength nearly equal to machined strength.

Kyocera Industrial Ceramics Corporation Blade Fabrication

Figure 5-10 is a flow chart of the process that KICC will use to fabricate SN-253 silicon nitride blades for the CSGT program. The shape is achieved through a proprietary Hybrid Molding Process that can provide the complete blade to near-net-shape or can leave the attachment as a "generic shape" from which developmental configurations can be machined. The Hybrid Molding Process utilizes a suspension of silicon nitride powder in a fluid plus special organic additives which are critical to the shape forming step. The organic additives are removed after forming and prior to densification (sintering). The sintering step does not utilize encapsulation. As-sintered parts have good surface finish and acceptable strength.

KICC has extensive experience with the Hybrid Molding Process for fabricating complex turbine shapes. KICC's sister division in Japan has demonstrated manufacture of up to 30,000 silicon nitride turbocharger rotors (integral radial turbine rotor shape) per month using the Hybrid Molding Process. The CSGT blade represents a smaller, simpler shape and is not anticipated to pose any fabrication problems.

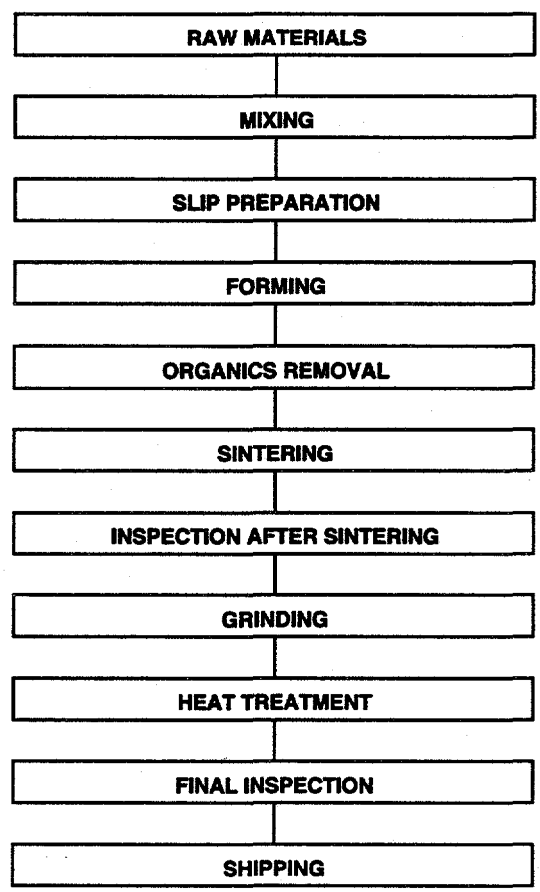

Figure 5-10. Blade Fabrication Flow Chart for Kyocera SN-253

Quality assurance is a top priority at KICC. The company philosophy of Total Quality Management seeks commitments of all staff within the organization together with suppliers, distributors and customers to achieve product quality conformance. A Total Quality Management System is well established at Kyocera in Japan and is being implemented at the new KICC facility in Vancouver, Washington, where the CSGT blades are planned to be manufactured. The system at KICC is using guidelines from ANSI/ASQC Q91, ISO 10012-1, MIL-Q-9858A and MIL-STD-45662. KICC plans ISO 9002 certification by April 1995.

KICC has provided a quality plan to Solar which details its methodology for QA and describes the specific controls and documentation. Much of the information is proprietary and shall not be disclosed. In general, KICC defines all procedures in their QA Manual and monitors each batch of product through Control Documents. These Control Documents include a detailed Process Specification, detailed Process Control Procedures and a Lot Card (with sign-off responsibilities). These provide the specific instructions for each step in the fabrication process, numerical comparisons between specified control points and measured data, and signed-off records of the process and raw materials traceable to each batch of product.

In summary, Solar believes that KICC is capable of meeting all the development needs of the CSGT program and has already demonstrated production levels comparable with those anticipated for subsequent commercialization of CSGT engines. The only concern is one of timing, ie., whether KICC will encounter problems or delays in transfer of technology from Japan and in start-up of the Vancouver, WA facility. However, if difficulties or delays are encountered, KICC can obtain assistance from its facilities in Kokubu, Japan.

Norton Advanced Ceramics Blade and Nozzle Fabrication

Figure 5-11 is a flow chart of the process that Norton Advanced Ceramics (NAC) will use to fabricate rotor blades and nozzles of their NT164 grade of silicon nitride for the CSGT program. The components will be formed to near-net-shape using pressure casting followed by hot isostatic pressing (HIP) using glass encapsulation technology licensed from ASEA. The final tolerances and surface finish will be achieved by grinding with diamond tooling. A proprietary post HIP heat treatment will be conducted to achieve crystallization at grain boundaries to optimize stress rupture and creep resistance properties. A post-machining oxidation treatment will be conducted to increase strength by removing/healing near-surface grinding damage.

NAC has been a major participant in the Advanced Turbine Technology Applications Project (ATTAP) since 1987. This program stimulated and supported substantial improvement in the properties and fabrication capabilities of NT154 and its subsequent development into NT164. Under the ATTAP program, NAC delivered 10 radial rotors (cross section of about 13 cm) to Garrett Auxiliary Power Division (GAPD) for proof testing. All 10 passed the 105,000 rpm proof test to qualify for engine testing. Successful engine testing was conducted in 1992. Two rotors were purposely spin tested to failure. Both failed at about 132,000 rpm, about 140 % of maximum engine speed, demonstrating that the material had substantial design margin.

NAC has also supplied engine-quality integral rotors to the Allison ATTAP program since 1990. Thirteen were NT154 and five were NT164 grade. All survived the 80,000 rpm proof test, and one has accumulated over 200 hours of hot rig testing at temperatures over 1300°C (2372°F). This has included over 1900 start/stop cycles.

NAC has also fabricated individual rotor blades designed for insertion into a metal hub. This effort was conducted for Garrett Engine Division under an Air Force contract. The blades are of a size similar to the Solar requirement and with an attachment similar to one of the Solar attachment concepts. NAC supplied about 170 blades. Three blades failed overspeed proof testing. Two blades were purposely spin tested to failure in excess of 140 % of engine design speed.

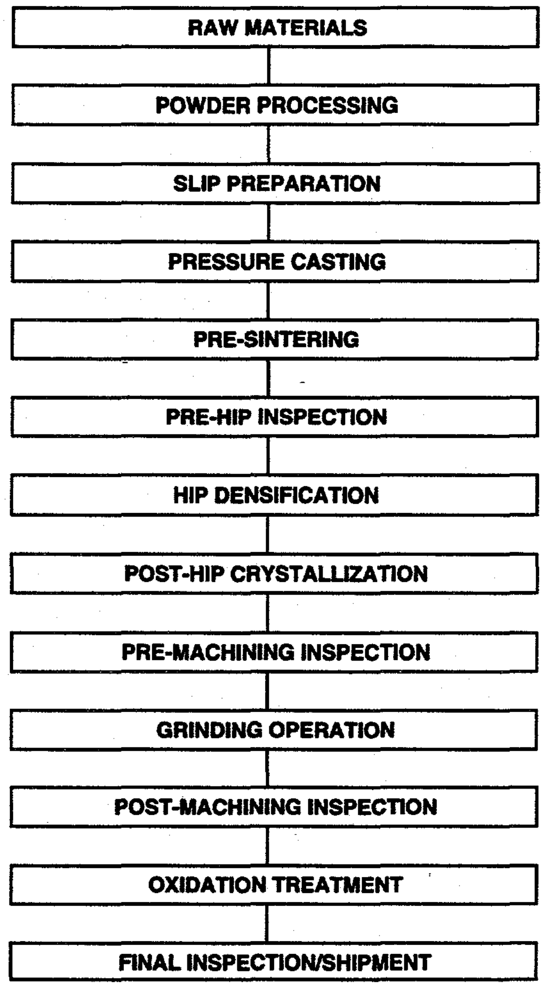

Figure 5-11. Steps for Fabrication of Blades and Nozzles of NT164 at Norton Advanced Ceramics

NAC initiated in 1990 implementation of a comprehensive Quality System under the ATTAP program. NAC has provided to Solar a detailed description of their Quality System. The system includes a Quality Manual, a Quality Organization description, and a Manufacturing Control System description. NAC is considering ISO 9000 certification in early 1996.

The Quality Manual includes: (1) Quality organization and management commitment, (2) Documentation and drawing control, (3) Control of product and process design changes, (4) Identification and control of procured material, equipment and services, (5) Identification and control of in-process materials, (6) Procedures for statistical process control, (7) Completed item inspection and test, (8) Test, measurement, and inspection equipment calibration, (9) Control of non-conforming materials, (10) Corrective action, (11) Collection and analysis of field performance data, (12) Quality information and (13) Contract administration and customer service.

All components and test samples for the CSGT program will be fabricated under the NAC Manufacturing Control System. This includes Standard Operating Procedures, a Job Record File, a Batch Record File, Specifications and In-process and Post-process Control. The Standard Operating Procedure defines each activity during each step of the process plus all measurement requirements and procedures. Process Control includes the documentation that follows each batch of product through the process. This documentation identifies each measurement, what the acceptable range is, and provides for sign-off. Formal procedures are defined for assessing and resolving a non-conformance.

In summary, Solar believes that NAC has a process, Quality System and experience base to successfully fabricate components for the CSGT program and that these parts will have a high probability of meeting CSGT engine requirements.

Carborundum Nozzle and Combustor Liner Tile Fabrication

Figure 5-12 is a flow chart of the injection molding process Carborundum will use to fabricate nozzles of the Hexoloy® SA grade of silicon carbide. The flow chart identifies the critical processing steps (in rectangular boxes) and some of the key in-process quality measurements (in diamond shaped boxes).

Injection molding involves hot mixing of the raw materials with a polymer binder and injecting this viscous fluid mixture at temperature under pressure into a metal mold cavity of the nozzle shape. The polymer binder is then carefully removed and the remaining compact of silicon carbide particles (and sintering aids) densified at high temperature by pressureless sintering. This is followed by hot isostatic pressing (without a requirement for encapsulation) to further increase density and to improve the strength by decreasing the size of failure-initiating material flaws. If the stress in the final nozzle design is low enough, the as-sintered SiC will have adequately low probability of failure and the HIP step will not be required. The Hexoloy® SA SiC is a relatively mature material. It is in large scale production for seals. Although these are not as complex in shape as the turbine nozzles, their production status has resulted in scale-up of many of the fabrication steps relevant to nozzles (powder preparation, sintering, grinding, quality control system). In addition, Carborundum has extensive experience starting in the late 1970s in the fabrication of complex turbine components. Efforts have included radial turbocharger rotors, axial and radial turbine rotors, combustor liners, individual nozzle vanes, scrolls and tip shrouds.

Two approaches have been evaluated by Carborundum for fabrication of combustor liner segments: (1) slip casting and (2) near-net-shape cold isostatic pressing and machining. Slip casting is preferred for thin wall components (up to 5mm/0.20 inch). Near-net-shape isopressing is preferred for greenware with thickness greater than 5 mm/0.20 inch. Other factors also must be considered in selecting between slip casting and isopressing. One is the shape of the combustor tiles and the other is the tolerances. Non-uniform cross section, dimensional control and avoidance of warpage during forming and sintering are easier with near-net-shape isopressing. Carborundum favors the fabrication of Solar combustor tiles by isopressing/machining and will use that approach unless the tile thickness is less than 5 mm/0.2 inch, in which case slipcasting would be used.

Figure 5-13 illustrates the Carborundum process of fabrication of combustor tiles by near-net-shape isostatic pressing. Carborundum has fabricated many prototype turbine components during the past 15 years using isopressing and machining.

The alternate fabrication slip casting process involves suspending particles of the ceramic material in a liquid, pouring the suspension into a shaped porous mold and allowing the fluid to separate from the particles through the mold by capillary action. The particulate compact is then removed from the mold, dried and densified at high temperature. Slip casting can produce complex shapes at low cost with low capital investment. The process is used for fabrication of figurines, mugs, sanitary-ware and many other items in large quantities. For example, over 10 million sanitary-ware parts are produced annually by slip casting.

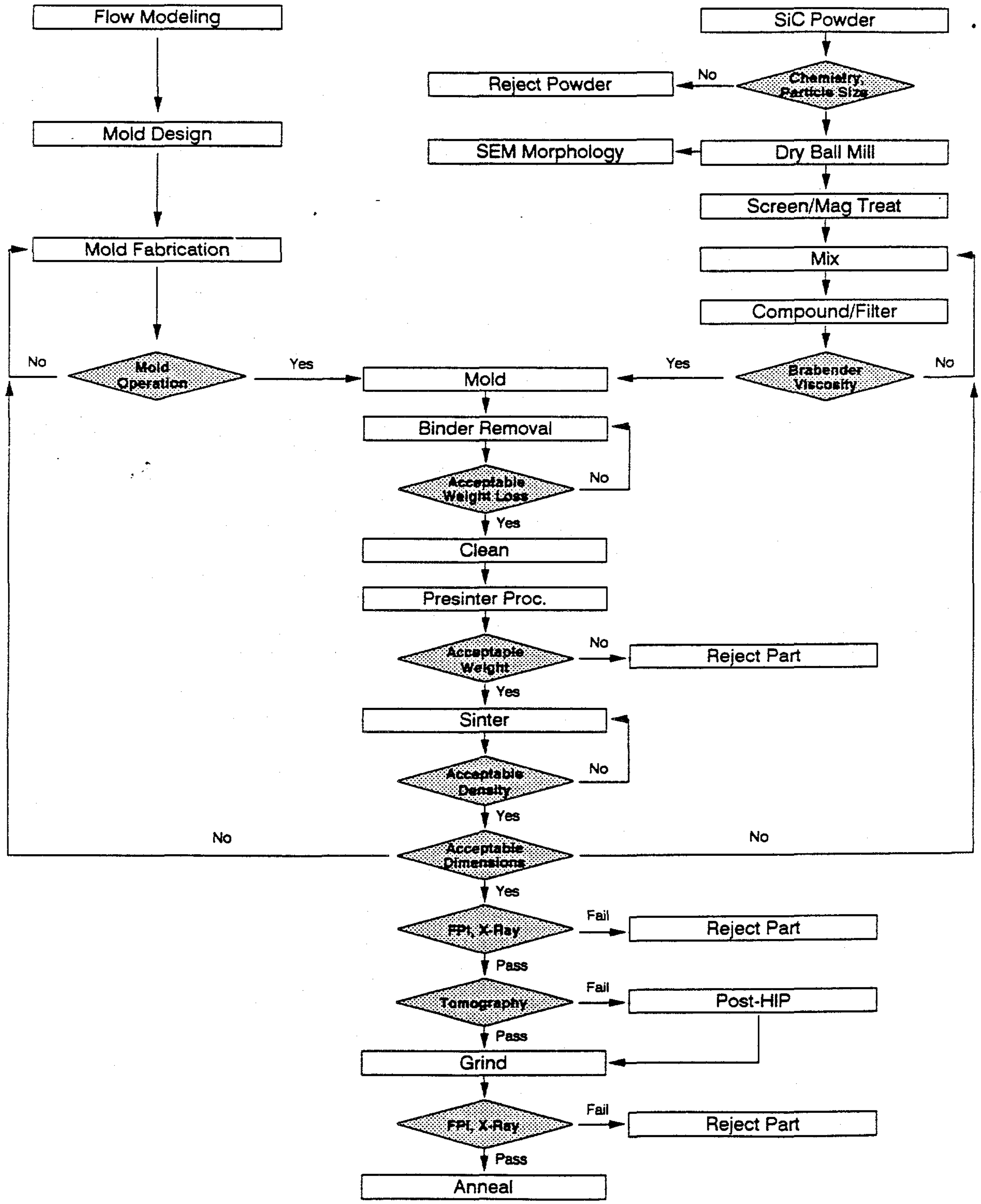

Figure 5-12. Nozzle Fabrication Flow Chart for Carborundum's Hexoloy® SA SiC

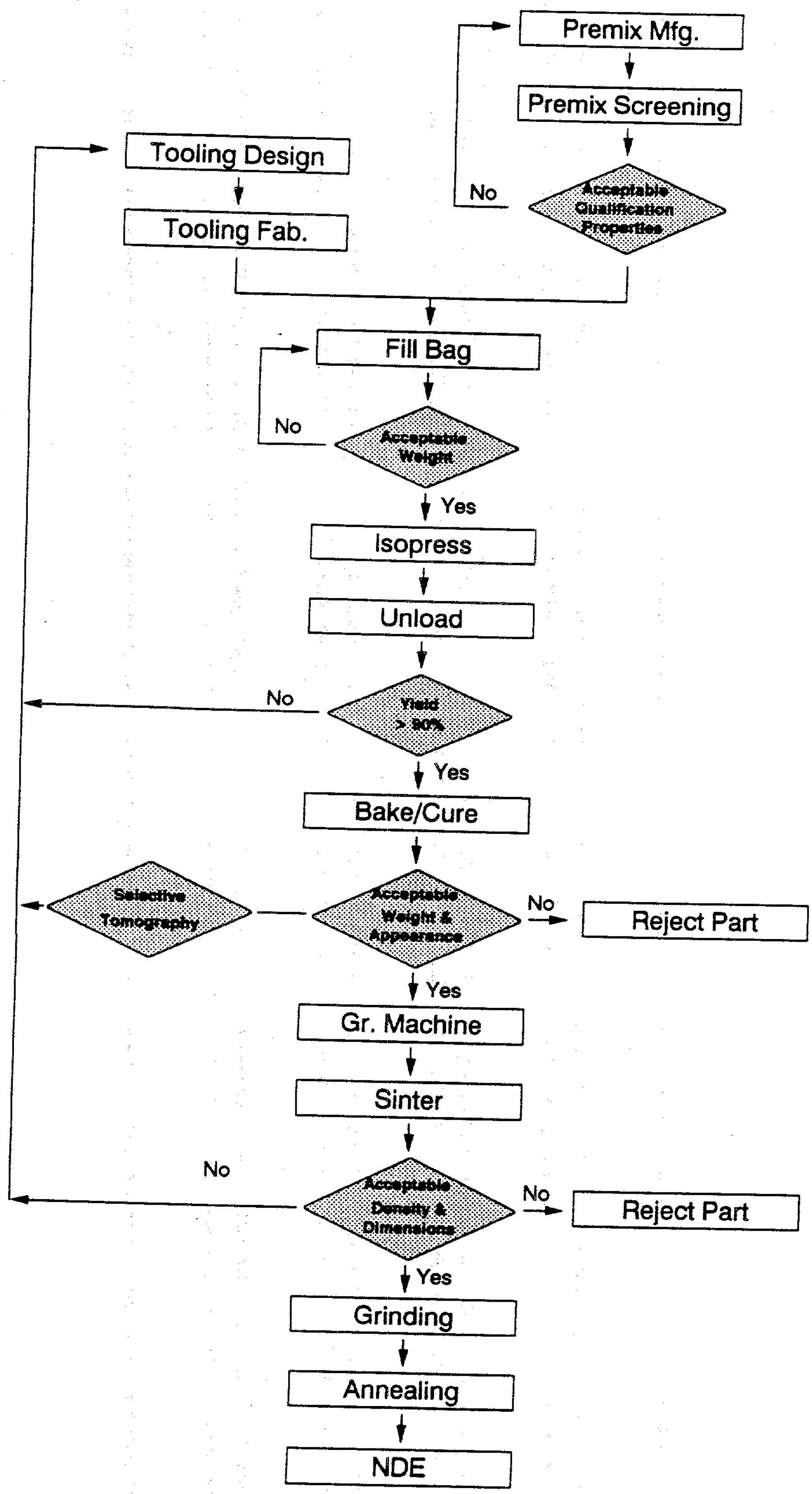

Figure 5-13. Combustor Tile Fabrication Flow Chart for Hexoloy® SA SiC

Carborundum has many years experience in slip casting. This has included many turbine components of Hexoloy® SA SiC during the past 12 years. During this time, Carborundum has identified optimum procedures for each process step and implemented measurements and standards to monitor and control the process. These procedures and standards are documented and a part of the Carborundum Quality System that will be used on the CSGT program.

Carborundum was a major supplier of prototype hardware for the CATE, AGT and ATTAP turbine programs. Quality is a high priority at Carborundum. The company has a program for Total Quality Management using the Malcolm Baldrige criteria. This includes training and daily involvement at all levels for each division of the company, including the Technology Division where the CSGT activities will be conducted. Key managers of the Technology Division are members of the Executive Steering Committee, the Quality Council and the Total Quality Management Support Teams. All employees are receiving quality training. The Technology Division is in the final stages of preparing a Quality System Manual which includes the following: (1) Management responsibility, (2) Quality System, (3) Contract review, (4) Design control, (5) Document control, (6) Purchasing, (7) Purchaser supplied product, (8) Product identification and traceability, (9) Process control (work instructions, cleanliness controls, preventative maintenance), (10) Inspection and testing (procured materials, in-process, final Inspection/test records), (11) Inspection, measurement and testing equipment, (12) Inspection and test status, (13) Control of nonconforming product (documentation, preliminary review disposition, materials review board), (14) Corrective action, (15) Handling, storage, packaging and delivery, (16) Quality records, (17) Internal quality audit, (18) Training and (19) Statistical techniques. The Quality System for the Technology Division is fashioned after the system that has been in use for years in the Carborundum Structural Ceramics Division. The Carborundum Structural Ceramics Division Quality System presently meets most U.S. and foreign standards.

In summary, Solar believes that Carborundum has a process, Quality System and experience base to successfully fabricate nozzles for the CSGT program and that these nozzles will have a high probability of meeting CSGT engine requirements. Furthermore, Carborundum has prior production experience with their Hexoloy® SA SiC material and has selected a fabrication process that is viable for the future levels of commercialization needed for ceramic industrial turbines.

DuPont Lanxide Composites Combustor Liner Fabrication

Figure 5-14 illustrates the general fabrication process that is planned by DuPont Lanxide Composites to fabricate CFCC inner and outer combustor liners by chemical vapor infiltration (CVI). First, a preform of SiC fiber (Nicalon from Nippon) is prepared by braiding or laying up woven layers on a mandrel.

The mandrel provides support for the preform and establishes dimensions. The common present procedure is to wrap layers of a 2-D woven cloth around the mandrel until the desired thickness is achieved. The second step is to deposit a thin layer of pyrolytic carbon on the SiC fiber. This performs as an interlayer to control the bond between the fiber and matrix. The SiC matrix is then deposited by a sequence of CVI cycles. Machining is conducted as needed between cycles and following the final cycle to achieve the desired dimensions.

The final component contains residual open porosity. The porosity plus the pyrocarbon interlayer can result in a composite with inadequate oxidation resistance. DLC has addressed the oxidation problem in several ways. One approach involved internal inhibition through control of chemistry and the process. Another strategy utilized an external coating. Substantial progress has been achieved in both approaches. A test coupon with modified composition/processing (DuPont CVI Modified Matrix material) has survived >4400 hours testing in air at 1204°C (2200°F) at a stress of 80 MPa (11.6 ksi). Coatings have been developed that can provide additional oxidation protection.

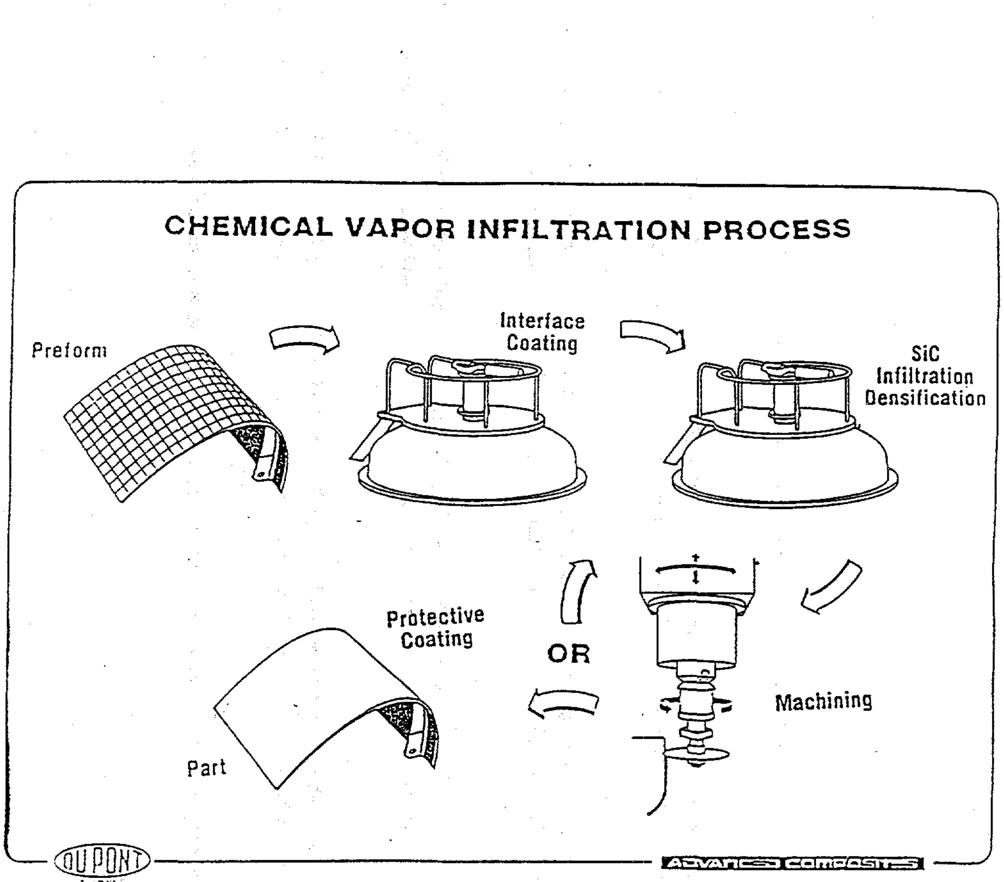

Figure 5-14. General Steps in the DuPont Process for Fabrication of a CVI SiC Continuous Fiber Ceramic Composite.

The DLC CVI process was licensed from the Sóciété Europénne de Propulsion (SEP). Equipment design and process control are relatively mature. The DuPont facility has been in operation since 1989. Parts have been successfully fabricated with a wide range in size and shape: (1) simple cylinders from pencil size to a 7-inch diameter by 42-inch long tube, (2) integrally-stiffened panels of 24 x 24 inches, (3) turbine blades and integral rotors with complex airfoil shapes and (4) rocket thrusters. Present CVI furnaces are capable of producing parts up to 137 cm (4.5 feet) in diameter by 213 cm (7 feet) high, which readily accommodates the Solar combustor liner configurations.

DLC has a comprehensive QA system. The company is currently MIL-I-45208 qualified and customers often require conformance to MIL-Q-9858. DLC places a high priority on QA. The Quality Control department has ultimate responsibility for ensuring the shipment of a quality product. This includes initial quality planning for measurement for each program. The first step is preparation of an Inspection Dimension Report (IDR) which lists each dimension to be measured, the nominal values and allowable tolerance for the measurement and the instrumentation to be used. A Standard Practice defines the proper use of each measurement instrument, and each person is required to complete training courses on Basic Measuring Instrumentation and Geometric Dimensioning and Tolerancing. Calibration of all instruments is checked routinely. All measurement information is recorded in comparison with the IDR and becomes part of the Quality Records Documentation. Traveler Packages accompany each part (or lot). The Traveler Package contains operation instructions and sign-off sheets for each step of the manufacturing process, the IDR, a record of any nonconformances and a work order establishing traceability. DLC is working towards becoming compliant to ISO 9002 requirements by 1996.

The CVI furnaces are controlled by a computerized Distributed Control System (DCS). Key data are gathered for each infiltration cycle and compared to the standard process. Any changes or deviations require review and decision by the process engineer and QA.

DLC includes multiple "tracking coupons" with each CVI furnace run. Coupons are removed at defined points in the process cycle to certify that the process is progressing according to specification.

In addition to the above general information, DuPont has provided details for QA methodology and procedures ranging from sub-tier supplier selection and control to packaging and shipping. Based on the information received, Solar believes at this time that DuPont has an adequate QA system that will ensure delivery of standard, reproducible product under the CSGT program.

Babcock and Wilcox Combustor Liner Fabrication

Figure 5-15 illustrates the general process that is planned by B&W to fabricate CFCC inner and outer combustor liners. A continuous alumina fiber (Mitsui) preform of the desired hollow cylinder dimensions is prepared by a traditional textile technique such as filament winding braiding or weaving. A thin coating (SnO_2) is then deposited on all the fiber surfaces to control fiber-matrix interface characteristics to achieve optimum strength and toughness in the final composite. The fiber coating has been successfully deposited by both CVD and sol-gel techniques. Fiber coating is followed by a sequence of matrix infiltration steps. Each step consists of vacuum infiltration of the preform with an aluminum oxide precursor sol, drying and a high temperature heat treatment to convert the precursor to aluminum oxide. Approximately 15 cycles results in a composite with about 23% porosity and optimum fracture behavior.

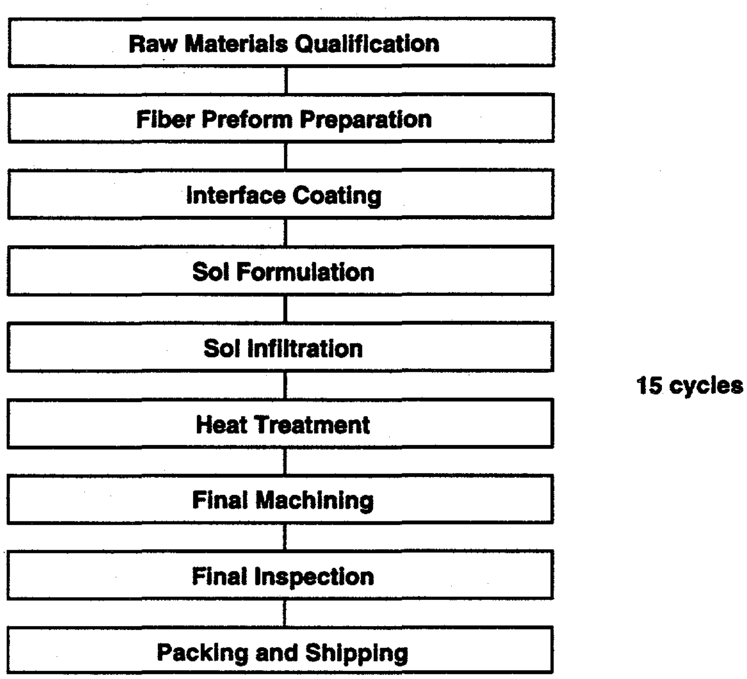

Figure 5-15. Flow Chart for Fabrication at Babcock and Wilcox of Oxide-Oxide Continuous Fiber Ceramic Reinforced Matrix Composites Using Sol Infiltration.

Babcock and Wilcox has been developing CFCC's for over ten years and has focused on oxide-oxide composites for more than five years. Part of the effort has been directed at demonstration of the feasibility of fabrication of large heat exchanger tubes, 10 cm (4 inches) in diameter and 90 cm to 150 cm (~3 to 5 feet) long. B&W successfully delivered five prototype tubes which survived a proof test and have also fabricated nine 150 cm (5 foot long) tubes for evaluation in the heat exchanger of a hazardous waste incinerator.

In spite of the progress, oxide-oxide CFCCs are still at an early stage of development and demonstration. Very little property characterization has been conducted, especially for the time, temperature, stress and environment that a combustor liner will be exposed to in a gas turbine engine. Some data will be available from the DOE CFCC program, but it will fall far short of the data needed to confirm viability for the CSGT program.

CFCC development and prototype fabrication are being conducted within the Research and Development Division of B&W. Procedures are defined by the R&D Division Standard Practice Manual. This manual addresses: (1) Project responsibilities, (2) Project authorization, planning and performance, (3) Safety, (4) Design review, (5) Review and documentation of calculations, (6) Software, (7) Drawing control, (8) Procurement control and vendor evaluation, (9) Receiving inspection, (10) Material identification and control, (11) Inspection, (12) Instruments, (13) Training, (14) Test data collection and documentation, (15) Project records, (16) Data transmittal and reports and (17) Audits. Other key procedures are contained in the following documents: (1) Quality Assurance Program for the R&D Division, (2) Preparation, Approval, Release, Review, Retention and Storage of Engineering Drawings, (3) Measuring Equipment Control and Calibration System and (4) Corrective Action System. ISO 9001 certification is scheduled by late 1995 to early 1996.

In summary, there are many uncertainties regarding the B&W CFCC material because of its early stage of development/characterization. However, it does appear that the B&W R&D Division has a Quality System that will be suitable for monitoring and documenting fabrication of prototype combustor liners and that will assure that key information is available to help correlate between material/processing/microstructure/behavior.

5.4 DATABASE AND LIFE PREDICTION

Critical stresses and temperatures for the CSGT components are listed in Table 5-8.

Table 5-8. Critical Stresses and Temperatures for CSGT Components

Component	Peak Stress MPa (ksi)	Peak Temperature °C (°F)
Blade	186 (27)	1093 (2000)
Nozzle	207-275 (30-40)	1291 (2356)
Combustor Tile	193 (28)	1371 (2500)
Combustor Ring	76 (11)	1371 (2500)

The primary silicon nitrides are likely to meet the requirements for the blades to survive 30,000 hours. Localized machining of parts of the airfoil for some silicon nitrides may be necessary to ensure reliable performance. The nozzle stress levels are high for the silicon carbide material (fast fracture probability of success is low). The primary silicon nitrides are likely to survive 4000 hours in creep, but survival for 30,000 hours may be more difficult. Life prediction studies will be required to assess the probability of survival for extended operation. It is recommended that the peak stress in the nozzle be lowered to the 138-172 MPa (20-25) ksi range. The 193 MPa (28 ksi) peak stress on the combustor liner tile may be an issue of concern for the Hexoloy® SA silicon carbide material. The ring concept has much lower stresses. NT230 (siliconized silicon carbide) was selected because NAC has indicated it has the furnace capability to fabricate the large (76 cm/30 inch) rings of the outer combustor liner. Long term data and life assessment is needed to assess the service life of the ring and tile components.

Solar and SPS Database/Life Prediction

Based on the specific time, temperature and stress conditions for each component, the database has been grouped into two primary categories: (a) Design and Analysis Database and (b) Life Prediction Database. Solar has assembled material database from the following sources: (1) Suppliers, (2) National Laboratories, (3) Universities, and (4) Technical literature.

Design Database

The design database includes properties essential for the preliminary design and analysis. These properties are:

- Elastic Modulus as a function of Temperature
- Poisson's Ratio as a function of Temperature
- Coefficient of thermal expansion as a function of Temperature
- Thermal Conductivity as a function of Temperature
- Specific heat as a function of Temperature
- Density
- Tensile strength and Fracture toughness as a function of temperature (for analysis)

Temperatures of particular interest are:

- Room temperature
- ~760°C (1400°F) - temperature at the root of the blade during steady state operation
- ~1093°C (2000°F) - steady state airfoil temperature of blade
- 1291°C (2356°F) - steady state nozzle airfoil hot-spot temperature
- 1149-1371°C (2100-2500°F) - steady state combustor hot wall temperature

Ideally, the above properties should be available up to a temperature of 1371°C (2500°F).

The design and analysis database for the five monolithic suppliers has been compiled. Property data at specific temperatures may have to be interpolated or extrapolated from available data curves. The specific areas where data needs to be generated have been identified in tables for each of the suppliers. The data required has been prioritized: (1) for essential; (2) for highly desirable, and (3) for useful properties. Data to be generated is identified in subsequent sections.

Life Prediction Database

The life prediction database is essential for designers and materials engineers to estimate if the ceramic component will meet requirements of at least 30,000 hours of continuous duty in the engine. This estimate is obtained by theoretically predicting lifetimes for the different failure modes. Four primary failure modes have been identified for the silicon based ceramics: (1) Fast fracture, (2) Slow crack growth, (3) Creep, and (4) Oxidation.

Fast Fracture

This mode represents stressing the material to a level where instantaneous instability results. It is a time independent failure mechanism, which results in the crack growing instantaneously beyond the critical flaw size. Tensile or flexural strength testing at a crosshead speed of 0.004 cm/sec is typically used to establish fast fracture strength. On the average about 25 specimens are tested under each condition to obtain an acceptable Weibull modulus. Fast fracture data are available for all the materials under consideration in this program.

Slow Crack Growth

If the load is applied slowly or is held at a level below that required for instantaneous fracture, flaws present in the material prior to loading can grow to larger sizes and result in fracture at a stress substantially less than the fast fracture strength. The formation of new flaws can result from chemical attack (oxidation, corrosion), erosion, impact or thermal shock. The extension of flaws at low temperatures typically involves interaction of chemical effects with stress (stress corrosion). Extension at high temperature involves interaction of stress with a thermally-activated mechanism. An example is grain boundary sliding for many Si_3N_4 materials.

An accepted procedure to determine the susceptibility of the material to slow crack growth is variable stressing rate testing. Samples are loaded at three different stressing rates (that differ by a factor of 100) to fracture at the temperature of interest, and the data is plotted as strength versus load rate. The values of constants A and n are determined from the test data, and the velocity of crack growth is calculated from the equation:

$$V = A \cdot K^n$$

where V is the velocity of crack growth and K is the stress intensity factor.

Variable stressing rate testing identifies susceptibility of a material to slow crack growth. Stress rupture testing (static fatigue) is utilized for long term tests to further study slow crack growth at a selected combination of stress and temperature. The creep testing discussed below can provide static fatigue information as well as creep information.

Creep

Creep refers to the plastic deformation that ceramics undergo at a constant stress as a function of time and temperature. The secondary creep region is the most useful for predicting the life of the component. It is typified by a constant rate of deformation and is often referred to as steady state creep. Silicon nitride based ceramic materials exhibit creep type behavior at temperatures in excess of approximately 1050°C (≈2100°F). The primary mechanism of creep in the silicon nitrides at these temperatures is related to the plastic deformation of the grain boundary phase (added as a sintering aid).

Steady state creep can be represented by the equation:

$$\dot{\varepsilon} = A\sigma^n e^{-Qc/RT}$$

where $\dot{\epsilon}$ is the steady state creep rate, σ is the stress, T the absolute temperature, Q_c is the activation energy for creep, A and n are constants for the material. Another important relationship that has been used extensively in quantitatively defining creep behavior of silicon nitride is the Monkman-Grant relationship given below:

$$t_f = A_c \cdot (d\epsilon/dt)^m$$

where t_f is the time to failure, A_c and m are Monkman-Grant parameters and $d\epsilon/dt$ is the strain rate. From a life prediction perspective the parameters that need to be established at the temperature of interest are the Monkman-Grant parameters A_c and m, the creep parameters A and n and the apparent activation energy for creep Q_c.

Oxidation

Elevated temperatures (>1300°C or about 2400°F) result in the formation of significant amounts of silica on the surface of the silicon base ceramics. These oxide layers serve as initiation sites for cracks, that propagate through the ceramic. The hot wall combustor application is likely to see the greatest extent of oxidation. Cyclic exposure tests of the candidate ceramic material have been planned as part of Phase II testing. Static exposure tests up to 1000 hours have already been carried out as part of in-house testing at Solar. Flexure tests, after exposure, have revealed the effects of oxidation on the strength of the material.

AlliedSignal Ceramic Components Database

Design Database for GN-10 Si_3N_4

Table 5-9 gives a list of the typical properties that characterize GN-10. Based on this table Solar has established properties that need to be evaluated and assigned priorities. This list is given in Table 5-10. CC has reviewed these tables. CC could generate the Elastic Modulus data in house using the C-ring test as well as the fracture toughness data at the relevant temperatures.

Life Prediction Database for GN-10 Si_3N_4

Fast fracture data is essential to obtain probability of success curves in the fracture maps that will be generated by Sundstrand Power Systems. Slow crack growth is likely to be the failure mode of primary concern for the blade. CC plans to perform a significant number of interrupted static fatigue tests using REV 17 GN-10 by the end of the third quarter of 1993. This data will be used to estimate the slow crack growth coefficient. CC also has the capability to generate cyclic fatigue data using their ATS Flexure Testing system. Oxidation of GN-10 is not a primary concern at the blade engine operation temperature. Table 5-11 identifies near-term database needs for GN-10.

Norton Advanced Ceramics Database

Design Database for NT154/NT164

Table 5-12 gives a list of physical and mechanical properties as a function of temperature for NT154 and NT164. The mechanical properties have been obtained on test bars that were cold isostatically pressed, HIPed and machined to final dimensions. The NT154 material has been very well characterized. The few gaps in the design database are being filled at this time. NT164 behaves very similarly to NT154. However, the design and analysis database for this material is incomplete. For initial design work with this material, some NT154 properties may have to be assumed for NT164. Table 5-13 lists the design database needs for NT154 and NT164.

Table 5-9. Typical Properties of GN-10 Si_3N_4

Property		Room Temp.	1000°C 1832°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Elastic Modulus:	GPa Msi	286 41.5	253 36.7	225 32.6	-	-
Poisson's Ratio		0.27	-	-	-	-
Tensile Strength:	MPa Ksi	634 92	-	496 72	-	207 30
Fracture Toughness:	$MPa.m^{1/2}$ $ksi.in^{1/2}$	6.5 5.9		5.8 5.27	-	-
CTE (/°C) (/°F)		$1.0x10^{-6}$ $0.66x10^{-6}$	$3.0x10^{-6}$ $1.66x10^{-6}$			
Therm. Cond.:	W/m°K $Btu.in/ft^2hr°F$	44 305	21.7 150	18 125	17.3 120	16.8 117
Density:	g/cc lbs/cuin.	3.3 .119	3.3 .119	3.3 .119	3.3 .119	3.3 .119
Specific Heat:	J/gK Btu/lb°F	.625 .149	1.18 .282	1.22 .292	1.24 .297	1.25 .299

Table 5-10. Prioritization of Design and Database Needs for GN-10

Property	Room Temp.	750°C/1 382°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/2 500°F
Elastic Modulus	-	-	-	3	3
Poisson's Ratio	-	2	2	-	-
Tensile Strength	-	-	-	-	-
Fracture Toughness	-	2	-	3	3
CTE	-	-	-	3	3
Therm. Cond.	-	-	-	-	-
Density	-	-	-	-	-
Specific Heat	-	-	-	-	-

1 = Essential; 2 = Highly desirable; 3 = Useful

Table 5-11. Life Prediction Database Needs for GN-10

Property	Room Temp.	750°C/ 1382°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/ 2500°F
Weibull Modulus	-	-	-	-	-
Slow Crack Growth Parameters	2	1	1	-	-

1 = Essential; 2 = Highly desirable; 3 = Useful

Table 5-12. Design Database For NT154/NT164

Property	Room Temp.	1000°C/ 1832°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/ 2500°F
Elastic Mod. (NT154): GPa Msi	315 45	300 44	292 42	285 41	272 39
Elastic Mod. (NT164): GPa Msi	315 45	-	-	-	-
Poisson's Ratio (NT154)	0.273	-	-	-	-
Poisson's Ratio (NT164)	0.273	-	-	-	-
Tensile Strength(NT154): MPa ksi	910-931 130-133		525-560 75-80	455-476 65-68	245-525 35-75
Tensile Strength(NT164): MPa ksi	553-710 79-101.5	-	-	-	392-574 56-82
Fract. Toughness NT154: MPa $m^{1/2}$ ksi $in^{1/2}$	4.54 4.12	5.72 5.2	5.58 5.07	5.55 5.04	5.26 4.8
Fract. Toughness NT164: MPa $m^{1/2}$ ksi $in^{1/2}$	5.41 4.92	-	-	-	-
CTE (/°C) NT154 (/°F) NT154	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}
CTE (/°C) NT164 (/°F) NT164	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}	3.93×10^{-6} 2.18×10^{-6}
Therm. Cond. NT154:W/mK Btu.in/ft^2hr°F	37.6 260	20.7 144	17 123	17 123	15.8 109
Therm. Cond. NT164:W/mK Btu.in/ft^2hr°F	37.6 260	20.7 144	-	-	15.8 109
Density NT154: g/cc lbs/cu in	3.23 .116	-	-	-	-
Density NT164: g/cc lbs/cu in	3.19 .115	-	-	-	-
Specific Heat NT154: J/gK Btu/lb°F	.9 .215	1.4 .335	-	-	-
Specific Heat NT164	-	-	-	-	-

Table 5-13. Design Database Needs for NT 154 and NT 164

Property	Room Temp.	750°C 1382°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Elastic Mod NT154	-	-	-	1	1
Elastic Mod NT164	-	1	1	1	1
Poisson's Ratio NT154	-	3	3	3	3
Poisson's Ratio NT164	-	3	3	3	3
Fracture Toughness NT154		-	-	-	-
Fracture Toughness NT164	-	1	2	1	1
CTE (/°C) NT154 (/°F) NT154	-	-	-	-	-
CTE (/°C) NT164 (/°F) NT164	-	-	-	-	-
Therm. Cond. NT154	-	-	2	2	-
Therm. Cond. NT164	-	-	2	2	-
Density NT154	-	3	3	3	3
Density NT164	-	3	3	3	3
Specific Heat NT154	-	-	2	2	2
Specific Heat NT164	2	2	2	2	2

1 = Essential; 2 = Highly Desirable; 3 = Useful

Life Prediction Database for NT154/NT164

As for the design database, most life prediction database generation has been done on the NT154 material. Since the temperatures of operation in the ATTAP program have been in the 1230-1371°C (2250-2500°F) range, creep has been the focus of most of the studies. However, data generated at the University of Dayton Research Institute has included slow crack growth behavior of this material.

Slow Crack Growth

Slow crack growth has been reported for NT154 Si_3N_4 at room temperature and high temperature by Hecht et al. at the University of Dayton Research Institute. Room temperature slow crack growth is thought to result from moisture-induced stress corrosion. High temperature slow crack growth is thought to result from softening of a grain boundary phase which allows grain boundary sliding under an applied stress. Slow crack growth is likely to be life limiting for Si_3N_4 materials, but substantial long term data are necessary before realistic life prediction can be made.

Creep

Tests at ORNL indicate that creep can occur in NT154 and NT164 above about 1260°C (2300°F). With the current CSGT temperature profile, the nozzle will operate above this temperature and will therefore be susceptible to creep. However, the implications on component life cannot be predicted at this time. If the creep mechanism is accompanied by slow crack growth or other modes of strength degradation, creep will be detrimental and limit life. If creep redistributes stress, it may reduce slow crack growth and actually increase life. Testing of samples and nozzles will be required to resolve this issue. Table 5-14 outlines the needs for life prediction analysis.

Design Database for NT230

Table 5-15 gives the list of material properties that are considered essential for designing ceramic nozzle support rings and combustor liner rings. Based on this table, priorities of properties needed have been established. Design database needs are outlined in Table 5-16.

Table 5-14. Life Prediction Database Needs for NT164

Property	Room Temp.	750°C 1382°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Weibull Modulus	-	-	-	-	-
As-Fired Surface Strength	-	-	-	1	-
Volume Strength	-	2	-	-	-
Slow Crack Growth Parameters	-	2	-	1	-
Monkman Grant Parameters A_c & m_c	-	-	-	1	-
Oxidation Weight Gain Parameter	-	3	2	1	1

1 = Essential; 2 = Highly Desirable; 3 = Useful

Table 5-15. Design and Analysis Database for NT230

Property	Room Temp.	1000°C 1832°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Elastic Mod: GPa Msi	402 58	300 44	292 42	285 41	272 39
Poisson's Ratio	0.17	-	-	-	-
Flexure Strength: MPa ksi	400-480 57-68	-	-	470-536 67-77	420-513 60-73
Fracture Toughness: MPa $m^{1/2}$ ksi $in^{1/2}$	3.2 2.9	-	-	5.55 5.04	8.1 7.3
CTE (/°C) (/°F)	4.7×10^{-6} 2.6×10^{-6}	4.7×10^{-6} 2.6×10^{-6}	4.7×10^{-6} 2.6×10^{-6}	4.7×10^{-6} 2.6×10^{-6}	4.7×10^{-6} 2.6×10^{-6}
Therm. Cond.: W/mK Btu.in/ft²hr°F	135 945	36 251	-	-	-
Density: g/cc lbs/cu in	3.05 .109	-	-	-	-
Specific Heat	-	-	-	-	-

Table 5-16. Prioritization of Design and Analysis Database Needs for NT230

Property	Room Temp.	1000°C 1832°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Elastic Modulus	-	1	-	3	3
Poisson's Ratio	-	2		-	-
Tensile Strength	1	1			1
Fracture Toughness	-	1	3	3	3
CTE	-	-	-	3	3
Therm. Cond.	-	-	-	3	3
Density	-	-	-	-	-
Specific Heat	1	1	3	2	2

1 = Essential; 2 = Highly Desirable; 3 = Useful

Life Prediction Database for NT230

Since the nozzle support ring is not likely to see long term exposure to temperatures greater than 870°C(~1600°F), the primary failure mechanism is likely to be fast fracture. The key life prediction concern is the large volume of material under stress in the ring compared to the small volume of test bars from which data have been generated. Stress rupture is not expected to be a problem up to at least 1093°C (2000°F) based on existing data. However, additional stress rupture or variable stressing rate testing is recommended as shown in Table 5-17.

The combustor liner rings will require higher temperature data than the nozzle support ring. This component will experience maximum temperatures of at least 1200°C (about 2200°F) or higher. Data up to 1371°C (2500°F) would be desirable. Key data is needed on thermal conductivity, oxidation, and thermal shock resistance.

Kyocera Industrial Ceramics Corporation Database

Design Database for SN-253 and SN-252

Table 5-18 lists material properties considered essential for designing ceramic blades with the Kyocera SN-253 silicon nitride material. SN-252 data are shown for comparison. Strength properties in the machined and the as-fabricated condition are also included. Tensile data over the entire temperature range are lacking. A noticeable feature of the SN-252/SN-253 material is the high thermal conductivity in the lower temperature ranges. This thermal conductivity, considerably higher than for any of the other commercial silicon nitrides, is attributed to the acicular grain structure, which is a feature of this material. The thermal conductivity of the Kyocera silicon nitrides assumes values similar to those of other commercial silicon nitrides at temperatures above 1000°C (1832°F). The Kyocera SN-252/SN-253 also has very good as-fabricated strength properties at the elevated temperatures. Table 5-19 identifies areas in the design and analysis database where data needs to be collected, and these areas have been prioritized, based on their criticality for this program.

Table 5-17. Life Prediction Database Needs for NT230

Property	Room Temp.	1000°C 1382°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Slow Crack Growth Parameters	-	1	2	-	-

1 = Essential; 2 = Highly Desirable; 3 = Useful

Table 5-18. Typical Properties of SN-252 and SN-253 Formed by the Hybrid Molding Process

Property		Room Temp.	1000°C 1832°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Elastic Mod. (SN-252):	GPa Msi	309 44.8	295 42.8	290 42	286 41.5	280 40.6
Elastic Mod. (SN-253)	GPa Msi	319 46.3	312 45.3	309 44.8	304 44.1	300 43.5
Poisson's Ratio (SN-252)		0.271	0.265	0.263	0.263	0.262
Poisson's Ratio (SN-253)		0.27	0.27	0.265	0.27	0.27
Flexural Strength (SN-252):	MPa/ksi MPa/ksi	606/88 462/67	537/78 427/62	-	-	482/70 400/58
Flexure Strength (SN-253):	MPa/ksi MPa/ksi	709/103 572/83	661/96 627/91	-	-	510/74 524/76
Fract. Toughness (SN-252):	MPa $m^{1/2}$ ksi in $^{1/2}$	6.8 6.18		6.7 6.09	-	-
Fract. Toughness (SN-253):	MPa $m^{1/2}$ ksi in $^{1/2}$	6.9 6.27	-	-	-	-
CTE (SN-252) °C CTE (SN-252) °F		$2.6x10^{-6}$ $1.44x10^{-6}$	$3.2x10^{-6}$ $1.78x10^{-6}$	$3.3x10^{-6}$ $1.8x10^{-6}$	$3.3x10^{-6}$ $1.8x10^{-6}$	$3.3x10^{-6}$ $1.8x10^{-6}$
CTE (SN-253) °C CTE (SN-253) °F		$2.8x10^{-6}$ $1.5x10^{-6}$	$3.2x10^{-6}$ $1.78x10^{-6}$	$3.3x10^{-6}$ 1.83x10	$3.3x10^{-6}$ $1.83x10^{-6}$	$3.3x10^{-6}$ $1.83x10^{-6}$
Therm. Cond. (SN-252):	W/mK Btu.in/ft²hr°F	67 465	33 231	22 153	-	-
Therm. Cond. (SN-253):	W/mK Btu.in/ft²hr°F	79 547	25 153	22 153	-	-
Density (SN-252):	g/cc lbs/cu in.	3.44 .124	-	-	-	-
Density (SN-253)c:	g/cc lbs/cu in.	3.5 .126	-	-	-	-
Specific Heat (SN-252):	J/gK Btu/lb°F	.65 .155	1.25 .299	1.30 .310	-	-
Specific Heat (SN-253):	J/gK Btu/hr lb°F	.64 .095	1.18 .282	1.23 .29	-	-
Thermal Shock Resistance		> 750°C				
Thermal Shock Resistance		-	-	-	-	-

Table 5-19. Design and Analysis Database Needs for Kyocera's SN-252/SN-253

Property	Room Temp.	750°C 1382°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Elastic Mod. SN-252	-	-	-	-	-
Elastic Mod. SN-253	-	-	-	-	-
Poisson's Ratio SN-252	-	-	-	-	-
Poisson's Ratio SN-253	-	-	-	-	-
Tensile Strength SN-252	1	1	1	2	2
Tensile Strength SN-253	1	1	1	1	2
Fracture Toughness SN-252	-	1	-	2	2
Fracture Toughness SN-253	-	1	-	1	2
CTE SN-252	-	-	-	-	-
CTE SN-253	-	-	-	-	-
Therm. Cond. SN-252				2	2
Therm. Cond. SN-253				1	2
Density SN-252	-	1	1	3	3
Density SN-253	-	1	1	2	3
Specific Heat SN-252	-	-	-	3	3
Specific Heat SN-253	-	-	-	2	3

* Interpolated from Curve
1 = Machined, 2 = As-Fired

Life Prediction Database for SN-253

Since the Kyocera material is presently being considered primarily for the blade, the failure mode is restricted to slow crack growth. However, the SN-253 could potentially be used for the nozzle application, for which it is a backup material. Therefore, creep information on SN-253 should be obtained, even if it is not of the highest priority. Life prediction database needs for SN-253 are listed in Table 5-20.

<u>Carborundum Database</u>

Table 5-21 gives the design and analysis database that is available for the alpha sintered Hexoloy® SA silicon carbide material. Hexoloy® SA has been in use from the early 1980's. The material has changed considerably in that time. The latest version of this material has the highest strength and has a HIPing step employed for injection molded parts of large wall thickness to ensure full densification while maintaining a fine microstructure. Based on the information that is available, a table of database needs has been generated, with priorities (Table 5-22).

Life Prediction Database for Hexoloy® SA

Hexoloy® SA SiC is a candidate material for both the nozzle and the combustor liner because it exhibits very good resistance to oxidation and creep at the design operating temperatures for these components. Tests, however, have not been run for the thousands of hours that these components are likely to see. Table 5-23 lists the areas where data need to be generated.

Table 20. Life Prediction Database Needs for SN-253

Property	Room Temp.	750°C/1 382°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/ 2500°F
Fast Fracture Tensile Strength	1	1	1	1	-
Weibull Modulus	-	-	-	-	-
Slow Crack Growth Parameters	2	1	1	-	-
Monkman Grant Parameters	-	-	-	2	-

1 = Essential; 2 = Highly Desirable; 3 = Useful

Table 5-21. Design and Analysis Database for Hexoloy® SA SiC

Property		Room Temp.	1000°C/ 1832°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/ 2500°F
Elastic Modulus:	GPa/Msi	427/62	401/58	390/57	-	394/56
Poisson's Ratio		0.16	0.18	0.19	-	-
Tensile Strength:	MPa/ksi	261/38	240/35	260/38	-	248/36
Fracture Toughness:	Mpa.m$^{/2}$ ksi.in$^{1/2}$	3.3 3.0	2.7 2.5	-	-	3.4 3.1
CTE (/°C) (/°F)		$4.0x10^{-6}$ $2.2x10^{-6}$	$5.3x10^{-6}$ $2.9x10^{-6}$	$4.7x10^{-6}$ $2.6x10^{-6}$	$5.3x10^{-6}$ $2.9x10^{-6}$	$4.9x10^{-6}$ $2.7x10^{-6}$
Therm. Cond.:	W/mK Btu.in/ft^{2}°F	164 1152	57 396	43 517	-	-
Density:	g/cc lb/cuin	3.14 .113	3.14 .113	3.14 .113	3.14 .113	3.14 .113
Specific Heat:	J/gK Btu/lb°F	.664 .16	1.18 .28	1.22 .29	1.24 .30	1.25 .30

Table 5-22. Design and Analysis Database Needs for Hexoloy® SA SiC

Property	Room Temp.	1000°C/ 1832°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/ 2500°F
Elastic Modulus	-	-	-	1	
Poisson's Ratio	-	-	-	3	3
Tensile Strength		-	-	-	-
Fracture Toughness	-	-	2	1	-
CTE	-	-	-	-	-
Therm. Cond.	-	-	-	1	1
Density	-	-	-	-	-
Specific Heat	-	-	-	-	-

NGK Insulators, Ltd. Database

Design Database for SN-88

NGK SN-88 silicon nitride is a candidate material for the nozzle. SN-88 is an improved version of SN-84, which was used in earlier ceramic application programs like AGT and ATTAP. Figure 5-16 outlines the steps involved in the processing of components made from SN-88. Table 5-24 lists typical properties of NGK's SN-84 and SN-88 materials. SN-84 information is being presented for comparison. SN-84 is presently not being considered as a candidate for any component.

Life Prediction Database for SN-88

The SN-88 material's life prediction database needs summarized in Table 5-25 are similar to those of the alternative primary nozzle material, NT164. High temperature data for slow crack growth, creep, and oxidation are the principal needs.

Table 5-23. Life Prediction Database Needs for Hexoloy® SA SiC

Property	Room Temp.	750°C/ 1382°F	1200°C/ 2192°F	1275°C/ 2327°F	1370°C/ 2500°F
Weibull Modulus	-	-	-	-	-
Slow Crack Growth Parameters	2	-	-	1	2
Monkman Grant Parameters	-	-	-	1	1
Oxidation Activation Energy and Weight Gain Parameters	-	-	-	-	1

1 = Essential; 2 = Highly Desirable; 3 = Useful

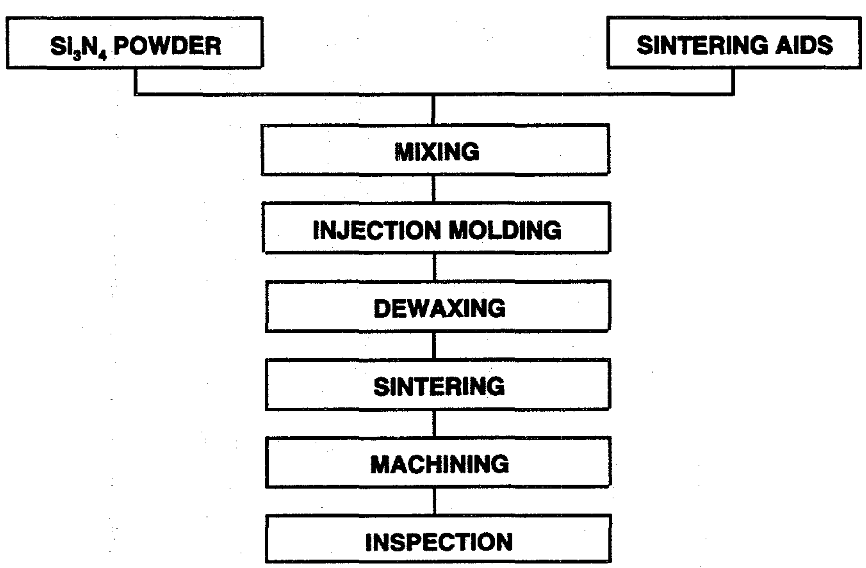

Figure 5-16. Fabrication Process of SN-88 Ceramic Turbine Components

Table 5-24. Typical Properties of NGK Si_3N_4 Materials

Property		Room Temp.	1000°C/ 1832°F	1200°C/ 2192°F	1300°C/ 2372°F	1400°C/ 2552°F
Elastic Mod. SN-84:	GPa/Msi	300/43.5				
Elastic Mod. SN-88:	GPa/Msi	300/43.5				
Poisson's Ratio SN-84		0.27				
Poisson's Ratio SN-88		0.26				
Tensile Strength SN-84:	MPa/ksi	454/66	-	-	-	
Tensile Strength SN-88		-	-	-	-	-
Flexural Strength SN-84:	MPa/ksi	970/141	970/141	900/131	690/100	-
Flexural Strength SN-88:	MPa/ksi	790/115	770/112	770/112	-	760/100
Fract. Toughness SN-84:	MPa $m^{1/2}$ ksi $in^{1/2}$	6.0 5.45	-	-	-	
Fract. Toughness SN-88:	MPa $m^{1/2}$ ksi $in^{1/2}$	7.0 6.36	-	-	-	-
CTE (/°C) SN-84		$3.8x10^{-6}$/C $2.1x10^{-6}$/F	$3.8x10^{-6}$/C $2.1x10^{-6}$/F	$3.8x10^{-6}$/C $2.1x10^{-6}$/F	-	-
CTE (/°C) SN-88		$3.5x10^{-6}$/C $1.95x10^{-6}$/F	$3.5x10^{-6}$/C $1.95x10^{-6}$/F	$3.5x10^{-6}$/C $1.95x10^{-6}$/F	-	-
Therm. Cond. SN-84:	W/mK Btu.in/ft^2hr°F	29 202	-	17 118	-	
Therm. Cond. SN-88:	W/mK Btu.in/ft^2hr°F	63 432	-	20 138	-	
Density SN-84:	g/cc lbs/cuin	3.2 .115	-	-	-	-
Density SN-88:	g/cc lbs/cuin	3.5 .126	-	-	-	-
Specific Heat SN-84:	J/gK Btu/lbs°F	.68 .163	-	1.20 .287	-	-
Specific Heat SN-88:	J/gK Btu/lbs°F	.64 .153	-	1.24 .3	-	-
Thermal Shock Resistance SN-84		1050°C				
Thermal Shock Resistance SN-88		1200°C				

Table 5-25. Life Prediction Database Needs for SN-88

Property	Room Temp.	750°C 1382°F	1200°C 2192°F	1275°C 2327°F	1370°C 2500°F
Weibull Modulus	-	-	-	-	-
As-Fired Surface Strength	-	-	-	1	-
Volume Strength	-	2	-	-	-
Slow Crack Growth Parameters	-	2	-	1	-
Monkman Grant Parameters A_c & m_c	-	-	-	1	-
Oxidation Weight Gain Parameter	-	3	2	1	1

1 = Essential; 2 = Highly Desirable; 3 = Useful

DuPont Material Lanxide Composites Database

Properties for the standard SiC/SiC composite are shown in Table 5-26. Mechanical properties for different thicknesses of the standard material are shown in Table 5-27. The 1.0 mm (0.040 inch) thick part had a slightly lower strength because of fabrication difficulties. The modified matrix properties currently available are shown in Table 5-28. A more extensive database will soon be available. The modified matrix material has a slightly lower density than the standard material and is slightly stronger in tension. However, its compression strength is 59 percent of the standard material's compression strength. Also, the modified material's stiffness is about 61 percent of the standard's. At this point, DLC is not at liberty to discuss the mechanism causing the lower compressive strength and tensile modulus. Stressed lifetimes in air under flexural load are shown in Table 5-29.

Table 5-30 gives stressed lifetimes in air under tensile load. Data for the modified matrix material were generated on specimens that had no external coating. The standard matrix material specimens had the Chromalloy external coating. None of the modified matrix coupons failed during test. The data shows that these coupons last at least as long as the coated standard matrix specimens for the same temperature and stress levels. In tension the modified material without a coating performed at least as good or better than the standard matrix material with a coating except at 1204°C (2200°F) and a 100 MPa (14.5 ksi) stress level. Another modified matrix specimen was exposed in stressed oxidation testing at 1204°C (2200°F) and 80 Mpa (11.6 ksi). The test was concluded after approximately 4400 hours. Residual strength was planned for this specimen; unfortunately, it was damaged upon removal from the test fixture. Tensile fatigue data for the modified matrix material is given in Table 5-31.

Table 5-26. Standard SiC/SiC Properties (0°/90°)

Property	Units	RT	1000°C (1832°F)
Fiber Volume	vol. percent	40	40
Density	lb/in^3(g/cc)	0.09(2.5)	0.09(2.5)
Porosity	vol. percent	10	10
Tensile Strength	MPa (ksi)	187 (27.6)	230 (33)
Tensile Modulus	GPa (Msi)	211 (31.2)	240 (35)
Tensile Elongation	percent	0.22	0.28
Cross-Ply Tensile Strength	MPa (ksi)	10.6 (1.53)	—
Compressive Strength	MPa (ksi)	800 (116)	—
Flexural Strength	MPa (ksi)	259 (37.4)	—
Flexural Modulus	GPa (Msi)	14.5(100)	—
Flexural Elongation	percent	0.27	—
Interlaminar Shear Strength	MPa (ksi)	32 (4.6)	—
Fracture Toughness	$MPa.m^{1/2}$ ($ksi.in^{1/2}$)	24 (22)	—
CTE (In-Plane)	10^{-6}/°C (10^{-6}/°F)	3 (1.7)	3 (1.7)
CTE (through thickness)	10^{-6}/°C (10^{-6}/°F)	1.7 (0.9)	3.4 (1.9)
Thermal Diffusivity (In-Plane)	$10^{-6}m^2/s$ ($10^{-6}ft^2/s$)	12 (130)	5 (54)
Th. Diffusivity (Through Thickness)	$10^{-6}m^2/s$ ($10^{-6}ft^2/s$)	6 (65)	2 (20)
Specific Heat	J/kg°C (Btu/lb°F)	620 (0.15)	1200 (0.29)
Total Emissivity	—	0.8	0.8
Thermal Conductivity (In-Plane)	W/m°C (Btu/hrft°F)	19 (11.0)	15.2 (8.8)
Th. Conduct. (Through Thickness)	W/m°C (Btu/hrft°F)	9.5 (5.5)	5.7 (3.3)

Table 5-27. Variation in Properties with Thickness in SiC/SiC 0/90 Composite

Thickness (mm/inches)	Property	Temperature	Units	Value
3.2 (0.125)	Strength	RT	MPa (ksi)	190 (27.6)
	Modulus		GPa (Msi)	215 (31.2)
	Elongation		percent	0.22
2.0 (0.080)	Strength	RT	MPa (ksi)	212 (30.8)
	Modulus		GPa (Msi)	213 (30.9)
	Elongation		percent	0.32
1.0 (0.040)	Strength	RT	MPa (ksi)	183 (26.5)
	Modulus		GPa (Msi)	219 (31.8)
	Elongation		percent	0.30
3.2 (0.125)	Strength	1010°C (1850°F)	MPa (ksi)	224 (32.5)
	Modulus		GPa (Msi)	232 (34.7)
	Elongation		percent	0.28

Table 5-28. Modified SiC/SiC Material Properties, 0°/90° Layup

Property	Units	RT
Fiber Volume	vol. percent	40
Density	g/cc (lb/in^3)	2.3 (0.083)
Porosity	vol. percent	8-12
Tensile Strength	MPa (ksi)	210 (30.5)
Tensile Modulus	GPa (Msi)	130 (18.9)
Tensile Elongation	percent	0.35
Compressive Strength	MPa (ksi)	469 (68.0)
Compressive Modulus	GPa (Msi)	119 (17.2)
Flexural Strength	MPa (ksi)	312 (45.3)
Interlaminar Shear Strength	MPa (ksi)	24.8 (3.6)

Table 5-29. High Temperature Stressed Lifetimes in Air under a Flexural Load for Both the Modified and the Standard SiC/SiC Composite

Temperature (°C/°F)	Stress (MPa/ksi)	Time to Failure (hours)		
		Modified Matrix (No Coating)	Standard Matrix (External Coating)	Bare Substrate
454/850	207/30	>312		
593/1100	172/25	>333	296	20
		>333	>305	
593/1100	207/30	>310		
1204/2200	172/25	>309	>308	0.02-0.10
		>309	>308	

> Indicates that test was stopped before specimen failure

Table 5-30. High Temperature Stressed Lifetimes in Air under a Tensile Load for SiC/SiC

Temperature (°C/°F)	Stress (MPa/ksi)	Time to Failure (hours)	
		Modified Matrix (No Coating)	Standard Matrix (External Coating)
593/1100	100/14.5	50	35-45
982/1800	60/8.7	>300	>300
1204/2200	80/11.6	1500	
1204/2200	100/14.5	50-60	150-230

> Indicates that test was stopped before specimen failure

Table 5-31. 1204°C/2200°F Tensile Fatigue Properties in Air at 1 Hz (R= 0.05) for SiC/SiC

Stress (MPa/ksi)	Number of Cycles	Time to Failure (hours) Modified Matrix (No Coating)
145/21.0	4000	1.1
100/14.5	38,000*	10.6
80/11.6	>105,000	No failure; test stopped at 30 hours

* Average of Three Tests

Babcock & Wilcox Database

The current database supplied by B&W is shown in Table 5-32 for the $Al_2O_3Al_2O_3$ CFCC. This material has a porosity of 23 percent. B&W's alumina/alumina composites with lower porosity levels do not exhibit graceful failure. The 23 percent porosity material has high permeability. The effects of permeability should be investigated during the design of the combustor with this composite.

Testing is continuing on the recommended alumina/alumina material. Cleveland State University will be generating a Weibull tensile modulus. A comprehensive listing of B&W's test plan is given in Table 5-33. B&W has generated tensile strength values on unidirectional coupons. At RT, a strength of 296 MPa/43.3 ksi and modulus of 170 GPa/24.6 Msi was obtained. These numbers correspond fairly well to the results given in Table 5-32 for a different batch tested at Cleveland State University. B&W has also generated a 1093°C (2000°F) value for tensile strength of 230 MPa (33.4 ksi).

5.5 MATERIALS AND COMPONENT TESTING RECOMMENDATIONS

Figure 5-17 illustrates the logic of the Solar program. The program essentially consists of iterations between component design, component fabrication and component testing. These iterations are supported by gathering database from existing sources, by generating new database (particularly long term slow crack growth, creep, stress rupture, oxidation and interface data), by conducting NDE and proof testing, and by conducting failure analysis of test bars, subcomponents and components. The roles of each of these material and component activities are discussed in subsequent paragraphs.

Table 5-32. B&W Alumina/Alumina Continuous Fiber Reinforced Composite RT Properties (23 percent porosity)

Mode	Property	Value	Units
Longitudinal Tensile	Strength	413 (45.6)	MPa (ksi)
	Modulus	179 (25.9)	GPa (Msi)
	Poisson's Ratio	0.22	
Longitudinal Compressive	Strength	>480 (>70)	MPa (ksi)
	Modulus	200 (29.1)	GPa (Msi)
	Poisson's Ratio	0.22	
Coefficient Thermal Expansion (RT to 1150°C)	Longitudinal	$8.56x10^{-6}$ $4.76x10^{-6}$	$°C^{-1}$ $°F^{-1}$
	Transverse	$8.35x10^{-6}$ $4.64x10^{-6}$	$°C^{-1}$ $°F^{-1}$
Shear Strength (in-plane)	Longitudinal	24.5 (3.56)	MPa (ksi)

Table 5-33. Test Plan for B&W Oxide/Oxide Material

Property	Orientation	Specimen Geometry
CTE	Longitudinal	Flat Coupon
CTE	Transverse	Flat Coupon
Thermal Conductivity	Longitudinal	Flat Coupon
Thermal Conductivity	Transverse	Flat Coupon
Emissivity		Flat Coupon
Tensile Modulus (RT)	Longitudinal	Flat Coupon; ±45° Tube
Ultimate Tensile Strength (RT, 982°C/1800°F, 1149°C/2100°F)	Longitudinal	Flat Coupon
Tensile Modulus (RT)	Transverse	Hoop Wound Tube; ±45° Tube
Ultimate Tensile Strength (RT)	Transverse	Hoop Wound Tube
Tensile Modulus (982°C/1800°F, 1149°C/2100°F)	Longitudinal	Hoop Wound Tube; ±45° Tube
Tensile Modulus (982°C/1800°F, 1149°C/2100°F)	Transverse	Hoop Wound Tube; ±45° Tube
Poisson's Ratio (RT)	Longitudinal	±45° Tube
Compressive Modulus (RT)	Longitudinal	Flat Coupon
Ultimate Compressive Strength (RT)	Longitudinal	Flat Coupon
Compressive Modulus (RT)	Transverse	Hoop Wound Tube
Ultimate Compressive Strength (RT)	Transverse	Hoop Wound Tube
Compressive Modulus (982°C/1800°F, 1149°C/2100°F)	Longitudinal	Hoop Wound Tube
Compressive Modulus (982°C/1800°F, 1149°C/2100°F)	Transverse	Hoop Wound Tube
Shear Modulus (RT, 1149°C/2100°F)	Longitudinal	±45° Tube
Shear Strength (RT, 1149°C/2100°F)	Longitudinal	±45° Tube
Shear Modulus (RT, 1149°C/2100°F)	Transverse	Hoop Wound Tube; ±45° Tube
Shear Strength (RT, 1149°C/2100°F)	Transverse	Hoop Wound Tube; ±45° Tube

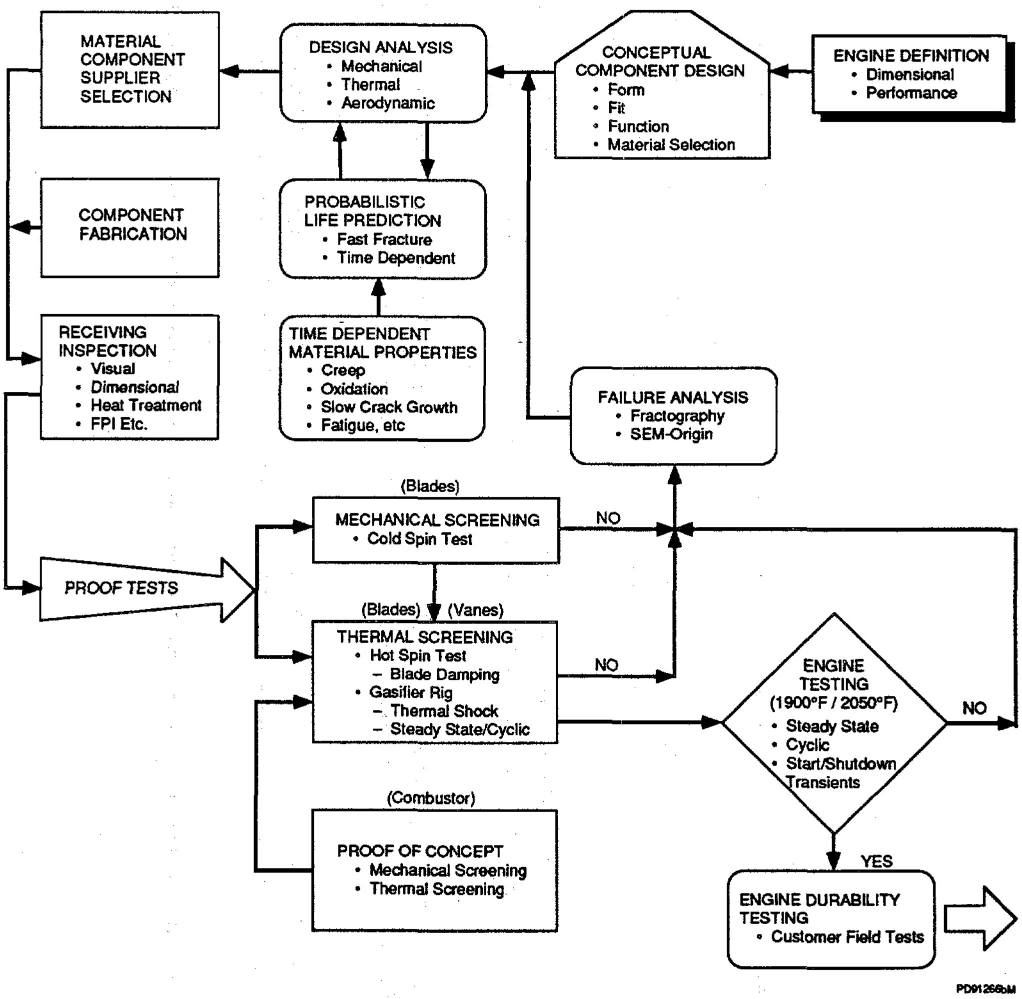

Figure 5-17. CSGT Program Logic Chart Showing Interrelationship Between Design, Database, Testing and Fabrication

Solar Materials and Component Testing

Database

Existing properties, where possible as a function of temperature (room temperature to about 1370°C/2500°F), have been gathered for each candidate material. These include elastic modulus, shear modulus, Poisson's ratio, flexure strength, tensile strength, Weibull modulus, coefficient of thermal expansion, thermal diffusivity, heat capacity, density and fracture toughness. Many of these properties are being used for thermal analysis, stress analysis and fast fracture life prediction to evaluate and optimize component designs. Time-dependent property data have also been gathered. These include creep, stress rupture, cyclic fatigue, dynamic fatigue (variable stressing rate) and oxidation kinetics. These data are being used to modify life prediction computer programs to account for time-dependent flaw growth mechanisms. Contact stress data and equations have also been gathered and are being incorporated into stress analysis and life prediction programs.

Extended Time-Dependent Properties Database

Long term creep, slow crack growth, oxidation and interdiffusion (at interfaces) data are not available beyond a few hundred hours for some materials and around 1000 hours for others. An important priority of the Phase II program is to extend the time-dependent database to at least 5000 hours for stress/temperature/material combinations relevant to each CSGT ceramic component. The emphasis of the testing will be to understand the mechanisms and their implications on component life prediction. The results of the testing will guide final material selection, indicate possible design modification requirements and define additional database needs.

Design Concept Testing

Solar's goal is to design ceramic components that will perform for at least 30,000 hours. To achieve this goal requires (1) that the transient and steady state stresses for each component are within the limits defined for the material by property testing and life prediction and (2) that the design is stable and does not impose abnormally high stresses during service. Abnormal stresses that occurred as a function of time or duty cycle have been a primary cause of failure of ceramic components in earlier programs, generally due to a shift in load path resulting in localized contact-induced high tensile stress. This can occur at an attachment or interface due to thermal expansion mismatch, distortion of adjacent metallic parts or even stackup of dimensional tolerances. It can occur for example in a conventional ceramic dovetail blade attachment by thinning of the compliant layer or by sticking at the dovetail/compliant layer/disk interface (such that the dovetail does not slide back to its room temperature position during engine shutdown and is pinched by the metal disk to cause very high biaxial contact loads).

During Phase I Solar has concentrated on achieving low stress designs that have a stable load path. This has resulted in some innovative designs for which no test experience exists. It is important to verify experimentally the validity of these designs as early as possible in Phase II. Solar has defined bench-scale tests for this purpose for each component.

Blade attachment concepts will be compared initially using a tensile pull test configuration from room temperature up to the projected engine temperature of the attachment. Tests will include mechanical cycling (simulating increasing and decreasing centrifugal loading), thermal cycling, long term hold at peak temperature and mechanical load, and testing to failure. Attachment durability will be compared for compliant layer versus no compliant layer concepts.

The second stage of blade attachment testing will be conducted in a spin chamber where the centrifugal loading and relative motion between the blade attachment and the metal rotor disk can be dynamically simulated. The test sample will have the actual blade attachment contour, but a simulated blade mass rather than an airfoil. Spin testing will be conducted at room temperature.

The blade attachment testing will either verify the validity of a design concept or provide guidance for design modification requirements.

Initial combustor testing will be conducted with subsize hollow cylinders of the CFCC candidate materials and segments assembled into a cylindrical configuration of the Hexoloy® SA SiC. The tests will be conducted in an existing rig and will include thermal cycling, holds at temperature and assessment of attachment concepts subscale combustor. Test samples will be cut from tested subsize combustor liners and the mechanical properties compared with samples cut from untested liners.

Proof Testing

Design concept testing will be completed during the first eighteen months of Phase II and will provide input to the final design of each ceramic component. These components will then undergo fabrication development at the ceramic suppliers. As components are successfully fabricated, they will be delivered to Solar for NDE and proof testing. All blades will be proof tested to about 125% overspeed at room temperature in the spin chamber to qualify them for gasifier rig testing. Some blades will be evaluated for vibration response using a shaker table and holographic interferometry.

Nozzles also will also be proof tested prior to gasifier rig testing. The proof testing, especially for the blades, will provide a first experimental evaluation of the fast fracture life prediction analysis.

Gasifier Rig Testing

Ceramic components passing dimensional, NDE and proof testing will subsequently be evaluated in the gasifier rig. The gasifier rig is essentially a highly instrumented engine. Rig testing will be conducted in stages, starting with mild conditions and working up to full engine conditions. Also, the ceramic hardware will be introduced as individual components first and then as a complete hot section. First gasifier rig tests will be with ceramic blades, metal nozzles and a metal combustor. The second series of tests will be with ceramic nozzles and metal rotor blades and combustor. As confidence is gained, ceramic blades and nozzles will be combined. Finally, the ceramic combustor will be added. The rig will then be operated for increased lengths of time.

As indicated in Figure 5-17, material and design integrity will be continually assessed during rig testing. All ceramic hardware will be removed and carefully examined after each rig test. Detailed failure analysis will be conducted on any failed or damaged components and the feedback used to guide material, design or rig modification. The program is scoped to allow redesign and procurement of a second generation of ceramic components.

Engine Testing

When sufficient rig testing has been conducted to provide confidence that all ceramic and metal components are performing satisfactorily, engine testing will begin. The engine will be built using ceramic components that have performed with no distress in the gasifier rig. All subsequent ceramic hardware will be qualified in the gasifier rig before being released to the engine.

Test Methodology Summary

In summary, long term materials testing will be conducted to determine material stability under projected engine conditions. Attachment samples and subsize ceramic components will be tested to evaluate the candidate design concepts. Selected concepts will be fabricated and evaluated in rig testing. Feedback from all these tests will be reviewed by the design and materials teams and modifications made as necessary to achieve reliable materials and designs. Rig and engine tests will be conducted in increments from mild to full engine conditions and from short to long time.

NDE Assessment

Solar worked with Argonne National Laboratory (ANL), Caterpillar Technical Center (CAT TC) and the ceramic suppliers to assess the status of NDE for qualification of ceramic components and to determine what advanced NDE should be considered in Phase II.

Two aspects of NDE were addressed in Phase I: (1) use of NDE to detect defects in ceramic hardware as part of accept-reject criteria and (2) potential use of NDE to monitor the growth of defects during service and to provide a means of predicting the remaining service life of the component.

The first step was to review what NDE is currently being used by the suppliers. In general, the suppliers rely primarily on visual inspection, density measurement, microfocus x-ray radiography and fluorescent penetrant inspection (FPI). Microfocus x-ray radiography is used to look for internal defects at both the powder compact and final part stages. FPI is used on the final part to inspect for surface defects, especially cracks or porous regions. Prior component experience has demonstrated that these NDE procedures and the fabrication process control systems in place at the suppliers have resulted in components which performed satisfactorily in rigs and engines. These rig and engine tests were of relatively short duration (typically less than 200 hours), so relatively little time-dependent flaw growth was assessed. Therefore, all we can conclude at this time is that existing NDE and process controls were adequate to assure that defects were not present that would cause fast fracture failure. Longer test times are necessary before we can judge the suitability of present techniques regarding time-depending defect growth mechanisms.

The second step was to review evolving NDE methods to determine which ones are worth evaluating. Several criteria were identified: (1) increased resolution capability compared to what suppliers are presently using, especially for detecting of subcritical defects that might grow to critical size during service, (2) potential for real time data acquisition and computer data analysis such that the system could be automated and (3) potential for cost savings when applied to component production. Several NDE methods were recommended by ANL and CAT TC: microfocus x-ray radiography using non-photographic data gathering and image enhancement, selected area x-ray computed tomography, laser scattering, infrared imaging, positron annihilation and high resolution FPI.

The third step was to prepare an NDE methodology/plan for Phase II which is compatible with the other Phase II tasks. While this methodology/plan is still evolving, it includes the following activities at present:

1. Characterization test bars of each material in the as-received condition will be examined to obtain a baseline NDE signature for each material and an initial assessment of the capabilities of the selected NDE methods to the material defect distribution in the materials. This will include comparison of the ANL NDE equipment resolution with that of the suppliers' equipment.

2. Some of the test bars will be fractured. The fracture behavior will be compared with the position and size of defects detected by NDE.

3. Some of the test bars will be exposed to oxidation for various times and temperatures. Samples will be reinspected by NDE prior to fracture. The objective will be to determine if information from NDE techniques correlates with time-dependent material changes and fracture behavior.

4. Selected tensile test bars will also be inspected by advanced NDE methods prior to long term creep testing. These will be reinspected after testing and prior to fracture in an effort to explore the role that NDE might play in life prediction by monitoring time-dependent growth of defects.

5. To assess the capability of advanced NDE methods to examine a non-uniform cross-section, a tapered standard with known defects (inclusions, surface cracks, pores, and holes) will be fabricated from some ceramic materials. This will be used in parallel to NDE of early Phase II component shapes such as blade attachment samples and initial prototype blades.

6. Early subsize composite combustor liners will be examined by selected NDE methods (probably through-wall radiography, medical CT and infrared imaging). One liner will be retained as-fabricated and the others will be rig tested under static and cyclic conditions. Rig tested liners will be reinspected by the NDE methods. These and the untested liner will be cut into bars and c-rings and evaluated for mechanical properties. The NDE results will be compared with the mechanical property results. Similar before and after NDE examinations will be conducted for separate test coupons exposed to long term oxidation and other tests.

7. The results of the above evaluations will be used to plan further NDE development and to select specific NDE procedures for first generation ceramic components.

5.6 ANCILLARY MATERIAL NEEDS

The design requirements for secondary components have been discussed previously in Section 4.6 (Secondary Components Preliminary Design). This section will focus on the materials requirements for these secondary components.

The basic philosophy of the CSGT program is to start with the standard Centaur 50 gas turbine and make the necessary structural changes to allow the incorporation of ceramic hot section components. The initial design assumes operation at 1121°C (2050°F TRIT) and a life of 10,000 hours. Preliminary combustor radial profile and aerodynamic data for the CSGT engine have been compiled. From this information, the turbine blade and nozzle temperatures have been calculated.

In assessing the ancillary material needs in the CSGT program, the materials of concern can be grouped into two categories, *viz.*, new non-ceramic components associated with the incorporation of the ceramic components and the existing turbine components. The first category is directly a function of the engine design and is a part of the final design. However, the second category depends only on the engine cycle, and with the preliminary definition of the engine cycle having been made, initial recommendations for the affected turbine components can be made.

The preliminary material recommendations are based on a design life of 10,000 hours for 1121°C (2050°F) operation. This represents a comfortable life margin over the program field test requirement of 4,000 hours. However, this falls short of the commercial goal of 30,000 hours TBO (Time Between Overhaul) and an ultimate life of 60,000-100,000 hours, which will be addressed as the product design matures.

Preliminary estimates of the disk rim temperatures were calculated as follows:

Stage 1:	671°C (1240°F)
Stage 2:	632°C (1170°F)
Stage 3:	577°C (1070°F)

The turbine components being considered at this time are the stage 1, 2 and 3 disks, stage 2 and 3 blades and nozzles, diaphragms, and the turbine nozzle case. As the detail design develops, the list of affected components may change. The basic materials approach will be modeled after the Solar Mars 100 (1121°C/2050°F TRIT) in order to minimize risk.

Stage 1 Disk

The current material is V-57, an iron based superalloy. The anticipated rim temperature of 671°C (1240°F) precludes its use despite the significant reduction in rim loading due to the use of ceramic blades. The disk lug stresses have been estimated by Design Engineering. Based on a metal temperature of 699°C (1290°F) (i.e., 671°C + 10°C (1240°F + 50°F)) and a life of 10,000 hours, a Larson-Miller parameter (L-M = T(R) x (log t (hours)+20)) of 42,000 is required. These conditions necessitate the use of Waspaloy, which has an L-M parameter of 43,000 (equivalent to a life of about 20,000 hours) at the design stress level.

Stage 2 Disk

The current material is the same as that of the first stage: V-57. The estimated rim temperature increases from the current 527°C (980°F) to the estimated temperature of 632°C (1170°F). Assuming a constant L-M parameter this increase in temperature reduces the life of a V-57 disk to 225 hours. Therefore the 2nd stage disk material must also be changed. By ratioing the L-M parameter for the Centaur 50 engine conditions to the new conditions, it is estimated that an increase of 3,000 in the L-M parameter is required to satisfy the new operating conditions. Preliminary analysis indicates that this amount of increase can be obtained with Waspaloy, and this the recommended alloy.

Stage 3 Disk, (Taurus)

The Taurus 3rd stage disk is currently Inconel 718. The disk lug stresses have been defined and with a rim temperature of 577°C (1070°F), the estimated stress rupture life would be approximately 1,000,000 hours. It is recommended that no change to the alloy be made.

The disk alloy recommendations should only be considered as preliminary because they are only based on stress rupture consideration. The detailed design will include other considerations such as blade shed and disk burst properties.

Stage 2 Blade

The current blade is uncooled and cast in IN-738LC. At the design life of 10,000 hours (L-M = 51400) neither conventionally cast IN-738LC nor MAR-M247 have adequate stress rupture lives. Preliminary analysis indicates that DS MAR-M247 is adequate and is suggested as the preliminary recommendation. As the detailed design is formalized and the stress conditions, temperature conditions, and dynamic environment are more precisely defined, the recommendation will be reviewed.

Stage 3 Blade, (Taurus)

The current blade is cast in IN-100. At the new design conditions the cast IN-100 blade has greater than 500,000 hours rupture life, well in excess of the 10,000 hr. design life. Because the IN-100 blade has already been optimized for the Taurus dynamic environment, continuing with this alloy is recommended.

Stage 2 Nozzle

The current stage 2 nozzle is uncooled and cast in FS-414. Provisions for airfoil cooling will be required at 1121°C (2050°F) TRIT operation in order to prevent airfoil burn-through in 4,000 hours.

Because the actual metal temperatures will depend on cooling effectiveness and the combustion pattern factor, only a hierarchy of material options can be presented at this preliminary stage. As the cooling affectivity decreases or conversely as the metal temperature is increased, the material choices would typically be FS-414, FS-414 with an aluminide coating, MAR-M509 (particularly if higher strength is required) generally coated, and finally a cast nickel-based alloy (such as, IN-738, IN-939 or MAR-M247) generally coated. Additional margin/temperature capability can be provided by directionally solidified alloys.

In the Mars 100, the second stage nozzle is MAR-M509 coated with a diffusion aluminide. The stress levels were excessive for FS-414, but due to hot corrosion concerns, the cobalt based alloy was preferred over a nickel-based alloy. Additionally, the cobalt-based alloys typically have better castability than the nickel-based alloys, which in a complex multi-vaned nozzle can be an important factor. As the design becomes more refined and the estimates of the metal temperatures improve, a better judgement on the alloy selection can be made. However, because the Centaur 50 stage 2 nozzle is not as highly stressed as the Mars stage 2 nozzle, it is expected that the current FS-414 nozzle can very likely be used, assuming a similar degree of cooling.

Stage 3 Nozzle

The current stage 3 nozzle is uncooled and cast in IN-713C. The airfoil metal temperatures for the CSGT engine are estimated to be a maximum of 857°C (1574°F). The alloy will provide adequate tensile strength and rupture life up to this maximum temperature. IN-713C is prone to hot corrosion attack and should be coated for enhanced durability. Alternate alloys, such as, IN-738LC and IN-939 should be considered. These alloys possess good mechanical properties with good environmental durability, eliminating the need for coating in all but the most demanding environments.

Stage 2 and 3 Diaphragms

The current materials for the stage 2 and 3 diaphragms are N-155 and D-5B respectively. A change in the stage 3 diaphragm material is unlikely, as the Mars 100, (1121°C/2050°F TRIT) engine has successfully used Ni-resist D-5B for a similar diaphragm. However, the N-155 stage 2 diaphragm may need to be upgraded to a stronger alloy with a higher temperature capability. The selection also is heavily dependent upon the thermal expansion matching requirements. Potential alternate alloys include the very low expansion Incoloy 903/909 family or the newer low expansion alloys, such as Haynes Alloy 242, Cartech's Thermospan or INCO's alloy 4005. The requirements defined by the detailed design will help guide this selection.

Nozzle Support Housing

The current material is Ni-resist D-5B, a high nickel ductile iron with a controlled low thermal expansion. D-5B has a fairly rapid drop-off in tensile and rupture properties at temperatures above 538°C (1000°F).

Predicted temperatures for this part exceed 538°C (1000°F), which suggests that the alloy may not be adequate for the application. The recommended alternate alloys are the same alloys previously suggested as alternate diaphragm alloys. A more detailed design analysis is required before a recommendation can be made. However, the low expansion Incoloy 903/909 family of alloys have performed well in similar applications.

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6.0

TASK 4 - TECHNICAL & ECONOMIC JUSTIFICATION AND MARKET POTENTIAL

6.1 INTRODUCTION

The effect of the ceramic components on the performance, economics, and emissions has been determined for the ceramic stationary gas turbine in simple cycle and cogeneration applications. The data have been compared with those for baseline all-metal engines. Based on the predicted performance gains a market penetration scenario has been proposed and the route to commercialization of the technology has been described.

6.2 CERAMIC COMPONENT COMMERCIALIZATION

The ceramic component suppliers that were involved in Phase I of the program have supplied commercialization plans for their components. These plans included cost data for commercial quantities of components based on preliminary designs for the CSGT engine described in Section 3 (Preliminary Design of Key Components). Solar has evaluated the data supplied by the ceramic fabricators and incorporated them into the economic analysis for the CSGT engine.

6.2.1 Solar Component Commercialization Assessment

The objective of the DOE CSGT program is to modify an existing stationary gas turbine and demonstrate the ceramic engine in a 4000 hr field test. The establishment of the potential for significant performance improvements in ceramic gas turbines compared to all-metal engines is a major program goal. This work will pave the way for eventual customer acceptance of the ceramic turbine technology, but ultimately, success will also depend on establishing the technology for cost effective manufacturing and assembly of ceramic engine components for commercially viable turbomachinery products.

The following factors are important when considering the commercial viability of the ceramic turbine technology:

1. Durability of Designs. Engine and component designs developed under the CSGT program are intended to meet acceptable standards of durability. Further development of the technology will be required, however, beyond the immediate objectives of the program, to adapt these designs for the more challenging conditions under which the ceramic gas turbine will achieve its full potential.

2. Potential for Significant Performance Improvements. The engine and component designs should be able to contribute to significantly improved power output, thermal efficiency, and reduced emissions when applied to optimized engines.

3. Cost Effective Product Designs. The technology must be amenable to incorporation into advanced turbomachinery products which offer the customer equipment that combines high performance with attractive pricing. Cost effective designs must reflect simplicity and utilize durable ceramic components available at costs that must be competitive with metallic components with due regard to efficiency and output.

4. Consistent Quality of Engine Components. The above requirements can only be met if all critical components in the gas turbine engine, including the ceramic components, be durable, reliable, and of consistent fabrication quality.

5. Reliable Ceramic Component Supplier Base. The current lack of a well established viable supplier base in the U.S. is a serious impediment to the commercialization of the ceramic gas turbine. U.S. ceramic suppliers have tended to be relatively small operations functioning in a R&D mode, producing small volumes of expensive development type components. Transformation to low cost, high volume production for the automotive industry is a major challenge for the development of production automotive gas turbines. Transformation to meet the needs of the industrial gas turbine will be a much easier task.

The first three of these factors are largely the responsibility of the gas turbine equipment manufacturer. The suppliers of ceramic components have a significant impact on the latter two factors. The suppliers have been assessed against the criteria listed below:

1. Ability to fabricate quality components

2. Projected component cost

3. Projected ability to scale fabrication process to commercial quantities

The ability of the suppliers to fabricate quality components has been addressed in Section 5 (Material Selection). The evaluation of materials data, preliminary fabrication plans and quality assurance practices was completed for each of the Phase I suppliers. It was established that the suppliers were qualified to fabricate the components for the program to Solar's specification and that quality systems were in place to fabricate the components in a reproducible and reliable manner.

All ceramic suppliers have provided cost data for commercial quantities of their components for the CSGT engine. The data have been grouped by component to obtain an overall cost profile while protecting the confidential nature of the data supplied.

Based on Solar's visits to the suppliers fabrication facilities and following evaluation of their commercialization plans it has been established that all suppliers should be able to fabricate annual volumes of components for Solar's ceramic engine products.

6.2.2 Supplier Commercialization Plans

6.2.2.1 Ability to Fabricate Quality Components

None of the suppliers have fabricated components exactly like the ones used on this program so their capabilities were assessed from an evaluation of their fabrication plans, quality assurance procedures and track record on fabricating components on related programs. The current state-of-the-art at the suppliers were considered in evaluating this aspect.

Of the blade suppliers KICC and NAC have both fabricated good quality blades on previous programs. CC has recently fabricated blades for Solar but has not fabricated prototype parts in significant quantities.

Both Carborundum and NAC have fabricated small vanes in significant quantities, but have no experience with the larger size shapes required for this program. CC, NAC, and Carborundum have fabricated good quality rotors for the AGT/ATTAP and other programs. NGK has produced large vane shapes of a size similar to that of the CSGT nozzle.

Carborundum's experience with combustor tiles is limited but this company has fabricated integral combustor liners of various shapes, and the tile designs are well within its capabilities. NAC has fabricated ring components for other customers. Neither DuPont Lanxide Composites nor B&W have fabricated the large ring type combustor shapes required for the program, but they have fabricated smaller rings and tubes. DuPont Lanxide Composites is believed to be more experienced than B&W since they have fabricated various small size combustors. On the other hand, B&W have fabricated large heat exchanger tubes.

6.2.2.2 Component Cost

Figures 6-1, 6-2, and 6-3 graphically represent the projected cost range of Phase I components for the ceramic first stage rotor blades, nozzles, and combustor liners respectively, to be fabricated by the Phase I suppliers. All component costs are based on best available technology projected to be in place at the time of commercialization of the technology. It can be seen that component cost decreases as part volumes increase for the rotor blades and the nozzles, but component cost remains nearly constant for the liners. Also, the range in part costs for the components increases in the sequence: blades < nozzles < combustor liners. These observations reflect particularities in the fabrication processes and economics of scale. In the case of the blade all parts are fabricated from silicon nitride while the nozzle is fabricated of either silicon nitride or silicon carbide. The combustor liners are either fabricated from silicon carbide tiles or rings or from SiC/SiC or alumina/alumina fiber reinforced ceramic matrix composites (CFCC's). Since the blades and nozzles are fabricated in relatively large (aerospace) quantities the proportioning of the cost of tooling over a large number of parts results in noticeable cost decreases with increased part quantities. This is much less the case with the combustor liners. The cost of CFCC liners is much less sensitive to tooling cost proportioning than for monolithic ceramics. Important cost contributors here are the price of fibers, and the cost of preforming and infiltration. These factors contribute in different ways to the total cost of the fabrication of CFCC liners.

The cost of ceramic blades and nozzles is competitive with the cost of cooled components with similar geometries fabricated from advanced superalloys (single crystal or ODS) materials. At the highest level of utilization the lowest cost for these ceramic parts is substantially less than that of comparable cooled advanced superalloys components at 1993 prices. Combustor liner cost (even at the lowest price) is higher than the cost of metallic liners, but this cost differential must be weighed against the environmental desirability and economic value of the low emissions potentially achievable with ceramic lined combustors at high turbine rotor inlet temperatures.

6.2.2.3 Scale Up of Process To Commercial Quantities of Components

None of the suppliers has scaled up part fabrication for designs similar to those of the Solar CSGT engine. However, there are indications that the ceramic industry will be able to scale up their processes to aerospace quantities on the basis of recent market experience.

Japanese ceramic suppliers (NGK, Kyocera) have successfully scaled up the fabrication process of ceramic automotive turbochargers to quantities of 10,000's per month and more. Over half a million ceramic turbochargers have been installed in Japanese automobiles to-date at a cost competitive with metallic turbochargers. The ceramic turbochargers have demonstrated better performance than the metallic components in this commercial application.

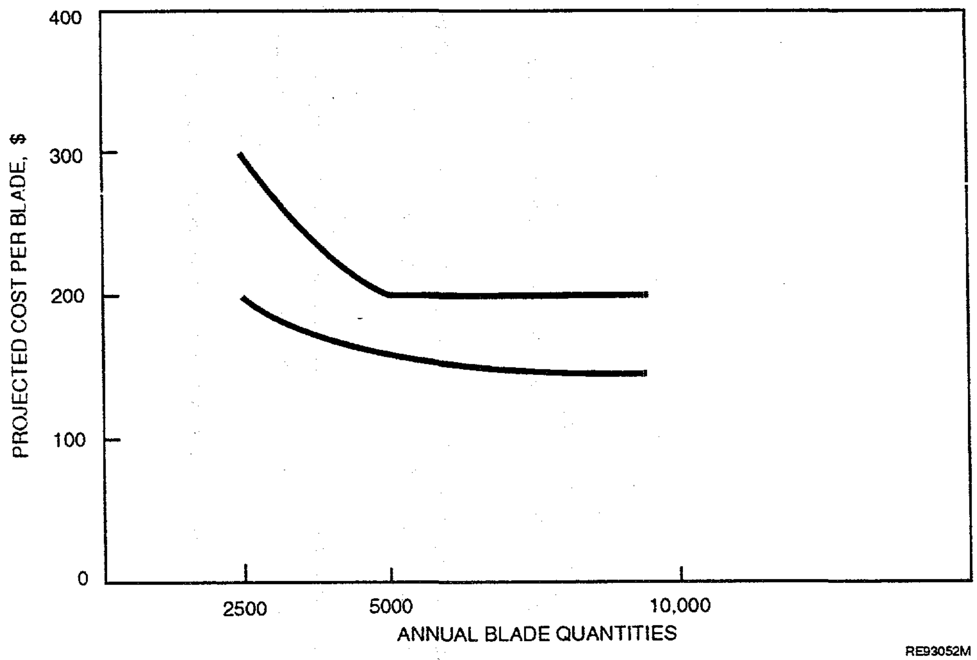

Figure 6-1. Cost Range for Commercial Quantities of First Stage Ceramic Rotor Blades

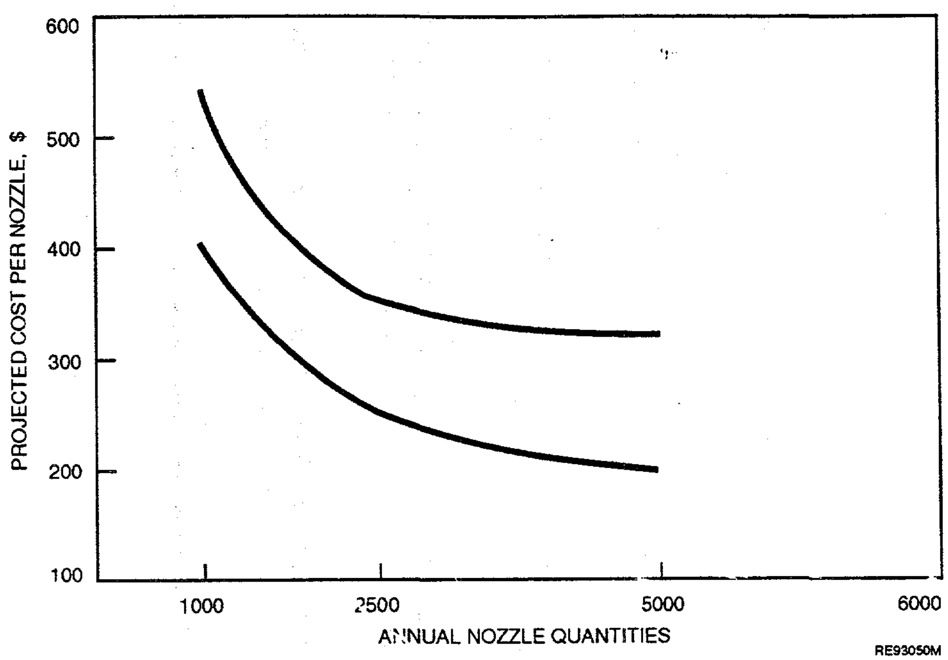

Figure 6-2. Cost Range for Commercial Quantities of First Stage Ceramic Nozzles

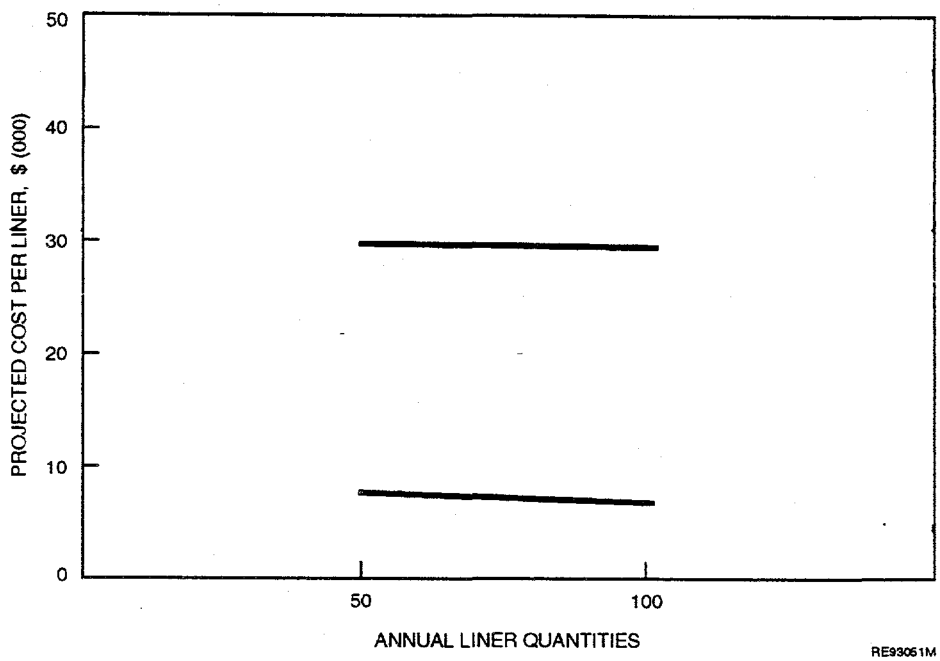

Figure 6-3. Cost Range for Commercial Quantities of Ceramic Combustor Liners

The prices for the ceramic blades and nozzles are competitive with those of cooled advanced superalloys at 1993 prices. One supplier estimated that a ceramic blade must sell for under $200 to be competitive with cooled metallic counterparts. Figure 6-1 shows that this cost target is obtainable. There is sufficient incentive for monolithic ceramic suppliers to commercialize their technologies.

Ongoing developments for ceramics for automotive turbine applications are also encouraging. The success of the AGT/ATTAP programs has resulted in the ceramic suppliers being able to fabricate complex components such as ceramic rotors that have shown good performance. Following the example of the Japanese scale up of turbocharger fabrication, U.S. industry can be expected to fabricate ceramic automotive parts competitively and with high reliability. The domestic suppliers are in the process of scaling up their fabrication technologies to meet the challenge of fabricating automotive quantities (millions) of components within the next decade. The scale up of the ceramic fabrication processes to meet these challenges will indirectly benefit the commercialization of the ceramic turbine as improved, more efficient, and cost effective process technologies become available.

The development of CFCC materials is envisioned to be more long term. These materials are still very much in the development phase. Significant improvements in fabrication technologies and properties of the CFCC materials are expected from ongoing programs such as the DOE Continuous Fiber-Reinforced Ceamic Matrix Composites (CFCC) and High Pressure Heat Exchanger System (HiPHES) programs, and the NASA High Speed Civil Transport (HCST) program, and DOD projects. The potential for the CFCC materials to fabricate integral parts of complex shapes that cannot be reliably fabricated from present day monolithic materials is good and Solar expects the CFCC materials to be serious candidates for low emission combustor equipment.

6.2.2.4 Summary of Supplier Assessment

The limited assessment conducted here indicates that none of the suppliers has actually fabricated parts similar to those designed under this program. Past experience in related projects and future commercialization plans are therefore a major measuring stick for evaluating economic viability. Those suppliers that have successfully fabricated parts for the automotive industry and scaled up their process to commercial quantities are best positioned to become reliable suppliers for ceramic gas turbine components. The suppliers on this program with offshore facilities (Kyocera, NGK) fall in this category. The recent establishment of a domestic manufacturing capability by Kyocera and accompanying transfer of technology to the U.S. is anticipated to boost the domestic supplier base.

There is a second tier of ceramic component fabricators that have manufactured good quality prototype turbine parts in research quantities (100's) and that could become reliable suppliers in the future. These suppliers will have to gain the experience associated with transitioning developmental turbine technologies to volume production. Fabricators of monolithic ceramic components such as AlliedSignal Ceramic Components, Norton Advanced Ceramics, and Carborundum can be expected to become reliable part manufacturers in the future. The experience of these companies with volume production of ceramic components for non-turbine related applications will be helpful in this respect.

The fabricators of fiber-reinforced ceramic matrix composites (CFCC's) can be expected to require more time than the manufacturers of monolithic ceramics to become reliable part suppliers. Substantial efforts will be required in the areas of process improvement and cost reduction. The need for development for the fabrication of large parts, materials property characterization, and the development of design and life prediction methodologies suggests that the composite manufacturers will lag behind the monolithic part fabricators in becoming reliable suppliers for ceramic gas turbines. However, the potential for fabricating large complex shapes of the CFCC materials, and the significant efforts made under a number of programs (e.g. DOE CFCC Initiative, NASA High Speed Civil Transport Initiative, DOD programs) indicate that these materials may eventually achieve commercial status.

6.3 EFFECT OF COMPONENTS ON PERFORMANCE, ECONOMICS AND EMISSIONS

The economic value of ceramic component substitution to the gas turbine user has been evaluated by comparing performance and life cycle costs for metallic baseline engines and CSGT uprates. Performance parameters for valuation include output power, thermal efficiency, changes in recoverable heat energy, and maintenance and overhaul cost differences. The capital and operating cost associated in meeting U.S. EPA standards have been included in the life cycle cost comparisons for component substitution. Traditional net present value comparisons have been used to perform life cycle cost as well as simple payback analysis of ceramic gas turbine procurement, installation, operation, and maintenance versus the same engine using traditional design materials in cogeneration and simple cycle operation.

6.3.1 Valuation Methodology

6.3.1.1 Customer Valuation Methodology

Commercial markets value all energy conversion devices using a similar methodology. Since the device is purchased with the intent to use it for many years two cost components can be distinguished: Equipment Cost (First Cost) and Operating Cost. The additive cost factors compared to the revenue generated by the energy conversion system is assumed to be the value of the system according to the basic formula:

Value = Revenue - {Equipment Cost + Operating Cost}

The value is measured over the life of the system and includes all revenues generated and cost incurred over that period. Clearly, revenue must be greater than cost for the energy conversion system to be viable. However, how much greater is dependent on the level of risk and return an investment expectations of the user. The value may be optimized by one system producing high revenue, even when this system requires high equipment and/or operating cost. It may be optimized also by a system with lower revenue but correspondingly lower cost. While the above equation has only three variables, the process employed in selecting the highest value system is often complex and time consuming.

When selecting from competing systems intended to generate the power needed, the revenue portion of the above equation may be ignored since it is assumed to be the same for the options being considered. Without revenue, the resulting equation is termed "the life cycle cost" of the system and since it represents negative cash flows, the lower this value the better the system economics. Life cycle cost comparisons of competing systems has become one of the accepted methods for assessment of competitive technologies as well competive offerings of the same technology.

However, if the options available to meet power requirements are mutually exclusive and based on different system approaches or competing technologies, it is best to determine the value of each solution (including revenue generated). While increasing the complexity of the analysis it does help insure that value is optimized.

6.3.1.2 Valuing Technological Change

Measuring the optimum value due to technological innovation is difficult to assess. Technical changes in products affect system design, installation, operation, and overall risk. Previous experiences, used as a basis for estimating cost and revenues to determine the value of a system, have to be carefully scrutinized to insure they are applicable. It is usually not appropriate to substitute the new element or component for the old one and just measure the cost difference. All benefits associated with the improved product or component (i.e more power, better efficiency, reduced emissions, lower maintenance, etc.) must be valued along with any difference in cost. The methodology employed to measure the impact of technological change begins with calculating value of the power generating system before the new technology was introduced and then comparing it to the system's value after incorporating the new technology. The value difference or delta indicates how economically beneficial the technical change is. The process can be summarized in the following flow diagram:

Value		Value		Value
System 1 (existing)	»	System 2 (new)	»	Delta

The 'value delta' must account for a number of cost elements incurred as a result of introducing the technical changes into the system. The value delta clearly must be significantly greater than the cost incurred for the technology to be justified. One could apply a detailed cost build up methodology, where the cost of each system plus an appropriate mark-up is fed into the valuation equation and the value delta (if positive) is used to justify system changes. With a proven product, incorporating proven technology, that calculation is rather straightforward. However, with new technology being introduced into key components of a dynamic system (such as ceramics into the hot section of a gas turbine), the cost build up methodology produces results that are speculative and are likely to change during product development. In lieu of the cost build-up approach, approximations of system installed cost based on historical averages are used to calculate economic value and from that the 'value delta' is generated.

The value delta must be carefully scrutinized to allocate the increased value to the appropriate element. As mentioned above, much of the improved performance results in known changes to the system which have added cost associated with them. For example, more power requires a larger and generally more expensive generator and gearbox; more exhaust heat will require a larger heat recovery system for cogeneration applications; reduced durability could result in higher maintenance cost; and of course, higher firing temperatures anticipated with ceramic components could require material upgrades in other parts of the engine. Thus, once the value delta is calculated a considerable amount of work remains to insure that the value of the technology introduced stays positive.

6.3.1.3 Cost Versus Value Comparison

Once the value of the system options have been calculated and the change in value is allocated to the appropriate elements, then a comparison must be made of the incremental value and the cost incurred in achieving the improved economics. This is an ongoing, dynamic process. The allocation of the value improvement due to the technology introduced gives the designer a cost target to aim for while maintaining the performance goals set for the development of the new product. The designer is constantly making decisions during development which have varying degrees of risk associated with them. The decision to select one option over another also has cost and performance impact associated with it. It is essential that the designer has the option to select the optimum path to achieve his goals of cost and performance. He must also have the ability to identify, as quickly as possible, when those objectives cannot be met.

The first priority is to achieve the performance objectives. If this can be done with the increased cost not exceeding the valuation delta, then the benefit of the new technology will clearly be met. The designer, knowing this, may try a number of potentially acceptable solutions to better insure performance goals are met. The ones producing acceptable results can be closely scrutinized to determine which has the lowest cost to manufacture.

If performance goals are not achieved at an incremental cost that is within the value delta, then one of three approaches should be taken. First, the valuation of the system should be recalculated with a 'new' expected performance based on the analytical or test results produced at the time the original performance goals were deemed unachievable. If the incremental cost is within the new value delta then the technology may be justified for incorporation in the product. Second, if the original performance goals are achieved but at a cost above the value delta, then the market and application for which the system was intended should be analyzed to see what, if any, portion of the market can be served with a higher product cost. If enough of the market remains accessible with the new technology then it again may be justifiable. Added work may be needed for reducing cost and/or improving the system's incremental value. And last, a combination of trading off performance with cost in an effort to maximize value and keep incremental cost within the value delta should be attempted. This effort will be time consuming and an indication that the technology may not be ready for full market acceptance.

As can be seen from the above discussion, the value to a customer of introducing new technology into a proven system compared with the cost of that technology is dynamic. Ultimately the market will evaluate the true benefit and place an economic premium or penalty on the technology.

Competitive pressures from other systems using similar technology as well as those incorporating new and different technical solutions will also impact the valuation of new technology. Therefore, it is the intent of the economic methodology employed during this development program to be consistent in approach and provide cost guidance to the designers and developers of the Ceramic Stationary Gas Turbine.

6.3.2 CSGT Engine Performance

In addition to the engine under development on this program (the CSGT), two additional ceramic hot section engines have been studied to evaluate the potential of this technology. The performance of the three engines will be evaluated from an economic viewpoint with the results to be presented in the next Section (6.3.3).

6.3.2.1 CSGT Engine Performance Specification

Basic Engine Specification. The CSGT engine development has been conducted on the basis requested by DOE, that is to say, ceramic components have replaced metallic components with the minimum number of design changes to the overall engine. In the design work in Phase I, it became evident that some changes were required in other components to avoid gross mismatching, but each of these changes has been justified elsewhere in this report.

Table 6-1 gives the characteristics of a current Centaur 50 single shaft T-5501 engine installed at ARCO, Bakersfield (based on nominal performance). There are two basic single shaft Centaur 50 engine types, one formerly designated as the T-5501 and the other formerly designated as the T-5701. The difference between these two Centaur 50 variants is the incorporation of a new first compressor stage in the T-5701 which results in about 230 additional shaft horse powers in the latter model. The historic designations of the two Centaur 50 variants have been retained in Table 6-1 for discussion purposes.

Table 6-1 also gives performance data for the T-5701 model. Both models are fired at a Turbine Rotor Inlet Temperature (TRIT) of 1010°C(1850°F). It should be noted that production engines in the T-5701 series consistently exceed the nominal.

Two models of T-5701 with ceramic components are included in Table 6-1. Both models include a T6501 third stage turbine to handle the higher volume of gas associated with firing at 1121°C(2050°F) TRIT. The first, CSGT-5701A has stage 1 turbine tip clearances of 0.76 mm (0.030 inch). The second, CSGT-5701B has tip clearances of 1.3 mm (0.050 inch) to ensure the absence of tip rubs at this early stage of development.

The specification for the minimum acceptance performance of the CSGT field test engine is:

Output	6900 SHP
Thermal efficiency	30.0%

Nominal Performance at Customer Site. The customer, ARCO at Bakersfield, California operates under conditions that differ from the standard conditions assumed for the calculations in Table 6-1. The specific site conditions are:

Elevation	259 m (850 feet)
Relative humidity	90%
Inlet loss pressure	7.6 cm (3 inch) water
Exhaust loss pressure	20 cm (8 inch) water

Table 6-1. Centaur 50 Single Shaft Engine Performance

Sea Level, 59 F, 60% R.H., Zero Duct Loss, No Water Injection

Engine Type	Item	Nominal
T-5501	SHP Thermal Eff.	5498 29.59%
T-5701	SHP Thermal Eff.	5732 29.59%
CSGT-5701A*	SHP Thermal Eff.	7217 31.25%
CSGT-5701B*	SHP Thermal Eff.	7125 30.85%
* Fired at 1121°C(2050°F) with ceramic combustor and stage 1 turbine and "T6501" Stage 3 turbine. Stage 1 tip clear; A = 0.76 mm (0.030 inch), B = 1.3 mm (0.050 inch).		

Table 6-2. Centaur 50 Genset Performance at ARCO, Bakersfield, CA

Baseline: Present Centaur 50 Gensets at ARCO, T-5501, Water Injected for NOx Control, Water/Fuel = 0.65.					
Inlet Air Temp, °C(°F)	-12(10)	-1(30)	10(50)	21(70)	32(90)
Generator Output, kW_e	4434	4195	3939	3664	3400
Heat Rate, Btu/kW_eh	12158	12323	12552	12849	13185
Engine SHP	6290	5951	5589	5198	4824
Engine Thermal Eff. %	29.7	29.3	28.8	28.1	27.4
Exhaust Temp, °C(°F)	507(945)	512(953)	517(962)	523(973)	531(987)
Planned: CSGT-5701A					
Inlet Air Temp, °C(°F)	-12(10)	-1(30)	10(50)	21(70)	32(90)
Generator Output, kW_e	5487	5215	4923	4601	4296
Heat Rate, Btu/kW_eh	11216	11427	11703	12060	12484
Engine SHP	7784	7399	6985	6528	6095
Engine Thermal Eff, %	32.2	31.6	30.8	30.0	28.9
Exhaust Temp, °C(°F)	567(1052)	573(1063)	579(1074)	587(1089)	597(1107)

The ambient temperature in Bakersfield frequently exceeds 100°F. To minimize output loss due to this high ambient, the installation is fitted with an evaporative inlet air cooler, so that the inlet air temperature to the gas turbine never exceeds 32°C (90°F). Table 6-2 shows the variation of the nominal performance of the current T5501 expected under these conditions. A water/fuel ratio of 0.65 is included in this estimation of performance to meet NOx control requirements. The planned CSGT-5701A engine will not require water injection because the ceramic lean premix combustor alone will meet emissions requirements. Table 6-2 gives the nominal performance of this engine. All performance values are nominal.

Review of the data in Table 6-2 versus ancillary equipment at ARCO showed that the higher nominal output could be handled by the existing equipment. The gearbox could handle the additional shaft horsepower readily; the electrical generator is rated at 5390 kW_e at 40°C(104°F) ambient. The heat recovery equipment is rated for an exhaust temperature of 560°C(1040°F). Closer examination of this factor is in progress but the anticipated exhaust temperature range is not expected to pose a significant problem.

Table 6-3 lists the conversion factors used to obtain Centaur 50 performance at the ARCO site. The examples are a T-5501 Centaur 50 engine with wet NOx control (Case I) and a T-5701 Centaur 50 engine (current all-metal, or ceramic) with dry low NOx control (Case II).

Table 6-3. Conversion Factors to Obtain Centaur 50 Performance at ARCO Site

Case I: T-5501 engine, wet NOx, water/fuel ratio = 0.65
Water @ 15°C (59°F) and 2.76 MPa (400 psi) water pressure

SHP (Site) = 0.983 x SHP (ISO)

kW_e (Site) = 0.693 x SHP (ISO)

Case II: T-5701 Engine, Dry or SoLoNOx

SHP (Site) = 0.940 x SHP (ISO)

kW_e (Site) = 0.662 x SHP (ISO)

<u>**For Either Case:**</u>

$$\text{Heat Rate (Btu/kW}_e\text{Hr)} = \frac{254{,}500 \times \text{SHP (Site)}}{\text{\%Th. Eff. (ISO)} \times \text{kW}_e\text{ (Site)}}$$

$$\text{Genset Eff @ Terminals} = \frac{3413}{\text{Heat Rate (Btu/kW}_e\text{h)}}$$

<u>**Performance Comparison of T5701 Versus CSGT-5701A**</u>. The first all-metal Centaur 50 T-5701 engine fired at 1010°C(1850°F) met the nominal output of 5732 HP. Subsequently, the next 20 engines had higher outputs. The average output of the first 21 engines has been 5880 HP with the lowest close to the nominal, all measured under ISO conditions. This average performance will be used rather than nominal for the economic analysis.

Table 6-4 compares the average performance of the metallic T5701 with that predicted for the CSGT-5701A engine under ISO conditions.

The ceramic modification of the T5701 gives 25.9% more power and 5.6% more efficiency in the simple cycle mode. In the cogeneration mode, the electrical generation efficiency increases by 5.3% and the fuel utilization efficiency increases by 6.6%. The electrical output increases by only 25.6% because of the back pressure created by the HRSG.

Table 6-4. Comparison of Metallic Centaur 50 (T5701) Fired at 1010°C(1850°F) and Ceramic Centaur 50 CSGT (5701A) Fired at 1121°C(2050°F)

Performance Factor	Average Metallic T5701	Predicted Modified Ceramic CSGT-5701A
In Simple Cycle Mode:		
Total Rotor Inlet Temp. °C(°F)	1010(1850)	1121(2050)
Shaft Output, SHP	5880	7402
Shaft Thermal Eff. %	29.63	31.29
Electrical Output, kW	4144	5217
Electrical Thermal Eff., %	28.01	29.58
In Cogeneration Mode:		
Electrical Output, kW	4051	5088
Electrical Thermal Eff., %	27.38	28.84
Overall Thermal Eff., %	75.39	80.33
Electrical/Thermal Ratio	0.570	0.560

The assumptions made in the cycle studies for cogeneration systems were:

- Heat recovery steam generator (HRSG) gas side pressure loss is 25 cm (10 in.) H_2O
- Steam produced at 1.12 MPa (150 psig), saturated
- Return feed at 66°C(150°F); 85% return of boiler steam flow quantity
- HRSG pinch-point temperature difference is 28°C(50°F)
- Feed pump outlet pressure 2.17 MPa (300 psig), pump efficiency 75%, electric motor efficiency 85%
- 5% HRSG blow-down
- 20% raw water make-up at 15°C(59°F)
- Live steam used for deaeration at 116°C(240°F)

These assumptions have been made for all cycles carried forward to the economic analyses.

6.3.2.2 Performance Advances with Ceramic Hot Stages in Other Solar Gas Turbines

Two other engines have been analyzed to extend the economic analysis to a wider range of Solar engines. One of these engines, the Mars 100 is second generation, that is it incorporates a ceramic hot section with redesign of the hot section flow path to optimize the gas producer and power turbine sections. In each of these cases, an all-metallic engine provides a baseline for comparison. The second engine, a modified recuperated Taurus engine, begins to approach the third generation engine (clean sheet of paper design for ceramics) and no metallic comparison is available.

Modification of an existing compressor from the Taurus engine series has been performed to provide a better match for a recuperated engine cycle. The single stage, ceramic gas producer turbine and the single stage power turbine are original designs matched for the overall cycle.

The evaluated second generation engine was formerly known as the Mars T14000. The engine approaching the third generation is designated a modified, recuperated ceramic Taurus engine.

Mars 100. Table 6-5 gives the ISO performance predicted for a CSGT Mars 100 engine when the firing temperature is increased to 1204°C(2200°F) with ceramic components in the first and second turbine stages. To handle the larger gas volume flow, the power turbine has been increased to 3 stages from the 2 stages used in the present Mars 100. The 3-stage power turbine produces a better match with the increased gas flow than an increase in size of the current power turbine would. The Mars 100 has a 16:1 pressure ratio which makes it better suited to take advantage of the increase in TRIT than the CSGT derived from the Centaur 50 (T-5701 baseline derivative).

Table 6-5. Predicted ISO Performance of a Hot-Section Optimized Mars Based "Ceramic" Engine (Simple Cycle)

Performance Factor	Baseline Metallic Mars 100	Optimized Ceramic Hot-Section
In Simple Cycle Mode:		
Total Rotor Inlet Temp. °C(°F)	1121(2050)	1204(2200)
Shaft Output, SHP	14069	19970
Shaft Thermal Eff. %	33.40	40.00
Electrical Output, kW	10002	14197
Electrical Thermal Eff., %	31.84	38.14
In Cogeneration Mode:		
Electrical Output, kW	9825	14005
Electrical Thermal Eff., %	31.28	37.58
Overall Thermal Eff., %	75.44	80.43
Electrical/Thermal Ratio	0.708	0.877

In the simple cycle mode, the relative increase in power output equals nearly 42% with a relative increase in efficiency of 19.8%. In the cogeneration mode, the estimated efficiency of over 37.5% and an overall fuel utilization efficiency of over 80% are very attractive numbers. The high electrical-to-thermal ratio of 0.877 represents a significant increase over the baseline metallic engine, and promises to provide a good fit to the marketplace.

Modified, Recuperated Taurus Engine. Another example that was evaluated was a recuperated engine derived from the current Solar Taurus engine. It could be said that this engine is approaching the third generation ceramic engine. The modification to the compressor is significant with omitted stages to reduce the pressure ratio to between 7.5:1 and 8:1 (depending on the firing temperature). This reduction in pressure ratio is close to the desired value to achieve the optimum cycle efficiency for recuperation. The turbine includes 2 stages. The first stage is ceramic and drives the gas producer turbine. The second stage is a single stage power turbine.

The performance of a simple cycle Taurus 60 baseline engine is given for comparison. Table 6-6 gives the predicted ISO performance of this modified, recuperated Taurus engine for three firing temperatures. The attainment of over 40% efficiency in electrical generation in both simple cycle operation and in cogeneration when fired at the higher temperatures is noteworthy. The overall efficiency is lower because of the high E/T ratio, as expected from the relationship:

$$\eta_{overall} = [1 + \frac{1}{E/T}] \times \eta_{electrical}$$

Installation of duct burners and an oversized HRSG will be frequently necessary to achieve lower E/T ratios to meet a customer's needs. This has the effect of raising $\eta_{overall}$ at the same time E/T diminishes.

Table 6-6. Predicted ISO Performance of a Modified, Recuperated, "Ceramic" Taurus Engine

Total Rotor Inlet Temperature , °C(°F)*	1010(1850)	1038(1900)	1121(2050)	1204(2200)
In Recuperated Cycle Mode:				
Shaft Output, SHP	0.6565	5986	6766	7536
Shaft Thermal Eff., %	30.69	40.83	42.35	43.58
Electrical Output, kW	4627	4223	4773	5317
Electrical Thermal Eff., %	29.01	38.64	40.08	41.24
In Cogeneration Mode:				
Electrical Output, kW	4549	4112	4647	5177
Electrical Thermal Eff., %	20.52	37.63	39.02	40.16
Overall Thermal Eff., %	74.32	59.63	62.55	65.09
Electrical/Thermal Ratio	0.623	1.710	1.658	1.611

NOTE: While equally applicable to all types of power producing systems involving a gas turbine prime mover, an electrical generating system was selected. The methodology employed would be equally applicable to a system used as a pump or compressor drive or in a transportation mode.

* Performance of a simple cycle Taurus 60 baseline engine is shown for comparison.

6.3.3 Net Economic Value

6.3.3.1 Economic Methodology

As previously described in 6.3.1.1 the value of an energy producing system over its operating life can be summarized using this equation:

Value = Revenue - {Equipment Cost + Operating Cost}

The initial focus was on the life cycle cost portion of this equation to eliminate one major degree of freedom. However, as the performance of the engines described in the previous section indicates the outputs of the various options considered were often dramatically different from the base case model and thus the revenue portion of the value equation was affected. It therefore became clear that the value must include variables from all three major categories. Elements making up the three categories include:

Revenue	Equipment and Installation Cost	Operating Cost
Electricity	Engineering	Fuel
Availability	Land	Waste Disposal
	Equipment	Maintenance
	Permits	Operators
	Legal	Down time
	Construction	Taxes
	Construction financing	Insurance
	Start-up	

Elements including engineering, land, legal fees, construction, construction financing, waste disposal, operators, taxes, and insurance are not expected to be affected by the technical change involving ceramic material substitution. This is expected to be true even if products are redesigned to be more optimally configured for the use of ceramics.

Availability, permit cost, start-up, down time, and maintenance are not expected to vary for the options being considered. However, until these factors are demonstrated in practical field testing they are considered variables which might have to be modified and reviewed in future economic analyses. In this analysis they are assumed to be unchanged.

The value of electricity consists of demand charges, usage charges, stand-by fees, supply voltage levels, the time of day, month or year the electricity is being supplied, etc. However, for systems of the approximate size of the one analyzed here, most of the fees are consistent and can be summarized in an average usage fee measured on a cents per kilowatt hour basis. It is assumed that for the sizes of the systems being considered here the power produced is not being sold back to the utility, and therefore only the value of the power being displaced is considered. The valuation formula for electricity generated during a year by the system is:

Electricity Revenue = (Electric Rate) X (Power) X (Utilization)

The value of steam generation, in the cogeneration mode, is based on a conservative average of $ 6.00 per thousand pounds of steam. Unlike electricity rates there is no true market rate for steam. Based on Solar's experience the $ 6.00 rate was the best estimate to provide credit for the steam generation. This rate was used as a credit in all cogeneration scenarios.

On the cost side, the value of fuel consumed is based on the net heat rate of the system measured on a lower heating value (LHV) basis and the cost of the fuel (also on an LHV basis). When the system is used for cogeneration the system heat is calculated after the heat used to generate steam has been subtracted from the fuel imput to the system. The valuation of fuel consumed during a year by the system is:

Fuel Cost = (Fuel Price) X (Heat Rate) X (Power) X (Utilization)

The equipment cost includes a number of items depending on the users' needs. However, based on Solar's experience of selling and installing gas turbine based generator systems for base-load and cogeneration application for the past 30 years the cost can be estimated with reasonable accuracy. The estimates are summarized in Table 6-7. The values are shown on a cost per kilowatt basis and represent averages for the type of system described. The following points should be made concerning the selection of system components and cost associated with them:

1. Systems typically vary with size, i.e. their cost increases with the size of the power plant. However, within the size classes presented here the price per KW remains fairly constant.

2. Application does make the cost per kW vary. The less complex the scope the lower the cost per kW, and vice versa. However, this variation is consistent for the options being considered and will affect each case equally.

3. When estimating the cost of changes made to the system which results from a change in power, the components associated with the change are scrutinized to insure they have been upgraded to handle the change in power. Equipment cost/sell price were not arbitrarily changed due to increased power.

Table 6-7. Product Cost Assumptions

Base Load	**Simple Cycle ($/kW)**	**Recuperated Cycle ($/kW)**
Gas Turbine (w/Enclosures and w/Ancillary)	400	400
Installation	175	175
Switch Gear	25	25
Recuperator	--	60
Total	600	660
Cogeneration:		
Gas Turbine	400	400
Installation	200	200
Switch Gear	50	50
Boiler	200	200
Gas Compressor	50	50
Duct Burner	50	75
Emissions	50	50
Recuperator	--	60
Total	1000	1085

The installed cost of the system is defined by the following formula:

Installed Cost = (Installed Cost per kW) X (Power)

In an increasing number of cases, the metallic engine installation is required to have additional components to reduce NOx to the locally acceptable level. Current dry low-NOx combustors can lower NOx emissions to levels approaching 25 ppmv or lower. To achieve significantly lower levels, post-combustion clean-up is used with Selected Catalytic Reduction (SCR) equipment. A recent EPA report gives examples of NOx reduction involving SCR for a number of installations. The EPA quotes a case for a continuous duty Centaur 40, an engine with a design close to that of the program engine. The addition of Selected Catâlytic Reduction (SCR) equipment increased the initial capital cost by $ 622,000 with total annual cost averaging $ 243,000. All costs are in 1990 dollars. The EPA report can be consulted for full details (1).

The costs for emissions control has been included under emissions, but the cost of installation and operation of SCR equipment is not incorporated in Table 6-7. It should be noted that these operating costs are $0.007/kWh whereas maintenance costs in continuous duty service are $0.003-$0.005/kWh. Stationary gas turbine engines with SCRs are rarely economically viable. Accordingly, comparisons would be meaningless. However, it is clear that achievement of low emissions with the CSGT would have a significant impact on the economics of gas turbine operation.

Net Present Value. While not significant to the concept of economic value as discussed and presented here, the concept of the 'time value of money' was utilized in this economic methodology for the results of this analysis to be truly useful. The concept that risk associated with future costs and earnings increases with time is widely recognized in business circles throughout the world. The further into the future the revenue and expense is, the greater the financial risk it represents. A common way to handle this risk is to discount the value of the cash flow stream more and more the further into the future it occurs. The discounting process when, applied consistently, allows the revenue and cost over the useful life of the system to reflect the risk of time associated with purchasing and installing a system today. If the discounted cash flows are added together, the resulting number become the overall value of the system today -- in other words, the 'Net Present Value'. A comparison of the net present value (NPV) of competing system options allows the user to select the one producing the best results. A detailed discussion of this process can be found in engineering economics or finance texts.

A single NPV equation incorporating all the pertinent methodology discussed can be expressed as:

$$NPV - kW \bullet [-IC + DCF + Util\ (EZ - MC) - (HR \bullet (FP/10^6)) - (SP/1000) \times 6.00kW)$$

where:

i	=	Option being considered
KW	=	Net electrical power produced (kW_e)
DCF	=	Discount factor
UTIL	=	Annual system utilization (hrs/yr)
ER	=	Average electric rate ($/kWh)
HR	=	Net system heat rate (Btu/kWh)
FP	=	Average fuel price ($/$10^6$ Btu)
MC	=	Average maintenance cost ($/kWh)
IC	=	System installed cost ($/$kW_e$)
SP	=	Steam production (lbs/hr)

The above formula is applied to each system option being considered to calculate the value to the customer.

6.3.3.2 Economic Assumptions

The economic variables utilized for the system valuation described above consist of the following elements:

- Discount Factor
- Maintenance Cost
- Fuel Cost
- Inflation
- Working Capital
- Insurance Cost
- System Utilization
- Electrical Rate
- Years
- Residual Capital Value
- Taxes

A conservative approach was used for this analysis. Therefore, inflation, residual capital value, working capital, taxes and insurance cost were excluded from consideration. It is recognized that these elements do affect the economic valuation, however their impact will be consistent for all cases being analyzed and not believed to produce a significant impact on the results.

Since the results of this program will be to have marketable ceramic gas turbines in about the year 2000, the remaining economic variables must be forecast for that time frame. The numbers utilized for this analysis will be in 1993 dollars but will represent estimates beginning in 2000. Further, these estimates are based on Solar's analysis of the global economic and energy markets over the next 10 years. A discussion of that forecast is contained in Section 6.4. The following is a brief discussion of the remaining economic variables and the assumed values used for this analysis:

1. **Discount Factor**. This factor represents a measure of an expected return from an investment. A hurdle discount rate of 30% before taxes was assumed for this analysis. This is a common rate expected in the power generation business.

2. **System Utilization**. The benefit derived from the insertion of ceramic materials in a gas turbine is more power and efficiency. These two criteria are valued by customers who utilize the equipment in continuous operation. Therefore, 8500 hours out of 8760 hours per year were assumed as the system utilization.

3. **Maintenance Cost**. It has been Solar's experience that the cost to maintain a gas turbine in continuous duty service averages between $.0030 and $.0050 per kWh. $.0040 is assumed for this analysis.

4. **Electric Rate**. The cost of electricity varies from region to region and for customer type. In addition, demand charges and standby charges as well as fees based on the voltage of the service also affects the cost of electricity. The application assumed for the analysis is a continuous duty or cogeneration base-load. Therefore, it is appropriate to utilize an average electric rate incorporating all these charges. Again to be conservative, industrial rates of $.06 and $.08 per kWh were assumed. These should represent a low and expected price for electricity.

5. **Steam Rate**. Unlike electricity, steam is not a traded commodity. This study has assumed a rate of $6.00/1000 lbs, based on Solar's recent experience. This rate will vary with time,

region, and application. For the purpose of this study the rate is considered a conservative estimate.

6. **Fuel Cost**. The cost of fuel will vary by type and by where it is used. This program assumes that natural gas will be utilized. Three different scenarios are envisioned, represented by a low, medium, and high price of $2, $3, and $4 per million Btu's, respectively. These are industrial burner tip prices based on lower heating value (LHV).

6. **Years**. The installed life of the system is expected to be in excess of 20 years. However, when using a high discount factor in the analysis, changes in economic value after year 10 have little impact on the analysis. Therefore, a 10 year life was assumed.

6.3.3.3 System Economic Value

The performance assumptions for the three major product options identified in Section 6.3.2 are summarized in Table 6-8. The price levels are from Table 6-7. The numbers are consistent and represent realistic operating system estimates using the gas turbines as they exist today as baseline values.

Table 6-8. Performance & Price Options

	Centaur 50 Baseline Metallic	Centaur 50 Modified Ceramic	Mars 100 Baseline Metallic	Mars 100 Optimized Ceramic Hot-Section	Taurus 60 Baseline Metallic 1850	Taurus 60 Recup Ceramic 1900	Taurus 60 Recup Ceramic 2050	Taurus 60 Recup Ceramic 2200
Performance Description								
Total Rotor Inlet Temp	1850	2050	2050	2200	1850	1900	2050	2200
Electrical Output, KW	4144	5217	10002	14197	4627	4223	4773	5317
Electrical Thermal Eff., %	28.01%	29.58%	31.84%	38.14%	29.01%	38.64%	40.08%	41.24%
Installed Price, $/KW	$600	$600	$600	$600	$600	$660	$660	$660
Cogeneration Mode:								
W/O Supplemental Firing:								
Electrical Output, KW	4051	5088	9825	14005	4549	4112	4647	5177
Steam Load	20,300	25,950	39,635	45,610	20,855	6,870	8,005	9,180
Overall Thermal Eff., %	75.39%	80.33%	75.44%	80.43%	74.32%	59.63%	62.55%	65.09%
Electrical/Thermal Ratio	0.57	0.56	0.708	0.877	0.623	1.71	1.658	1.611
Installed Price, $/KW	$1,000	$1,000	$1,000	$1,000	$1,000	$1,085	$1,085	$1,085
With Supplemental Firing:								
Electrical Output, KW	4051	5088	9825	14005	4549	4112	4647	5177
Steam Load	30,000	30,000	55,000	55,000	35,000	35,000	35,000	35,000
Net Steam Supplementally Fired:	9,700	4,050	15,365	9,390	14,145	28,130	26,995	25,820
Overall Thermal Eff., %	87.30%	86.68%	85.70%	86.93%	88.64%	91.91%	91.62%	91.13%
Electrical/Thermal Ratio	0.39	0.48	0.51	0.73	0.37	0.34	0.38	0.42

It should be noted that there are two cogeneration modes identified in Table 6-8. These represent a cogeneration system without supplemental firing in the exhaust and with supplemental firing. The use of supplemental firing allows the use of steam production to be equal for the two installations. A customer with the need for the selected level of steam production can compare the two installations more readily. Also, it can be seen that efficiency gained in the production of electrical power reduces the overall system efficiency if supplemental firing is not utilized. In addition, by allowing the steam production to be different for each option one more degree of freedom has been added making meaningful conclusions difficult. Therefore, supplemental firing to a steam production level consistent for each option of the three engine models analyzed was used. Excessive supplemental firing would not significantly change the system economics since process steam is produced at near 100% efficiency with this method.

Table 6-9 contains the NPV calculations of the three engines and ceramic options considered. Again, the performance is based on the data shown in Table 6-8. The economic assumptions were those presented in Section 6.3.3.2. The equipment cost and installation data were from Table 6-7.

Tables 6-10 through 6-12 contain the economic value calculations of the Centaur 50 (formerly T-5701), Mars 100, and modified recuperated Taurus options, respectively. Each system is considered under assumptions presented in Section 6.3.3.2. Negative values indicated in () represent conditions where the cost to generate power and heat is greater than the value of the energy replaced. Those situations are unrealistic since no reasonable person would purchase a system which produces a negative return. Therefore, any option which produces a negative value is ignored in the analysis.

From the variations in operating parameters and system performance a 'value delta' is calculated. This represents the change in value to the customer from the insertion of ceramic components into the three model options considered. Minimum and maximum value deltas are highlighted for each operating mode. The minimums and maximums form a basis for bracketing the expected value of ceramics.

Table 6-9. NPV Results

	Variables	Centaur 50 Baseline Metallic	Centaur 50 Modified Ceramic	Mars 100 Baseline Metallic	Mars 100 Optimized Ceramic Hot-Section	Taurus 60 Baseline Metallic 1850	Taurus 60 Recup Ceramic 1900	Taurus 60 Recup Ceramic 2050	Taurus 60 Recup Ceramic 2200
Simple	Elect. RateGas Cost								
	1 0.06/KWH$2/MMBTU	956,292	1,381,140	3,078,209	5,689,725	1,169,841	1,464,757	1,735,092	1,999,748
	2 0.06/KWH$3/MMBTU	(369,943)	(199,877)	262,242	2,352,929	(259,926)	485,047	667,569	844,004
	3 0.06/KWH$4/MMBTU	(1,696,177)	(1,780,893)	(2,553,724)	(983,866)	(1,689,694)	(494,664)	(399,954)	(311,740)
	4 0.08/KWH$2/MMBTU	3,133,135	4,121,630	8,332,259	13,147,409	3,600,404	3,683,099	4,242,349	4,792,768
	5 0.08/KWH$3/MMBTU	1,806,901	2,540,613	5,516,293	9,810,613	2,170,637	2,703,388	3,174,826	3,637,024
	6 0.08/KWH$4/MMBTU	480,666	959,597	2,700,326	6,473,818	740,869	1,723,678	2,107,303	2,481,280
Cogen									
	1 0.06/KWH$2/MMBTU	2,513,508	3,401,249	5,339,815	7,198,457	2,617,060	761,300	975,822	1,193,545
	2 0.06/KWH$3/MMBTU	1,217,037	1,859,326	2,573,681	3,906,788	1,211,395	(192,659)	(63,521)	68,232
	3 0.06/KWH$4/MMBTU	(79,434)	317,403	(192,453)	615,119	(194,270)	(1,146,618)	(1,102,863)	(1,057,081)
	4 0.08/KWH$2/MMBTU	4,641,498	6,073,975	10,500,887	14,555,283	5,006,650	2,921,333	3,416,891	3,913,023
	5 0.08/KWH$3/MMBTU	3,345,027	4,532,052	7,734,754	11,263,614	3,600,985	1,967,374	2,377,548	2,787,710
	6 0.08/KWH$4/MMBTU	2,048,556	2,990,130	4,968,620	7,971,946	2,195,319	1,013,415	1,338,206	1,662,397
With Supplemental Firing									
	1 0.06/KWH$2/MMBTU	3,706,464	3,977,503	7,308,902	8,499,625	4,306,688	3,961,427	4,055,918	4,149,408
	2 0.06/KWH$3/MMBTU	2,242,160	2,404,587	4,316,626	5,118,655	2,631,281	2,391,029	2,429,553	2,467,540
	3 0.06/KWH$4/MMBTU	777,855	831,672	1,324,351	1,737,685	955,874	820,630	803,188	785,672
	4 0.08/KWH$2/MMBTU	5,834,454	6,650,229	12,469,974	15,856,451	6,696,277	6,121,461	6,496,987	6,868,886
	5 0.08/KWH$3/MMBTU	4,370,150	5,077,314	9,477,699	12,475,482	5,020,871	4,551,062	4,870,622	5,187,018
	6 0.08/KWH$4/MMBTU	2,905,845	3,504,398	6,485,423	9,094,512	3,345,464	2,980,664	3,244,257	3,505,150

KEY ASSUMPTIONS

Discount Factor, %	30.00%		
Use, Hrs/Yr	8500		
Maintenance Cost,$/ kwhr	$0.004		
Electrical Rate, $/kwhr	$0.06	$0.08	
Gas Cost, $/MMBTU	$2.00	$3.00	$4.00
Time Period,Yrs	10		
Steam Value, $/1,000 Lbs. -- hr	$6.00		
Inflation	Excluded		
Residual Capital	Excluded		
Working Capital	Excluded		

Table 6-10. NPV Scenarios - Centaur 50

Operating Parameters	Elect. Rate/Gas Cost	Base Case Metallic	Ceramic	NPV DELTA
Base Load	0.06/KWH$2/MMBTU	956,292	1,381,140	$424,848
	0.06/KWH$3/MMBTU	(369,943)*	(199,877)	N/A
	0.06/KWH$4/MMBTU	(1,696,177)*	(1,780,893)	N/A
	0.08/KWH$2/MMBTU	3,133,135	4,121,630	$988,495
	0.08/KWH$3/MMBTU	1,806,901	2,540,613	$733,713
	0.08/KWH$4/MMBTU	480,666	959,597	$478,931
		Minimum Value............	$424,848 0.06/KWH	$2/MMBTU
		Maximum Value............	$988,495 0.08/KWH	$2/MMBTU
Cogen	0.06/KWH$2/MMBTU	2,513,508	3,401,249	$887,741
	0.06/KWH$3/MMBTU	1,217,037	1,859,326	$642,289
	0.06/KWH$4/MMBTU	(79,434)*	317,403	N/A
	0.08/KWH$2/MMBTU	4,641,498	6,073,975	$1,432,477
	0.08/KWH$3/MMBTU	3,345,027	4,532,052	$1,187,026
	0.08/KWH$4/MMBTU	2,048,556	2,990,130	$941,574
		Minimum Value............	$642,289 0.06/KWH	$3/MMBTU
		Maximum Value............	$1,432,477 0.08/KWH	$2/MMBTU
Cogen-Supp	0.06/KWH$2/MMBTU	3,706,464	3,977,503	$271,039
	0.06/KWH$3/MMBTU	2,242,160	2,404,587	$162,428
	0.06/KWH$4/MMBTU	777,855	831,672	$53,817
	0.08/KWH$2/MMBTU	5,834,454	6,650,229	$815,775
	0.08/KWH$3/MMBTU	4,370,150	5,077,314	$707,164
	0.08/KWH$4/MMBTU	2,905,845	3,504,398	$598,553
		Minimum Value............	$53,817 0.06/KWH	$2/MMBTU
		Maximum Value............	$815,775 0.08/KWH	$2/MMBTU

*** Power generation under these assumed conditions are not feasible: therefore, are not considered when determining NPV delta.**

Table 6-11. NPV Scenarios - MARS 100

Operating Parameters	Elect. Rate/Gas Cost	Base Case Metallic	Ceramic	NPV DELTA
Base Load	0.06/KWH$2/MMBTU	3,078,209	5,689,725	$2,611,516
	0.06/KWH$3/MMBTU	262,242	2,352,929	$2,090,687
	0.06/KWH$4/MMBTU	(2,553,724)*	(983,866)	N/A
	0.08/KWH$2/MMBTU	8,332,259	13,147,409	$4,815,149
	0.08/KWH$3/MMBTU	5,516,293	9,810,613	$4,294,320
	0.08/KWH$4/MMBTU	2,700,326	6,473,818	$3,773,491
		Minimum Value..........	$2,090,687 0.06/KWH	$3/MMBTU
		Maximum Value.........	$4,815,149 0.08/KWH	$2/MMBTU
Cogen	0.06/KWH$2/MMBTU	5,339,815	7,198,457	$1,858,642
	0.06/KWH$3/MMBTU	2,573,681	3,906,788	$1,333,107
	0.06/KWH$4/MMBTU	(192,453)*	615,119	N/A
	0.08/KWH$2/MMBTU	10,500,887	14,555,283	$4,054,396
	0.08/KWH$3/MMBTU	7,734,754	11,263,614	$3,528,861
	0.08/KWH$4/MMBTU	4,968,620	7,971,946	$3,003,326
		Minimum Value..........	$1,333,107 0.06/KWH	$3/MMBTU
		Maximum Value.........	$4,054,396 0.08/KWH	$2/MMBTU
Cogen-Supp	0.06/KWH$2/MMBTU	7,308,902	8,499,625	$1,190,723
	0.06/KWH$3/MMBTU	4,316,626	5,118,655	$802,029
	0.06/KWH$4/MMBTU	1,324,351	1,737,685	$413,334
	0.08/KWH$2/MMBTU	12,469,974	15,856,451	$3,386,477
	0.08/KWH$3/MMBTU	9,477,699	12,475,482	$2,997,783
	0.08/KWH$4/MMBTU	6,485,423	9,094,512	$2,609,088
		Minimum Value..........	$413,334 0.06/KWH	$3/MMBTU
		Maximum Value.........	$3,386,477 0.08/KWH	$2/MMBTU

*** Power generation under these assumed conditions are not feasible: therefore, are not considered when determining NPV Delta**

Table 6-12. NPV Scenarios - Modified Recuperated Taurus

Operating Parameters	Elect. Rate Gas Cost	Base Case Metallic	2200 Recuperated Ceramic	NPV DELTA
Base Load	0.06/KWH $2/MMBTU	1,169,841	1,999,748	$829,907
	0.06/KWH $3/MMBTU	(259,926)*	844,004	N/A
	0.06/KWH $4/MMBTU	(1,689,694)*	(311,740)	N/A
	0.08/KWH $2/MMBTU	3,600,404	4,792,768	$1,192,364
	0.08/KWH $3/MMBTU	2,170,637	3,637,024	$1,466,387
	0.08/KWH $4/MMBTU	740,869	2,481,280	$1,740,411
Cogen	0.06/KWH $2/MMBTU	2,617,060	1,193,545	($1,423,516)
	0.06/KWH $3/MMBTU	1,211,395	68,232	($1,143,163)
	0.06/KWH $4/MMBTU	(194,270)*	(1,057,081)	N/A
	0.08/KWH $2/MMBTU	5,006,650	3,913,023	($1,093,627)
	0.08/KWH $3/MMBTU	3,600,985	2,787,710	($813,275)
	0.08/KWH $4/MMBTU	2,195,319	1,662,397	($532,922)
Cogen-Supp	0.06/KWH $2/MMBTU	4,306,688	4,149,408	($157,280)
	0.06/KWH $3/MMBTU	2,631,281	2,467,540	($163,741)
	0.06/KWH $4/MMBTU	955,874	785,672	($170,202)
	0.08/KWH $2/MMBTU	6,696,277	6,868,886	$172,608
	0.08/KWH $3/MMBTU	5,020,871	5,187,018	$166,147
	0.08/KWH $4/MMBTU	3,345,464	3,505,150	$159,686

Base Load	Minimum Value..........	$829,907	0.06/KWH	$2/MMBTU
	Maximum Value.........	$1,740,411	0.08/KWH	$4/MMBTU
Cogen Mode	Minimum Value..........	($1,423,516)	0.06/KWH	$2/MMBTU
	Maximum Value.........	($532,922)	0.08/KWH	$4/MMBTU
Cogen Mode	Minimum Value..........	$159,686	0.08/KWH	$4/MMBTU
	Maximum Value.........	$172,608	0.08/KWH	$2/MMBTU

*** Power generation under these assumed conditions are not feasible: therefore, are not considered when determining NPV Delta**

Table 6-13 gives Return On Investment (ROI) calculated for various scenario. The assumption of this analysis is that the choice between metallic and ceramic engines is mutually exclusive. That is, we can choose either ceramic or metallic, or reject both, but we cannot accept both projects. However, if the two projects were independent, then the NPV and Return on Investment (ROI), sometimes referred to as Internal Rate of Return (IRR), criteria always lead to the same accept/reject decision. This is not true in a mutually exclusive analysis.

For instance, the metallic Centaur 50 consistently has a better ROI than the ceramic engine in the supplemental firing scenario, however, the NPV results for the ceramic Centaur 50 engine are better than for the metallic Centaur 50. Thus, a conflict exists. NPV says choose mutually exclusive ceramics, while ROI suggests metallic. In the case of this analysis, the conflict is a result of the project size (kW output, more capital for the initial outlay) differences.

This conflict is only apparent when supplemental firing is introduced. This is because in supplemental firing, we are adding a duct burner that has an efficiency near 98 percent to an finite steam load. This is favorable to the less efficient metallic engine as depicted in the ROI calculation. In having a finite steam load the study limits the capacity which could be obtained when introducing ceramics to a metallic engine which will have an higher exhaust temperature; therefore limiting the return on investment.

Table 6-13. ROI Results Under Various Scenarios

	Variables	I	II	III	IV	V	VII	VIII	IX
		Centaur 50 Baseline Metallic	Centaur 50 Modified Ceramic	Mars 100 Baseline Metallic	Mars 100 Optimized Ceramic Hot-Section	Taurus 60 Baseline Metallic 1850	Taurus 60 Recup Ceramic 1900	Taurus 60 Recup Ceramic 2050	Taurus 60 Recup Ceramic 2200
Simple	Elect. RateGas Cost								
	1 0.06/KWH$2/MMBTU	43.50%	45.50%	47.70%	53.00%	44.80%	48.20%	48.70%	50.00%
	2 0.06/KWH$3/MMBTU	24.40%	26.60%	31.50%	39.70%	26.50%	35.80%	37.60%	38.50%
	3 0.06/KWH$4/MMBTU	0.00%	0.00%	13.20%	25.70%	0.00%	23.30%	25.30%	26.60%
	4 0.08/KWH$2/MMBTU	72.50%	74.50%	76.50%	85.00%	74.00%	74.50%	75.50%	76.00%
	5 0.08/KWH$3/MMBTU	55.50%	57.80%	61.40%	69.00%	56.50%	63.20%	64.50%	66.50%
	6 0.08/KWH$4/MMBTU	36.90%	40.75%	45.40%	56.20%	39.30%	51.50%	53.00%	54.20%
Cogen									
	1 0.06/KWH$2/MMBTU	51.50%	53.00%	48.80%	47.70%	50.10%	36.20%	36.90%	37.60%
	2 0.06/KWH$3/MMBTU	40.60%	42.80%	39.30%	39.80%	39.30%	28.30%	29.60%	30.40%
	3 0.06/KWH$4/MMBTU	29.20%	32.30%	29.20%	31.60%	28.30%	20.20%	21.70%	22.90%
	4 0.08/KWH$2/MMBTU	68.50%	70.50%	66.70%	65.55%	67.00%	52.80%	53.20%	54.00%
	5 0.08/KWH$3/MMBTU	58.00%	60.30%	57.20%	57.40%	57.20%	45.50%	46.50%	47.00%
	6 0.08/KWH$4/MMBTU	47.50%	50.20%	47.50%	50.00%	46.80%	38.10%	39.30%	40.25%
With Supplemental Firing									
	1 0.06/KWH$2/MMBTU	61.30%	56.50%	55.50%	51.00%	62.50%	60.20%	57.40%	55.40%
	2 0.06/KWH$3/MMBTU	49.30%	46.50%	45.50%	42.80%	50.20%	48.50%	46.70%	45.50%
	3 0.06/KWH$4/MMBTU	36.80%	35.80%	34.80%	34.50%	37.30%	36.60%	35.40%	34.90%
	4 0.08/KWH$2/MMBTU	77.00%	74.50%	72.50%	68.50%	80.00%	76.00%	73.00%	71.00%
	5 0.08/KWH$3/MMBTU	66.70%	64.00%	62.80%	60.30%	67.50%	65.00%	62.80%	61.60%
	6 0.08/KWH$4/MMBTU	55.00%	53.30%	52.80%	52.50%	55.00%	53.00%	52.20%	51.50%

6.3.3.4 Component Value Apportionment

In Section 6.3.1.2 the methodology for apportioning the economic value to the appropriate components in a power generating system was described. The cost of known system components changes (i.e. generator, gear box, boiler, etc.) must be subtracted from the value delta. The specific process is as follows:

1. Identify and total up the typical cost of the engine and power generation package.

2. Apply the appropriate General and Administrative (G&A) cost rate to the factory cost. A G&A rate of 30% was used.

3. Once the above has been sub-totaled, then apply the appropriate profit margin. A margin of 10% was used.

4. The end result of the above represents the expected package sell price of the metallic gas turbine generator package.

5. The remainder of the plant and the installation are not expected to change due to engine performance changes from ceramic component insertion. Therefore, the change in value or value delta is added to the sell price of the package. This represents the economic equivalent sell price of the CSGT and its metallic counterpart.

6. Once the final ceramic price has been determined then the next step requires extracting the identical profit and G&A rates to identify the overall CSGT package cost.

7. Since the CSGT engine cost must be identified, the same metallic engine packaging cost will be used plus the cost of the package component changes required due to increased performance. For the three models being analyzed (two simple cycle plus one recuperated version), the package cost adders are estimated to be $50,000 (Centaur 50), $100,000 (Mars 100), and $125,000 (modified recuperated Taurus), respectively.

8. The CSGT packaging costs are subtracted from the total CSGT package and engine cost number resulting in the incremental cost allowed for the ceramic engine alone. This cost must be compared to the metallic engine cost to determine the maximum material and manufacturing cost increases allowed. The allowable cost increase will reflect the differences in output and efficiency between the two engines.

The above methodology was applied to each engine option in the base power generation mode and in the cogeneration mode using the minimum, maximum and average value delta's presented in Section 6.3.3.3.

Table 6-14 summarizes the range of cost additions associated with the insertion of ceramics that the Centaur 50 engine, the primary focus of this program, could support.

6.3.3.5 Ceramic Product Cost Estimates

Table 6-15 identifies the product cost estimates for the proposed engineering design changes that are expected to be implemented into the Centaur 50 CSGT engine design.

Table 6-14. Summary of Cost Additions for the Centaur 50 CSGT Engine

Description	Base Load	Cogeneration
Maximum Cost Allowed	$ 641,255	$ 951,732
Mid-Point Cost Allowed	$ 444,176	$ 675,443
Minimum Cost Allowed	$ 247,095	$ 399,153

Table 6-15. Summary of Estimated Cost Differences for the Centaur 50 CSGT Engine

Description	Current Material	Proposed Material	Estimated Cost Delta
Stage 1 Nozzle	FS-414 (Cooled)	Ceramic (Uncooled)	($9,100)
Stage 2 Nozzle	FS-414 (Uncooled)	FS-414 (Cooled)	($1,100)
Stage 1 Blade	MAR-M247 (Cooled)	Ceramic	$3,700
Combuster Liner	Hastelloy X	Ceramic	$7,900
Nozzle Case	D-5B (Uncoated)	INCO 909 (Coated)	$4,500
Stage 1 Turbine Disk	V-57	Waspaloy	$1,700
Stage 2 Disk	V-57	Waspaloy	$1,700
Stage Diaphragm	D-5B	INCO 903 (Coated)	$ 320
Stage 2 Diaphragm	N-155	INCO 903 (Coated)	$ 320
Total			$9,940

As depicted, the majority of the design changes involve material exchanges. Currently, the estimated results are rough order of magnitude (ROM) estimates at the time the Centaur 50 CSGT engine goes into production. The non-recurring and tooling cost will have been fully amortized at the time of production release. Furthermore, the expected learning curve will have eliminated inefficiencies. The results indicate the expected costs are not going to increase to the point that the ceramic package is not economically feasible for either application, Base Load or Cogeneration.

6.3.3.6 Ceramic Cost Versus Value Comparison

Based upon the ceramic cost estimates in the previous section, Table 6-16 illustrates the total possible benefit of the Centaur 50 CSGT. Essentially, Table 6-16 summarizes and identifies the possible value of the Centaur 50 CSGT by keeping the installation price of this engine equal to that of the metallic Centaur 50 baseline measured on a $/kW basis

As depicted in Table 6-16, the deltas range from a little under a quarter of a million to almost a million dollars depending on the application and scenario being analyzed. These deltas represent the value to the manufacturer that can be proportioned between a price discount to the end user and increased profit margin.

Table 6-16. Estimated Ceramic Cost Versus Value Comparison

Description	Cost Est. Delta Cost of CGST (Table 6-11)	Value Base Load Applications	Value Cogeneration Applications	Delta Base Load (Net Value)	Delta Cogeneration (Net Value)
Min. Cost Allowed	$ 9,940	$247,096	$399,153	$237,156	$389,213
Mid. Cost Allowed	$ 9,940	$444,176	$675,445	434,236.00	$665,503
Max. Cost Allowed	$ 9,940	$641,255	$951,732	$631,315	$941,792

6.4 TOTAL DOMESTIC AND WORLDWIDE MARKET POTENTIAL

The market potential for gas turbines incorporating ceramic components has been evaluated against the background of the rapidly growing market activity for stationary gas turbines in electrical power generation and cogeneration, liquid pumping, and gas compression applications. Historical turbine equipment market trends have been correlated with energy supply and demand forecasts to project the market penetration potential of new installations. The same process will be used for turbines incorporating ceramic hot section components. Projections also incorporate long term turbine technology development options. The installed base of gas turbines by market and applications has been analyzed to assess retrofit applicability. Competing technologies which may preclude or inhibit the success of ceramic gas turbine introduction or speed its market need and acceptance have been evaluated.

6.4.1 Market Forecast and Background Scenarios

There are a number of organizations which forecast worldwide gas turbine demand. However, the methodology and basis for those forecast are not readily available nor does Solar believe that they accurately reflect the true opportunity. Solar generates is own market projections based on its industry experience over the past 35 years. Solar bases its projections for energy conversion prime movers, such as gas turbines, on worldwide energy and macro economic growth projections. The following is the basis for the assumptions and scenarios analyzed in the economic evaluation as well as providing a foundation for forecasting gas turbine demand into the 21st century.

The variables which have been determined to be key are those which have and will continue to have an effect on the turbine business . These variables are strictly externally focused. The subsequent sections will provide the basis of assumptions and key factors in determining the potential market for ceramic turbine engines:

A. Energy Supply and Demand Outlook
B. Market Segmentation
C. Key Market Variables
D. Customer's Buying Criteria

6.4.1.1 Energy Supply and Demand Outlook

The sources for this data are the following:

- Oil and Gas Journal
- International Gas Report
- International Energy Agency Report
- B.P. Statistical Review of World Energy
- Solomon Brothers
- American Gas Association Outlook
- Inside F.E.R.C.'s Gas Market report
- Petroleum Economist
- Oil Industry Outlook
- The Oil Market in the 1990's

A five year projection for energy consumption is presented in Table 6-17. The energy supply and demand provides the key basis for future sales of gas turbines. The relationship is not linear although gas turbine demand generally matches the supply and demand trend.

As indicated from the table the amount of increase projected in the next five years ranges from an annual increase of 2.0 percent up to 2.6 percent. The amount of increase varies by region. The largest increase is projected to be in the Pacific and Middle East regions, which is due to the rapidly growing economy and population in these regions. The only region with a forecasted decrease in demand is the Commonwealth of Independent States (CIS), which is caused by a collapsing infrastructure and the faltering economy.

Table 6-17 includes consumption of various fuel types (i.e. coal, oil, gas ...). The mix has a major impact on the type of energy conversion device which will be in demand. History has indicated that natural gas and oil, both production and consumption, have a major impact on demand for gas turbines. The total percentage in column 8 is the percentage increase between 1992 and 1997 and the last column represents the average annual percentage increase.

Table 6-18 is the projected gas consumption in billion cubic feet (BCF) by World-Wide regions for the next five years. The increase averages about 2.6% percent a year. The increase relative to the total energy consumption reflects a shift in a higher utilization of natural gas. For instance, in the high growth areas such as the Pacific and Middle East the total energy consumption was forecasted to increase 5 percent annually and within that 5 percent gain is an increase in natural gas consumption of approximately 10 percent. This is due to the use of a cheaper indigenous fuel, natural gas, in lieu of an easily exportable product, oil. In addition, the establishment of a stable gas infrastructure will enhance the use of natural gas in many more areas than exist today.

Table 6-17. Projected Energy Consumption in Million Tonnes Oil Equivalent (MTOE) by World-Wide Regional Areas

Region	1992	1993	1994	1995	1996	1997	Total %	Annual Avg. %
USA	1,998	2,018	2,048	2,079	2,110	2,141	7.20	1.44
CAN	246	250	254	257	261	265	7.73	1.55
LAT AMER	502	518	536	553	571	590	17.63	3.53
EUR	1,481	1,520	1,559	1,600	1,641	1,684	13.69	2.74
CIS	1,319	1,305	1,279	1,267	1,267	1,281	-2.87	-.57
AFR	240	248	256	264	273	282	17.63	3.53
JAP/KOR/TAI	602	616	631	645	660	675	12.04	2.41
ME	266	279	293	308	323	339	27.63	5.53
ASEAN	139	146	153	161	169	177	27.63	5.53
OTH. PAC	1,078	1,132	1,188	1,248	1,310	1,376	27.63	5.53
AUS/NZ	113	116	118	120	123	125	10.41	2.08
TOTAL	**7,984**	**8,147**	**8,314**	**8,501**	**8,708**	**8,936**	**11.93**	**2.39**
ANN %	–	2.05	2.05	2.25	2.43	2.62	–	–

Table 6-18. Projected Gas Consumption in Billion Cubic Feet (BCF) by World-Wide Regions for the Next Five Years

Region	1992	1993	1994	1995	1996	1997	Total %	Annual Avg. %
USA	20,075	20,677	21,401	22,043	22,815	23,818	18.65	3.73
CAN	2,261	2,329	2,387	2,435	2,508	2,609	15.35	3.07
LAT AMER	3,429	3,515	3,603	3,675	3,785	3,899	13.69	2.74
EUR	12,035	12,276	12,767	13,086	13,478	13,883	15.35	3.07
CIS	24,090	24,210	23,605	23,487	23,722	23,746	-1.43	-.29
AFR	1,366	1,387	1,408	1,436	1,457	1,487	8.793	1.76
JAP/KOR/TAI	2,072	2,135	2,224	2,313	2,406	2,514	21,31	4.26
ME	3,239	3,498	3,848	4,156	4,447	4,713	45.52	9.10
ASEAN	906	987	1,086	1,178	1,273	1,374	51.74	10.35
OTH. PAC	1,724	1,879	2,067	2,211	2,388	2,579	49.64	9.93
AUS/NZ	898	930	939	949	963	987	9.841	1.97
TOTAL	**72,096**	**78,823**	**75,334**	**76,969**	**79,241**	**81,608**	**13.19**	**2.64**
ANN %	–	2.40	2.05	2.17	2.95	2.99	–	–

In summary, the demand for energy is mainly dependent upon the level of economic activity and the rate of economic growth. These are the key factors in determining the growth of natural gas utilization. The growth of natural gas consumption is not only predicated upon economy, but also on the relationship of the natural gas price to other fuel prices. Furthermore, as new environmental regulations come to fruition natural gas and clean distillates will become the fuels of choice.

6.4.1.2 Market Segmentation

The market forecast is based on gas turbine engines in the size range of 1 to 20 MW in two main market segments, the oil and gas market and the power generation market. The market and economic analysis focuses on the power generation market and its applications, but the ceramic components can also enhance the performance of gas turbines used in the oil and gas market for various applications.

The oil and gas market is divided into three segments and each of those are divided by various applications. The three segments are:

1. Oil and Gas Production - Gas turbines are used for many different oil and gas recovery techniques such as waterflood, steamflood, gas reinjection and gas lift. Turbines are also used to gather associated and non-associated gas from recovery wells and to produce electricity at the site.

2. Oil and Gas Transmission - These applications include gas turbines that are used to transport oil or gas through a pipeline, inject or withdraw gas from storage facilities or to provide electrical power to these stations.

3. Hydrocarbon Processing - Gas turbines are used in the processing market to provide refrigeration, compression, pre/re-compression of the gases throughout the process and electricity production with heat recovery that is also made available to the process.

The oil and gas market is mostly located in remote areas. Therefore, the gas turbine is ideal in this application as it can operate unmanned and be controlled at a more centrally located facility. The gas turbine is reliable, durable, easily maintained and it offers fuel flexibility. These are all critical needs of the oil and gas market. Gas turbines are often used in offshore applications because they are lightweight, have a small footprint, and produce low vibrations compared to other engines.

As mentioned, the study will focus on power generation applications normally associated with the Power Generation market. These include standby, peakload and continuous duty applications. The standby and peakload gas turbine is used by both the industrial and utility customer. They are used to produce electricity for emergency and during peak hours when the rates are high to the industrial user and the power is in short supply by the utility. Cogeneration is a continuous duty application which recovers the waste heat from the turbine exhaust. This heat can be used in various industrial processes such as heating, drying, steam production, air conditioning and additional power generation. The overall efficiency of these systems can be as high as 80%. This market would benefit greatly from ceramic components because they enable increased heat production.

6.4.1.3 Key Market Variables

The following is a summary of the key energy and economic factors effecting the demand for industrial gas turbines as prime movers for the markets described above:

- Economic Growth is expected to increase at an average of 3.0 percent in the O.E.C.D. countries, 5.2 percent in the Newly Industrialized Countries (N.I.C.), and 2.1 percent in other countries.

- Environmental Regulations continue to become more stringent. Therefore, natural gas and clean distillates become the fuels of choice.

- Natural Gas Demand will follow trends described in 6.4.1.1

- Natural gas prices will consistently increase just above inflation in North America. In Europe gas prices are projected to remain flat due to competing supplies. For other countries the price of gas will be tied to the price of oil.

- Electricity demand for the world will approximately average 3 percent increase annually.

- The demand for electrical capacity is expected to be driven by environmental concerns within North America to approximate a 4 percent annual increase. Outside North America capacity additions are expected to expand at a rate of 6 percent annually.

6.4.1.4 Buying Criteria

The criteria applied in the selection of gas turbine prime movers by the various types of customers in the market previously described are numerous. The industries utilizing gas turbines are very diverse, and while they all use economic methodology similar to what has been described in earlier sections, there are a number of intangibles and subjective estimates used in the actual selection process. A summary of the most significant buying criteria is best illustrated in Figure 6-4. The intent of this figure is to best describe the product characteristics that customers perceive as valuable in the 1990's and the expected trends to 2000 and beyond.

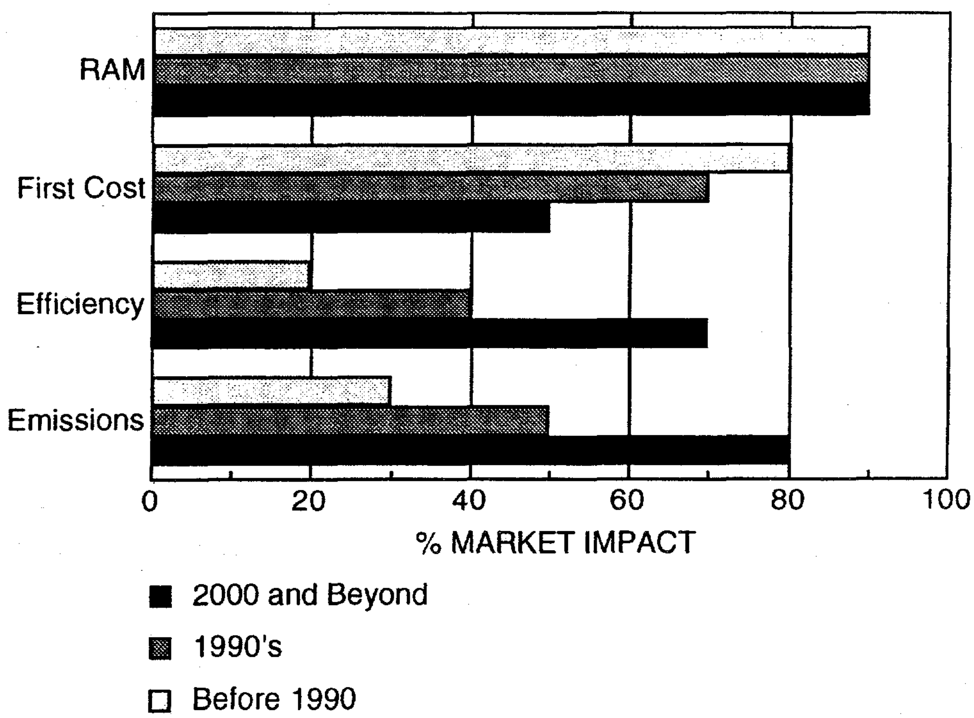

Figure 6-4. Key Buying Criteria - Mid-Range Gas Turbines

As Figure 6-4 indicates, the two most prevalent trends are going to be the emphasis on reduced emissions and increased efficiency, whereas first cost will not be as pertinent as in the 1990's. However, it must also be pointed out that reliability, availability and maintainability (RAM) can not be allowed to deteriorate in achieving those goals.

6.4.2 Market Outlook

Based on the energy supply and demand forecast, the key market variables and the buying criteria presented in the preceding section, the base case market outlook for industrial gas turbines is contained in Table 6-19. The forecast is in annual megawatt shipments for unit sizes from 1 to 20 megawatts. It does not include gas turbines for transportation applications (marine, land or air). It assumes evolutionary gas turbine development throughout the planning period (2010). The effect of major technical break-throughs which may result from this and similar R&D programs are not incorporated into the forecast.

Table 6-19. Industrial Gas Turbine Market - 1-20 MW Size Class - Annual Shipments (MW)

Region	1995	2000	2005	2010
United States	330	380	450	450
Canada	120	130	140	140
Latin America	210	300	350	350
Europe	600	610	600	600
Middle East/Africa	370	410	450	500
Japan	150	220	260	280
Pacific/Asia	545	650	730	800
Total	2,325	2,700	2,980	3,120

The outlook is for the market to expand worldwide by 16% from 1995 to 2000, 10% from 2000 to 2005, and 5% from 2005 to 2010. The predominant share of the growth will be outside the United States. However, a significant share of the gas turbine shipments will be in the U.S. which is expected to account for 14%, 14%, 15% and 14% of the megawatts shipped in 1995, 2000, 2005, and 2010 respectively. All units in the range of 1 to 20 megawatts are expected to be continuous duty rated machines being utilized in excess of 6,000 hours per year. It should also be pointed out that gas turbines for members of the C.I.S. are not included in the above forecast. Gas turbines to the C.I.S. could account for a significant number of megawatts in addition to the above. However, timing and volume are very uncertain and not included in the analysis.

6.4.3 Market Penetration Methodology

The penetration of the market with a new technology, such as ceramics, is dependent on a number of factors. Unless an entirely new market is opened up with the technology (as occurred with the personal computer for example), then the new technology must meet the basic specifications of the systems which utilize the current technology. This is the case with ceramics. Once the basic specifications for the current generation of gas turbines in industrial applications are met with ceramics, then the rate at which the new technology penetrates and displaces the old technology is dependent on the value demonstrated to the customer. The value calculation is the same as that presented in Section 6.3.1. However, each customer may place a slightly different emphasis on the risk he perceives the new technology presents. This is usually done by estimating lower reliability and availability for the new system or adding higher cost for the maintenance or support required for the new system. Economists use behavioral lag models to describe the rate at which new technology penetrates a market. Figure 6-5 illustrates the market penetration phenomena. The lag time is shortened when the benefits derived from the new technology are demonstrated.

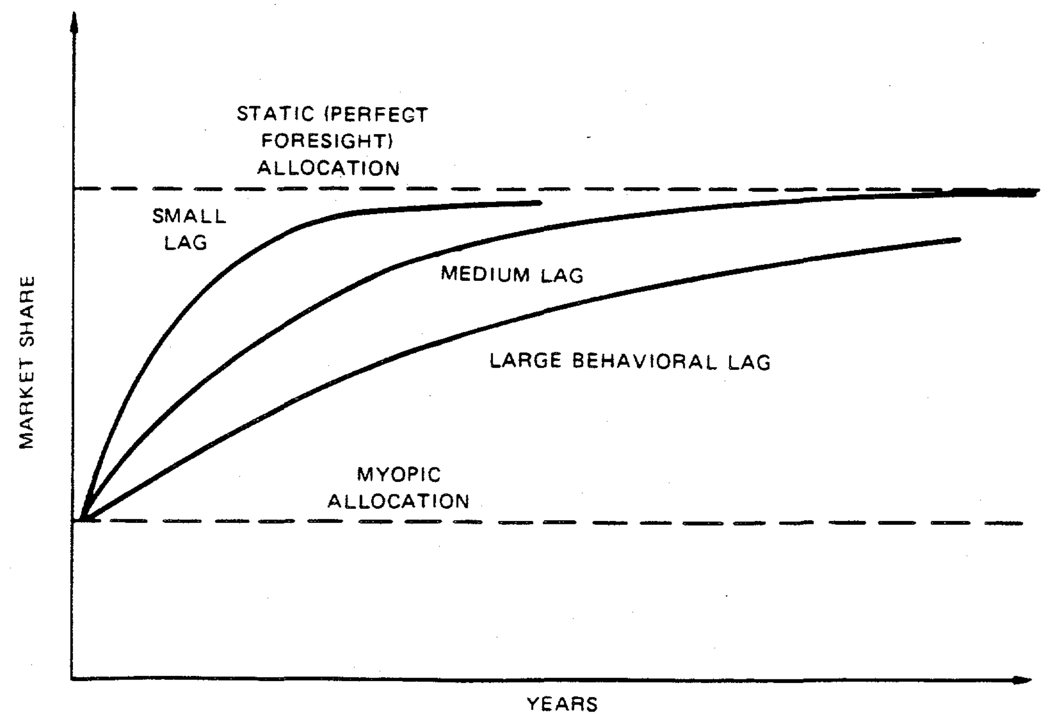

Figure 6-5. Market Penetration Behavioral Lag Curve

A more practical approach to forecasting the anticipated penetration of a new technology requires that some assumptions must be made regarding the technical achievement and the equipment economics at the time of introduction. The following are key assumptions which apply to all market penetration scenarios:

1. The 4,000 hour field endurance evaluation (which is part of this program) is completed on schedule and is successful in all aspects.

2. Material cost of new components (both metallic and ceramic) remain close to current estimates, and more importantly their relative cost relationship with the metallic components they replaced must not change dramatically.

3. Equipment economic assumptions applied in Section 6.3.3 will not change dramatically so as to not favor efficiency of power improvements from the insertion of ceramic technology.

4. The final product meets the traditional reliability, availability and durability standards established with current industrial gas turbine products.

5. The design of the production version of a ceramic gas turbine with an anticipated time between major inspections of 30,000 hours must be completed and a successful 8,000 hour field endurance test in a production configuration must be demonstrated prior to full release for production.

The following are the optimistic, expected and pessimistic market penetration scenarios for the Centaur 50 ceramic gas turbine. While limited to the Centaur 50 engine, the methodology and timing for introducing ceramic components into other products would occur in the time frame. However, totally new products, such as a ceramic recuperated gas turbine, which is designed from a clean sheet of paper, will take an additional two years to develop and two more years to reach mature levels of production due to its lack of a successful operating history. The penetration scenarios and forecast of product volume levels are limited to the Centaur 50 since it is the only product with reasonably accurate cost and performance estimates available at this time. With the completion of Phase II of this program extrapolations of this methodology to other gas turbine products can developed with reasonable accuracy and with meaningful results.

6.4.3.1 Optimistic Market Penetration Scenario

With the successful 4,000 hour field demonstration of the Centaur 50 ceramic engine at the ARCO enhanced oil recovery facility in Bakersfield, California, ceramic technology will have passed a major milestone toward market acceptance. While a few inexperienced customers will accept this demonstration as satisfactory proof that ceramic gas turbines are commercially available for extended industrial service, most customers will not. In addition to the assumptions applied in the previous section, the following assumptions apply to this optimistic scenario:

1. Equipment economics will more strongly favor fuel efficiency. That is, the high energy price scenarios presented in Section 6.3.3 will apply at the time the product is introduced.

2. Component costs are well within current estimates.

The scheduled time line for design to production release for the Centaur 50 CSGT is:

Complete Product Design	Ship Prototype		Production Release		
1998	1999	2000	2001	2002	2003

The forecast for full ceramic replacement of metallic Centaur 50 gas turbines is 4 years from production release.

6.4.3.2 Expected Market Penetration Scenario

Under this scenario the assumptions are as presented for the equipment economics of Section 6.3.3 and the general penetration conditions contained in Section 6.4.2. The time line for development and field evaluation of the production product is the normal 4 years traditionally experienced for development of industrial gas turbine products. It is depicted on the following time line:

Complete
Product
Design Ship
Prototype
Production
Release

1998 1999 2000 2001 2002 2003

The forecast for full ceramic replacement of metallic Centaur 50 gas turbines is 5 years from production release. This has been Solar's experience for new product introduction where an existing product is already well established.

6.4.3.3 Pessimistic Market Penetration Scenario

Under this scenario the equipment economics still favor ceramics and the cost are marginal but acceptable. Without these two assumptions along with demonstrated successful field operation, ceramics would not be introduced at all. However, some delays in the design and successful field testing of a 30,000 hour capable engine would result in a slower penetration of the market with this product. It is assumed that some initial design flaws appear in the 4,000 hour field evaluation which require redesign and another 4,000 hour demonstration. Total development time extends to 8 years from the successful initial 4,000 hour test. The following time line depicts the pessimistic development scenario:

Complete
Product
Design Ship
Prototype 1
Complete
Test 1
Complete
Re-design/
Ship
Prototype 2
Production
Release

1999 2000 2001 2002 2003 2004

The forecast for full ceramic replacement of metallic Centaur 50 gas turbines is still 5 years as was presented for the expected case since the reputation of the technology was not tarnished by premature release of the product prior to successful field demonstration of the mature design.

6.4.4 Competing Technologies

Existing technologies in the market place and new technologies under development may affect the acceptance of the ceramic turbine technology by providing alternative pathways to performance and/or environmental goals targeted for the ceramic stationary gas turbine. Five technologies have been selected for discussion here since they are potentially competitive in achieving the major objectives of the ceramic stationary gas turbine: achieve improved performance (thermal efficiency and output power), and/or achieving reduced emissions (NOx and CO).

Table 6-20 lists these five technologies and their potential benefits together with those of the ceramic gas turbine technologies. Each of these technologies will be briefly discussed in turn.

Table 6-20. Ceramic Gas Turbine Technology and Competing Technologies

	Thermal Efficiency	Output Power	Emissions	Growth Potential For Higher TRITs and/or Efficiency
Ceramic Hot Section Components	Improves	Improves	Reduces	Good, releases cooling air for combustor
TBC Coated Hot Section Components	Improves	Improves	Reduction limited by demands of air for cooling	Limited
Advanced Cooled Superalloys	Improves	Improves	Reduction limited by demands of air for cooling	Limited
Advanced Combustor Cooling Technologies	Could improve	No effect	Reduces	Moderate
SCRs	Some Loss	Some loss	Reduces	Good
Fuel Cells	Improves	Not applicable	Reduces	Good

6.4.4.1 Advanced Superalloys

The benefits of ceramics in enhancing performance are based on their ability to be utilized in component designs requiring substantially less or no cooling while operating at temperatures in excess of what is currently achievable with conventional cooled superalloy components. The performance benefits are primarily derived from the advantages of operating at increased firing temperatures. The reduction or elimination of cooling provides an important although secondary benefit. The incorporation of sophisticated cooling techniques in superalloy hot section components does provide the benefits of operation at high firing temperatures but without the advantages of cooling reduction or elimination.

Current state-of-the-art gas turbine technologies in aeroderivative engines enables firing temperatures in excess of 1260°C (2300°F), but components are expensive because of material (single crystal or ODS alloys), coatings for oxidation protection, and sophisticated cooling schemes. Even higher temperatures are achieved in shorter life military applications. The benefits of ceramics, potentially simpler designs and lower cost have to be weighed against the advantages of more complex shape capabilities of the advanced superalloys. Additionally, stragegic materials issues would be of less concern with ceramics than with metals.

Although future advancements in alloy compositions and properties may be made the application temperature must be limited by the melting point of nickel-base superalloys. Major advances have been made with superalloys in the last fifty years so that these materials are being used at a much higher fraction of their melting point than any other metallic material. Fifty years ago it was common to hear that no cast materials could be used in rotating parts and no alloys with less than 10% ductility would be used. It should be recognized that ceramics, today, are where superalloys were in the 1950s and 1960s. The progress in superalloys has resulted from several advancements in technology including: understanding of the factors controlling the stability of the gamma-prime phase; improvements in manufacturing processes to increase reproducibility; introduction of oxide dispersion strengthening; control of grain boundaries by orientation (e.g. directional solidification) or elimination (e.g. single crystals); and increase of melting point (to a minor extent) by elimination of impurities, zirconium, boron and other elements. Similar steps can be identified in the case of ceramics, but the process is in a state equivalent to that of the superalloys in the 1950s and 1960s. Some of these steps are: elimination of calcium oxide from hot pressed silicon nitride to raise creep strength; introduction of sintering; control of impurities; identification of sintering aids; control of grain shape to raise fracture toughness; and surface treatment methods. These technological advances are expected to continue with ceramics so that the demonstrated technologies represent the beginning of a new material growth curve that does not have the melting point cap that must limit superalloys.

In addition to the material limitation discussed above, there is a limitation on cooling of superalloys imposed by the need for more cooling air in the combustor to meet the needs of the lean pre-mixed combustor to achieve low emissions as discussed in Section 6.4.4.2.

6.4.4.2 Advanced Combustor Cooling

State-of-the-art low emissions technologies can significantly reduce emissions of NO_x and CO from all-metal combustor systems. The technologies are based on either lean or staged (rich/lean) combustion with enhanced fuel-air mixing and increased combustion volume. With conventional combustor configurations the low emissions technologies are limited by the properties of the metal liners. For good durability liners should have maximum wall temperatures below about 871°C (1600°F). This wall temperature limit constrains the maximum turbine rotor inlet temperature (TRIT) consistent with low emissions to about 1200°C (≈ 2200°F). At TRIT values above this upper limit demands for cooling air to maintain the liner temperature at acceptable levels are so high that insufficient air is available for dilution trimming to maintain NOx control.

The benefits of ceramics lie in their ability to operate at much higher wall temperatures than metal liners reducing cooling air requirements in the combustor. As a result higher TRITs can be achieved with good emissions characteristics. The increased liner wall temperatures also beneficially reduce CO emissions by allowing more complete combustion along the liner wall.

Advanced more efficient combustor liner cooling technologies can also reduce cooling air requirements. As a result the practical limitations posed by conventional combustor alloy cooling are being gradually relaxed. However new techniques, such as transpiration and effusion cooling are costly to implement, and ceramics will have the advantage of simplicity and lower cost.

6.4.4.3 Thermal Barrier Coatings

The use of thermal barrier coatings provide an alternative pathway to achieving the higher TRIT values responsible for performance improvements. Conventional TBC technologies have been used successfully to lower the substrate temperature of metallic combustor liners, nozzle shrouds and vanes, and even critical regions of turbine blade airfoils. To be functional TBC coated parts must be cooled, however. The benefits achieved with TBCs are in proportion to the cooling air available and the coating thickness. These limitations constrain their usefulness. Typical TBC's consisting of yttria-stabilized zirconia are applied as about 0.25 mm (0.010 inch) thick coatings over a 0.005 inch thick MCrAlY bondcoat. Temperature reductions of ≈ 100°C (≈ 200°F) are easily achieved in combustor liner walls where sufficient cooling air is easily accessible. Depending on the temperature benefits targeted thick TBC coatings of the order of 0.25-1.0 mm (0.010-0.040 inch) will be required for nozzle and blade airfoils. These thicknesses seriously influence the aerodynamic efficiency of these components and they cannot be simply applied as an add-on to existing metallic designs. Also, coatings of this thickness have serious life limitations particularly under conditions of cyclic operation. Solutions to these problems tend to involve complex functionally gradient configurations and other stress reduction solutions such as the presence of a compliant metallic strain isolation (SI) pad under the TBC.

Hara et al. report the application of a four-layer TBC to a turbine blade according to the schematic of Figure 6-6 (2). The inner metallic layer is a CoNiCrAlY bond coat that provides an adherent surface to a stress-reducing metal ceramic mixture layer which in turn is overlayed by an oxidation/corrosion resistant metal layer. The outermost layer is formed by an 8% yttria-stabilized zirconia TBC. This four layer coating which was up to about 0.37 mm (0.015 inch) thick resulted in a temperature reduction of about 90°C (≈ 160°F) for the particular conditions of cooling design and flow. Thinner TBC's applied by EB-PVD are now routinely used in aircraft engine hot section components.

Figure 6-7 compares five scenarions involving various combinations of uncooled ceramic, cooled TBC coated, and cooled all-metal components from the beforementioned study by Hara et al. (2). It can be seen that the relative thermal efficiency increases in the order:

metal < TBC < ceramic

Evidently, ceramics do present the design solution with the highest thermal efficiency. Trade-off studies will be required to weigh the risks of utilizing ceramic hot section components versus more established metallic and TBC design solutions.

6.4.4.4 Alternate Emission Control Approaches

The principal alternate technology for emissions controls which competes with the CSGT low emissions combustor concept is Selective Catalytic Reduction or SCR. An SCR is a post-combustion NOx control technology which is applicable to exhaust streams with significant oxygen content. A schematic of an SCR system is shown in Figure 6-8 (3).

A typical reaction occurring on the catalyst surface is:

$$NH_3 + NO + \frac{1}{4}O_2 \rightarrow N_2 + 3/2H_2O$$

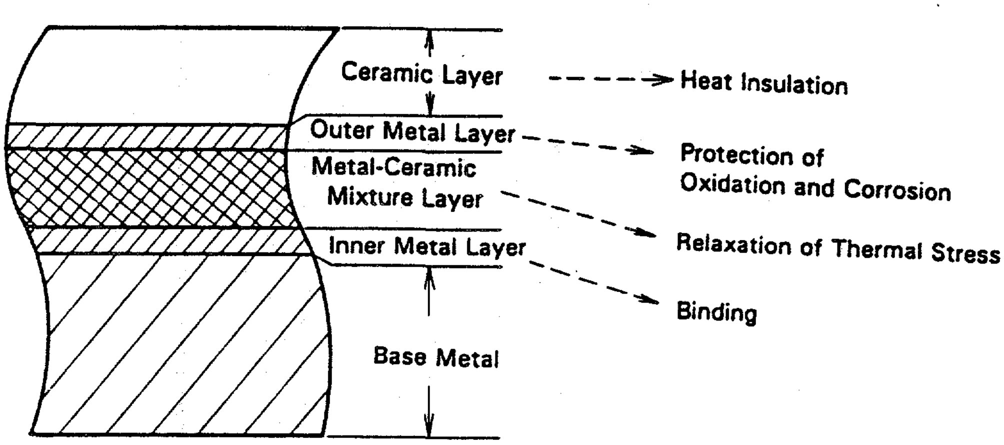

Figure 6-6. Schematic of TBC Coating for Turbine Blade (2)

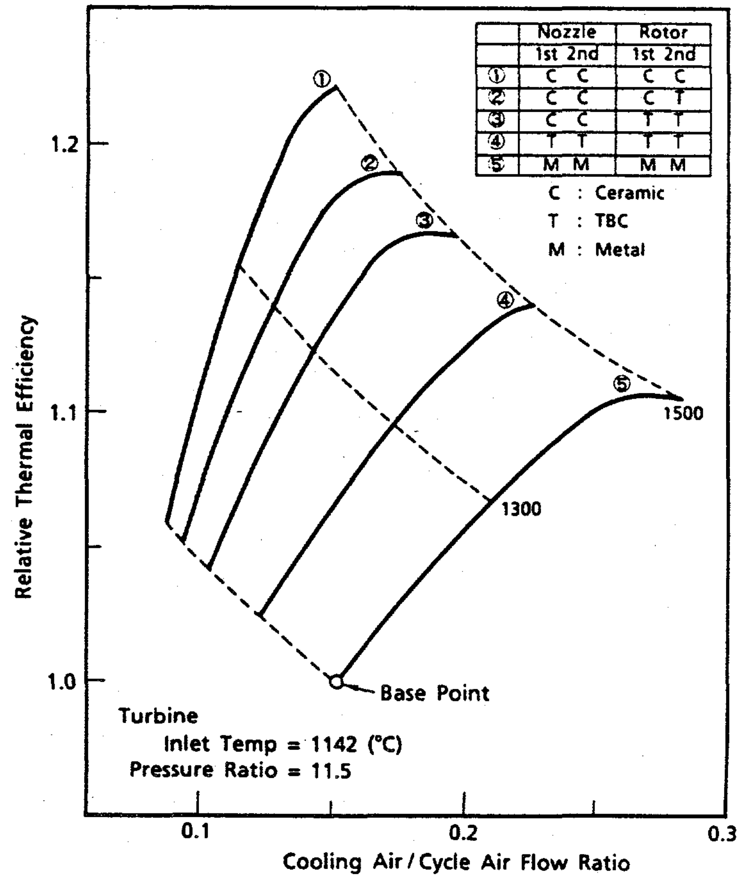

Figure 6-7. Comparative Performance of Gas Turbine with Ceramic, TBC Coated and All-Metal Hot Section Components (2)

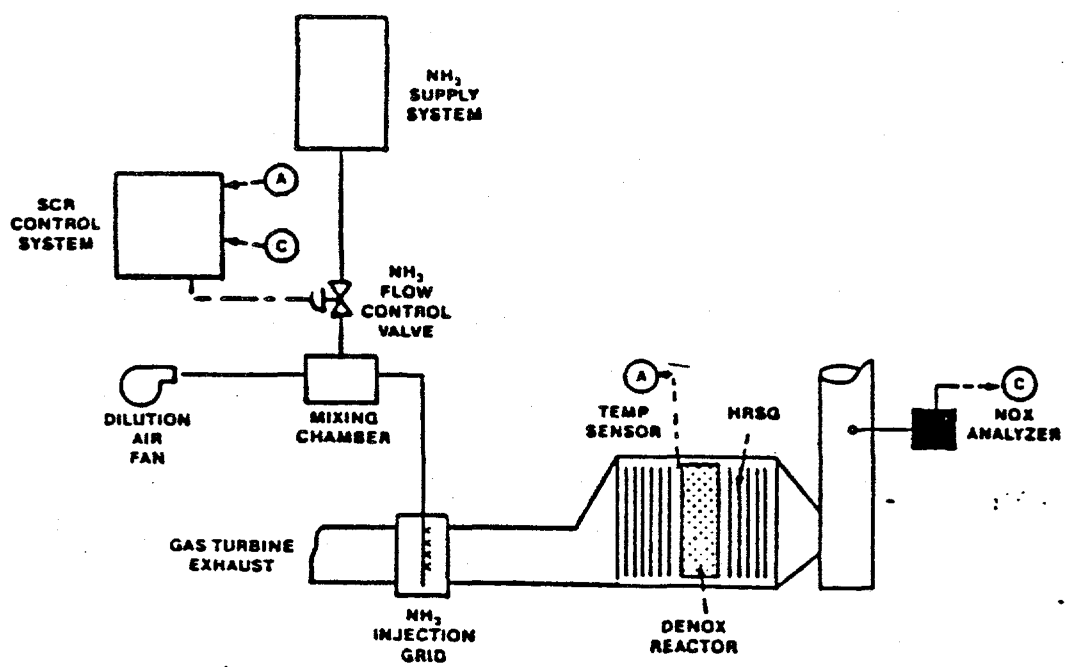

Figure 6-8. SCR System Components (3)

However, the Arthur D. Little Report of November 1988 lists fourteen other reactions that may occur(4). These reactions include the direct oxidation of NH_3 to nitrogen oxides at higher temperatures. The side reactions that occur depend on many factors including exhaust gas temperature and the type of SCR selected.

The SCR has demonstrated the capacity to reduce the level of NOx emissions by up to 90% of the original NOx level. Few SCR units on gas turbines below 15,000 HP have been operational since 1986. The longest operating unit is installed at a cogeneration facility and had logged about 30,000 hours (6). Of the 26 SCR units installed as of the end of 1992 on gas turbines at 17 sites, only 11 units were operational at 7 sites in 1990 (5). All installations use water injection to reduce the NOx level to ~42 ppm followed by the SCR to achieve <10 ppmv NOx.

Table 6-21 presents some comparisons of the SCR and the projected ceramic combustor for eight characteristics. The comparison is valid for gas turbines producing around 5000 H.P.

Table 6-21. Comparison of SCR with Ceramic Combustor

Characteristic	SCR	Ceramic Combustor
Reduction in Total Emissions	Minimum emissions limited by increase in ammonia slip as NOx is reduced	Lowest total emissions
Initial Cost	Typical installed cost is very high	No additional costs
Flexibility in Cogeneration	Limited, especially with duct burner to maintain SCR within narrow limits of temperature	Designed for a wide range of loads
Cost to Remove NOx	High at low NOx	No additional cost
Other emissions	As much as 75% of the added ammonia may be emitted	None
Operational cost	Very high due to limited catalyst life, high manpower requirements, etc.	No additional cost
Adverse Effect on Gas Turbine	0.5% power loss due to backpressure of SCR	No additional losses
Water Usage	Water injection ahead of SCR may require 1 million gallons of treated water per year	Not used

In spite of this overwhelming advantage for an integral, low NOx ceramic combustor in the CSGT, it is necessary to consider whether the various Air Quality Control Boards (AQBs) will require SCRs on the back of cogeneration units using small CSGT-type engines. Some AQBs regard the emission of excess ammonia as acceptable because it has not yet been classified with regard to its hazardness. If the total emissions are not considered but only the NOx, then an AQB may require installation of an SCR. Such a decision will have an important bearing on commercialization.

It is a goal of the Solar CSGT program to demonstrate emissions of NOx in the CSGT engine of 10 ppmv or less. Incorporation of a SCR in a CSGT engine may have the potential of reducing emissions of NOx from < 10 ppmv to < 5 ppmv. Solar's experience has been that environmental regulatory bodies will mandate emission goals based on best available current technologies (BACT) and NOx emission limits of < 5 ppmv could become the mandated standard. Serious consideration must therefore be given to design strategies that will result in emission levels comparable or better than those achievable with either the CSGT (< 10 ppmv NOx) or the CSGT+SCR (< 5 ppmv NOx).

Potential design strategies to achieve these ultra-low emission goals may involve a combination of the best "dry" low-NOx technologies achievable with ceramic hot wall combustors as envisioned under the DOE CSGT program with the addition of, for example, in-line catalytic combustion to further reduce NOx levels to < 5 ppmv. Such technologies can be potentially cost-effective compared to SCR's without the disadvantages of emissions of ammonia (NH_3) that are currently under less scrutiny of environmental regulators but that are nevertheless contaminants in their own right.

To achieve <5 ppmv NOx over the entire operating range with dry low NOx will require significant new resources and additional time.

It can be seen that it is imperative for future siting that the ceramic ultra-low NOx combustor be developed and demonstrated in the field. Compared with the expense of SCR's there is considerable leeway for cost increases in both installed cost and in operating costs for the ceramic low-emissions combustor. The ceramic combustor system to be developed and demonstrated under this program could be the basis for further reduction in emission levels by incorporating new features, while remaining below the costs for all competing systems. Current estimates are that the ceramic combustor engine can be introduced to the marketplace at much lower costs than an engine with SCR + water injection. At the same time, the emissions of CO, NH_3 and other pollutants will be significantly lower.

6.4.4.5 Competing Technologies - Fuel Cells

The only significant energy conversion technology that appears to be a possible competitor to the CSGT in the year 2000 is the fuel cell. The current status of fuel cell technology and its projected status by the year 2000 will be assessed in three steps. The first will be to summarize the technical and economic base; the second will be to assess the advantages and disadvantages of this base versus that of the CSGT; and the third will be to explore the probability of success of this technology. Estimation of the probability of success will be the critical step in evaluation of the challenge to commercialization of the CSGT. Particular attention will be paid to the advantages/disadvantages associated with specific market niches so that the differences in competitive challenge in different applications may be assessed.

6.4.4.5.1 Technical and Economic Base of Fuel Cells

Three major classes of fuel cells are under development. The phosphoric acid fuel cell (PAFC) after 18 years of development has reached the prototype stage at 40% efficiency with installations of 200 kW units at a cost of $3000 per kW (6). Molten carbonate fuel cells (MCFCs) have higher efficiencies (eg. 50%) but are higher in cost at $4000 per kW (7). The third major class is the more recently introduced, solid oxide fuel cell (SOFC) that may cost above $10,000 per kW at the present time (8).

It is estimated that more than $200 million is being spent annually to develop and commercialize fuel cells worldwide (9). Further, it is estimated that 90% of this funding is from the public-purse so that assessment of the current market-controlled economic base is difficult. This percentage has not decreased with time.

A common characteristic of all fuel cells is the voltage decay that occurs with time. This ranges from slightly under 1% per 1000 hours for the best PAFC to nearly 2% for the best SOFC (8).

Nearly all fuel cells are designed to operate with natural gas using a reformer to convert the natural gas to hydrogen. The size and operating costs of the reformer may dominate the installation. Current technology requires that sulphur compounds be removed to less than 1 ppm (8) to minimize electrode and electyrolyte degradation. Other impurities such as chlorides may be even more serious source of degradation. More advanced anodes may permit the SOFC to operate without a reformer.

6.4.4.5.2 Comparison of Fuel Cells with CSGTs

Table 6-22 presents a comparison between fuel cells and the CSGT power plant. Emissions are listed as the first factor to be compared. The goal of 10 ppm NOx for the CSGT equals 14 g/GJ of useful power. In contrast, the PAFC is quoted to produce 1.1 g NOx/GJ and the MCFC produces 4.1 g NOx/ GJ (9). However, all fuel cells are very sensitive to the purity of the gas feed. A SOFC produced 14.2 g NOx/GJ when gas is fed from a coal gasifier. In contrast, the CSGT will be little affected by the source of gas. High electrical efficiency for fuel cells is the second major advantage, although this is offset by the low voltage, high current (D.C.) produced. Either the electricity must be used locally (eg. for high current needs such as electroplating) or additional electrical losses occur with inverters and transformers (typically 5%) as well as with transmission lines.

At the present time, fuel cells have lower overall thermal efficiencies, much higher costs, much larger site area requirements and the RAM (reliability, availability, and maintainability) is much lower.

It is difficult to predict how some of the current major disadvantages of fuel cells will respond to continued development work. A semi-quantitative projection has been made for the cost based on an estimated cost of $5000 per kW in 1986 versus a cost of $2750 per kW in 1993 for the PAFC. The usual log-log relationship characteristic of a learning curve places attainment of a cost of $1500 per kW in or after the year 2005 (10). On the other hand, EPRI has projected a more optimisitic scenario by scaling up to a 2 MW size when the cost of $1500 per kW will be attained in 1997 (7). Table 6-22 shows that this cost will remain higher than the projected cost for the CSGT but within the competitive range.

6.4.4.5.3 Competitive Position of Fuel Cells and CSGT

The CSGT and fuel cell installations will have different E/T ratios that will affect their fit in the cogeneration market. Fuel cells with 55% electrical generation efficiency, acceptable cost and availability may be developed by the year 2005. Thermal energy recovery of these fuel cells is not expected to exceed 20% so that the E/T ratio will be nearly 3. The thermal energy from the fuel cell is low grade and may be hot water.

The CSGT to be developed on this program will have an E/T ratio that will be a little above 0.5. However, it will be able to generate steam. Subsequent ceramic hot section gas turbines of the second and third generations (Section 6.3.2.2) will have higher E/T ratios and greater flexibility. In the final analysis, ceramic hot section engines being considered for Advanced Turbine Systems (ATS) may have electrical generation efficiency goals approaching or exceeding 50% with high E/T ratios.

Table 6-22. Comparison of Fuel Cells and CSGT Units

Factor	Fuel Cells	CSGT
Emissions (NOx)	1-4 g/GJ	10 ppm NOx (current program) equal to 14 g/GJ
Electrical Efficiency	40-60% (low voltage D.C.)	40% (high voltage A.C.)
Overall Thermal Efficiency	80% (80°C/180°F hot water)	85% (1.03 MPa/150 psi steam)
Cost (1992 Dollars)	$3000-10,000/kW	$1000-1100/kW
Footprint	0.23 m^2/kW($2.5 ft^2/kW)	.023 m^2/kW(0.25 ft^2/kW)
Noise	Low (mainly reformer)	Moderate
Load Following	Moderately good (limited to slow rates of load change)	Excellent
Fuel Flexibility	Limited (H_2 or reformed CH_2)	Good
Scale-Up/Technology Transfer	Thermal management difficult	No problems
Reliability/Availability/Maintainability (RAM)	Poor, under evaluation	Well established for basic engine
Operating Costs	Round the clock operation of reformer system currently required	Can be operated without personnel
Start-Up	Typically 8 hours	Rapid

Both fuel cells and CSGTs will have major advantages in distributed power generation planning that will avoid some of the constraints facing electrical utilities today. However, the major competitive factor between these two power plants will result from the demands of the Clean Air Act. Siting permits will be controlled by the emissions at the site. For this reason, it is concluded that continued development to improve efficiency and to reduce emissions of the CSGT is of critical importance. A reduction of emissions of the CSGT to less than 5 ppm NOx and an increase in efficiency to 50% will reduce the emissions to less than 5.6 g NOx /GJ of useful power. Although this is higher than the emissions of the PAFC fuel cell, account needs to be taken of the disposal of the phosphoric acid electrolyte (currently once a year) and of the chemicals generated by clean-up of the natural gas to remove sulphur, chlorine, and other impurities. The much greater simplicity of the ceramic "hot wall" combustor to produce low emissions compared with the chemical plant needed to process the fuel for the fuel cell, has much to recommend it.

It is believed that the CSGT and its successor engines will be successful in the market place versus the fuel cell, in spite of the $200 million per year being spent to develop the fuel cell (9). Each type of power plant will find special market niches. The CSGT, as part of a cogeneration unit, when fitted with the ultra-low NOx combustor, will be able to offer steam plus electricity at a lower cost and with lower emissions than a fuel cell plus a separate, gas fired boiler. The fuel cell will have a special market niche where high current D.C. power is required without the need for steam. But, unless the installed cost and operating costs of the fuel cells can be drastically reduced, it is believed that the general market will be dominated by the CSGT.

6.5 DEFINITION OF COMMERCIALIZATION DEVELOPMENT PLAN

In this section the elements of a commercialization plan are being defined that is responsive to the needs of the future user of ceramic gas turbines. The elements of a commercialization plan include:

- Demonstration of the technical feasibility of the ceramic turbine technology to gain customer confidence.
- The establishment of a reliable component supplier base.
- The presence of a trained sales force and technical installation personnel.
- An appropriate warranty program.
- An infrastructure for product support.

6.5.1 Demonstration of Technical Feasibility

The DOE CSGT program will culminate in a 4000 hr performance test at the cogeneration test site of ARCO Oil & Gas in Bakersfield, California. If successful this test will demonstrate the feasibility of the ceramic gas turbine technology to the end user community and accelerate its acceptance as a commercial viable product. As outlined under section 6.4 this demonstration will significantly contribute to customer acceptance, but it will be by no means sufficient. Other factors such as high energy prices and acceptable materials cost must also be satisfied for initial market acceptance to translate into ceramic gas turbine equipment sales. Additional field tests will likely be required to firm up customer acceptance and optimize equipment performance and reliability. Full market penetration will take anywhere from four to eight years to become a reality.

Strategically, it would be advisable to continue the 4000 hour field test planned at ARCO. This could be achieved by returning the engine after inspection and overhaul with new ceramic components and let it remain in service for a prolonged time to be decided after the engine inspection. If the initial 4000 hr test was fully successful the customer will likely be willing to take advantage of the favorable economics and continue the test. The additional service time gained would accelerate end user acceptance significantly.

6.5.2 Establishment of a Reliable Component Supplier Base

An adequate component supplier base is essential to justify major Solar investment in the ceramic gas turbine technology, and to generate customer confidence in its future. Retention of multiple suppliers from domestic and off-shore sources in this program was regarded essential for its commercial success. The ceramic component commercialization plans provided by the suppliers and the cost profiles summarized in Section 6.2 are critical in this respect. Growth of the market for CSGT-type engines will aid to suppliers to develop their manufacturing base. Any upsets along the route to commercialization will delay the establishment of an adequate supplier base with the resultant financial pressures on the ceramic component manufacturers. It is for this reason that Solar has adopted a conservative design philosophy, i.e. focusing on a minimum number of ceramic components, reduction of service stresses to the lowest possible levels; opening of turbine tip clearances to ensure the absence of rubs; and a conservative increase in TRIT to 1121°C(2050°F).

Close involvement in the development and subsequent commercialization of the ceramic turbine technolgy of the suppliers is also believed to be a key to the establishment of a solid manufacturing base. Solar has communicated high standards of quality control to the suppliers of the ceramic components. The attention to appropriate NDE technology development and life prediction are expected to result in the development of the tools that will help improve ceramic manufacturing practice and lead to the fabrication of durable and reliable components. Again, this will help the ceramic manufacturers gain acceptance as component suppliers and strengthen their position in the market place. The success of the ceramic turbocharger technology in Japan shows that ceramic components can be fully accepted by the market place in a short period of time if rugged component design, materials reliability, and quality control issues are given high priority.

6.5.4 Warranty Program

For the ceramic gas turbine to become an accepted product appropriate warranty policies must be instituted as part of new equipment sales and overhaul procedures. Particularly, during the initial stages of ceramic equipment sales the presence of policies that protect the end user against malfunctioning of equipment with new largely untested desings will be a necessary ingredient in gaining customer acceptance. Solar and its parent company, Caterpillar Inc., have a long standing tradition for standing behind its products. An important element in a warranty policy will be to have a replacement engine available to minimize downtime, particularly where severe penalties are associated with downtime.

6.5.5 Product Support Infrastructure

The establishment of an infrastructure for aftermarket support is another vital element in the commercialization plan. It is expected that such an infrastructure will develop organically along with the progress on the program. At the time of the field engine demonstration at ARCO, Bakersfield, there will be embryonic customer support. Expertise in design, materials and testing, supplier liaison and monitoring, component acceptance procedures, materials and component testing and proof testing, component handling and assembly, green engine test runs, systems support, packaging and installation, warranty policies, operator training and after-market support from the basis for effective customer support. Solar's approach of concurrent engineering will facilitate the establishment of the infrastructural support since all company functions required for product development, engine and component manufacturing, marketing, sales and customer services will contribute to the life cycle of the ceramic gas turbine from conception to a mature product.

The embryonic infrastructure will be fully integrated into the aftermarket support network following initial customer acceptance of the technology.

6.6 END-USER PERSPECTIVE: THE ARCO VIEWPOINT

Section 7.0 of this report reviews many factors from the viewpoints of the Nation, the end user, and the equipment manufacturer. It is shown that there are significant differences in the way each of these views the program. On the other hand, these viewpoints are global, that is to say, general viewpoints are expressed rather than site- or customer-specific viewpoints. This section will review the development from the point of view of the ARCO installation in Bakersfield.

The primary concern of ARCO is to maintain electrical production to meet the contractual obligations, i.e., high reliability, availability, and maintainability. The contract to supply power to PG&E includes penalties for unscheduled interruptions in service. On the positive side, uninterrupted delivery of power provides the cash flow that makes operation of this oil field attractive in spite of the limited price for this heavy crude. The production of steam for injection down the well is also essential to maintain flow of the heavy crude below ground.

ARCO believes that reliability and availability must be at least equivalent to that currently experienced. Operating costs must be predictable and low. In view of the cogeneration at this installation, efficiency does not rank as No. 1 in its effect on operating costs. Downtime avoidance and long TBOs are important factors in contributing to positive cash flow generated from oil production and electricity sales.

The incorporation of ceramic components in related applications in automotive gas turbines and diesel engines will provide additional support for strengthening the supplier base. The success of the AGT/ATTAP programs provides the basis for supplier viability that will assist related gas turbine commericialization plans.

There remains a great deal of work to be done to make ceramic components attractive to the gas turbine equipment manufacturers. The current long lead times for components varying from 8 to 12 months for a set of 100 prototype parts and the high cost of components are unacceptable for commercial viability. It will be necessary to rationalize the manufacturing process by shortening delivery times and reducing component cost to the levels described under Section 6.2. Concurrent manufacturing readiness initiatives aimed at streamlining and accelerating the ceramic component manufacturing process to handle the expected quantities (2500-1000/year) of components demanded by the gas turbine equipment manufacturer will be necessary. This includes the integration of the processing of components at the suppliers with in-house finishing operations at the gas turbine equipment manufacturer which will be required to facilitate ceramic component acceptance. These factors will require the attention and support by the suppliers as well as the equipment manufacturers and mechanisms to assist with this process should be explored throughout the program.

6.5.3 Training - Sales and Technical

Commercial development plans must include adequate training of sales and technical personnel. This factor has always been an important elements with all gas turbine manufacturers. For the ceramic turbine technology the training will be particularly necessary since there is no precedent for the use of these materials in commercial industrial gas turbine equipment. Training must involve basic education in the science and technology of ceramic materials and processing, materials and component evaluation methodology, component handling practice, and quality control procedures. The expertise for this assignment will have to come initially from engineering staff at the equipment manufacturers and suppliers that have had a long standing acquaintance with ceramic materials. Skills transfer from engineering personnel will be mandatory. Personnel transfer from design and materials engineering functions to customer technical support and equipment sales and servicing functions will also be a key factor in making the ceramic components an integral part of the future ceramic gas turbine product integration.

Technical training for customers and their personnel will also be invaluable for the successful integration of ceramic turbine technology in the product line of the gas turbine manufacturer. Solar has traditionally had a strong focus on customer training in equipment installation, operation and maintenance. For example, over 30 courses for customer personnel are offered on a regular basis and at 3 or 4 months intervals. These are operational and maintenance courses for all Solar products. In addition, control system logic courses are offered on most products. Advanced courses range from troubleshooting to vibration analysis. These courses are offered at many regional centers in the United States and Canada, as well as in Singapore, Grosslies (Belgium) and Dublin (Ireland). Most of the courses are of 5 day duration but some may last longer. Over 25,000 students from customers have been through these training programs.

Similar programs are offered to Solar personnel covering every aspect involved in the operation of a major business. Recently a major new education center was opened to provide courses for all level of personnel. In view of this background extending over more than 30 years, it is certain that training will not provide any barrier to commercialization of the ceramic gas turbine.

If unscheduled downtime does occur, minimization of losses requires fast response on the part of the OEM and their after-market service group. This response may range from field repair at ARCO in Bakersfield to engine replacement.

There are several attractive features that led ARCO to offer the Bakersfield site for the 4000 hour test of the CSGT. These are:

1. The additional 1000 kW of output will increase the cash flow for this site.

2. The additional steam generation will allow oil production to be increased or to maintain the same production with fewer engines in use.

3. Solar support personnel will be at the site more frequently and will reduce the chance of unscheduled shut-downs on any of the engines.

4. The reduction in emissions will allow electric, steam, and oil production to be increased.

In the long term, the concerns of ARCO are that the engine price be reasonable in relation to its greater productivity, that TBOs be at least equal to that of existing Centaur-type engines, that the cost and time of overhaul be acceptable, and that the cost of spare parts be reasonable.

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7.0

TASK 5 - CONCEPT ASSESSMENT

7.1 INTRODUCTION

Against the background of the requirements for successful commercialization, the fit of the CSGT engine in gas turbine product development and commercialization has been examined. Projected benefits and possible detriments resulting from the development plan of Task 4 (Section 6.0) have been ranked in order of importance. The probability of success has been estimated and explained. In this assessment technical, cost and environmental issues have been taken into account to define and project the probable risk and solutions to the critical activities to be overcome to complete the engine testing phase. A follow-up strategy has been defined to relate the development of the Centaur 50 CSGT engine to other engines.

7.2 FIT OF THE DEVELOPMENT OF THE CERAMIC GAS TURBINE IN PRODUCT DEVELOPMENT AND COMMERCIALIZATION

The technical and economic analysis of Task 4 forms the basis for an assessment of the fit of the Centaur 50 CSGT engine into engine product development. The following factors affecting commercialization have been considered in this section: economic and environmental factors (fuel and electricity prices, emissions targets), and markets for the technology.

7.2.1 Economic and Environmental Factors

The Net Present Value analysis of Section 6.3.3 showed a strong dependence of the benefits of inserting ceramics in gas turbines on fuel and electricity prices in the time frame for introduction and significant market penetration of ceramic engines, forecast to be between 2000 and 2010.

Fuel price predictions vary between sources. Figure 7-1 shows predictions for industrial gas prices up to the year 2010 from three sources (1-3). Prices range from about \$3.50 - \$5.00. Solar's current forecast is that industrial fuel prices will tend to be towards the lower end of this range. Electricity prices fluctuate also depending on regional factors and end use. A price in the 6-8 c/kWh range is Solar's current forecast for industrial cogeneration (price levels are in 1993 dollars). Actual fuel prices may vary depending on economic growth factors, price of oil, implemented energy conservation programs, and regional and end use variables. Assuming the referenced conditions ceramic insertion provides an economic benefit over metal engines as described in Section 6.0, because of the value associated with increased power output, improved fuel efficiency and reduced emissions.

Of these factors the benefit of lower emissions applies to all engine classes and modes of operation. Levels of NO_x below 10 ppmv and of CO below 20 ppmv will be expected from the gas turbine equipment manufacturers in the long term and ceramic hot wall combustors could be an important enabling technology to achieve these levels. For even lower emission levels advanced technologies such as catalytic combustion will be needed in conjunction with ceramic hot wall combustors. Although the drive to achieve lower emissions will favor the use of ceramic hot wall combustion at all firing temperatures, the need will become more urgent for engines with higher turbine inlet temperatures since maintaining NO_x control will become increasingly more difficult with all metal combustors because of increased cooling requirements of the combustor hardware.

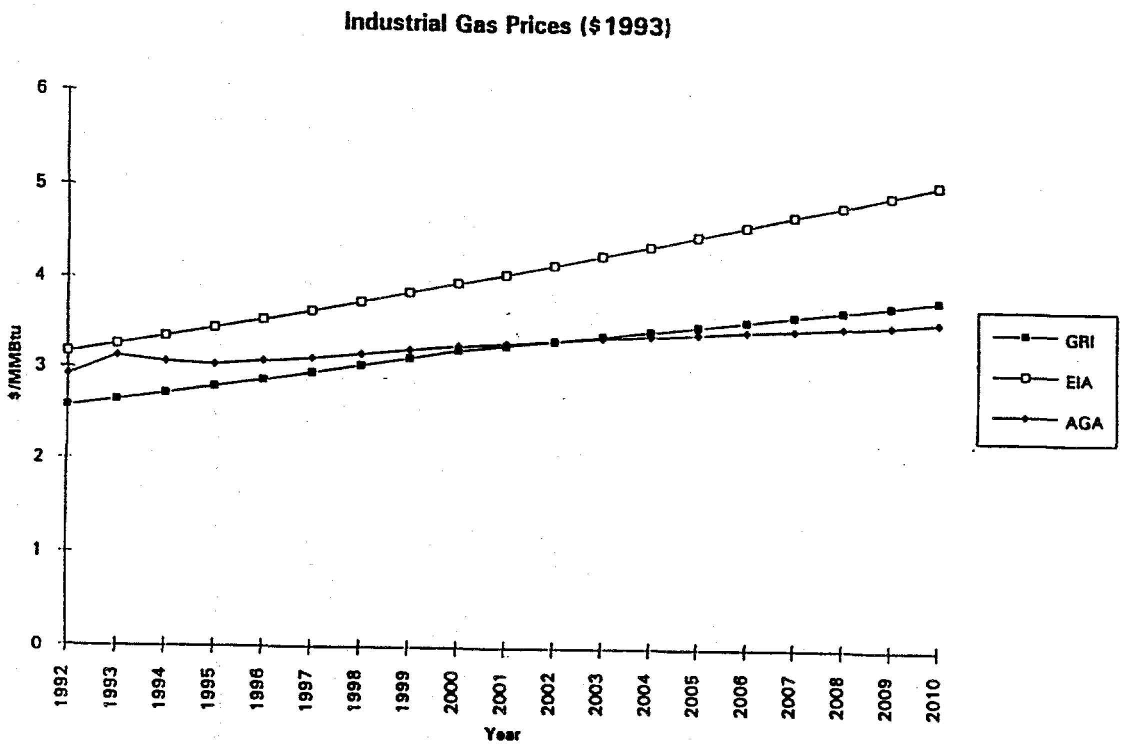

Figure 7-1. Three Scenarios for Industrial Gas Prices (1-3)

It has been Solar's experience that once a new technology is introduced and its efficacy in maintaining RAMD (Reliability/Availability/Maintainability/Durability) is demonstrated market acceptance is rapid. Because of the equipment manufacturer's strategy to unify its product line, the ceramic hot section technology is expected to be incorporated into all engines of a new model once the decision to use ceramics is made. Solar's experience also shows that once a new model has been accepted by the market place it tends to replace older models rapidly in customer's purchasing decisions. In a typical market cycle a new engine model can outsell an existing engine within two to three years.

Another factor of importance is the gas turbine equipment maker's product strategy to sell the same engine models to the international and domestic markets. This strategy is aided by global trends towards higher efficiencies and environmental regulations. Product improvements in performance and emissions levels will benefit end users anywhere in the world. The ripple effect of CSGT technology implementation can be expected to contribute to energy conservation and lessening the burden on the environment globally.

Solar estimates that the introduction of turbines with several ceramic components into the market place will take place somewhere in the 2000-2004 time frame if fuel and electricity prices are favorable. The actual date of introduction will depend on the success of field tests in demonstrating the ceramic gas turbine technology and necessary product development to commercialization as described in Section 6.5. Significant market penetration in the 2005-2010 time frame is likely, with all new engines sold after 2005 incorporating ceramic turbine technology. This market penetration scenario corresponds to a forecast supplied by Battelle Memorial Institute (BMI) (4). The BMI study envisioned market introduction of the ceramic gas turbine technology by 2003, with ceramic engine sales replacing metal engine sales within two years.

7.2.2 Market Segments and Capacity

The commonality in technology between simple cycle and cogeneration equipment for industrial gas turbines ensures that all market segments will benefit from the ceramic gas turbine technology. Industrial gas turbine market segments have been grouped as power generation and cogeneration markets for equipment outputs in the 0.5 - 25 MW range. The power generation market includes simple cycle and recuperated engines for mechanical drive and electricity generation. The cogeneration market focuses on end users which have a simultaneous need for power and steam. Combined cycle applications have been included in the cogeneration section. Retrofit opportunities have been discussed separately since this is a primary focus of the CSGT program. The potential application of ceramic hot section technology to larger utility size engines (outputs > 25 MW) and aeroderivative engines has also been described. Although these engines are outside the Solar product line the CSGT technologies are applicable to these gas turbines and deserve mention for the benefit of those companies working with these engines. The applicability of the CSGT designs to third generation engines of advanced turbine systems is also discussed.

Table 7-1 summarizes Solar's estimate of capacity in various sectors for the U.S. industrial turbine market (0.5 - 25 MW output) installed between 1974 and 1993. The time frame was chosen based on an average useful service life of 20 years for a gas turbine. Total installed capacity is estimated at 13.1 GW. The U.S. capacity installed prior to 1974, estimated at about 18.1GW was assumed to be retired or replaced by 1993. An estimate by BMI (4) indicates about 18.1 GW of installed non-utility engine capacity around 1990. The BMI data includes reciprocating engines not included in the Solar estimate.

Table 7-1. 1993 U.S. Industrial Gas Turbine Capacity by Market Segment

Market Sector	Capacity	% Total Capacity
Mechanical Drives	4,855 MW	37.0
Oil & Gas Electrical Generators	1,512 MW	11.5
Industrial/Commercial Generation Applications	1,904 MW	14.5
Industrial/Commercial Cogeneration Applications	2,158 MW	16.5
Other Applications	2,677 MW	20.4
Total	**13,106.00**	**100.0**

Table 7-2 forecasts capacity growth for various scenarios. The low growth scenario based on Solar's forecasts is based on an average annual increase in installed capacity of 2.0%. This growth rate is conservative. An intermediate growth scenario incorporates a higher estimate of cogeneration capacity growth published in the literature (5). The third scenario which represents the highest capacity growth assumes a mature ceramic gas turbine technology by 2005 with all engines produced after that date having ceramic parts. The installed capacity in the latter estimate is perhaps the most realistic. It lies in between capacity figures ranging from 31,000 MW and 41,500 MW quoted in the literature (4).

Table 7-2. U.S. Gas Turbine Capacity Forecasts by 2005 and 2010

Description	1993 (MW)	2005 (MW)	2010 (MW)
All metal engines (1)	13,106	16,620	18,350
All metal engines (2)	13,106	25,650	29,160
Ceramic engines (3)	13,106	27,410	33,730

(1) Assumes 2.0% annual growth rate for all market sectors.
(2) Assumes 2.0 annual growth rate for all applications except cogeneration. A 10 MW baseline industrial cogeneration capacity is assumed by 2000 which is forecasted to grow by 3.3% from 2000-2010 (5).
(3) As (2) with an additional 15% growth by 2005 and 33% by 2010 because of ceramic components (5).

7.2.2.1 Power Generation Market

This market includes mechanical drives, mostly for gas compression in the oil and gas industry, and power generation for industrial and commercial applications. Applications in the oil and gas market for mechanical drives and electric generation generally do not have need for steam. In addition, the cost of fuel is lower than the costs assumed for the scenarios in Section 6.0 where delivered gas was to be used. Even on gas pipelines, the value of gas is less than the price quoted to commercial and industrial customers located at the destination of the line. In these cases, the installed cost per HP will remain the dominant factor. The major increase in output power and reduced emissions of ceramic engines such as the Centaur 50 CSGT versus the metallic Centaur 50 will be the first appeal to such customers with better fuel efficiency being a secondary factor.

On the other hand, the well-head price of natural gas will rise faster than that of delivered gas. For example, Cambridge Research Associates report that from 1970 to 1990, the wellhead price of gas in the lower 48 states rose tenfold (from $0.17 to $1.70 per 1000 cu. ft) whereas the price of industrial gas rose less than eight-fold (from $0.37 to $2.90 per 1000 cu. ft.)(6). The more rapid rise in the cost of gas at the well-head and along the pipeline compared with delivered gas, will cause customers in such locations to put increased value on equipment efficiency. Thus, the 5.6% higher efficiency estimated for retrofit applications such as the Centaur 50 CSGT over the all-metal Centaur 50 engine will become more significant with time. It should be noted that, in most cases, the gas pipeline market cannot turn to cogeneration to reduce costs.

Future generation ceramic gas turbines of the type illustrated with the Mars 100 derived CSGT with 19970 SHP output at 40% efficiency, and the modified, recuperated ceramic Taurus engine producing 7536 SHP at 43.6% efficiency, can expected to become increasingly important in the power generation marketplace.

7.2.2.2 Cogeneration Market

The industrial cogeneration market is a rapidly expanding sector, as illustrated in Table 7-3 which is an extrapolation of literature data (5). The availability of ceramics is anticipated to result in additional industrial cogeneration capacity over traditional markets. About 4,600 MW of additional cogeneration capacity over a market with only metallic engines is anticipated to be installed by 2010 all of which based on ceramic engines with improved performance.

Table 7-3. Industrial Cogeneration Forecast (Estimated from Ref. 5)

Year	Estimated Capacity	
	Without Ceramics	With Ceramics
1990	5,000 MW	5,000 MW
1995	7,000 MW	7,000 MW
2000	10,000 MW	10,000 MW
2005	11,800 MW	13,570 MW
2010	13,800 MW	18,400 MW

Value of Output Power and Flexibility

One of the benefits of ceramic gas turbines is the increased value of the output produced because of a shift to higher E/T ratios towards the more valuable electrical output component. The outputs of the engines described in Section 6.0 has been analyzed by Anson et al. (7) by means of a Value Added Factor (VAF) which is the ratio of product value to fuel cost.

$$VAF = \text{Fuel Cost} \times (1.25\ \eta_H + P.\eta_H)$$

P: ratio of electrical value of electrical power value to fuel cost
η_H: heat recovery efficiency
η_H: power generation efficiency

Assuming a fuel cost of $ 3.00/MMBtu and an electricity cost of $ 0.06/kWh a value of electrical power to fuel cost of 4.77 was calculated. In practice values of P can range from 2 to 10. Figure 7-2 shows VAF factors for the engines of Section 6.0. It can be seen that significant improvements in the value of the power result from ceramic insertion. Recuperated engines show a particularly large increase in the VAF factor compared to their simple cycle baseline indicative of the high value added in conversion from fuel energy to output.

A high E/T (electrical-to-thermal) ratio is beneficial in terms of the value of output generated, but actual end user electricity and steam demands determine to what extent improvements in this factor can be capitalized upon. Figure 7-3 shows the percentage of plants in the United States with requirements for different E/T demands. A large plant with a low E/T demand may install a small gas turbine to generate electricity with a large, separately fired boiler. Industries that require a low E/T ratio include: chemicals, food, lumber, petroleum, and others (8). High efficiency, small gas turbines will be of interest for these applications.

Figure 7-4 shows industrial cogeneration plants with up to 30 MW electrical demand and up to 300,000 lbs per hour (pph) of steam demand, based on a Dun and Bradstreet survey (9). The Centaur 50 CSGT will produce 5088 kW and 25,950 pph steam and is identified by a circle. The modified recuperated Taurus CSGT will produce 5177 kW and 9180 pph steam and is identified by a second circle. The Mars 100 CSGT is shown by the third cycle.

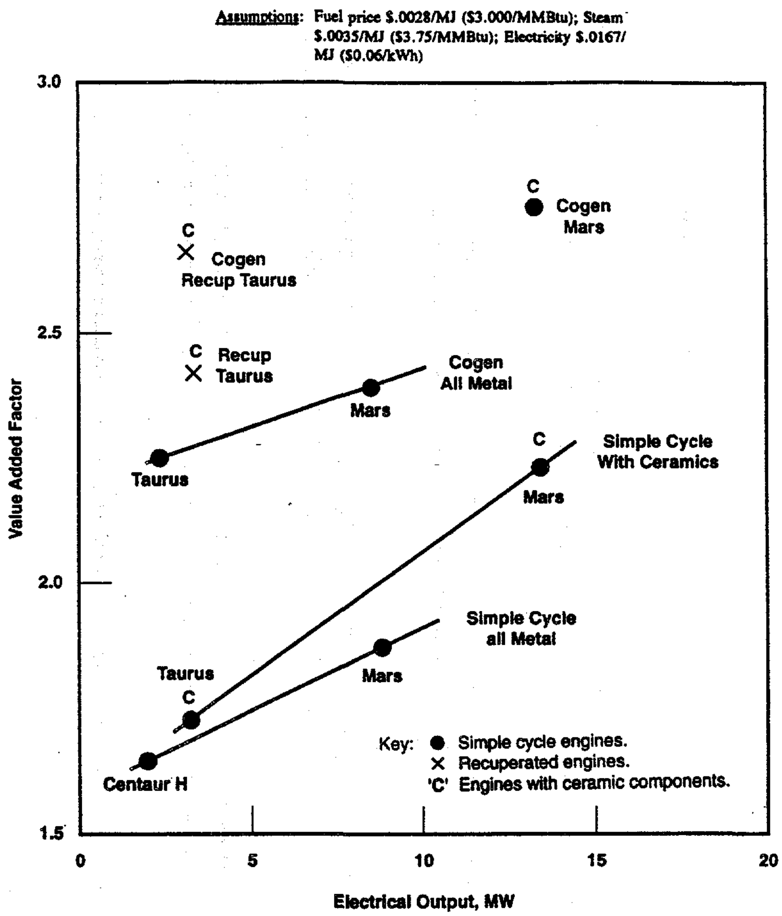

Figure 7-2. Value Added Factor vs. Electrical Output for Cogeneration Systems Described in Section 6.0 (7)

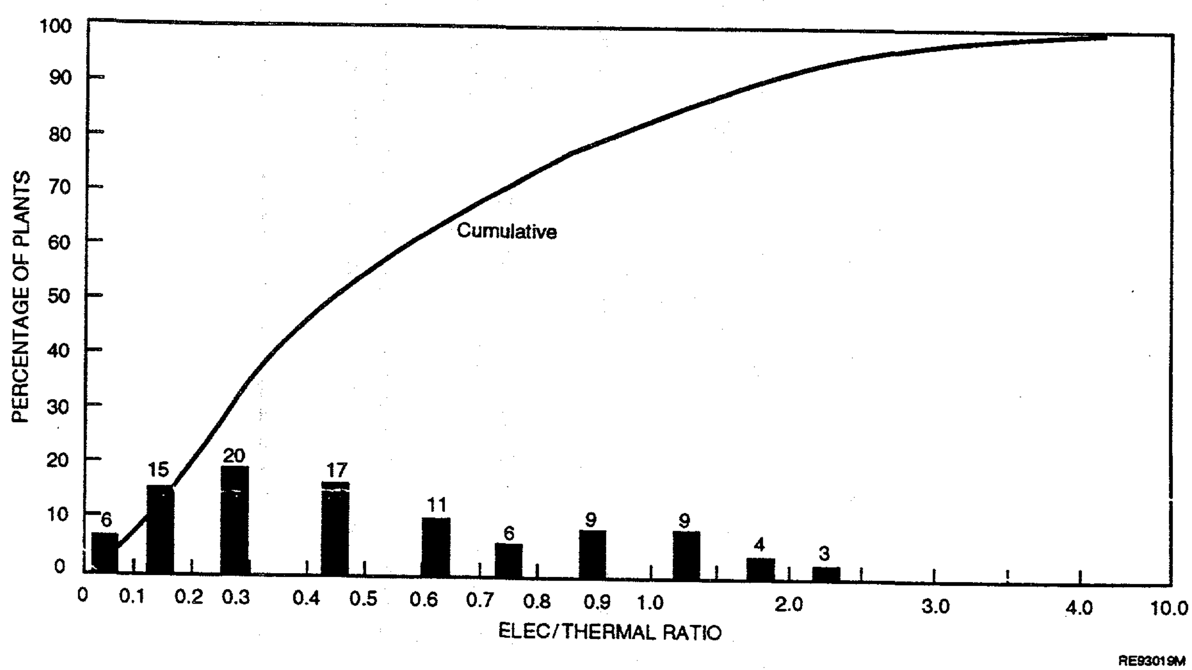

Figure 7-3. Percentage of Plants Versus Electrical/Thermal Ratio (8)

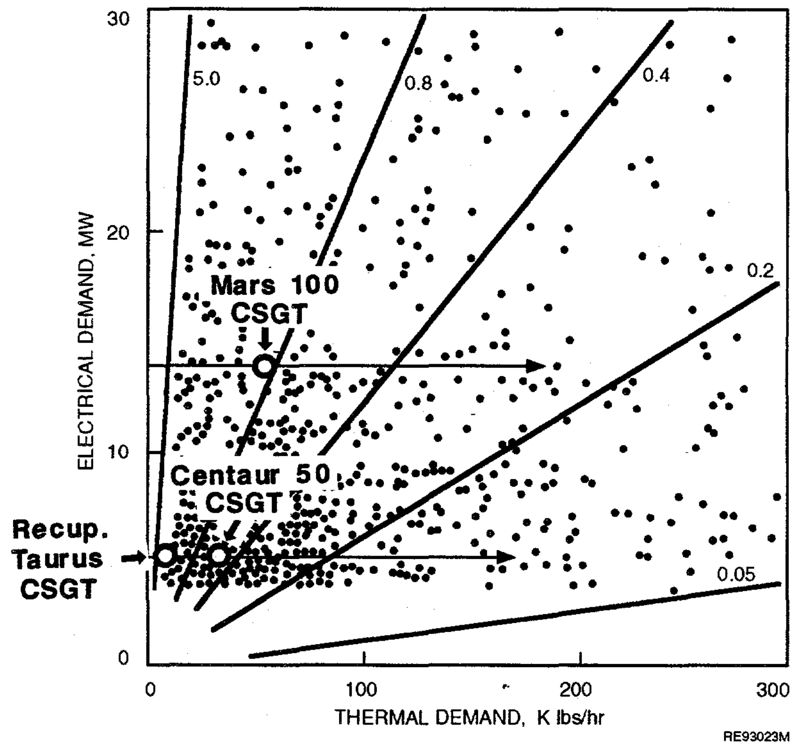

Figure 7-4. Industrial Cogeneration Plants with up to 30 MW electrical demand and 300,000 lbs. per hour (pph) of steam demand. Superimposed is the electrical output of the Mars 100 CSGT and the electrical outputs of the Centaur 50 CSGT and the modified recuperated Taurus CSGT. Beyond the full-rated outputs based on the exhaust gas flows, duct burners can extend the range of steam generated.

The lines radiating from the origin are for E/T ratios of 5.0, 0.8, 0.4, 0.2, and 0.05. The increases in output and thermal efficiency of the CSGT engines compared to the all-metal baseline engines will facilitate commercialization. In addition to increased output and efficiency, flexibility of output is essential. Customers needs require variable outputs that extend beyond the circles shown in Figure 7-4.

Flexibility in meeting steam demand is readily accomplished by installation of a duct burner. The major losses in boiler operation result from the heat losses by the stack gases. The addition of a small amount of fuel to the duct burner barely affects the mass flow in the stack so that a duct burner can be regarded as operating at very close to 100% efficiency. Typically, the amount of additional fuel supplied to the duct burner, and hence, the additional steam, will be limited by the emissions allowed at each site. In all cases, the duct burner firing is limited by the amount of additional fuel that can be burnt with the 16% oxygen remaining in the exhaust. The Mars 100 CSGT will be limited to a practical maximum of 250,000 pph of steam and the Centaur 50 CSGT and modified recuperated Taurus CSGT will be limited to 140,000 pph of steam.

The degree of flexibility required in the electrical output will influence the customer's choice of basic gas turbine. Figure 7-5 shows the variation of efficiency of two engines of the Centaur series. The ability of a recuperated engine to operate over a wide range of loads with acceptable loss of efficiency is an important factor. (These engines are operating in the simple cycle mode with electrical generators and are not entirely representative of operation in the cogeneration mode). Table 7-4 lists the range of industrial plants that can be covered by these ceramic component engines based on the assumption that 90% of full load efficiency would be readily acceptable to the customer.

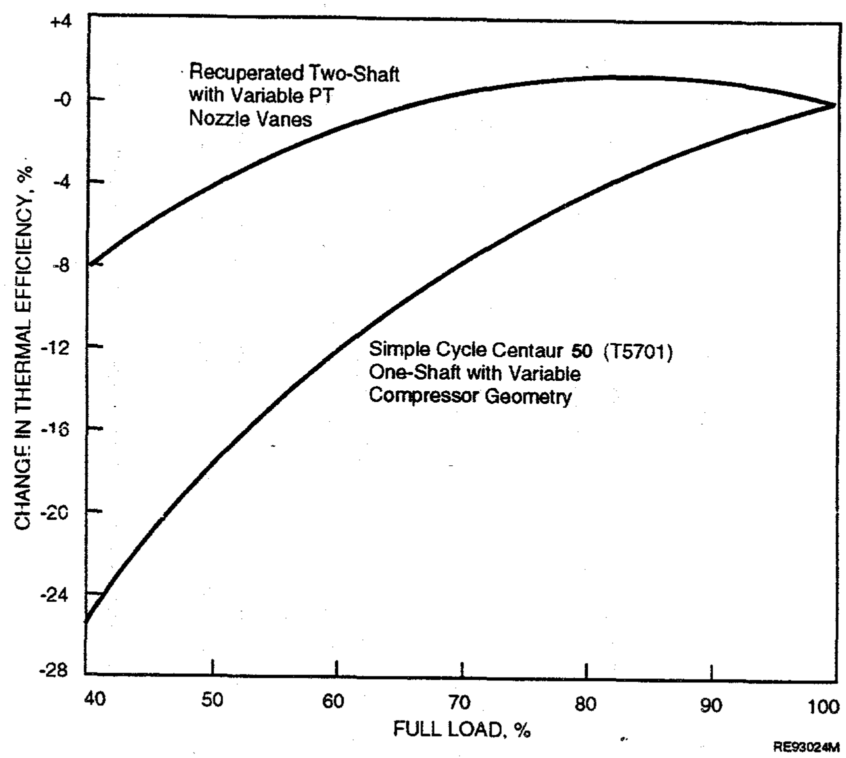

Figure 7-5. Approximate variation in thermal efficiency with load in different engine types. Generator application only.

Table 7-4. Industrial Plants Covered by CSGT Models

Engine	Electrical Output	Steam Output
Centaur 50 CSGT	4460 to 5088 kW	0 to 140,000 pph Steam
Modified Recuperated Taurus CSGT	2000 to 5177 kW	0 to 140,000 pph Steam

Distributed Power Cogeneration

An important development in the power generating industry is the growth of distributed power. Smaller size gas turbines burning natural gas with superior performance and low emissions could become a significant contributor to the new capacity to be installed in the next decades. Several factors are contributing to this trend. Important is the reduction in transmission losses that can reach as much as 15% (10). An additional benefit of distributed power over centralized power generation is the reduction in electromagnetic fields (EMFs) generated by high voltage transmission lines. This factor is becoming more prevalent as public concern over potential environmental risks has recently intensified. There are also the other longstanding environmental disadvantages associated with utility coal or nuclear based plants, including high emission levels of SO_x (for coal based plants) and disposal of nuclear waste and risk of contamination in case of a malfunction (for nuclear plants).

Small gas fired turbines based on the CSGT can provide very high overall efficiency when operated in the cogeneration mode at sites where the steam or hot water can be used locally without these environmental concerns. The incorporation of ceramic hot section technologies can improve the economics by lowering installation and life cycle costs and by providing significantly lower emissions levels. Ceramic gas turbines could therefore become an attractive component of distributed power generation strategies absorbing new capapcity traditionally served by centralized power stations. It has been estimated that the displacement of utility generating output with new cogenerating capacity from gas turbines under 25 MW could result in annual fuel savings of the order of 0.2 Quads by the year 2010 (5). An extrapolation of current trends indicates that ceramic gas turbines could contribute close to about 5 GW in additional new turbine cogeneration capacity by the year 2010 (5).

Combined Cycle Cogeneration

The highest efficiency in electrical generation is obtained when the steam formed in cogeneration is used to generate additional electricity by means of a steam turbine. This does not preclude steam availability for process heat when extraction or back-pressure steam turbines are used. Combined cycles can provide efficiencies in electrical generation that exceed 50%. They are standard in the large utility generation installations (e.g., over 100 MW) and in the large PURPA installations that supply electricity to the grid. On the other hand, for small cogeneration installations (below 60 MW electrical demand), again perhaps the most important need is for flexibility. These installations will differ from the large PURPA installations where electrical efficiency is emphasized and relatively small process steam outputs reduce the overall fuel utilization efficiency. Where "third party PURPA" strategy is selected, it demands very high E/T ratios typical of combined cycles using condensing, extraction steam turbines. These have had a negative impact on overall fuel utilization that tends to be below 60%.

Duffy et al. (11) have shown that wide ranges of the E/T ratio can be met with back pressure steam turbines with a duct burner to extend the range to lower values of E/T. Below an E/T of 0.2, non gas turbine cogeneration plants become the choice; this includes 22% of the Dun and Bradstreet plants surveyed (9). The highest concentration of plants, especially below 10 MW of electrical need, fall within the range that can be serviced by gas turbines.

High exhaust temperatures from the gas turbine reduce the need for additional gas to the duct burners. One of the benefits of the CSGT engine is its ability to operate at increased turbine rotor inlet temperatures (TRIT) resulting in increased exhaust gas temperatures. For example, the exhaust gas temperature of the Centaur 50 (T5501 Genset model) of 517°C (962°F) is predicted to increase to 579°C (1074°F) for the Centaur 50 CSGT (T5701 Genset model). This feature will favor a combined cycle plant, if there is limited demand for steam.

Combined cycles can reach E/T ratios as 5 at high efficiencies. However, the high efficiency steam turbines needed to achieve this are not commercially available in small sizes. The modified recuperated Taurus CSGT is predicted to achieve E/T ratios of 1.6-1.7 with over 40% electrical efficiency and over 65% of overall thermal efficiency without a second piece of rotating equipment. Operating costs measured in $/kWh rise significantly with the second piece of rotating equipment compared to a stationary recuperator.

Another feature of the combined cycle relates to scale. Combined cycles are universally accepted under conditions where: (1) production of electricity for the grid is the primary requirement; and (2) the installation is large. Size is a critical factor. Studies have shown that the smallest Solar gas turbine, the 1.2 MW Saturn, could never be the basis for an economically viable combined cycle. On the other hand, the 10 MW Mars engine can compete in the market place as a combined cycle, although a multi-engine installation may be needed to ensure viability. (Excellent returns have been found at an installation in York, Pennsylvania where six Mars engines in a combined cycle produce 66 MW.) At the Centaur size of engine, it is clear that the present price structure and the lack of efficient steam turbines do not favor combined cycles.

It is concluded that the commercialization of the ceramic gas turbine will benefit from application to the combined cycle market to a slowly increasing extent in future years.

7.2.2.3 Retrofit Market

Upgrade to the performance level of a ceramic hot section engine will always be an option at the time of overhaul. Key issues in decision-making by the customer on upgrade will include:

1. The customer's needs for increased output and thermal efficiency.

2. Cost of overhaul of the metallic engine versus the cost of upgrading with ceramic components (and upgraded metallic components as required).

3. The net present value of the increased output and thermal efficiency improvement (electrical and steam) versus the incremental cost of upgrade over the cost of overhaul and/or repair.

4. Return on investment considerations.

5. The customer's additional expense by upgrades of ancillary equipment (gearbox, switchgear, generator, boiler, and so on) in case of ceramic retrofit.

6. Special factors such as environmental and other issues peculiar to the customer's specific location.

The development of the retrofit market for the CSGT is governed by factors similar to those controlling the development of other markets. Where the economics justify it ceramic retrofitting of the Centaur 50 and other all-metal engines will proceed at the rate of the new engine introduction and significant market penetration can be achieved in the 2005-2010 timeframe (see Sections 6.4.3.1-6.4.3.3). Retrofit opportunities will continue to exist when the availability of new advanced engine models lessen the interest of the customers in new Centaur 50 CSGT engines. On the other hand, certain customers may not wich to retrofit their engines with ceramics while new engine installations may incorporate ceramics at the 100% level.

Table 7-5 lists part operating temperatures at which insertion of ceramics in metallic hot sections becomes advantageous. The insertion of ceramics must present a tangible benefit through improved efficiency and output power through increased operating temperature, the reduction or elimination of component cooling, or lower emissions. There may be other benefits, e.g. lowering of stress on a disk when lower density ceramic blades are used in place of metallic parts.

Each engine scenario has to be evaluated on its own merits. Generally speaking there is no advantage in replacing uncooled metal components of conventional superalloys since their cost is well below that predicted for uncooled ceramic parts. The cost of coated cooled conventional components is roughly comparable to that of uncooled ceramics. For engines utilizing such components the advantages of ceramics without increasing firing temperature are small and generally do not justify ceramic insertion. Combining ceramic insertion with an increase in TRIT is often sufficiently beneficial since this results in improvements in efficiency and output power which provide tangible benefits. The opportunities for ceramic insertion listed in Table 7-5 are provided with these considerations in mind. A few examples from the Solar product line are supplied here to illustrate this strategy.

Table 7-5. Opportunities for Ceramic Insertion in Gas Turbines

Component	Component Temperature	Reason For Insertion
Combustor, Transition Liner	All temperatures	• Reduce emissions of NO_x and CO
Blade	900°C (≈1650°F)	• Increase TRIT • Eliminate cooling air • Reduce part cost • Eliminate coatings • Lowering stress on the disk
Nozzle	850°C (≈1560°F)	• Increase TRIT • Eliminate cooling air

The Saturn 20 engine operates at a TRIT of 832°C (1530°F). Both blades and nozzles are uncooled conventional superalloy components. Without increase in firing temperature there would be no advantage in replacing blades and nozzles with ceramic parts. Still a significant benefit can be achieved by insertion of a ceramic liner in the combustor to lower emissions of NO_x and CO.

The program engine, the Centaur 50, currently has a TRIT of 1010°C (1850°F). Without increasing the firing temperature emissions benefits are anticipated from insertion of a ceramic liner in the SoLoNO$_x$ combustor. The benefits associated with replacing the coated cooled first stage metallic blades and nozzles are too small to justify ceramic insertion for these parts. Increasing the firing temperature to 1121°C (2050°F) provides the incentive because of increased efficiency and output power following ceramic insertion. Moreover uprating the metallic engine to this new TRIT level would require the use of expensive coated cooled single crystal blades which can be avoided by using less expensive ceramic parts.

Engines that are currently operating at 1121°C (2050°F) such as the Solar Taurus 70 and Mars 100 could benefit from ceramic insertion even without increase in TRIT. Emissions benefits are expected from the use of a ceramic liner and a cost advantage from replacing coated cooled single crystal blades with uncooled ceramic parts. Replacing the cooled first and second stage nozzles with ceramics will provide a benefit because of the elimination of cooling, and part cost of metal and ceramic parts is expected to be comparable. Together these advantages will be sufficient to justify ceramic insertion without TRIT increase.

7.2.2.4 Utility Gas Turbine Engines

While the CSGT program is aimed at retrofitting intermediate size and industrial gas turbines and does not target the utility gas turbine market directly ceramic hot section technology developed under this program could be incorporated into engine designs for the latter market. Development programs ongoing in the U.S., Western Europe, and Japan all consider ceramic technologies as potentially important for advanced utility engine designs.

Ceramic engine development under programs sponsored by the Japanese utilities and gas turbine companies is particularly relevant. Tokyo Electric Power Co., Ltd. (TEPCO), in a cooperative program with Hitachi Co.,Ltd., Mitsubshi Heavy Industries (MHI), and Toshiba Corporation has designed and tested ceramic rotor blades, nozzles, and low emissions ceramic combustor liners for a 20 MW engine. Under a related program the Tokyo-based Central Research Institute of the Electric Power Industry (CRIEPI) is working with Hitachi Co., Ltd. to evaluate nozzles and low emissions combustor liners for a 20 MW engine. Reports of these development programs have been presented (12-16). The 20 MW engine was chosen as a convenient prototype engine size to demonstrate ceramic turbine technology. Applications are targeted for engines up to 200 MW with firing temperatures up to 1500°C (2760°F).

While modifications of the CSGT ceramic component designs may be required to accommodate the larger part configurations of industrial turbines (e.g. component segmentation or cooling to lower stress levels), ceramic gas turbine technologies for utility engines are feasible. The potential energy savings from ceramic insertion in the utility engine class are substantilly greater than for industrial gas turbines based on the much larger current installed capacity of the utility markets.

7.2.2.5 Aeroderivative Engines

Aeroderivative engines in the industrial and utility size range generally operate at higher turbine inlet temperatures and pressure ratios than industrial turbines, using more intricate cooling schemes and advanced superalloys. In principle, the design solutions developed under the CSGT program are applicable to aeroderivative engines as well and could result in significant cost savings because of design simplification. Design modifications may be required to accommodate the high pressure ratios and firing temperatures of the aeroderivative engine designs.

7.2.2.6 Advanced Turbine Designs

The CSGT program since its inception has become an integral element in the DOE Advanced Turbine Systems (ATS) program. The ATS program is focused on developing a new generation of gas turbine products for the industrial and utility markets of the future. Challenging goals are to be met to achieve the ATS targets for fuel efficiency, output power and emissions. The ceramic technologies developed under the CSGT program are key enabling technologies for the ATS program.

The CSGT program focus is on first generation ceramic hot section designs primarily for retrofit of existing engines such as the Centaur 50 CSGT. Optimized ceramic hot section technologies can be incorporated into second generation designs of the Mars 100 and modified recuperated Taurus CSGT's. The full potential of ceramics will be realized with third generation ATS type turbomachinery products.

The current time frame for this program includes testing of fully developed ATS engines in 1998-2000. Fully optimized highly efficient ATS products incorporating ceramics could become commercially available around 2000 thereby accelerating introduction and market penetration of the CSGT technologies. Performance characteristics of the ATS engines include high TRIT's, ultra-low emissions, and efficiencies approaching 50% or better in fully optimized industrial gas turbines.

7.3 BENEFITS AND DETRIMENTS

The benefits and detriments resulting from the development plan for the ceramic stationary gas turbine have been projected and ranked in order of importance and their probability of success has been assessed. Potential benefits include increased power output and thermal efficiency resulting in fuel savings, higher electric-to-heat ratio in cogeneration, a decrease in installation cost per kW or HP, lower levels of emissions, improved component durability, and lower future component cost. CSGT technologies will also enhance the competitiveness of U.S. industry by developing superior product technology. Slow customer acceptance, unknown component reliability, the lack of an established supplier base, and the lack of a reliable data base for long term properties were perceived as detriments.

Critical success factors that will favor the commercialization and market penetration of the ceramic gas turbine are:

1. Prices of fuel and electricity that favor the economics of the ceramic turbine versus alternative power generating technologies.

2. Successful development of the turbine technology base, including ceramic component designs, ceramic-to-metal interfaces, low emissions combustion technology, materials property data base, life prediction and component diagnostic methodologies.

3. Following adequate development the ceramic gas turbine must meet the expectations of performance improvement and emissions reductions envisioned for optimized engines.

4. A successful 4000 hour field test under this program followed by continued successful operation in subsequent tests.

5. Dedicated development of retrofit and new engine products that meet end users requirements for RAMD (reliability, availability, maintainability, durability).

6. The new engine products must meet objectives of installed cost, life cycle cost, and represent and attractive return on investment to the end user.

7. Establishment of a reliable ceramic component supplier base that can fabricate commercial volumes of components that meet criteria of reproducibility, product quality, cost effectiveness, and can be delivered on schedule.

7.3.1 Benefit-Risk Factors

Table 7-6 lists benefit-risk factors for the nation, the end user and the manufacturer of turbomachinery equipment. The distinction is made because they present different aspects of the issues. Each of the three aspects will be discussed in turn.

7.3.1.1 The National Viewpoint

Energy Savings

Energy savings are perceived as the most important benefit resulting from the ceramic gas turbine technology. Previous estimates of potential energy savings of the ceramic turbine technology have been as high as 0.359 Quads by 2010 (4) assuming significant conversion of existing all-metal installations to ceramic gas turbines and new applications for ceramic gas turbines in cogeneration. The latter category may represent potential energy savings on the order of 0.2 Quads by 2010 (5). A separate analysis has been provided here to complement the literature data.

Fuel savings as a result of the introduction of the ceramic gas turbine technology can be expected to occur in the following categories:

1. Retrofit of existing engine fleet
2. New engine sales either to replace existing equipment or for new installations.

Table 7-6. Benefit-Risk Analysis for Ceramic Stationary Gas Turbine

	Nation (DOE)		End User		Gas Turbine Manufacturer	
	Benefits	Risks	Benefits	Risks	Benefits	Risks
1.	Energy savings, *reduced fuel usage*, replace C-rich fuels	Energy savings not *realized*	Higher output	Downtime	Improved performance of equipment	Delay in ROI ("Hockey stick"), high investment
2.	Lower emissions of NOx, CO, and SOx. Lower CO_2 (Greenhouse effect)	Lower emissions not realized	Reduced fuel cost	Maintenance cost and reduced TBO	Reduced emissions	Low durability, inadequate design and data base, uncertain TBO
3.	Increased domestic competitiveness and balance of Trade	Early foreign development of ceramic turbine	Reduced emissions, avoid stack treatments	Low equipment durability	Improve competitiveness	Low emissions not realized
4.	Increased siting freedom	Inadequate designs, database	Improved ROI, shorter payback	Low emissions not realized	Broaden and expand market, increase in volume	Slow customer acceptance
5.	Reduced trans*mission Losses*	Inadequate domes*tic supplier base*	Lower cost of *electricity*	Unfavorable ROI	Increased competi*tiveness vs. alter*nate power sources	Competition devel*ops technology first*
6.		Ceramic materials cost remains high		Unfavorable life cycle cost	Savings can be shared with End User	Inadequate supplier base
7.		Competing technologies hinder development of ceramic turbines				High cost of ceramics

The target point for the analysis will be 2010, at which time significant market penetration of the ceramic gas turbine will have occurred, assuming CSGT engines will become available in the 2000-2005 time frame. Two scenarios have been evaluated against the baseline of an all-metal engine fleet with current performance levels:

A. A 30% ceramic retrofit rate for the metal engine fleet installed up to 2005. The 30% ratio, adopted in a previous study (4), presents a reasonable estimate of penetration of an established product market with a superior technology. A modest average thermal efficiency improvement of 5.6% is assumed for the retrofits similar to that achievable with the first generation Centaur 50 CSGT. All new engines installed after 2005 are assumed to be second generation ceramic engines with an average thermal efficiency improvement of 19.8% similar to that of the Mars 100 CSGT.

B. This scenario shows the potential of the CSGT technology if by 2010 100% of gas turbine installations in the U.S. were uprated to Mars 100 CSGT performance levels.

The status of the installed capacities by 2005 and 2010 from Table 7-2 has been selected to evaluate these scenarios. Scenario "A" represents the benefits from the introduction of ceramics into industrial gas turbines at a modest level of penetration of the existing market with first generation ceramic retrofits and Scenario "B" provides an upper level of energy savings achievable when the installed capacity consists of second generation advanced turbine designs optimized for ceramics. The latter scenario shows more fully the potential for ceramics in advanced turbine designs.

Table 7-7. Installed Capacity and Projected Fuel Savings from Ceramic Gas Turbines by 2010

Description	Installed Capacity	Ceramic Installations	Fuel Savings (3)
Scenario A			
Capacity to 2005 (1)	27,410 MW	30%	0.024 Quads
Capacity from 2005 to 2010 (2)	6,320 MW	100%	0.052 Quads
All Markets	33,730 MW		**0.076 Quads**
Scenario B (3)	33,730 MW	100%	**0.28 Quads**
Fuel savings = Installed Capacity(kW) x Utilization(hrs/yr) x ΔHeat Rate(Btu/kWh) = Utilization: assume continuous duty: 6500 hrs/yr ΔHeat Rate: change in heat rate from metal baseline to CSGT (1) ΔHeat Rate = 456 Btu/kWh for CSGT Centaur 50 (2,3) ΔHeat Rate = 1257 Btu/kWh for CSGT Mars 100			

Table 7-7 summarizes fuel savings computed for the engine fleet by 2010 using baseline data from Table 7-2.

The estimate of 0.359 Quads from a study by Anson et al. is higher because it compared optimized ceramic engines with low performance utility engines (4).

Emissions Reductions

The CSGT engine will have a beneficial effect on NOx and CO emissions in two ways. First, the ceramic combustor liner will enable higher wall temperatures which reduces cooling air requirements leaving air for dilution and profile trimming. Secondly, the improved fuel efficiency of the CSGT compared to the all-metal engine by itself will also reduce emissions since less fuel is combusted to produce a specific output.

A sample calculation illustrates the beneficial effects of the CSGT by estimating the reduction in emissions if the entire U.S. industrial turbine fleet (0.5-25 MW) output met the 25-10 ppmv NOx target by 2010. Solar's data base shows unregulated Nox values for equipment without dry or wet NOx control to be in the 80-200 ppmv range. A current baseline of 100 ppmv has been assumed as an average for industrial gas turbines for unregulated NOx. this should give emissions reductions values that are conservative, i.e. the potential for emissions reduction is likely better than estimated here. The Centaur 50 engine is used in the sample calculation assuming that this engine is representative for the U.S. industrial installed capacity.

Table 7-8 shows the details of the calculation. The CSGT combustor at the efficiency target range for this program would result in NOx emissions reductions between 3.9-4.7x10^5 tonnes/year by 2010 compared to NOx levels of current unregulated engines.

Table 7-8. NOx Emissions Levels Estimated for All-Metal and CSGT Mars-100 Engines

Description	Emissions Benefit
Estimated Installed U.S. Capacity by 2010 (MW)	33,730 (Table 7-2)
Capacity of Centaur 50 (All-Metal) (kW)	4,384
Centaur 50 Field Units Equivalent	7,694
Centaur 50 Airflow (kg/s)	18.1
Typical Average NOx (ppmv)	100
Δ NOx to 10 ppmv (25 ppmv)	90 (75)
Δ NOx to 15.7 ppmw (39.2 ppmw)	143 (119)
NOx Saved (tonnes/year/engine)	61 (50)
Total Savings (tonnes/year/U.S. Fleet)	4.7×10^5 (3.9×10^5)

The effect of incorporating ceramic turbine technologies on increasing the competitiveness of the domestic gas turbine manufacturers and the balance of trade should not be overlooked. The gas turbine manufacturing business is international (for example, Solar's international sales account for more than 70% of its annual sales), and the U.S. industry is experiencing strong competition from European and Japanese turbine manufacturers. Future competition from the CIS (Commonwealth of Independent States, or countries of the former Soviet Union) is also expected. The development of the ceramic turbine technology is expected to provide a significant technological edge to the domestic gas turbine manufacturers competing in the international market place. It should be noted that four of the major players in the current or future international gas turbine market place (U.S., Japan, Germany, Russia) now have ceramic gas turbine technology programs.

The risks associated from the perspective of the nation (DOE) have also been summarized in Table 7-6. The projected energy savings could fail to materialize if the ceramic technology is not implemented or if market penetration remains below expectation. This could be because technological barriers remain such as inadequacies in the ceramic engine designs discouraging end user utilization of the ceramic gas turbine, or an inadequate component supplier base or high materials cost prevents implementation of the technology at the level of the gas turbine equipment manufacturer.

Another significant risk is the failure of the ceramic turbine technology to achieve the low emissions required to capture a significant market share of new industrial and commercial cogeneration capacity. In this respect it should be noted that even successful achievement of < 10 ppmv NOx may not be sufficient if regulatory bodies require lower NOx levels. Serious consideration should therefore be given to examining the need to develop ceramic combustor technologies that can achieve ultra-low (< 5 ppmv NOx) emissions levels. A combination of a "hot wall" combustor with catalytic features may provide a route in this respect.

A further risk is the possibility of foreign sources developing the ceramic turbine technology ahead of U.S. industry and through patent protection prevent U.S. industry from capturing the market opportunities of the ceramic turbine.

Finally, competing technologies such as fuel cells may lessen the attractiveness of the ceramic turbine over the long term. This poses a risk to the nation in that it prevents full implementation of the ceramic turbine technology. On the other hand comparable energy savings would be realized.

7.3.1.2 End User Viewpoint

The benefits to the end user of turbomachinery equipment pertain mostly to the improved performance (increased output, improved fuel efficiency, lower emissions) of the ceramic gas turbine over the all-metal engine and the risk is the failure to achieve these benefits. For retrofit applications such as the Centaur 50 CSGT engine these benefits can be obtained without expensive package modifications in most cases since there is no increase in foot print required for the cogeneration equipment. The favorable Net Present Value estimates described in Section 6.3.3 can be expected to result in advantages in terms of first cost and life cycle cost for the ceramic gas turbine equipment. The anticipated increase in output power is the principal benefit for the end user while improved return on investment (ROI) and reduced cost of electricity are also attractive. For example, the shaft output will increase from 5880 HP to 7402 HP for the Centaur 50 CSGT engine (Table 6-4). Even more dramatic increases in output power are projected for second generation ceramic turbine equipment over all-metal engines from which they have been derived (see Tables 6-5 and 6-7).

Risks for the end user are predominantly related to the possibility of increased downtime and increased maintenance cost of the ceramic turbine equipment related to engine failures resulting from low equipment reliability because of design or materials reliability flaws. These risks are particularly high during field testing and during the introduction of first generation CSGT engines, and are expected to decrease as the technology matures. They can also be caused by the need for more frequent inspection during the field testing and early commercialization stages. Both of these factors combined with the possibility for more frequent overhauls would negatively affect life cycle costs.

7.3.1.3 Viewpoint of Gas Turbine Manufacturer

There are substantial benefits balanced by significant risks in the CSGT technology for the gas turbine equipment manufacturer. The improved performance (increased output power, higher efficiency) and lower emissions achievable with the ceramic engines compared to the all-metal baseline engines translate into improved competitiveness in the international market place, increased volume of sales, and the opportunity to broaden the product base and expansion into new markets.

Important from the gas turbine equipment manufacturer's point of view is also the enhanced ability to increase competitiveness vis-a-vis alternate power sources which may pose a long term competitive threat to the gas turbine industry. An example of a competitive source would be the fuel cell where low emissions and good efficiency are attractive features. Advances in gas turbine design made possible by ceramics, will contribute to maintaining the competitive advantage for these products. The performance and emissions advantages of ceramic turbine technology, particularly when incorporated into high performance second generation CSGT engines and third generation ATS type engines are particularly attractive in dealing with the competition from alternative power sources.

There are several risks to the gas turbine equipment manufacturer, a major one being not realizing the return on investment. The ROI risk is related, in large measure, to the depth of the negative cash flow resulting from the requirement of up-front funding of the development work for the ceramic gas turbine to the point of commercialization feasibility. The negative cash flow will continue over several years until cash flow becomes positive with increasing customer acceptance. This cash flow curve, often termed the "hockey stick curve" has three characteristics that determine the merits of the investment decision: (1) the depth of the negative cash flow; (2) the number of years before reversal occurs; and (3) the number of years before the original investment is recovered. These risks are being shared with DOE under the CSGT program. However, the risks will continue for a number of years as the gas turbine manufacturer will likely have to fund equipment improvements and the development of future generation ceramic engines.

There are further risks related to uncertain component life in an industrial gas turbine. Various factors contribute to this risk. Examples of these are: lack of an established design methodology for time-dependent processes such as creep and contact stresses, inadequate data base, especially for multi-thousand hour exposures typical of industrial gas turbines, and inadequate knowledge of the behavior of ceramics in the engine environment. These factors lead to uncertainties in the time required for overhaul of the engine (TBO), especially during the initial commercialization phase.

Another risk is the possibility that the low emissions if achieved will have no marketable benefit. This pertains to the program goal of ≤ 10 ppmv NOx. Even if successful the equipment manufacturer may face regulatory pressures to reduce emissions to levels below the target NOx level of this program. As ≤ 10 ppmv becomes achievable, regulatory bodies may impose a level of < 5 ppmv NOx which could be obtained by adding costly selected catalytic reduction (SCR) equipment to the ceramic "hot wall" combustor. Further, this risk may require combustor development necessary to obtain this ultra-low NOx level. This may be achieved by combining the ceramic hot wall with catalytic features or in other ways using ceramic technology. In addition, areas with less severe emissions regulations will not economically value nor require suppliers to provide combustion systems capable of achieving the emission levels of the program.

The risk in uncertain component life will slow down customer acceptance of the new technology jeopardizing the investments made to develop the ceramic turbine equipment. Customer acceptance is also slow to achieve because of the lack of years of operational experience against which the customer can compare his case. Although this deterrence to acceptance is perhaps the most important, deterrents also arise from external constraints. These additional deterrents relate in many cases to consistency of Government policies and governmental-influenced economic factors. Examples of these are:

- Tax Policy: This includes - depreciation, investment tax credit, corporate tax rates and so on. Each change in tax policy results in delays in investment decisions until the full impact is appreciated.

- Fiscal Policy: This includes the effect of government policies on interest rates and business climate.

- Environmental Policy: This includes: changes in permitting; emissions of NOx, SOx, CO_2, and particulates; noise regulations; and so on.

It is in this area more than any other that consistency of policy for a period of more than 10 years is essential to permit business decisions, especially investment in new technology.

There are also risks related to the success of the ceramic turbine concept. International competition could result in the ceramic gas turbine being developed by foreign gas turbine manufacturers aided by substantial government funding ahead of the U.S. Supported by patent protection these foreign competitors would have a formidable advantage in the market place and pose a serious threat to U.S. industry. Obviously, there are significant risks associated with not proceeding at a rapid pace with the ceramic turbine development, and industry and government should provide sufficient funding to reduce this risk to the lowest possible level.

Then there is the risk related to inability of component suppliers to deliver quality parts. Few suppliers have the experience of delivering commercial quantities of ceramic turbine components of complex designs, and a learning curve is expected for the suppliers to meet the expectations of the turbine equipment manufacturer used to dealing with suppliers of mature metal components. A further risk originates in the weak market for ceramic turbine components at this time and the potential for key suppliers to go out of business. This risk has been mitigated under the CSGT program by the multiple supplier strategy for each component. The development of a broad supplier domestic supplier base is a prerequisite for the successful commercialization of the ceramic turbine. The current high cost of ceramics because of low part volumes could pose an additional risk to the equipment manufacturer. The data presented in Section 6.0, however, have indicated that ceramic components can be fabricated at a price level competitive with metal parts and that there is sufficient margin in the NPV of the ceramic turbine to mitigate this risk.

7.3.1.4 <u>Reconciliation of Viewpoints</u>

The differences in viewpoints pertaining to benefits and risks for the nation, end user, and equipment manufacturer, summarized in Table 7-6, are inherent in a development effort of this type. Certainly, there are no viewpoints that are diametrically opposed to each other.

Changes in viewpoint will occur with the passage of time and will change the assessment of risk. For example, there is a risk that the lower emissions planned for the CSGT may be unacceptable by the year 2000, the earliest date that CSGT-type engines are expected to become available in the marketplace. Energy taxes, carbon-emission taxes, and other restraints may have been introduced and could affect the acceptability of this technology. The price of natural gas, the need for dual fuel capability, matching electrical and thermal loads needed by the customer, and other site-specific factors will influence the viewpoints.

However, the relative viewpoints expressed for the "global" scenarios summarized in Table 7-6 are expected to remain valid.

7.4 CRITICAL ACTIVITIES AND SOLUTIONS

Based on the benefits to be achieved and the risks perceived in Section 7.3 activities that are critical for the success of the ceramic stationary gas turbine have been identified. The focus has been on optimization of benefits and minimization of risks.

Critical activities for the development, test and commercialization of the CSGT are identified in Table 7-9.

7.4.1 Engine Design

There appear to be no engine design problems that cannot be solved on this program. However, some of the solutions may lack the elegance to avoid some loss of efficiency and/or performance. The effort required for some of the solutions may constitute impediments along the road to commercialization.

Table 7-9. Twelve Areas of Potential Critical Activities

1.	Engine Design	7.	Assembly and Manufacturing
2.	Data Base	8.	Green Runs
3.	Component Fabrication	9.	Shipping and Installation
4.	Component Acceptance, and Proof Test	10.	Warranty
5.	Component and Engine Life	11.	Operation
6.	Component Handling	12.	After-Market Support

At this early stage in the development of the CSGT, it is possible that some of the impediments may diminish in importance as the program progresses. On the other hand, it is recognized that new problems may arise or old problems may increase in importance during the course of the program. Prior experience from automotive and military ceramic turbine programs used as a starting point for the designs for the CSGT engine may not be fully applicable because:

- Prior automotive and military ceramic turbine designs for relatively short life with frequent transients and high operating temperatures are not directly applicable to the long life with few and slow transients at an intermediate temperature required for the CSGT design.
- The critical design parameters for the CSGT are based on slow crack growth and creep and not on fast fracture that dominates the automotive and military applications.
- The larger diameters of the CSGT compared with automotive engines may create problems in manufacturing, such as out-of-roundness distortions and metallic-ceramic interfacing.

The design problems have been categorized as two types. The first are design-critical and the second are performance-critical. Design-critical problems must be solved to achieve operational status and performance critical problems must be solved to achieve the efficiency, low emissions and output that must be achieved for commercial success.

Design-Critical Problems:
- Design limitations from slow crack growth and creep
- Design limitations imposed by interfaces
- Gas temperature profiles needed to protect metallic components

Performance-Critical Problems:
- Achievement of low emissions
- Blade tip clearance control
- Airfoil optimization

Again, it should be noted that the technology base to solve these problems has not been generated by the extensive automotive gas turbine programs.

7.4.1.1 Design for Slow Crack Growth and Creep Resistance

Problem Statement. Slow crack growth is the major concern for the ceramic rotor blade and creep the major concern for the ceramic nozzle.

Slow Crack Growth. As results became available from the SPSLIFE component life assessments, it became clear that the limiting factor in design of some of the ceramic components in the CSGT program was slow crack growth (SCG). Reference is made to the ASME paper summarizing the SPSLIFE data for the Phase I designs to appreciate the severity of this limitation (17). Slow crack growth is the major limiting factor for the blade because: (1) The low TRIT of 1121°C (2050°F) removes oxidation and creep as life-limiting factors; and (2) the desired life of 30,000 hours makes slow crack growth more important than fast fracture. Yet, data on slow crack growth properties of ceramics are scarce. This issue is discussed more fully under life prediction. The slow crack growth concern in the blade design arises because of a stress of about 172 MPa (25 ksi) observed in the center of the blade airfoil near the platform. The high stresses at the prevailing part temperature of about 1092°C (2000°F) could result in SCG failure in the blade airfoil during 30,000 hours of service.

Creep. Reduction in the cooling air flows has been possible with ceramic components but it has resulted in major design problems. Whereas the airfoil temperatures were limited to about 870°C (≈1600°F) with cooled metallic structures, these maximum temperatures can approach 1296°C (2366°F) with uncooled ceramics at nozzle airfoil "hot spot" areas in the Centaur 50 CSGT. But the shrouds of platforms must remain at about 870°C (≈1600°F) to accommodate the adjacent and downstream secondary metallic components. The large ΔT generates high airfoil stresses in the nozzle. The current preliminary hot section design shows high stresses 240-275 MPa (~35-40 ksi) in the trailing edges of the nozzle airfoil at "hot spots". These high stresses at the nozzle trailing edge temperature approaching 1296°C (2366°F) could result in creep failure in the nozzle airfoil during 30,000 hours of service.

The current high stress levels on the nozzle airfoil occur because of a substantial temperature gradient imposed by the combustor radial profile. The radial profile exiting the combustor is due to the requirement for cooled streamlines along the inner and outer meridional flowpath for secondary components. In turn, the cooled streamlines are due to one of the limitations in the present program where the minimum number of ceramic components are introduced so that the adjacent structures remain metallic.

Solutions. Some of the solutions to be considered include:

1. Begin to develop a better database for slow crack growth and creep to reflect the great importance of these properties for industrial gas turbines which require long service life.

2. Modify the radial profile exiting the combustor to lower the temperature gradient experienced over the nozzle airfoil. Modifying the radial profile and increasing the temperature of the cool streamlines near the outer and inner shrouds will result in a lower temperature gradient from the airfoil region adjacent to the shrouds to the high temperature region at the trailing edge and thus, to a lower stress in the airfoil. In general, creating a more isothermal condition over the nozzle will be required. A trade-off study will be needed to reconcile the needs for lower nozzle airfoil stresses and secondary component cooling flows.

3. Cutbacks of the trailing edge in the high stress areas of the nozzle airfoil. As described in the Task 2 section (Section 4.0) nozzle airfoil stresses can be lowered by cutting back the trailing edge in the high stress regions. The maximum lowering of the stresses is estimated to be about 30% of the current values. Cutbacks may have to be accompanied by adding nozzle segments and restaggering the airfoils to eliminate performance losses from the cutbacks.

4. Modifying the nozzle airfoil geometry to lower the stresses. This could include adding or removing material to the trailing edges and leading edges, shortening chord, and

restaggering nozzles. The retrofit nature of this program puts certain limitations on the extent to which these changes can be incorporated in the nozzle design.

5. Segmentation of the nozzle to reduce stresses in the hot spot areas.

6. Changes in the disk material. The limitation of the current V-57 disk material restricts creep life at the operating temperatures of the Centaur 50 CSGT engine. Replacement of the disk with a more creep resistant material such as Waspaloy or U-720 will allow more air to be diverted from the disk and thereby enable higher temperatures in the nozzle airfoil near the inner shroud which will reduce airfoil stresses.

7. Directing secondary cooling flow to the neck region of the blades between the platform and the attachment to the disk. Modifications in blade design to lengthen the neck region under the platform combined with improved first stage disk material will have an additional benefit over modification of the disk material alone.

It is hoped that such strategies will lower the nozzle airfoil stresses to the point where creep life becomes acceptable. A trade off in the detailed design during Phase II will be conducted to lower these stresses while maintaining acceptable performance and secondary cooling.

The high stresses in the blade airfoil are of concern although not as much as the high nozzle airfoil stresses. Modifications to the blade including altering the airfoil mass and altering the position of the airfoil relative to the platform are expected to result in a lowering of the stresses and thereby increase component SCG resistance. Slow crack growth is believed to be the life limiting factor for the blade.

7.4.1.2 <u>Design Limitations Imposed by Interfaces</u>

<u>Problem Statement</u>. The design limitations imposed by interfaces are two-fold. The first type arises from Hertzian contact stresses and the second originates from the need to allow relative motion between components. Relative motion is the most severe problem and arises at metallic-ceramic interfaces because of differential thermal expansion of the metal and ceramic. Relative motion may also occur in situations where out-of-roundness of components due to thermal effects leads to displacement of one component with respect to the other.

<u>Contact Stresses</u>. At the present time the effect of contact stresses is not incorporated into the finite element analyses (FEAs). The FEA provides the most important input to the SPSLIFE and NASA reliability programs for life assessment. Hence, an important source of failures in earlier programs does not receive the consideration needed for complete life prediction.

Dynamic coefficient of friction data have been used to perform analyses of contact stresses because translation of one surface relative to another is a potent source of surface damage from which component failure can originate. However, concern exists that after long periods of steady state operation there will be component-to-component sticking that will lead to a high value of the static (or breakaway) coefficient of friction. This may occur at either ceramic-to-ceramic or at metal-to-ceramic interfaces.

<u>Component Displacements</u>. These create some of the most severe design problems for the CSGT program. An example is the dovetail root design which involves differential motion along the length of the dovetail neck between the high expansion metallic disk and the low expansion ceramic. Another case is the integral 51 cm (20 inch) diameter ring nozzle assembly design which requires accommodation of relative motion due to out-of-roundness of the nozzle ring and nozzle support.

Finally, the combustor requires relative motion between the cylindrical ceramic portion and the metallic structure at both inner and outer liner positions.

Solutions. Compliant layers are under study for the dovetail blade root and appear to have a high probability of success. The principal unknown is the life of the compliant layer. Rollers and balls are under study for other moving components. These solutions have been implemented successfully under other programs.

7.4.1.3 Achievement of Low Emissions

Problem Statement. Commercial success of a ceramic hot section industrial gas turbine will require further increases in the TRIT beyond the 1121°C (2050°F) goal for this program. At the same time, goals for emissions in the future can be expected to be more stringent than present day goals. The technology based for the lean premixed combustion process under development on this program has certain limits to the potential for achieving both of these goals. It is pointed out in the section on SCR (Section 6.3.4.1) that a long term goal of 5 ppmv NOx needs to be set to ensure that SCRs are not specified because this requirement would drastically affect the commercialization of the CSGT family of engines.

Solutions. The lean, premixed combustor achieves low NOx by limiting the adiabatic flame temperature to well below the stoichiometric temperatures that result in the absence of the premixing. However, to achieve 5 ppm NOx requires very low adiabatic flame temperatures. As TRITs increase and NOx levels are required to decrease, ever lower primary zone or reaction zone temperatures are necessary in the lean premixed combustor. Three technologies will allow higher TRITs to be achieved at low NOx levels with ceramic combustors: (a) lean-premixed combustion with hydrogen enrichment and hot walls; (b) rich-lean combustion with steam or water injection; and (c) catalytic combustion.

7.4.1.4 Blade Tip Clearance Control

Problem Statement. A major unknown in ceramic engine performance is the ability of a ceramic blade to permit a rub against a shroud. There is evidence to suggest that a rub against a ceramic shroud will lead to failure. For this program a "no-rub" design philosophy has been adopted. Encounters with a metallic shroud have been claimed to result in "machining" of the metal, but reliance on such experience would not be prudent. No abradable coatings have been developed for this application.

Solutions. To realize the initial goal of 4000 hours of field test operation with a TRIT of 1121°C (2050°F) requires conservative design. This has been equated with a "no rub" philosophy, and an initial clearance 1.3 mm (0.050 inch) (3% of blade height) has been adopted although this may be reduced as experience is gained. The approach is summarized in Table 7-10.

The thermal expansions of the components along the path to the blade tip (primarily disk and blade expansions) and along the path to the shroud (case, nozzle and shroud ring support) must be controlled by passive means to control the clearance. Heat transfer coefficients, thermal mass and material expansivities are the primary design factors. But, other factors introduce uncertainty into the analysis. Stack-up tolerances of components, rear bearing "droop" in hot steady state operation, metallic nozzle case distortion and inequality of thermal masses are the principal factors that introduce uncertainty. Consideration of these led to the selection of a design target of 1.3 mm (0.050 inch), or less, for blade tip clearance.

Table 7-10. Design Plan for Blade Tip Clearance Control

- Low Risk No Rub Design
- Achieved by: Programmed Start-Up and Shut-Down
  Equal Thermal Mass Density
  Use of Low Expansion Alloys
- For Each Decrease of 0.13 mm (0.005 inch) in clearance:

Increase in Power	23 HP
Increase in Efficiency	0.1%

- Reduce Clearances as Experience is Gained

Solutions exceeding the approach proposed will be beyond the scope of the present program. Blade tip clearance control has always been a difficult assignment in any gas turbine design. Even the best aircraft engine designs experience rubs from time to time. From a practical viewpoint it will be necessary for the blade tip to rub into the tipshoe to a limited extent, or risk loosing valuable turbine efficiency due to over-conservative tip clearances. Further development efforts beyond this program will be required to achieve this objective.

7.4.1.5 Airfoil Optimization

Problem Statement. Replacement of a cooled metallic section airfoil by an uncooled ceramic section of the same cross-section represents a non-optimum design. Two major effects need to be considered:

1. Trailing edge thickness suitable for cooling holes in metallic airfoils needs to be redesigned for uncooled ceramic airfoils.

2. Volume and mass of material in the ceramic airfoil may be increased over that of the hollow airfoil of the metallic airfoil resulting in:

   (a) increased difference in thermal response of airfoil to transients, thereby increasing thermal stresses.

   (b) increased centrifugal stress on the attachment (for blade airfoils).

Solutions. A complete redesign of the airfoil for ceramic blades and nozzles will allow advantage to be taken of the less dense material to create thinner sections. These will generate lower stresses on the attachment, improve aerodynamic airfoil efficiency, and result in faster and more uniform thermal response. In addition, there would also be a benefit in reducing the number of blades to allow for a larger (and lower stress) root load carrying area. This will lead to an increase in the work that the blade performs. At present, blade to blade space restrictions are forcing non-optimized root designs since the dovetail root covers a larger arc length than a comparable standard firtree design. On the other hand, thinner airfoils increase the chance of foreign object damage (FOD). Trade-off studies must be conducted to arrive at the component design that balances the advantages and disadvantages of the above factors.

Significant redesign of the blade and nozzle airfoils is not planned for this program, but it can be expected to be an integral part of second and third generation ceramic engine designs.

7.4.2 Database

Problem Statement. The present database is not adequate for detailed design for 30,000 hours. On the other hand, the database is improving as a result of long term tests at ORNL, UDRI, and other laboratories. These tests are primarily generating creep data. But, as noted in 7.4.1.1, an additional critical property needed for design is "slow crack growth" resistance.

Solutions. A redirection of effort to determine the slow crack growth database is needed to provide adequate data for design.

7.4.3 Component Material Selection and Fabrication

No specific problem areas have been identified. However, in order to make an estimate of the probability of success of the overall program, a general review of this factor has been performed.

General Review. The timing is excellent to proceed with a program to take the first step in achieving increased performance and lower emissions for commercial industrial turbine engines through the use of ceramic components. Major improvements in the properties and fabrication of advanced ceramics have been achieved over the past 25 years in parallel to major advances in design methodology for brittle materials. The following paragraphs briefly highlight the progress and the reasons for confidence that the timing is right.

The technology in 1970 for ceramics in turbines was embryonic: (1) a design methodology had not been developed, and survivability of ceramics in a gas turbine operating environment had not been demonstrated, (2) the primary candidate materials (reaction bonded silicon nitride and silicon carbide) had strengths below 138 MPa (20 ksi) and Weibull moduli were typically less than 8, (3) the newly-developed hot pressed silicon nitride had strength close to 700 MPa (over 100 ksi) at room temperature, but only around 70 MPa (10 ksi) at ≈1204°C (≈2200°F) and had very poor stress rupture life above ≈ 982°C (1800°F), and (4) none of the materials had been fabricated into the complex shapes required for gas turbine components.

Major programs funded by the U.S. government and developments at materials companies began to aggressively address the issues of design, properties, and fabrication during the early 1970's. DARPA funded the Brittle Design, High Temperature Turbine program which demonstrated that ceramic components could be designed probabilistically and could survive the severe transient and steady state operation in a gas turbine engine. Norton Company developed a hot pressed silicon nitride material (NC-132) with a 4-point flexure strength over 758 MPa (110 ksi) at room temperature and over 345 MPa (50 ksi) at ≈ 1204°C (2200°F). This material had an order of magnitude improvement in stress rupture life, improved oxidation resistance and improved Weibull modulus in the 8-12 range. Reaction bonded silicon nitride materials were developed by Norton Company, Ford Motor Company and later by AiResearch Casting Company (ACC) with strengths greater than 207 MPa (30 ksi). All three companies developed capabilities to fabricate turbine static structure components, including integral axial nozzles.

Utilizing the NC-132 hot pressed silicon nitride for rotor blades and the Norton and ACC reaction bonded silicon nitride materials for static structure components, Garrett Turbine Engine Company demonstrated in the late 1970's under DARPA funding that a turboprop engine could operate with 30% increase in output power and 7% reduction in fuel consumption compared to the baseline metallic engine. The Garrett engine was axial with ceramic blades inserted into a metal hub, which is analogous to the CSGT engine design. Hot pressed silicon nitride inserted blades survived 15 hours testing (with no problem) over a simulated cruise missile operation cycle with an average turbine inlet of 1204°C (2200°F).

Material property improvements continued through the 1970's and 1980's into the 1990's at Norton, Garrett/ACC (now AlliedSignal Ceramic Components), Kyocera, NGK, Carborundum, and other companies. Pressureless sintered and hot isostatically pressed (HIP) silicon nitride and silicon carbide materials were developed which had properties better than prior hot pressed materials and could be fabricated to complex shapes. Four-point flexure strengths over 965 MPa (140 ksi) at room temperature and close to 700 MPa (over 100 ksi) at 1204°C (2200°F) are routinely achieved, and stress rupture life and oxidation resistance have been substantially improved. Through statistical process control, processes have been greatly improved and several current materials have Weibull modulus values of about 20. This means that the scatter in property data due to material variation has been greatly decreased, and that the turbine industry can be much more confident in the design and application of the materials. The major remaining problem relates to the difference between as-processed and machined surfaces and its effect on material strength properties.

This improvement in materials properties, and the maturing of the design, and fabrication methodologies, and the growth of the engine test data base have been the result of extensive programs in the United States, Japan, and Europe. The AGT and ATTAP programs in the United States are the most important in this regard. Several programs in Japan, ranging from the small 100 kW automotive and the 300 kW small ceramic gas turbine programs to the large Tokyo Electric Power Company (TEPCO) and Central Research Institute of the Electrical Power Industry (CRIEPI) 20 MW engine programs have contributed to the development of the technology base as well. Out of these programs have come several commercial ventures that validate the viability and maturity of the ceramics technology. Over 500,000 ceramic (silicon nitride) turbochargers fabricated by Kyocera and NGK have been installed in automobiles and these rotors are reportedly performing trouble-free.

The experience gained by Kyocera and NGK in scale-up and application is very valuable. Demonstration that volume production of turbine components is possible with close control on quality, costs, and delivery augurs well for the future scale-up of industrial turbine parts.

The Solar CSGT program will also test ceramic combustor components fabricated from continuous fiber-reinforced ceramic matrix composites (CFCCs). The development of these materials has been greatly accelerated by the DOE CFCC and the NASA fiber and High Speed Civil Transport (HCST) initiatives. A substantial number of ceramic companies are now involved in improving the properties of their CFCC materials for a variety of applications including combustor liners. Solar is involved in a number of programs as a subcontractor and will be testing various CFCCs under the DOE CFCC initiative and under the CSGT program.

The progress is most encouraging. The Solar CSGT program will utilize the most up-to-date materials, fabrication, design concepts and life prediction methodology. However, prior engine programs have only demonstrated 10s to 100s of hours of operation. The major challenge of the Solar program is to extend this engine experience initially to 4000 hours and later to over 30,000 hours in commercial applications.

7.4.4 Component Acceptance and Proof Testing

General Review. The acceptance and testing of components in the initial phase will be be based on 100% inspection. This will ensure that the component conforms to specifications and requirements and it will prove the efficacy of the manufacturing processes. The only weakness envisioned in this task is that some specifications are for relatively new materials and processes and the properties are not as well known as those of the metallic components currently in use. A database will be under development to understand the impact of variations resulting from the manufacturing process.

There is no widespread experience with the materials being used and a relative lack of accepted industry testing procedures and standards. These are considered risk factors. In the realm of parallel metallic components, materials testing techniques are consensus standards documented by industrial societies and substantiated by a wealth of empirical data. This does not exist for all ceramic materials and testing techniques.

Another area of risk in component acceptance and test is concerned with cost. The plan for the Centaur 50 CSGT is to perform 100% inspection. Inspection techniques such as microfocus X-ray are expensive. The extent of inspection at all points will be reduced as a result of experience and knowledge is gained of failure modes in relation to the stress analysis. The question remains whether the cost of acceptable components can be reduced to make the ceramic engine competitive?

Figure 7-6 presents an analysis showing the beginning of a progressive decrease in ceramic engine costs relative to the all-metal simple cycle engines (4). This decrease begins 3-5 years after introduction of the first CSGT and must be achieved by a coordinated effort to lower ceramic component costs (e.g. by improving process yields), inspection costs, and the costs of engine design and manufacture. Solar believes that this type of cost reduction can be achieved. This data is also supported by the cost data supplied by the ceramic component manufacturers (see Section 6.2.2.2).

7.4.5 Component and Engine Life Prediction

Problem Statement. The CARES/LIFE and SPSLIFE assessment programs adopted for component and engine life prediction for the CSGT program are powerful design tools. However, these computer codes are still relatively new and few empirical test data are available for comparison.

There are two major concerns that have been identified as CARES/LIFE and SPSLIFE have been applied to several preliminary ceramic component designs. These are:

1. The finding that the slow crack growth resistance is the critical design parameter for a life of 30,000 hours in the case of the CSGT. Data on this parameter was lacking or less reliable than for other parameters at the conclusion of Phase I.

2. CARES/LIFE addresses three failure modes: fast fracture, slow crack growth and cyclic fatigue. Work to include a creep module is in progress. SPSLIFE currently addresses four failure modes: fast fracture, slow crack growth, creep, and oxidation. It does not include a module to asses cyclic fatigue.

The "slow crack growth" phenomenon involves more than one process so that analysis is complex. Hecht at UDRI has confirmed the existence of low temperature stress corrosion on NT154 in addition to slow crack growth that appears to occur above 1000°C. However, the slow crack growth equation $V = AK_I^n$ has been applied as a mathematical description of the processes occurring over the range of temperatures of interest. The value of "n" appears to decrease to a low value around 1000°C, according to dynamic fatigue data for short times, and to have higher values on either side of the minimum.

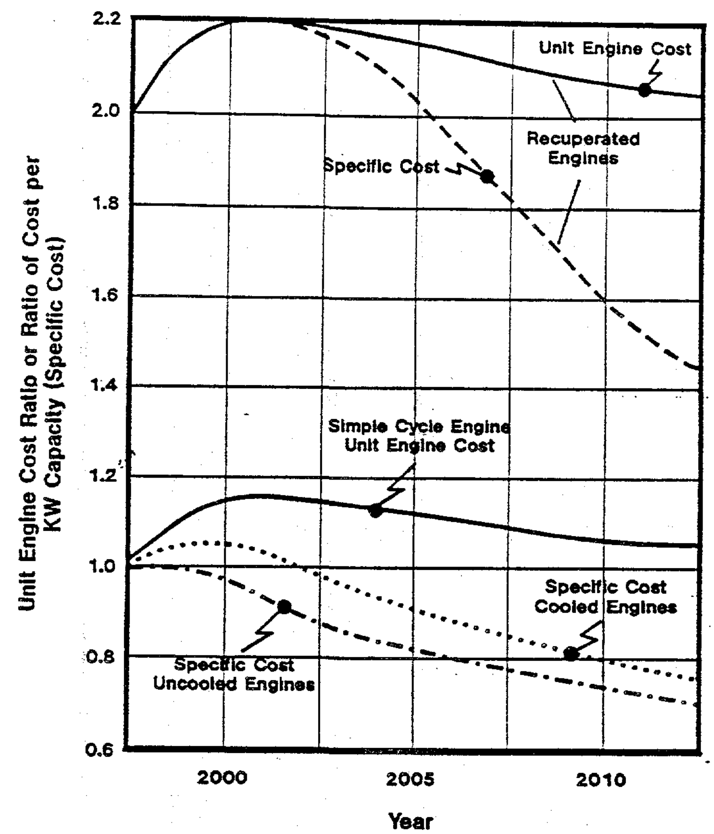

Figure 7-6. Unit engine cost and specific cost of engines with ceramics, relative to 1995 cost of all-metal simple cycle engines (4)

In addition, there is reason to believe that a large precrack does not represent service conditions. Average crack velocities are required in the range of 10^{-13} m/s (approximately 1 atom diameter in 1000 seconds) and there are few data below 10^{-8} or 10^{-9} m/s even when measured with large precracks.

Solutions. The inadequacy of data on the slow crack growth process must be addressed. There are plans to include the acquisition of this data under the CSGT UDRI subcontract, and dynamic fatigue data will also be generated at Solar. Also, the concern about creep must be reconsidered. The creep will be localized and limited to "hot spot" areas in about two or three nozzles. No single component is expected to become hot enough for general creep to occur, as it does, for example, in a metallic turbine blade. The creep process will be limited to less than 0.1% strain and peak stresses generated by creep are anticipated to relax when loads will be redistributed.

New technology paths are being followed in the development of a 30,000 hour life engine and will demand continued vigilance to ensure that new failure processes are identified as early as possible should they occur. The life prediction codes should be modified to include these failure modes if feasible.

7.4.6 Component Handling

General Review. Major challenges to ceramic engine commercialization are: (1) ceramic component traceability, and, (2) physical handling of the ceramic components from the supplier through to the actual engine installation. Prior ceramic engine programs have demonstrated the feasibility of laser marking ceramic components as a means of tracing a specific component since no other means of marking ceramics has proven effective. Each ceramic component must successfully undergo inspections and proof testing before it is qualified for engine installation and must therefore have traceability through these required tests. Development of identification techniques such as laser marking for component traceability is a critical issue for commercialization of ceramic components.

The second issue relates to the physical handling of ceramic components in an environment familiar with the handling of metallic components. Specific techniques for the fixturing of ceramics for inspections, proof testing, and engine assembly must be assimilated and disseminated via written literature and visual training sessions for all personnel that will be handling the components. Additionally, these training sessions must be periodic in nature such that a continuous reinforcement of the special handling considerations is fresh in the mind of the operator.

7.4.7 Manufacture and Assembly

General Review. Ceramic component manufacturing has evolved to the point that consistent/reliable material properties have been demonstrated in high volume production applications through the use of statistically based-computer process control of all manufacturing processes. Since the flaw population in the materials is primarily process related, and the critical flaw size is statistical in nature, the need for a highly controlled process is paramount to high yields and component reliability.

Ceramic engine commercialization requires component reliability at an affordable cost which equates to the necessity for high yields. The critical issue to commercialization relative to ceramic component manufacturing must therefore address a means of achieving adequate process control from starting powders through to the temperature control zone of the final densification and machining steps.

7.4.8 Green Runs

General Review. The test work in the gasifier rig will be as severe as the green runs performed on the assembled engine for acceptance. Also, a 500 hour instrumented engine test is planned at Solar prior to the 4000 hour field test in Phase III. For this reason, it is not thought that there will be any factors affecting commercialization arising at this stage.

7.4.9 Packaging, Shipping, and Installation

General Review. No significant differences are seen for the benefit-risk analysis in any of these areas. Gas turbines are packaged and shipped to all parts of the world and may be subject to unscheduled rough handling. Transportation over dirt roads in third world countries can lead to severe shock loadings that could possibly result in bearing damage. By comparison, the shipping from San Diego to Bakersfield and unloading will be carefully controlled. Installation is not expected to differ from standard machinery installation.

7.4.10 Warranty

General Review. Solar's standard warranty period is 12 months. However, each prototype or development engine is reviewed individually to assess risks to the customer and the equipment manufacturer. No significant factors need to be considered in the benefit-risk analysis.

7.4.11 Operation

General Review. Again no significant risks are seen that will differ from that of the standard engine. Operator training will be a key issue and will be performed by Solar after-market support personnel. The principal difference in operation will be the programmed start-up and shut-down to reduce the transients. This may require some operator training because one of the reasons customers buy gas turbines is the fast start-up. A lengthened start-up procedure may tempt operators to short circuit the system. Frequent checking will be needed to assure operator compliance. Specifications for hot start will be a critical element in the operations manual. Details of permissible hot starts will need to be determined.

7.4.12 After-Market Support

General Review. After-market support and warranty are closely tied together. An OEM with a large fleet of spare engines in the field and the availability of technical support staff in most of the major countries can ensure rapid response. This can be very important to customers with fiscal and production penalties for down-time. However, no difference in risk factors arising from after-market support with the CSGT have been identified in review with the specialists in this critical area.

7.5 ASSESSMENT OF THE PROBABILITY OF SUCCESS

Table 7-11 summarizes the assessment of the probability of success to achieve the benefits and minimize the risks of the global economic and environmental factors outlined in Table 7-6 both for the engine to be developed on this program, and for subsequent commercialization by the gas turbine equipment manufacturers. The lowest ratings are assigned to increased thermal efficiency and to lower emissions. These low ratings result from the need to sacrifice thermal efficiency to ensure mechanical success (e.g., blade tip clearance) and from the difficulty of the test to reduce emissions so that the resources available on the CSGT program may be inadequate. The original goal of DOE of 25 ppmv NOx will be achieved within the resource restraints.

Table 7-11. Summary of Key Factors and Probability of Success to Achieve Global Economic and Environmental Goals of the CSGT

Factors	Probability of Success for CSGT-H		Commercialization of First, Second, and Third Generation Ceramic Engines	
	POS	Comments	POS	Comments
Increased Output	High	Output power is largely a function of TRIT. The program goal of a 25% increase in output power should be obtainable.	High	Performance scenarios in Task 4 show good potential to obtain significant output gains.
Increased Thermal Efficiency	Medium	Efficiency is more difficult to obtain since it is intricately linked with the engine and component designs. The program goal is 6% increase in efficiency.	High	Performance scenarios in Task 4 show good potential. The design experience gained with the Centaur 50 CSGT engine will help in optimizing engine and component efficiencies.
Lower Emissions	Medium	Solar's background in low-NOx technology suggests the < 10 ppmv NOx goal is achievable.	Medium	It will be much more difficult to achieve the < 5 ppmv NOx goal anticipated for future ceramic engines at higher TRITs.
Lower Installed \$/kW or \$/HP	High	NPV analysis shows this goal is readily obtainable	High	NPV estimates show good potential.

Table 7-12 summarizes the probability of success anticipated in the twelve potential problem areas given in Table 7-9. Reference is made to the discussions in Section 7.4 for justification for the ratings.

7.6 REVIEW BY ARCO

The end user on this program ARCO Oil & Gas has been asked to provide input into the concept assessment to represent the end user point of view. The two critical activities form the point-of-view of ARCO are:

1. The CSGT should be able to replace the existing Centaur 50 engine in the same footprint, and that the existing auxiliary equipment be able to operate with this engine; and,

2. The CGST have both availability and reliability equal to that of the Centaur 50 engine.

No specific problems have been identified in the first critical area. ARCO will continue to work with Solar to ensure no potential problem areas are overlooked.

Solar Turbines Incorporated is working to meet a target of at least 97.5% availability and 98.5% reliability. These terms are defined as:

$$\% \text{ Availability} = \frac{\text{Period Hours - Planned Downtime - Unplanned Downtime}}{\text{Period Hours}} \times 100$$

$$\% \text{ Reliability} = \frac{\text{Period Hours - Unplanned Downtime}}{\text{Period Hours}} \times 100$$

The critical activity planned by ARCO is to work closely with Solar Turbines to ensure meeting these targets.

7.7 RECOMMENDATIONS FOR ADDITIONAL WORK

To ensure that the ceramic turbine technology is developed to its full potential industry and government must continue to work hand-in-hand to provide solutions to problems that can be characterized as impedimenta. The issues that must be resolved have been ranked in this section in order of decreasing urgency. It is not envisioned that all of the recommendations be addressed under the CSGT program; some are more appropriate dealt with by other initiatives.

7.7.1 Combustor for Low Emissions

Development of an effective low NO_x/low CO ceramic combustor is perhaps the most important factor that will lead to acceptance of ceramic gas turbines in the marketplace. Analysis of the current potential of the SCR leads to the conclusion that a target of better than 5 ppmv NOx and 10 ppmv CO should be the long term goals. These numbers are selected because at this level of NOx, there will be no advantage in adding an SCR. Indeed, there will be distinct disadvantages because there will be well over 5 ppm of ammonia slip added to the exhaust by the SCR, and because the SCR adds significant cost to the system and makes most systems uneconomic.

Table 7-12. Probability of Success in Overcoming Problem Areas Identified in Critical Activities and Solutions

	Problem Area	Probability of Success for Centaur 50 CSGT		Commercialization of 1st, 2nd, and 3rd Generation Ceramic Engines	
		POS	Comments	POS	Comments
1.	Engine Design				
	• SCG and Creep - Limited	Medium	Low stress design must be used in conjunction with improved data on SCG and creep	High	Experience with Centaur 50 CSGT, better understanding of problem and contributions from material suppliers will increase POS.
	• Interface - Limited	Medium	Experience with compliant layers and innovative design will aid solutions	High	The cumulative experience of the Centaur 50 CSGT and further work for commercialization should be adequate to address the contact stress and design issues.
	• Low Emissions	High	Original goal of 25 ppmv NOx is readily achievable	Medium	It will be much more difficult to achieve the < 5 ppmv NOx goal anticipated for future ceramic engines at higher TRITs.
		Medium	Solar's background in low-NOx technology suggest that the 10 ppmv NOx goal is achievable		
	• Blade Tip Clearance Control	Medium	Clearance control will not likely be fully optimized since preventing blade rub will be priority	High	The experience with the Centaur 50 CSGT and with metallic engines will enable design optimization for clearance control.
	• Airfoil Optimization	Low	This issue will not likely be addressed in this program	High	Aerodynamic redesign of the blade and nozzle airfoils will be an integral part of future ceramic engine development.
2.	Data Base	Medium	Database is not adequate for the design-critical property of SCG. Long term database (to 10,000 hours) will be generated for creep in Phase II. Effect of high moisture atmosphere not known.	Medium	Multi-thousand hour data must be developed in combustion gases and under complex stress systems.
3.	Component Material Selection & Fabrication	High	Multiple suppliers and iterative design/fabrication/testing schedule gives high POS	High	As for Centaur 50 CSGT engine, plus added experience will increase POS further.
4.	Component Acceptance & Proof Testing	High	Methodology developed under CSGT program for quality control, NDE characterization, and testing provides good POS	High	As for Centaur 50 CSGT engine, plus added experience will increase POS further.
5.	Component & Engine Life Prediction	Medium	POS reflects inadequate database on SCG and uncertainty on new modes of failure such as cyclic fatigue. Life prediction of CFCCs is in its infancy	High	Life prediction methodology should have been well validated in the next decade and models for CFCCs should be in place from developments at NASA and other work.
6.	Component Handling	High	There is substantial experience from AGT/ATTAP programs	High	As for Centaur 50 CSGT plus additional experience gained over the coming years.
7.	Manufacture & Assembly	High	Suppliers will be able to fabricate small lots of prototype parts	High	Japanese ceramic turbocharger experience shows that scale up can be done cost effectively and reliably.
8.	Green Runs	High	There will be ample engine testing in Phases II and III to ensure high POS packager/shipper	High	As for Centaur 50 CSGT plus added experience.
9.	Packaging, Shipping, & Installation	Medium	There will be a learning curve, but Solar is an experienced packager/ shipper	High	Experience gained from Centaur 50 CSGT and early commercial shipments should ensure high POS
10.	Warranty	High	Solar is experienced in this area	High	As for Centaur 50 CSGT plus added experience.
11.	Operations	Medium	Learning curve expected, but Solar experience in this area will be helpful	High	As for Centaur 50 CSGT plus added experience.
12.	Aftermarket Support	High	Solar has organization in place to deal with aftermarket	High	As for Centaur 50 CSGT plus added experience.

Achieving the ultra-low emissions levels will be critical for achieving acceptance of the ceramic turbine technology by regulatory bodies and by the end users. It is therefore recommended that DOE consider incorporating combustor development work addressing this concern to the program. It is not recommended that work is performed to achieve 5 ppmv NO_x and 10 ppmv CO at this time in the program. Targets of 10 ppmv NO_x and 20 ppmv CO are realistic targets that should be achievable under the program. Further reductions could be the objective of the ATS program.

7.7.2 Design Methodology for Creep

Currently there is no established design methodology for creep and yet creep relaxation may be an important process in redistribution of stresses within a component. The silicon nitride materials have the potential to allow more than 1% of creep. The differential expansion between two parts of a ceramic component with a temperature difference of 278°C (500°F), causes a uniaxial strain of 0.1%, and a uniaxial stress of 297 MPa (43 ksi) (based on an elastic modulus of 297 GPa (43×10^6 psi). Hence significant relaxation of this uniaxial stress level would be possible in the creep regime. A relaxation design methodology is needed for real components with more complex stress systems.

7.7.3 R&D into the Mechanism for Slow Crack Growth

Of the four mechanisms of failure, Solar and SPS feel most confidence in the fast fracture analysis. The creep analysis is believed to rank second in confidence followed by slow crack growth and the placement of the oxidation boundary being last in confidence. Fortunately, the Centaur 50 CSGT engine with a TRIT of 1121°C (2050°F) is more limited by slow crack growth and creep than by oxidation. Slow crack growth, placed last in the assessment of confidence, is the most critical factor limiting life prediction.

The phenomenological and mathematical background on slow crack growth was established in large measure with glass. Three modes of testing have been used and correlated with each other. These modes are:

- Static Fatigue (life under constant load)
- Dynamic Fatigue (strength at different loading rates)
- Crack Propagation Rates (da/dt versus K_1)

There is persuasive data to show that slow crack growth from unnaturally large pre-existing cracks is not representative of the failure process in ceramic components. For example, it has been shown that precracks will suppress the dynamic fatigue phenomenon and will suppress surface reactions with moisture (stress corrosion). On the other hand, correlation between the different modes of testing has been shown for some materials, although the exponent "n" in the equation,

$$V = A K_I^n$$

may have artificial values that can range from 25 to 100. Clearly more work is needed to explore this area, to define the processes occurring and to develop the equations (and parameters for these equations) to permit life predictions to be made.

Work in the last five years on the behavior of ceramics under cyclic fatigue (i.e., stress cycles) has shown alarming acceleration of crack rates in some materials under alternating stresses (18). Again, more work is needed to define processes occurring with particular reference to cyclic rate, atmosphere and temperature.

An over-riding consideration in this work will be that if the process is slow crack growth, it will be the growth of a 25 micron crack to a 100 micron crack in a period up to 30,000 hours. If the process is not growth of a crack, as has been shown for low temperatures for silicon nitride, then the characteristics of this process over periods up to 30,000 hours must be established.

7.7.4 Improve Life Prediction Methodology

Life prediction for long-life monolithic ceramic components is in a very early stage of development. The AGT/ATTAP programs at Allison Engine Company and AlliedSignal Engines have limited applicability to this industrial gas turbine program. The approach adopted by Sundstrand Power Systems is new and is hindered principally by the lack of adequate technology and databases for concept validation. However, the approach has been restricted to monolithic ceramics and there is a growing need for a life prediction method for CFCCS. Further improvement of CFCC life prediction methodologies such as C-CARES as well as an integrated approach to life assessment for composites using the approach taken by Sundstrand with SPSLIFE is recommended. The lack of any suitable method for these CFCCs causes the remainder of this review to be limited to the monolithic ceramics.

7.7.5 Database

Although it is believed that the database will be adequate for the 4000 hour engine run, it is recognized, also, that an inadequately recognized effect may occur. This is made more likely by the paucity of data extending beyond a few thousand hours, and by the very limited amount of data on the effect of high water-content combustion gases on the properties of ceramics. The CARES/LIFE and SPSLIFE analyses have shown that the database is quite inadequate for design to 30,000 hours. The deficiency is most apparent in slow crack growth. However, measurement of more properties in multi-thousand hour tests is strongly recommended, both to establish design type data as well as to provide assurance that side effects do not occur. These tests will require significant investment that is beyond the scope of the CSGT program. Particular reference should be made to residual properties after such exposures, especially of thermal conductivity and fracture toughness after extensive creep induced porosity.

7.7.6 Blade-Tip Clearance Control

It seems impractical at the present time to expect that future designs will be able to control tip clearances during fast transient behavior to within a few thousandths of an inch, despite the best care at minimizing adverse stackups and thermal paths. There are two solutions to this problem for immediate consideration:

1. Develop a tipshoe/coating system which can accommodate the 'impact' of a blade rub without damaging either the blade or the tipshoe.

2. Develop a shrouded ceramic turbine blade. The shrouded blade will experience a much more benign rub than its unshrouded counterpart, and also the efficiency loss for shroud knife edge clearance is not as severe as unshrouded blades.

The principal need is for a technology base to be developed for ceramic blades to match that available for metallic engine design.

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8.0

TASK 6 - PROGRAM PLAN FOR PHASES II AND III

8.1 INTRODUCTION

The Program Plan for Phases II and III is a summary of the Management Plan submitted to the program sponsor during the Phase I performance period (1). It includes a description of the logical steps for Phases II and III including technical tasks to cover engine design, engineering, procurement, fabrication, and development or test needs for the selected ceramic materials; schedule; duration; and milestones. The Management Plan and accompanying Timeline computer program includes details of program organization, schedule, resources and cost for all three program phases. The program plan description provided here is a summary at the level of the Major Tasks. Figure 8-1 shows the organization of the Phase II/III program, including the subcontractors.

8.2 CONCLUSIONS AND OUTSTANDING ISSUES FROM PHASE I WORK

A summary is provided here of the major conclusions of the Phase I work and of outstanding issues that need resolution during the work in Phases II and III of the program. Specific activities have been conceived to resolve these issues in Phases II (Section 8.3) and III (Section 8.4). Some of the issues are beyond the current scope of work in the program, but they have been listed here because it was felt that their resolution is important for the success of the program.

Component Design

1. **Nozzle.** A radial combustor profile has been conceived that provides sufficient cooling to keep temperatures and stresses low on the secondary metallic components in the hot section. However, this same profile results in stress/temperature combinations at critical locations on the nozzle airfoils that are life limiting for the engine in service. Design strategies must be developed in Phase II to lower these high stresses. Potential approaches include:

    1. Modifying the combustor radial profile to give lower temperature gradients
    2. Incorporating airfoil trailing edge cutbacks to reduce stress levels
    3. Modifying the airfoil geometry to lower the stresses within the limits of the retrofit goal of the CSGT program
    4. Segmentation of the nozzle to reduce stress levels
    5. Modifying (increase and or redirection) of secondary cooling flows on inner and outer flowpath components and support structures
    6 Uprate secondary components (e.g. disks, diaphragm) to enable higher temperatures in the airfoil to lower stresses

2. **Blade.** The blade design with the "dovetail" attachment will require a compliant layer material to prevent the ceramic component loads to react directly with the interfacing blade disk, and result in possible failure during transient operation. The selection and evaluation of compliant layer materials that will meet the long (30,000 hours) engine service requirement will be a critical activity in Phase II.

3. **Combustor.** The combustor design has been unified to include the same component envelope for monolithic and continuous fiber-reinforced ceramic matrix composite (CFCC)

liners. Within this envelope several preliminary design geometries are being evaluated for testing in Phase II. Each of these designs has challenges that will require solutions.

1. Monolithic tiles have the problem of "sticking" at high (≈1371°C, 2500°F) liner temperatures. The use of coatings will be explored to prevent "sticking".
2. The segmented monolithic liner designs also provide the potential for leaking between the segments and strategies to minimize leakage need to be addressed.
3. Various monolithic liner designs (axial tiles, continuous rings) have different stress levels and different stressed volumes. A trade-off study will be conducted to select an optimal combination of component geometry, low stress and minimum stressed volume. Life assessment studies using the SPSLIFE and NASA CARES/LIFE computer codes will be essential elements in this evaluation.

The combustor development task needs to be broadened to explore alternate ways of meeting the CSGT system NOx goal of <10 ppmv. Combustor designs incorporating off-line can type geometries offer a potential route to achieving this NOx emissions goal.

Data Base and Life Assessment

4. Slow crack growth (SCG) and creep have been identified as life limiting failure modes for the ceramics from CARES/LIFE and SPSLIFE assessment studies on the basis of a limited data base. The development of a long term materials property data base to enable life assessment of the key ceramic components will be an important subtask in Phase II. The initial designs may have to be modified for improved SCG and creep resistance as new long term property data becomes available. Long term data for oxidation also needs to be generated. For the purpose of the CSGT program 10,000 hr test data will be required. For commercialization of the CSGT technology 30,000 hr test data will be needed to assess component life between typical overhaul intervals.

5. Design of the integral CFCC combustor liners is limited by the absence of an effective component reliability/life assessment code for CFCC materials/components. In the absence of such a code design for CFCC components will have to rely on finite element analysis supplemented by the extrapolation of specimen and subscale component testing to gain confidence in designing with composites. There is a need for the development of a user-friendly computer code to assist the designer of CFCC components.

6. Nondestructive evaluation (NDE) to (1) detect defects in ceramic hardware as part of accept-reject criteria, and (2) monitor the growth of defects during service and as a means to predict the remaining service life of the component will be an integral subtask of the Phase II/III work.

Ceramic Supplier and Processing Issues

7. Components fabricated by processes that utilize HIP-densification with a glassy surface layer show significantly lower strength in the as processed state compared to the machined state and are consequently limited in SCG resistance. Localized surface finishing in critically stressed area may need to be explored to improve SCG resistance and enhance the life of components fabricated using this process.

8. The development of a reliable supplier base that is able to supply commercial quantities of

components at costs and delivery schedules that are competitive with metallic components is critical for the commercialization of the ceramic stationary gas turbine.

Component Testing

9. Although low stress designs and an adequate materials data base including long term critical materials properties are essential elements in the success of this program, a well-designed testing program is needed to demonstrate the effectiveness of the designs in the engine. The test program designed for Phase II consists of a logical sequence of experiments to test materials and component designs under projected engine conditions. Attachment samples and subsize components will be tested to evaluate design concepts. Selected design concepts will be fabricated and tested in rigs. Subsequent design and materials selection iterations will be performed to optimize performance in testing.

Commercialization

10. An economic analysis has been presented that correlates predicted engine performance with fuel and electricity prices and with extrapolation of historical trends in the gas turbine industry. The economic scenario is generally favorable for the commercialization and market penetration of the ceramic stationary gas turbine. The scenario presented here envisions introduction and market penetration in the 2000-2010 time frame.

8.3 PHASE II - FINAL DESIGN, MATERIAL, AND COMPONENT TESTING (WBS 2.0)

The Phase II work will address material testing, component development, rig testing, and final design of the engine and its components. The work is structured in the following major tasks and work breakdown structure (WBS) elements:

Task 7 - Test Engine (WBS 2.7.0)
Task 8 - Test Facilities (WBS 2.8.0)
Task 9 - Ceramic Components (WBS 2.9.0)
Task 10 - Low Emission Combustor (WBS 2.10.0)
Task 11 - Plan For 4000 Hour Performance Test (WBS 2.11.0)
Task 16 - Program Management and Reporting (WBS 2.16.0)

Figure 8-2 shows the Major Tasks and Subtasks to the greatest level of detail in the Work Breakdown Structure for Phase II. Figure 8-3 shows a summary Timeline for a 3.5 year Phase II performance period.

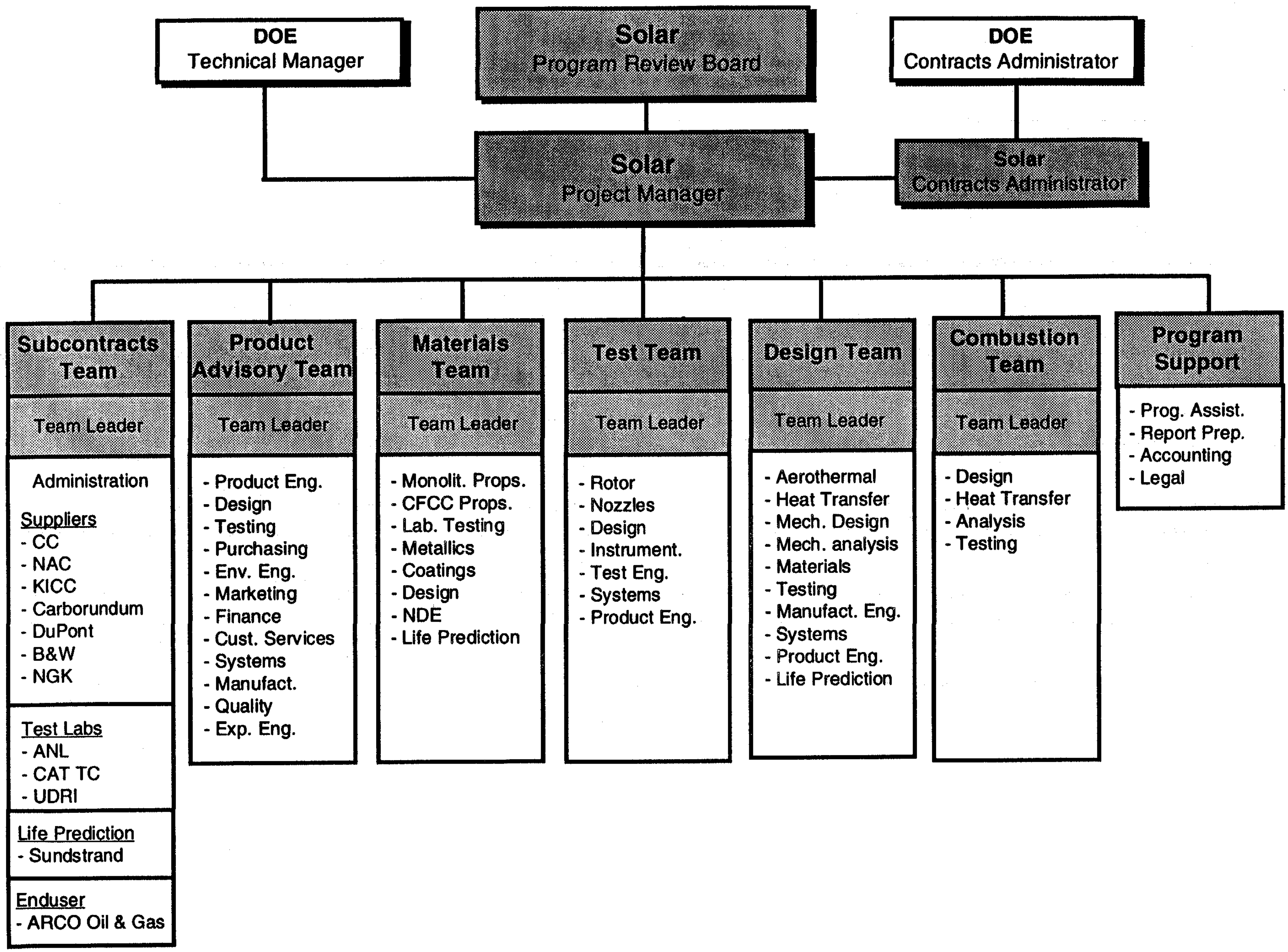

Figure 8-1. Phase II/III CSGT Program Organization

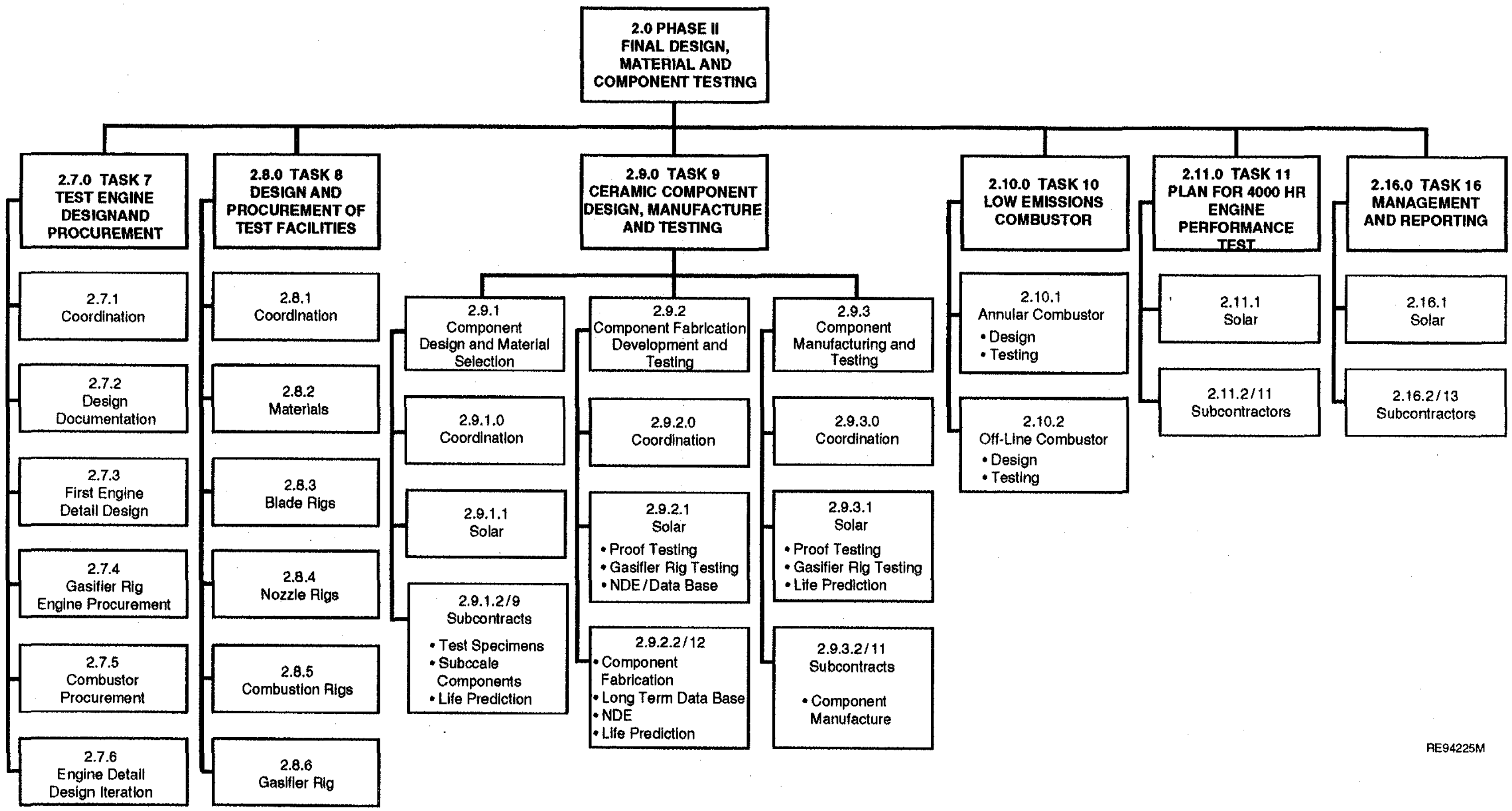

Figure 8-2. Major Tasks and Subtasks in the Work Breakdown Structure - Phase II

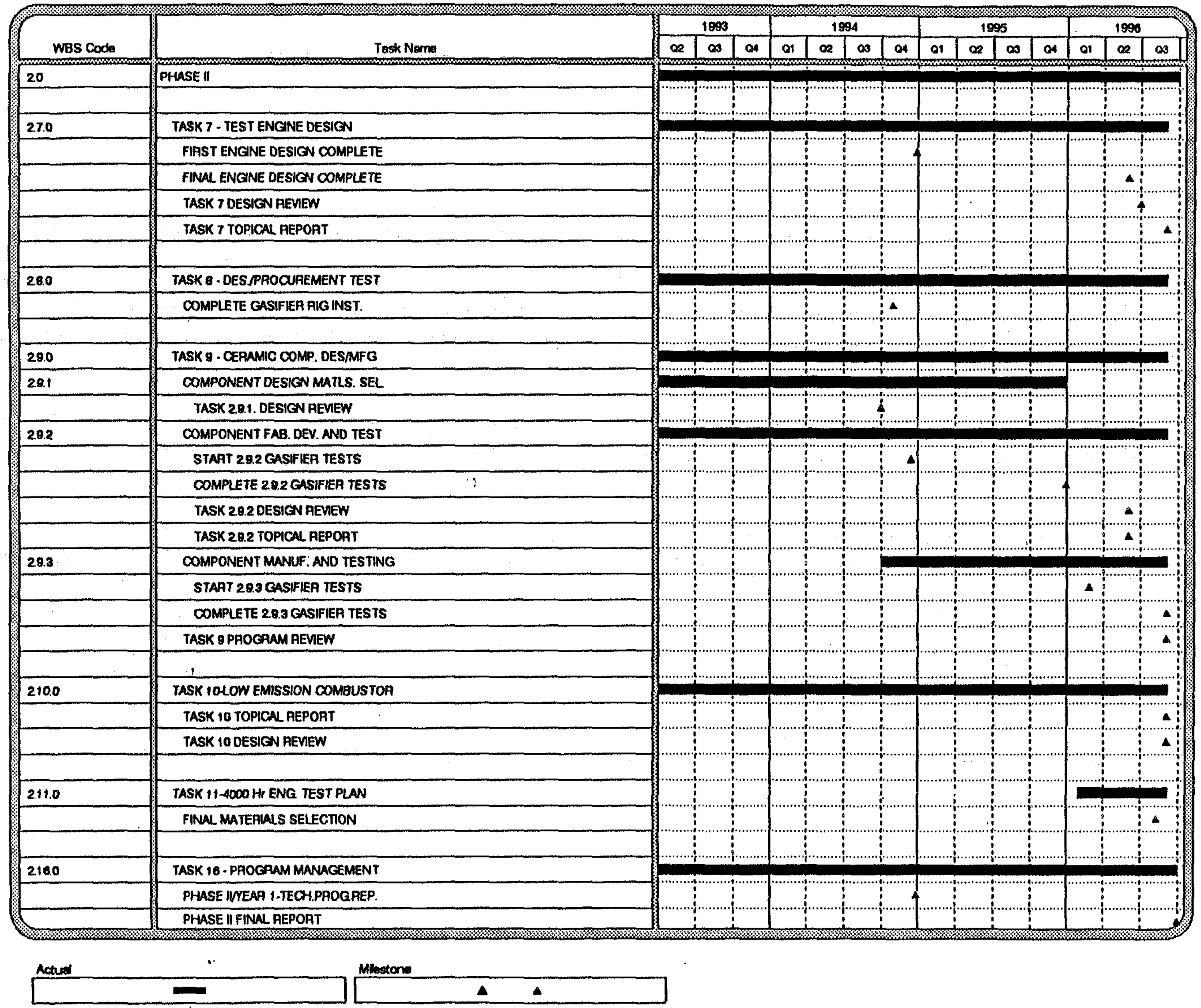

Figure 8-3. Phase II Timeline

8.3.1 Task 7 - Test Engine

Task 7 involves completion of the detailed design for the key ceramic components selected in Phase I, as well as procurement and modification of the engine to accept the selected ceramic components. The Solar plan envisions the procurement of two engines. One engine will be procured in Phase II under Task 7. This engine will be modified to function as a gasifier rig. A second engine will incorporate all the design and testing experience of Phase II and will be procured and modified in Task 12 of Phase III.

The engine selected for the program is the Solar Centaur 50 (formerly known as Centaur 'H'). An extensive study in Phase I has established target performance under a variety of conditions in field service. A specification has been written for the Centaur 50 CSGT engine for operation at the end user site at ARCO in Bakersfield.

Work under this task will focus on the broad issues to be addressed in the detailed design of the gasifier rig and field test engine. Key issues will be definition of the engine package for gasifier rig testing, engine performance specification and measurement at target TRIT's with various ceramic components, and the definition of an all-metal engine baseline.

This task also involves completing the detailed design of the ceramic components and modifying the program engine to accept the ceramic components. This involves a definition of the ceramic/metallic interfaces and the secondary metallic components in the hot gas flow path required to accommodate the sequential introduction of ceramic components.

Work further includes heat transfer analysis and stress analysis for all primary ceramic and secondary metallic components. Life prediction of ceramic components will also be performed. Results of these analyses will be documented in engineering design memos. Modifications to the electronic control unit will be recommended based on ceramic component transient stress analysis.

An unique hardware matrix will be defined for each configuration of the gasifier rig. This matrix will include the all-metal baseline as well as the engine with various ceramic components substituting for the metallic components. A initial unique hardware matrix will also be defined for the field test engine. This matrix will be reviewed in Task 11 to reflect the cumulative design and testing experience gained under the program. The engine specification developed in Phase I will be updated throughout the Phase II performance period.

Modifications to the Centaur 50 engine to accommodate gasifier rig engine testing of sequentially introduced ceramic components will be defined. Included in this task is the definition of the electronic control unit modification and other instrumentation needs for the gasifier rig. Modifications of the engine for the Phase III field test will also be addressed.

Engine procurement involves planning; engine, subassembly, and component specification, new component drawings and modification of existing drawings, sourcing of suppliers for standard and non-standard components, scheduling of component fabrication and delivery, timing for engine hardware assembly, and instrumentation needs. The procurement strategy for the gasifier rig engine will follow the above plans.

The end user on the program ARCO Oil and Gas will review modification of the Centaur 50 engine with ceramic components. Performance analysis in cogeneration service from design data will be used. ARCO will also be informed of the test plans for gasifier rig testing to verify the design performance data.

The engine and gasifier rig design and procurement strategies will be presented in a review meeting for the DOE and a topical report will be submitted. Following approval by the DOE the gasifier rig engine and ancillary components will be procured. Procurement of the ceramic components is included in Task 9.

8.3.2 Task 8 - Test Facilities

This task involves providing the test facilities to evaluate the ceramic stationary gas turbine components. Existing test facilities for materials property testing, spin testing, and combustor liner testing will be modified if needed for the testing envisioned. A Centaur 50 engine procured under Task 7 will be modified to accept the ceramic hardware. A listing of all the test rigs and their application under the program is given in Table 8-1. Several of the rigs to be used under the program are shown in Figures 8-4 through 8-8.

8.3.3 Task 9 - Ceramic Components

This task involves iterative design, life prediction, fabrication, and testing of ceramics. This task will extend over the entire duration of Phase II. Figure 8-9 is a schematic showing the integrated design/procurement/test strategy. The work will be performed in three subtasks focused on test specimen and subscale procurement and evaluation (Task 9.1), first generation prototype procurement and evaluation (Task 9.2), and second generation prototype procurement and evaluation (Task 9.3). Figure 8-10 summarizes the testing approach for this task.

Table 8-1. Rig Test Requirements For Phase II

RIG	PURPOSE	EXISTING/NEW	MODIFICATION
Cold Spin Rig	Cold spin testing of rotor blades (including proof testing)	Modify existing cold spin rig	Adapt to test ceramic blades
Attachment Test Rig	Test blade attachment configurations	Modify existing attachment test rig	Adapt to accept various root designs
Nozzle Rig	Proof testing of nozzles	Fabricate new rig	New rig
Small Scale Combustor Rig	Testing of combustor cans	Use existing rig	
Small Scale Combustor Rig	Long term testing of combustor cans	Modify existing rig	Modify existing combustor rig for long term testing
Full Scale Atmospheric Combustor Rig	Test full scale monolithic and CFCC liners	Modify existing rig	Modify rig to accept ceramic liners
Full Scale High Pressure Combustor Rig	Test full scale monolithic and CFCC liners	Modify existing rig	Modify rig to accept ceramic liners
Gasifier Rig	Test ceramic components in engine environment	Procure and modify Centaur 50 engine	Modify 50 engine with non-standard hardware to accept ceramics

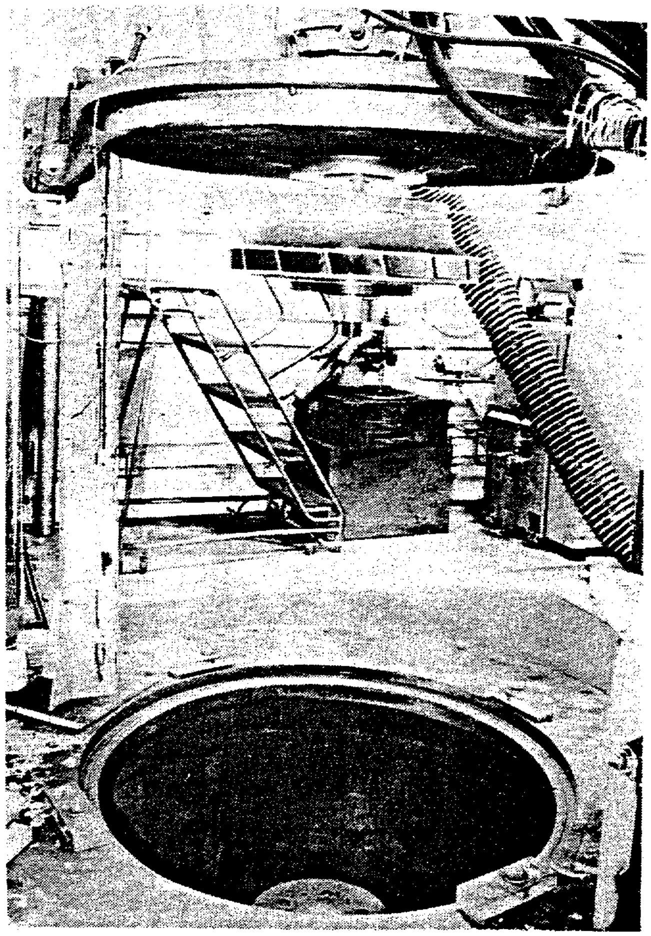

Figure 8-4. Solar's Cold Spin Test Facility

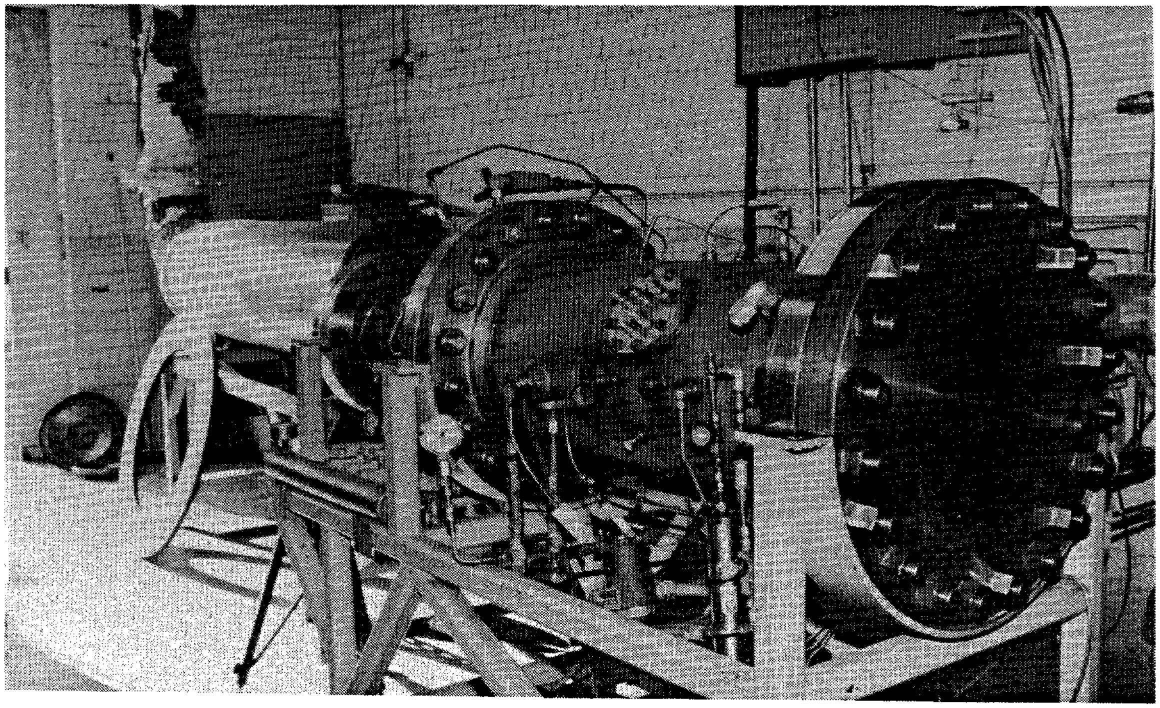

Figure 8-5. Small Scale Combustor Rig

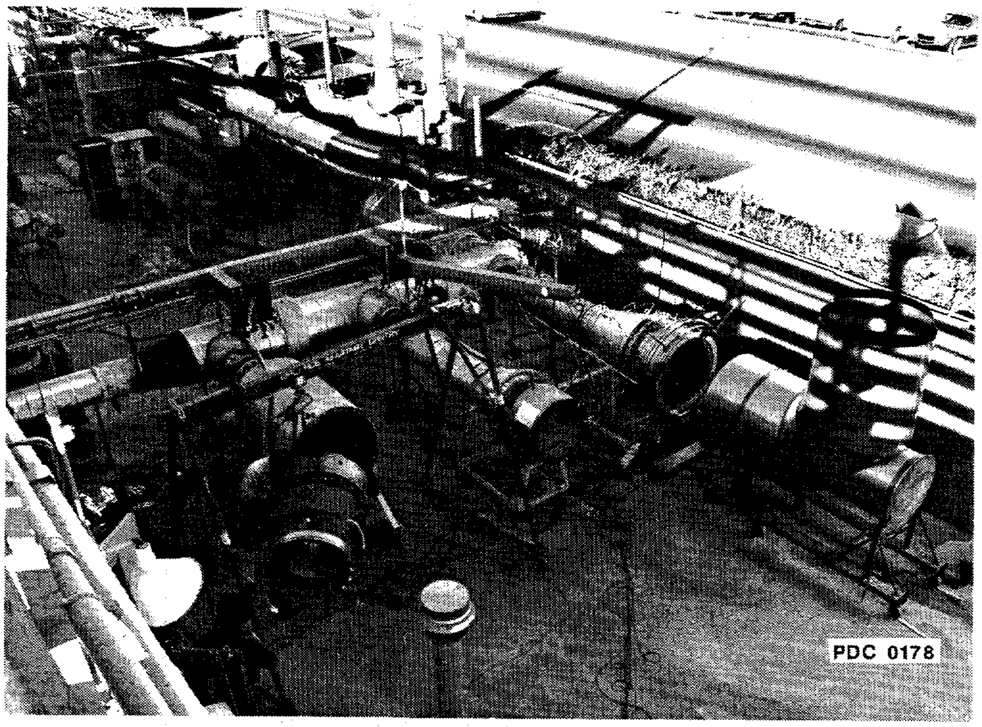

Figure 8-6. Atmospheric Combustor Test Facility

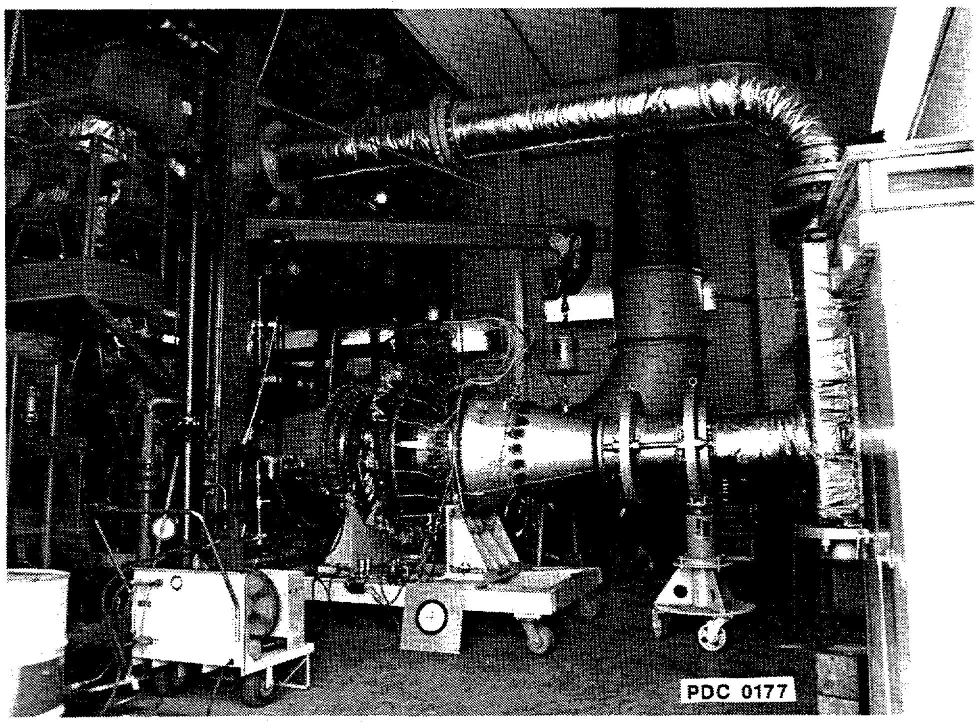

Figure 8-7. High-Pressure Combustor Test Facility

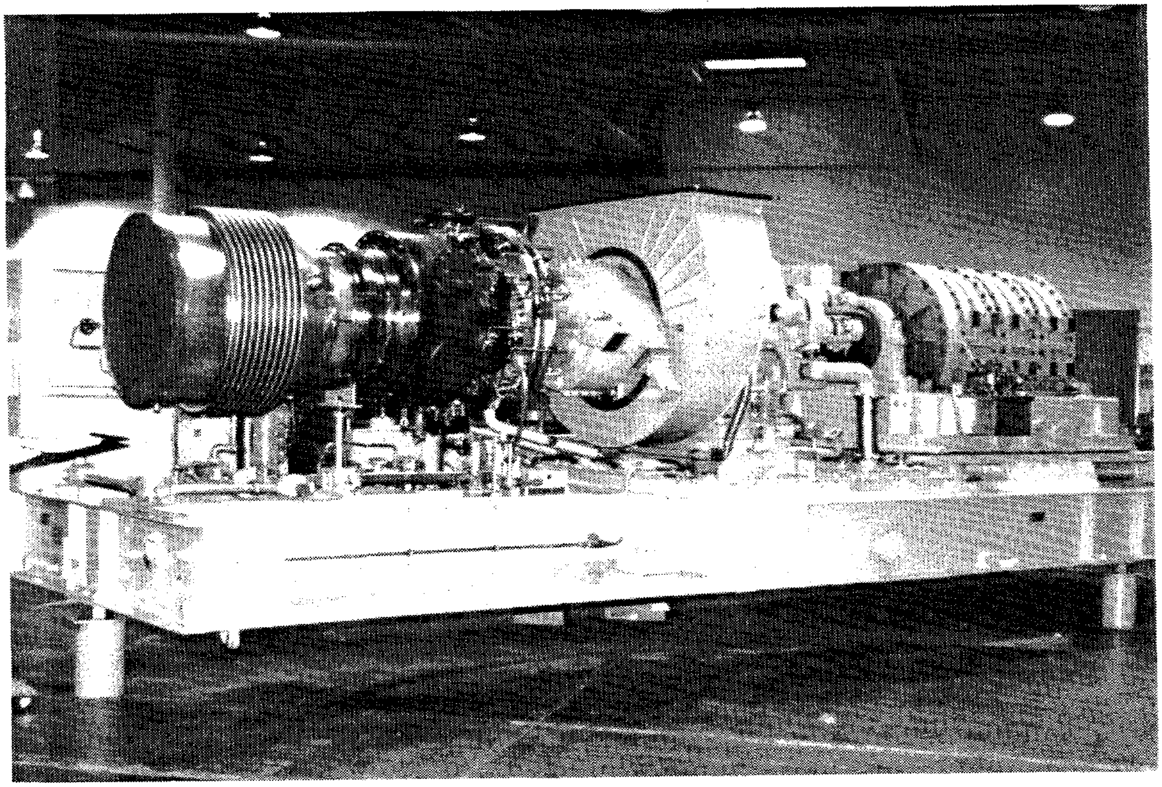

Figure 8-8. Gasifier Rig

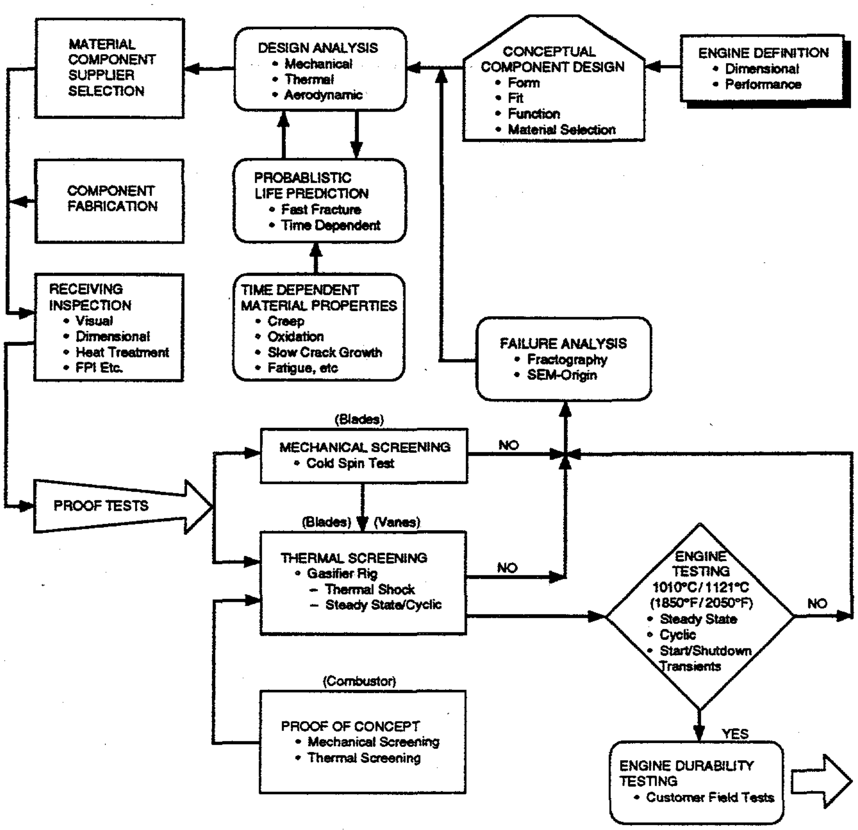

Figure 8-9. Schematic of Iterative Design/Fabrication/Testing Strategy for CSGT Program

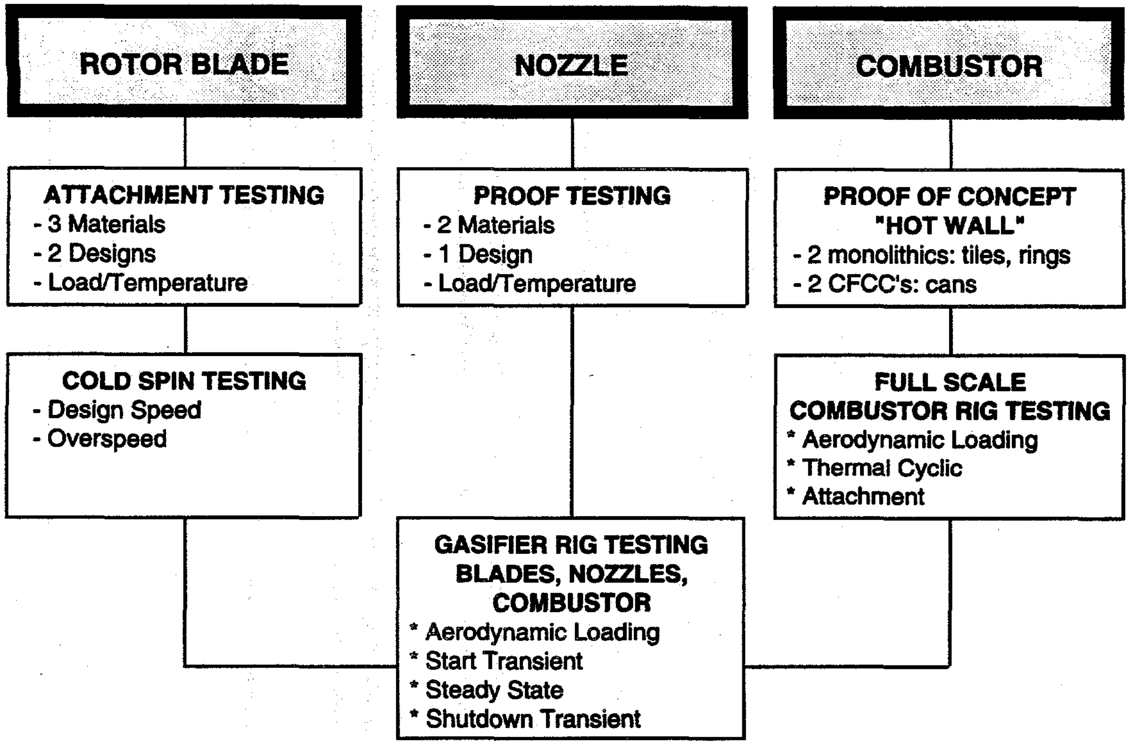

Figure 8-10. Flowpath of the Sequential Testing of the Three Program Components

8.3.3.1 Task 9.1 - Component Design and Material Selection

The detailed design of the key ceramic components defined in Task 7 will be used to definitize manufacturing methodology, proof testing, and interfacing with the engine including seals and joining. Test specimens will be procured for short term and long term testing. Simulated component specimens will be procured to evaluate blade, nozzle, and combustor liner designs.

The preliminary design in Phase I defined the component shapes and basic attachment configurations of the three program components. The detailed design in Task 7 will define the actual shapes of components for the gasifier rig and field engines. The design will be validated by testing and iterated until an overall design with high predicted reliability and performance, and low probability of failure of ceramics has been achieved. The iterations will be guided by laboratory and rig testing. Subsequent design iterations will be guided by gasifier rig testing as described under Tasks 9.2 and 9.3, and by combustor testing in Task 10. The ceramic suppliers will provide ongoing feedback on the design and test results of their components. The results of the life prediction studies performed by Solar and Sundstrand will be incorporated into the iterative design. A design review will be conducted for DOE for the program components.

Preliminary rotor blade designs developed under Phase I will be detailed. The blade root designs will be evaluated using root attachment test specimens and simulated blades procured from the ceramic suppliers. Instron type attachment testing using various load and temperature regimes will be used to evaluate root configurations, blade-disk interactions, and compliant layers. Spin testing will be used to test the ruggedness of the attachment designs. The testing will assist in deciding which of the candidate attachment designs will be incorporated into prototype blade designs to be procured and tested in subtasks 9.2 and 9.3.

Preliminary nozzle designs developed under Phase I will also be detailed. Results of iterative stress/temperature analysis will be particularly critical. Materials testing will be used to evaluate nozzle materials in preparation for component procurement and testing in subtasks 9.2 and 9.3.

Several combustor liner designs will be evaluated including monolithic tiles and rings, and integral continuous fiber-reinforced ceramic matrix composite (CFCC) liners. Critical issues are thermal shock resistance, oxidation resistance, and the development of methods to prevent "sticking" of adjacent combustor segments (tiles, rings). Liner attachments will also be evaluated. Subscale components will be procured and tested in a single-injector can-type configuration under temperature and pressure conditions that will generate stresses typical for full scale combustor liners. All combustor testing is performed under Task 10 of the program.

Interfaces, seals, and secondary component designs will be carefully evaluated. Further iterative design/test activities may be required following prototype testing. The work under this subtask also involves the establishment of a methodology for manufacture, inspection, and proof testing. Fabrication plans and quality assurance plans developed under Phase I will be refined on the basis of the experience gained under this subtask.

Thermo-mechanical properties testing is an important element of Task 9.1. The goal is to augment the database for the materials selected for component fabrication. Test specimens will be procured for this purpose. Critical materials properties required will be slow crack growth, creep, fatigue, and oxidation resistance. Properties will be determined for specimens in the as received condition and after exposure. Long term testing for creep and oxidation will be performed under Task 9.2. Effect of machining will be included where appropriate. Flexure bars and ORNL buttonhead tensile specimens will be procured from the ceramic suppliers for materials property evaluation.

Table 8-2 lists the components, simulated components and test specimens required for each of the candidate materials for this subtask.

8.3.3.2 Task 9.2 - Component Fabrication Development and Testing

This subtask involves the procurement of first generation prototype ceramic components from the ceramic suppliers which will be proof tested in the test rigs defined in Task 8. Of particular importance is the testing of prototype ceramic blades and nozzles in the gasifier rig. Long term testing of the ceramic materials for critical materials properties such as creep and oxidation is also included in this subtask. All findings will be correlated with life prediction and NDE studies. Under this task a design review will be held to obtain DOE's approval on the production procedures and a topical report will be prepared. The supplier subcontractors will be asked to contribute to both items.

Component fabrication development will be conducted using the detailed component designs from Task 7. The results of simulated component testing will be iterated into the designs as soon as they become available. Ceramic component suppliers will design and procure tooling to fabricate first generation prototypes of the basic component designs. Fabrication will closely follow the fabrication plans described in Section 5 (Task 3 - Materials Selection). In-process control includes inspection for cracks, sectioning to assure uniform density, avoidance of internal pores or defects, sintering of uniform green parts, measurement of density and dimensions, NDE and other quality assurance at designated steps in the fabrication process. Initial lots of parts will be submitted to Solar for dimensional inspection and proof testing. The findings of these tests will guide further design iterations and component fabrication. The parts to be procured and their suppliers are listed in Table 8-2.

Table 8-2. Components and Test Specimens from the Ceramic Suppliers

SPECIMEN	CC	KICC	NAC	NGK	CARBORUNDUM	DUPONT	B&W	PURPOSE
ATTACHMENT SPECIMENS	✓	✓	✓					ATTACHMENT TESTING
TENSILE SPECIMENS + COPROCESSED FLEXURE BARS		✓	✓	✓	✓			SLOW CRACK GROWTH, CREEP, FATIGUE TESTING
FLEXURE BARS	✓	✓	✓	✓	✓			FAST FRACTURE, SLOW CRACK GROWTH, OXIDATION TESTING
SUBSCALE TILES					✓			COMBUSTOR RIG TESTING
SUBSCALE RINGS			✓					COMBUSTOR RIG TESTING
SUBSCALE CFCC COMBUSTOR CANS						✓	✓	COMBUSTOR RIG TESTING
FLEXURE, TENSILE, SHEAR SPECIMENS, RINGS						✓	✓	STRESSED OXIDATION, RING BURST TESTING
FIRST GENERATION BLADES + COPROCESSED FLEXURE BARS	✓	✓	✓					FIRST GENERATION COMPONENT TESTING
FIRST GENERATION NOZZLES + COPROCESSED FLEXURE BARS			✓	✓	✓			FIRST GENERATION COMPONENT TESTING
FIRST GENERATION FULL SCALE COMBUSTOR TILES + COPROCESSED FLEXURE BARS					✓			FIRST GENERATION COMPONENT TESTING
FIRST GENERATION FULL SCALE COMBUSTOR RINGS + COPROCESSED FLEXURE BARS			✓					FIRST GENERATION COMPONENT TESTING
CFCC COMBUSTOR LINER PRE-PROTOTYPES + COPROCESSED TEST SPECIMENS						✓	✓	FIRST GENERATION COMPONENT TESTING
SECOND GENERATION BLADES + COPROCESSED FLEXURE BARS	✓	✓	✓					SECOND GENERATION COMPONENT TESTING
SECOND GENERATION NOZZLES + COPROCESSED FLEXURE BARS			✓	✓	✓			SECOND GENERATION COMPONENT TESTING
SECOND GENERATION COMBUSTOR TILES OR RINGS + COPROCESSED FLEXURE BARS			✓		✓			SECOND GENERATION COMPONENT TESTING
CFCC FULL SCALE COMBUSTOR LINERS + COPROCESSED TEST SPECIMENS						✓	✓	SECOND GENERATION COMPONENT TESTING

Proof testing for rotor blades will involve cold spin testing at design rotational speed and overspeed. If needed hot spin testing may be performed to evaluate blade performance under conditions that will simulate the critical loads at the temperature of the root attachments. Blades will be inspected following spin testing for surface and compliant layer condition (where applicable). Some blades may be sectioned for destructive analysis. Holographic vibration testing will be used to determine key vibrational modes and safe operating conditions for the blades.

Both blades and nozzles will be evaluated in the gasifier rig under conditions that are typical for the Centaur 50 engine. Ceramic components will be substituted in subsequent runs; ceramic blades will be tested first, followed by ceramic nozzles. Eventually, nozzles and blades will be tested simultaneously. Test temperatures will be increased gradually, starting at the current Centaur 50 TRIT of 1010°C (1850°F). The temperature will be incremented by intervals of 28-56°C (50-100°F) till the final design temperature of 1121°C (2050°F) is reached. The ceramic components will be inspected after each run and removed for more extensive evaluation if desirable. ARCO, the end user, will be involved in the gasifier rig testing and evaluations in preparation of the 4000 hour field test.

Monolithic combustor tiles and CFCC liner segments will be procured under this task. The testing of the combustor components (subscale and full scale) will be performed under Task 10.

Non-destructive evaluation will be conducted at Argonne National Laboratory and Caterpillar Technical Center on selected test specimens and components. Specimens and components will be compared in the as-processed condition and following exposure. Observation of morphological changes and defects will be used to identify failure mechanisms. The findings will be used to develop a methodology for part characterization during gas turbine maintenance inspections and engine overhaul.

Long term testing of ceramic materials is another critical subtask in support of the development of a component design database. An extensive program for the evaluation of fast and slow fracture tensile strength, cyclic fatigue, and creep is envisioned. A comprehensive program for long term testing will be performed by the University of Dayton Research Institute (UDRI).

8.3.3.3 Task 9.3 - Component Manufacture and Testing

Ceramic components for installation into the ceramic stationary gas turbine for the 4000 hour field test in Phase III will be procured and tested in this task. Second generation ceramic components incorporating design modifications based on test data under Tasks 9.1 and 9.2 will be procured and evaluated in spin proof testing and in the gasifier rig. Life prediction and NDE studies will accompany this subtask. At the conclusion of successful gasifier rig testing a major program review will be conducted for the DOE, and the recommendation to progress to Phase III program testing will be made.

At this time the manufacturing process will have matured to the point that all parts are being manufactured according to an approved Quality System. This will include complete process and in-process QA specification/verification procedures plus suitable documentation for process control and materials traceability. The components to be procured under task 9.3 are listed in Table 8-2. The designs and supplier base under Task 9.3 will likely be reduced by retaining the designs and materials/components/suppliers that are most likely to be used for the Phase III field test.

The testing under this task should confirm the suitability of the second generation blade and nozzle components for longer term field testing in Phase III of the program.

Final lots of blades and nozzles will be procured from three or two suppliers together with coprocessed flexure bars. Monolithic tiles and/or rings will be procured together with coprocessed flexure bars from one or two suppliers and full size integral CFCC combustor liners from either one or two suppliers.

The blades will be subjected to cold and hot spin proof testing (if needed) as described under Tasks 9.1 and 9.2. Nozzles will be proof tested in the gasifier rig. Both nozzles and blades will then be tested in the gasifier rig, first separately, and then jointly. As for Task 9.2, the firing temperature of the rig will be gradually increased, and the test time will be gradually increased up to 50 hours. Combustor rig testing will be conducted separately under Task 10.

8.3.3.4 Task 10 - Low Emission Combustor

This task involves the development, design, and fabrication of a hot-wall low emissions combustor. The DOE statement of work requires demonstrating 25 ppmv NOx or better and showing the potential of 10 ppmv NOx. The Solar program has set a target of demonstrating 10 ppmv NOx or better for the combustor to be developed under this task. Subscale tiles, rings, and integral CFCC liners will be evaluated in combustor rig testing, and subsequently actual scale combustor hardware will be tested in full scale combustor rigs and in the gasifier rig. The test rigs have been listed in Table 8-1. Design and test results will be correlated with NDE evaluation (under Task 9.2) and life prediction.

The candidate designs/materials that demonstrate satisfactory performance in the subscale testing will be subsequently evaluated as full scale parts in full scale combustor and gasifier rig testing. The latter testing is planned towards the end of the Phase II performance period, and the ceramic combustor liners will be tested together with second generation ceramic blades and nozzles.

The results of the combustor development under this task will be presented in a review meeting for the DOE and in a topical report.

8.3.3.5 Task 11 - Plan For 4000 Hour Performance Test

The plan for the 4000 hour performance test to be conducted under Phase III will be completed under this task. Based on the results of the materials testing to be conducted under Task 9 and the component testing to be performed under Tasks 9 and 10 a final selection of the designs/materials/suppliers for the Phase III field test engine will be made. A preliminary engine test plan will be devised that will link the gasifier rig tests with the 4000 hour field test. A 500 hour interim test/evaluation at Solar will be incorporated in Phase III in this section to provide the confidence in structural integrity needed for the 4000 hour test.

All specific ceramic and metallic hardware, support equipment, instrumentation, critical test conditions, and sequence required for the successful performance of the 4000 hour engine test will be defined. The bill-of-material and engine specification prepared for the gasifier rig will be modified for definition of the field test engine.

A complete test plan will be prepared for on-site instrumented engine testing at Solar including the 500 hour instrumented engine test. A comprehensive plan for the 4000 hour field test will be prepared as well. Input will be sought from ARCO who will supervise the 4000 hour field test at their Bakersfield site. ARCO and Solar Customer Services will work closely together on site review, engine performance specifications, requirements for shipment, installation, inspection, maintenance, technical assistance, warranty issues, and regulatory requirements.

Ceramic component evaluation will be an important aspect of the engine testing. CAT Tech Center and Argonne National Laboratory will contribute to developing the methodologies and procedures for NDE component characterization prior to and upon completion of the 500 hr instrumented engine test and the 4000 hr field test. The ceramic suppliers will also contribute by preparing a detailed plan for their participation in the characterization of their components to be tested in Phase III. Ceramic component characterization data will be used as input to and correlated with life prediction studies by Solar and Sundstrand.

The current plan for Phase III involves the fabrication of monolithic combustor liner tiles and CFCC integral liners, as well as monolithic ceramic nozzles. The fabrication of these components is planned to provide one additional iteration on the nozzle and combustor liner components as well as back-up parts for the engine tests.

8.3.3.6 Task 16 - Program Management and Reporting

This task includes the program management and reporting functions on the program for Solar and its subcontractors.

8.4 PHASE III - 4000 HOUR ENGINE TEST

In this phase a 4000 hour engine test will be conducted to evaluate the performance and durability of the ceramic components. The Phase III work is structured in the following tasks:

Task 12 - Prepare and Mount Engine On Test Stand (WBS 3.12.0)
Task 13 - Engine Start-Up and Shake-Down (WBS 3.13.0)
Task 14 - 4000 Hour Performance Test (WBS 3.14.0)
Task 15 - Characterize Ceramic Components (WBS 3.15.0)
Task 16 - Program Management and Reporting (WBS 3.16.0)

Figure 8-11 shows the Major Tasks and Subtasks to the greatest level of detail in the Work Breakdown Structure for Phase III. Figure 8-12 shows a summary Phase III Timeline. A two year performance period is planned for the Phase III activities.

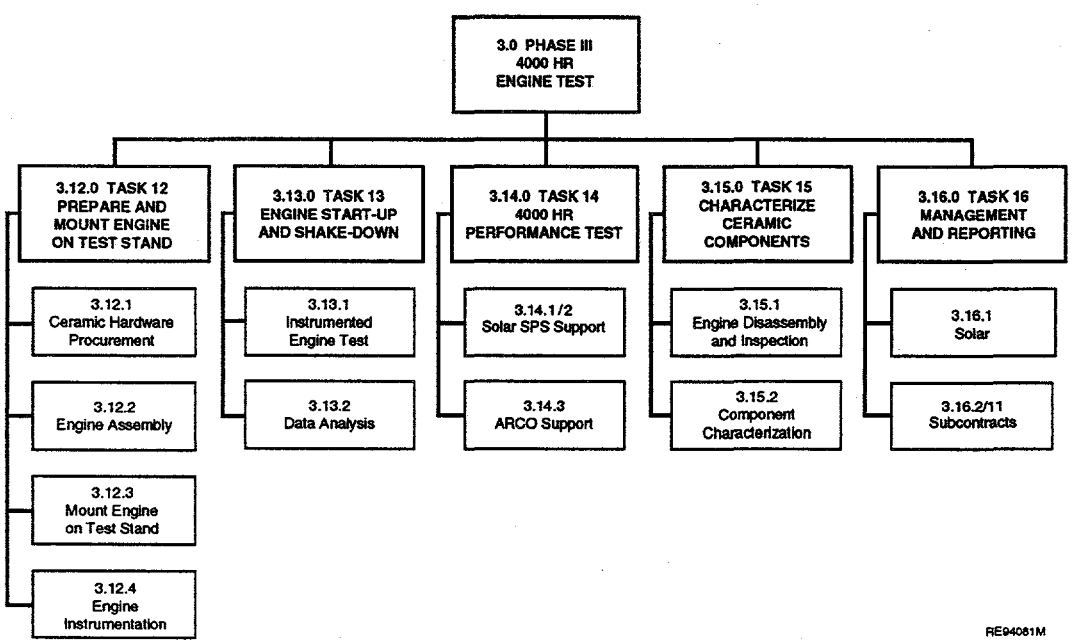

Figure 8-11. Major Tasks and Subtasks in the Work Breakdown Structure - Phase III

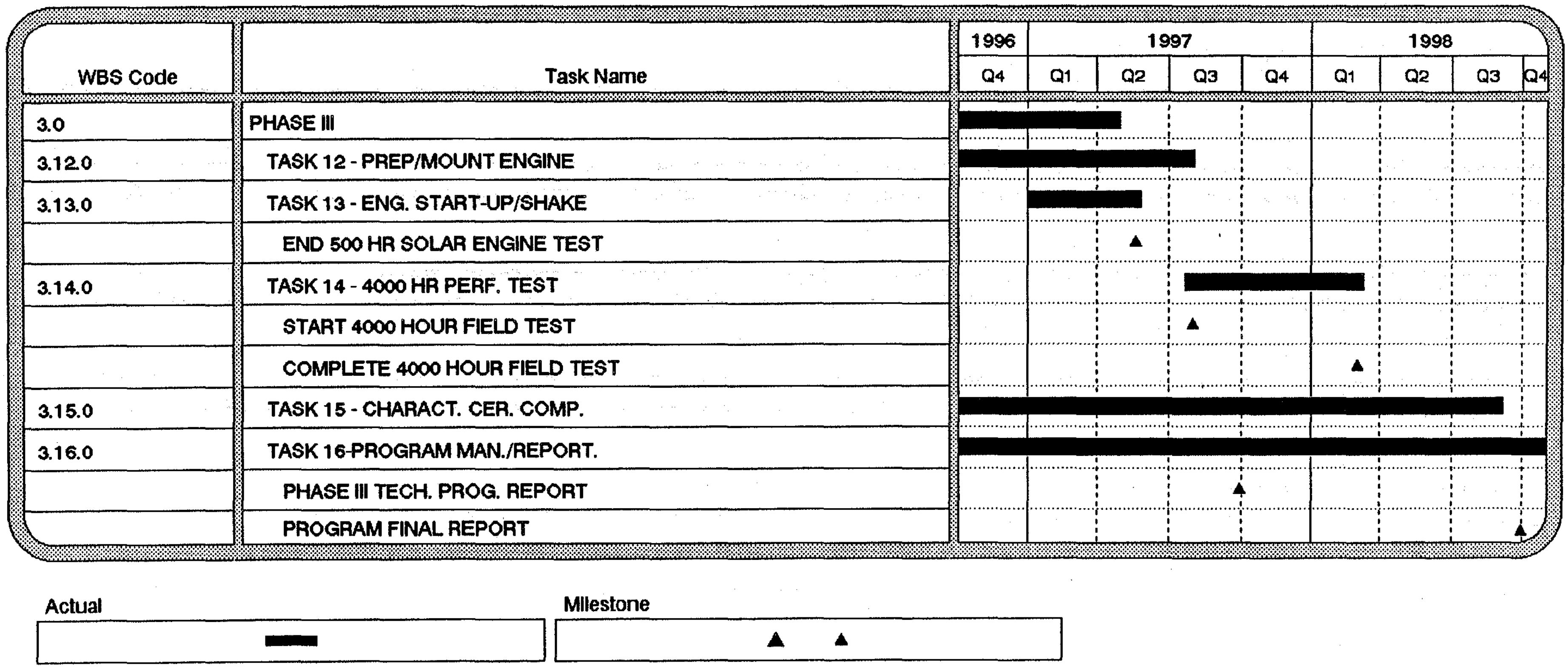

Figure 8-12. Phase III Timeline

8.4.1 Task 12 - Prepare and Mount Engine On Test Stand

Solar will procure the field test engine, including all additional ceramic components and secondary metallic engine components, for the 4000 hour engine test. The engine will be assembled and mounted on the test stand with all ancillary devices and monitoring equipment. An additional design iteration and procurement of nozzles is also incorporated.

Under this task the Centaur 50 commercial engine assembly procedures will be defined. Instrumentation requirements will be included in the engine assembly instructions. The engine will be mounted on the test stand. Instrumentation coupling and dynamic loading equipment to be used for "in-house" engine testing will be installed. Definition of the instrumentation requirements for "real time" performance, vibration, and electronic control monitoring will be provided. Annunciator panels and fault circuits will be used to warn the operator of anomalies in critical engine parameters.

8.4.2 Task 13 - Engine Start-Up and Shake-Down

The engine will be started up and monitored to ensure construction is proper and performance is satisfactory for long term operation with ceramic components. Measurements of boundary conditions for the ceramic component analysis used in Phases I and II, and verified in gasifier rig testing in Phase II, will be made to ensure conformity between predicted and actual component stresses and temperatures in service. Instrumentation control modifications may be required to achieve the soft transient conditions required for adequate component life. A test sequence will be followed that will verify consistency between the gasifier rig engine tested in Phase II and the engine designated for use in the 4000 hour durability test. A baseline engine vibration signature will be generated to establish enunciator limits for the field test. A 500 hour instrumented engine test at Solar included in this task will be performed prior to the field test. Engine performance parameters during test intervals will be established and long term performance will be predicted.

8.4.3 Task 14 - 4000 Hour Performance Test

The 4000 hour performance test will be conducted according to the plan developed under task 11 of the program. The engine test will be conducted at the ARCO Bakersfield site.

Following final shake-down the engine will be shipped to the ARCO Bakersfield site. The engine will be installed and instrumented on a real time basis to monitor ongoing performance. Installation will be supervised by experienced Solar personnel in collaboration with ARCO engineering staff. ARCO personnel will be responsible for engine operation, and they will be in close contact with Solar engineering personnel to take corrective action if required. Engine performance will be closely monitored.

Monthly inspections supervised by Solar personnel are planned. It is envisioned that DOE staff will visit the ARCO field site during the engine test. Following completion of the test the engine will be shipped back to Solar for performance evaluation, disassembly, and component inspection and evaluation.

Sundstrand will support the 4000 hour performance test and contribute to the analysis of test data related to the long term performance of the ceramic components as they become available, and life predictions will be made.

8.4.4 Task 15 - Characterize Ceramic Components

Following disassembly and inspection at the Solar overhaul facility in Dallas the performance of the engine will be documented in a comprehensive overhaul report. The performance of the engine and the durability of each ceramic component will be characterized. All engine test data will be analyzed and related to materials performance. Hot section components will be shipped to Solar San Diego for characterization. Component evaluation will include complete visual examination, photographic documentation, metallographic analysis of selected components, and residual property testing on test specimens from selected components. NDE evaluation at CAT Tech Center/Argonne National Laboratory will be an important aspect of the program. It is envisioned that designated components will undergo complete NDE characterization before and upon completion of the field test to evaluate the emergence of flaws during engine testing. Suppliers of the ceramic components will have an opportunity to participate in the evaluation of their components tested in service. The results of the component characterization will be correlated with the life prediction at Solar and Sundstrand.

8.4.5 Task 16 - Program Management and Reporting

This task includes the program management and reporting functions on the program for Solar and its subcontractors.

REFERENCE

1. M. van Roode, "Ceramic Stationary Gas Turbine Development", Management Plan, DOE Contract No. DE-AC02-92CE40960, SR92-R-5921-01, October 1992.

9.0

TASK 16 - MANAGEMENT AND REPORTING

The project management and reporting functions of Solar and its subcontractors on the program are included in this task, as well as contract and subcontract administration. All project travel for reviews, conferences, and meetings at subcontract facilities is also included. The DOE was regularly informed of all program management activities via Task 16 summaries in the monthly status reports and through program reviews.

Figure 9-1 shows the Timeline baseline Phase I bar chart. Phase I work for Tasks 1,3,4,5, and 6 was completed at the conclusion of Phase I except for residual efforts remaining on Task 2, pertaining mainly to completion of the initial life assessment by Sundstrand Power Systems for the ceramic blade, nozzle and combustor liner preliminary designs. In consultation with DOE the decision was made to continue the remaining work into Phase II.

A comprehensive Management Plan for Phases I, II, and III was prepared. The plan which is based on the Solar proposal for the program incorporates all aspects of managing the statement of work according to a format outlined in the contract for the program.

9.1 PUBLICATIONS

The following papers were prepared for work performed during the Phase I performance period:

1. "Ceramic Stationary Gas Turbine Development" by Mark van Roode, William D. Brentnall, Paul F. Norton, and Gregory P. Pytanowski (Solar), ASME paper 93-GT-309, presented at the International Gas Turbine and Aeroengine Congress and Exposition in Cincinnati, Ohio, May 24-27, 1993. The paper discusses the approach, conceptual component design, and materials selection for the program.

2. "Advanced Small Gas Turbines for Cogeneration" by Don Anson (Battelle Memorial Institute), William P. Parks, Jr. (DOE Office of Industrial Technology), Oskar Evensen, and Mark van Roode (Solar), was submitted and approved for presentation at the ASME Cogen-Turbo Conference to be held in Bornemouth, U.K., September 21-23, 1993. The paper describes the potential for performance improvements in small gas turbines for cogeneration achieved by incorporating ceramic components in the hot section.

3. "Ceramic Retrofit Program" by Mark van Roode (Solar), presented at the Joint Contractors Meeting FE/EE Advanced Turbine Systems Conference, U.S. Department of Energy, Morgantown Energy Technology Center, Morgantown, West-Virginia, August 3-5, 1993. The paper presented the program status and results through the completion of Phase I.

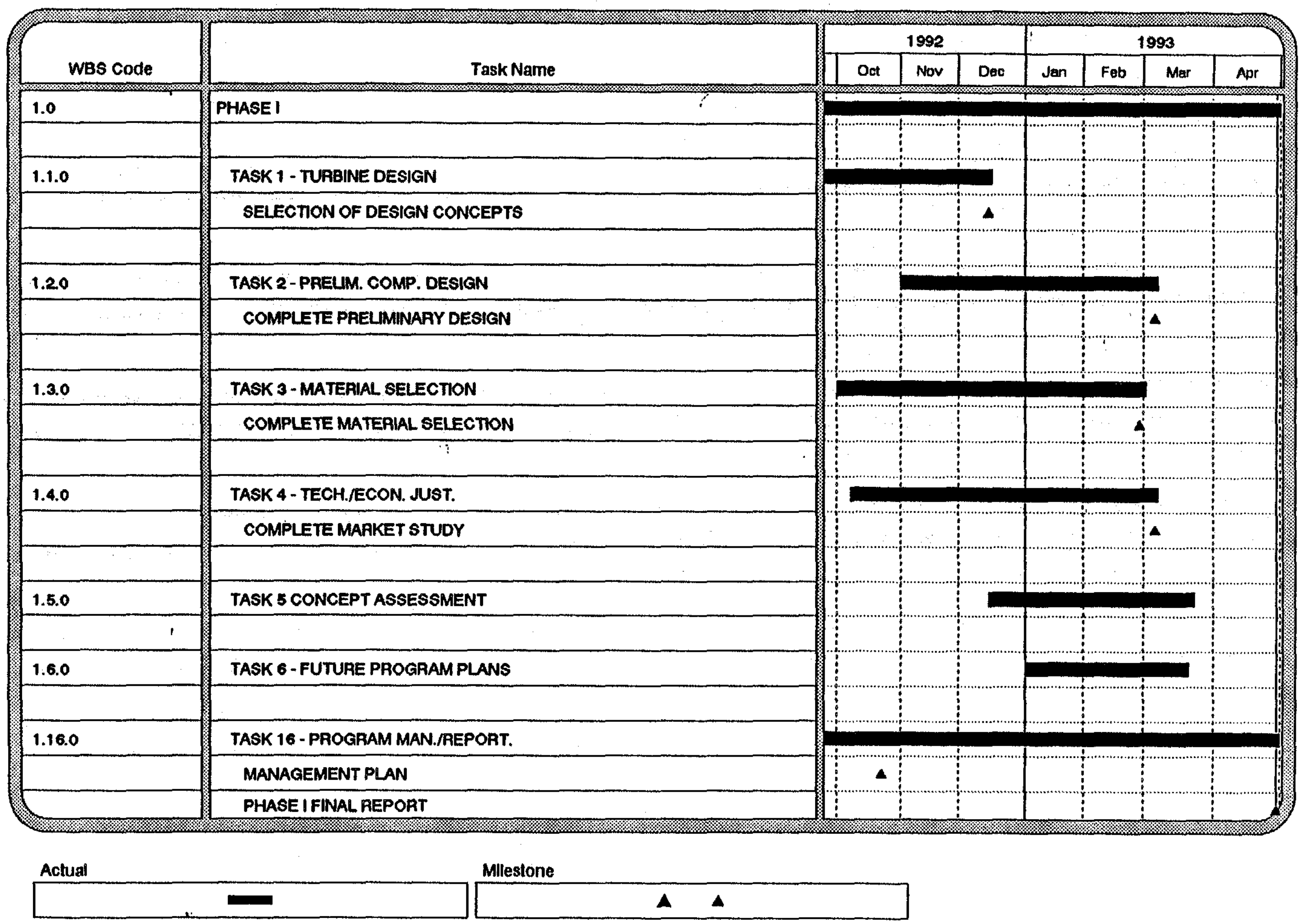

Figure 9-1. Phase I Timeline Bar Chart