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CERAMIC COMPOSITES FOR INDUSTRIAL GAS TURBINE ENGINE APPLICATIONS: DOE CFCC PHASE 1 EVALUATIONS

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ABSTRACT

Conceptual design evaluations of the use of continuous fiber ceramic composite (CFCC) turbine shrouds and combustor liners in an industrial gas turbine engine were performed under Phase 1 of the DOE CFCC program. Significant engine performance improvements were predicted with the use of CFCC components. Five composite systems were evaluated for use as shrouds and combustor liners, the results of which are discussed with particular reference to Toughened Silcomp. Several current CFCC materials were judged to be relatively close to meeting the short term performance requirements of such a system. However, additional CFCC property data are required for significant component design optimization and life prediction, two key design steps that must be completed before ceramic composites can be utilized in large gas turbines.

INTRODUCTION

Continuous fiber ceramic composites (CFCCs) represent a relatively new class of materials which have the potential to incorporate the refractoriness and environmental stability of ceramics with the toughness and damage tolerance of composites. The increased toughness and damage tolerance of the CFCCs is expected to result in increased reliability of these materials compared to typically brittle monolithic ceramics, thereby making them suitable for a variety of new applications. Nevertheless, significant development of the material systems, fabrication processes, design and life prediction methodologies is still necessary before CFCC materials can be utilized to a significant extent.

This situation has been recognized by the U.S. Department of Energy, which is currently sponsoring work on CFCC development (Karnitz et.al. 1991). The purpose of the CFCC program is to aid in the development and commercialization of ceramic matrix composite materials in applications with significant potential for reducing energy consumption and pollutant emissions. An application which fits these criteria very well, and which is of business interest to GE, is the industrial gas turbine engine.

Those components which now require the greatest amount of compressor discharge air for cooling, such as first stage buckets, nozzles and shrouds, will likely provide the greatest benefits when ceramics are substituted for the current metal components. Other components which are expected to yield significant payoffs are the combustor liner and combustor to turbine transition piece. Currently all of these components are manufactured from superalloys, sometimes with thermal barrier coatings, and require aggressive air cooling to maintain metal temperature below 930°C (1700°F). The use of ceramic materials capable of operating at 1200°C (2200°F) or higher would greatly reduce the cooling air requirements. This would in turn allow more of the compressor discharge to be used for combustion and for performing work in the turbine, thereby increasing engine efficiency and decreasing pollutant emissions. The two specific turbine components selected for analysis in the CFCC program are the 1st stage turbine shroud and the combustor liner. This paper describes the preliminary evaluations performed under Phase 1 of the CFCC program as to the use of CFCC materials for these two components. Specific design analysis results are presented using Toughened Silcomp as the example material. Future material data needs, for Phase 2 of the CFCC program and beyond, are also described.

PHASE 1 RESULTS

Toughened Silcomp Development

A viable candidate CFCC material for use in these applications is Toughened Silcomp. This is a ceramic matrix composite material produced by melt infiltration of molten silicon metal into a porous, carbon-containing preform. The

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composite thus produced consists of a fully dense matrix of SiC and Si, reinforced with continuous SiC fibers. Moreover, the melt infiltration process is net shape (there are no dimensional changes during infiltration) and fast (objects several cm in size can be fully infiltrated in a matter of minutes). The fabrication and properties of Toughened Silcomp have been recently reviewed by Luthra, et. al. (1993) and Corman, et. al. (1994), so only a brief description is given here.

Toughened Silcomp can be processed by several methods using many different fibers and various preform constituents. Although the fabrication of various forms of Toughened Silcomp has been demonstrated, our greatest experience, by far, has been with Textron SCS-6 reinforced composites made by a tape lamination process. Prior to the CFCC program the tape fabrication process was practiced using batch CVD coated reinforcement fibers and a tape casting approach.

It is obvious that various changes would be required to the pre-CFCC program process to allow for effective scale-up and automation of composite fabrication. Other changes are desirable to improve the capabilities of the material. The material/process changes demonstrated during Phase 1 of the CFCC program are summarized in Table 1. Among the modifications demonstrated were 1) the development and use of a continuous fiber coating technology (done at Textron Specialty Materials) for BN-based fiber coatings to replace a labor-intensive batch process, 2) the use of an easily scalable drum winding technique for producing flat panels and cylindrical specimens, which replaced a more complicated tape casting process, 3) the incorporation of the smaller diameter (79 μm) SCS-9 fiber in place of the standard (142 μm) SCS-6 fiber for improved shape capability, and 4) the use of an alternate fiber coating, rather than BN, for improved oxidation resistance. Each of these modifications taken individually were found to improve the mechanical properties of the composite system over that of standard, pre-CFCC Toughened Silcomp. These modifications and their effects on composite properties can be summarized as follows:

- The development of the continuous fiber coatings and the drum winding technique allowed for an increase in fiber loading from 20 vol% up to 30 vol%, with a concurrent doubling of composite ultimate strength to over 60 ksi (400 MPa) at room temperature.
- Fabrication of SCS-9 reinforced composites by tape casting and/or drum winding gave substantial improvements in ultimate strength values with the strengths of some uniaxially reinforced specimens exceeding 100 ksi (690 MPa).
- The use of alternate fiber coatings raised the matrix cracking stress to over 20 ksi (140 MPa), a 40% improvement, and raised room temperature ultimate strengths to 50 ksi (350 MPa), a 60% improvement. Because of long-term oxidative degradation concerns, a high matrix cracking stress is considered to be crucial to the success of any CFCC component.

Component Requirements

Clearly the benefits to be derived by the use of CFCC components could be maximized through the complete design of an engine around the unique capabilities and limitations of these materials; however, such an undertaking was far beyond the scope of this program. This phase of the program focused on identifying and analyzing a specific engine system for which the CFCC components would be considered a retrofit or upgrade. The engine system chosen is the MS7001FA, a 160 MW turbine typically used for base load electric power generation (Brandt 1987). This engine contains 14 combustor assemblies, each of which utilizes a nominally 16" (40.6 cm) diameter by 36" (91.4 cm) long, cylindrical combustor liner. The first stage inner shroud assembly consists of 96 nominally 3"x5.7" (7.6 cm x 14.5 cm) sections arranged in an 8' (2.4 m) diameter ring which surrounds the first stage buckets. A cross sectional diagram of the hot section of the turbine, indicating the positions of the shroud and combustor liner, is shown in Figure 1. Also shown are other metallic components that could be replaced with CFCC materials in the future.

As will be shown below, the benefits to be realized by the use of CFCC shrouds and combustors are substantial and offer a strong incentive for the use of these materials. Nevertheless, introduction of any new material into industrial gas turbines has traditionally been slow because of undemonstrated reliability which is a serious concern to utility customers and engine manufacturers. Components of these engines must operate under very demanding conditions for long periods of time. In the case of CFCCs with reduced cooling, projected component surface temperatures are on the order of 1100° to 1300°C. Components must operate for 24,000 to 48,000 hours (3 to 6 years) under oxidizing and potentially corrosive conditions with minimal changes in strength, toughness or dimensions. During this time the components must withstand steady state thermal and structural tensile stresses which can be over 15 ksi (100 MPa) based on initial design calculations. In addition the components are designed to withstand up to 500 normal start-stop cycles (thermal cycles) and 35 load rejection (trip) cycles (emergency shut down of the turbine which effectively quenches the hot stage components from operating temperature to 450°C in a few seconds). Numerous other conditions must be met to ensure compatibility of the components with the overall turbine system. Assuring the reliability of any component under such conditions is extremely difficult, but of the utmost importance. The economic consequences of engine down time are so severe that no utility is willing to allow the introduction of "experimental materials" until their reliability has been proven.

Potential Benefits of CFCCs

Current first stage turbine shroud designs rely on coated nickel based super alloys (IN738), which are cooled using compressor discharge air in order to keep metal temperatures below ~930°C. Substitution of CFCC shrouds would allow a significant reduction in cooling air requirements, estimated to be equivalent to 1% of the compressor discharge. Since this air is not used for cooling it adds to the mass flow through the combustor and turbine, with two important consequences. First, the extra combustion air acts as a heat sink during combustion, thereby lowering the flame temperature. The formation of nitrogen oxides (NOx) by the thermal oxidation of molecular nitrogen is very sensitive to flame temperature. Based on laboratory testing, an additional flow of 0.5% of compressor discharge through the combustor is expected to cool the flame sufficiently to give a 10% to 25% reduction in NOx emissions. Thus for a 1% increase in combustor flow, as would be expected from reduced cooling of a CFCC shroud, even more significant reductions in NOx would be expected. Secondly, air not used for cooling the shroud would add to the mass flow traveling through the entire turbine section. The additional mass flow causes an increase in turbine efficiency which could be utilized to increase the turbine output power by 1% at the same fuel consumption, or reduce fuel consumption for the same power output. The economic consequences of the increased power and/or reduced fuel consumption would be a projected fuel cost savings of nearly $0.5M per year for a 160 MW machine.

The source of benefits for the use of a CFCC combustor liner are similar to those for the shroud. Current combustor liners are made from Hastelloy X with a thermal barrier coating and are extensively cooled by impingement and film cooling. The use of film cooling produces a low temperature zone near the combustor wall which quenches the combustion reaction. This quenched combustion in turn increases the formation of unburned hydrocarbons (UHC) and CO. Elimination of film cooling would substantially reduce UHC and CO emissions, though the amounts have not yet been quantitatively determined. Also, the air used for film cooling would now be used as combustion air, thereby reducing flame temperature and NOx emissions analogous to that described above for the shroud. Reduced requirements for film and impingement cooling air would also allow for enlargement of the combustor flow sleeve, which is currently used to direct and control cooling air flow. The enlargement of the flow sleeve would effectively give a reduced pressure drop through the combustor. It is estimated that the use of a CFCC combustor liner would allow for a 1.25% reduction in the pressure drop, resulting in a 0.75% increase in power output or a reduction of fuel consumption. Savings based on the higher output or reduced fuel consumption are expected to be nearly $0.4M per year in fuel costs for a 160 MW machine.

Conceptual Design Studies

Initial designs for both the shroud and combustor liner were developed and analyzed during Phase 1. Generation and analyses of the designs were greatly hampered by the lack of CFCC material data. Requests were made of each supplier (DOE CFCC prime contractors) for a set of measured material data, including elastic constants, strengths, cracking stresses, heat capacities, thermal expansivities, and thermal conductivities, at each of four different temperatures, necessary for performing thermal and elastic stress analyses of the shrouds. The responses varied greatly between suppliers with anywhere from 56% to less than 10% of the requested property data being available. For only four of the composite systems could the missing material property values be estimated using micromechanical models and/or engineering judgment. Because of the lack of, and uncertainty in, the material property data it was impractical to optimize the shroud and combustor designs for each CFCC material separately. Rather, only a single design was generated for each component. The appropriate material properties were then incorporated into the model and the thermo-mechanical response was calculated seperately for each of the four systems.

The CFCC shroud design mimics the metallic design in the flow path area and makes allowances for a modified mounting scheme. A schematic of the design is shown in Figure 2. The CFCC design is roughly a 7.6 cm x 14.5 cm (3"x5.7") rectangular dish 3 mm (1/8") thick with 1.3 cm (1/2") high side and end walls. There is some minor curvature to the major face in the radial (equivalent to a 3.75° section of a 2.4 m (8') diameter circle) and axial directions. Elongated holes in the side rails allow for mounting by hanging the shroud sections from metallic rods. Mounting using the double rod hangers allows for differential expansion of the CFCC inner shroud and metallic outer shroud and support structure without introducing structural loads onto the ceramic.

The combustor design chosen in Phase I was segmented in both the radial and axial directions, as shown in Figure 3. Individual tiles are 36° sections of a 40.6 cm (16") diameter cylinder, 12.7 cm (5") long and 3 mm (1/8") thick. Again, 1.3 cm (1/2") high side and/or end rails will be used for mounting to the superstructure.

Conceptual design evaluations of both the combustor and shroud were done using ANSYS finite element modeling (FEM). Only steady state, full load thermal, pressure and structural loads were considered. The analyses were done for two levels of cooling air flow; flow equivalent to that used for the current metallic designs, and a reduced cooling level (33% of metallic cooling air for the shroud and elimination of the flow sleeve for the combustor). Four material systems were studied for the shroud application, and three systems for the combustor liner.

Component surface temperatures and thermal gradients were generally found to scale with material thermal conductivity. For example, surface temperatures for the reduced cooling analyses of both the shroud and combustor are listed in Table 2. In both instances the temperatures are lowest for Toughened Silcomp, which has the highest thermal conductivity, and highest for the lowest thermal conductivity composite. In all cases the thermally induced stresses, which generally scale inversely with thermal conductivity, were found to predominate over the pressure and structural stresses.

In order to compare the analysis results from the different materials the areas of "high stress" for each mode of loading were first identified. The calculated stress levels in these areas were then compared to the material strength values at the appropriate temperature to determine a "margin of safety" (MOS), defined as

$$MOS(\%) = 100\left(\frac{\sigma_a - \sigma_c}{\sigma_c}\right)$$

where σ_a is the allowable stress level (based on material strength data) and σ_c is the calculated component stress from the FEM analyses (a negative MOS indicates that the calculated stress exceeds the material cracking stress). Table 3 gives the results of the shroud stress analyses for Toughened Silcomp under full cooling and reduced cooling conditions. Two sets of allowable stress levels are listed in Table 3. The first set are based on the materials properties of Toughened Silcomp prior to the start of the CFCC program and the second set are for the improved system as described above.

The stress analyses for both components indicate that Toughened Silcomp would be able to withstand the predicted stresses under full cooling conditions in the current shroud design. In fact, material improvements made during the CFCC program allowed Toughened Silcomp to meet the design stress requirements even under reduced cooling conditions.

As explained previously, the component designs were not optimized for any particular material system. It is likely that the design stress levels can be reduced with further design optimization taking into account the strengths and weaknesses of each material system. It should also be noted that the allowable stress levels used in all MOS calculations are based on average cracking stresses for the composites in the as-fabricated state. Consequently the existence of thermal, mechanical or oxidative degradation and their potential impact on component life have not been considered. Other time dependent properties, such as creep, creep rupture and cyclic fatigue, also need to be evaluated. Likewise, the extent of material/property variability and its impact on the allowable stress levels need to be examined.

FUTURE MATERIAL DATA NEEDS

Materials Data for Gas Turbine Design and Manufacturing

The design engineering process for new hardware involves three major phases: Conceptual Design, Preliminary Design, and Detailed Design. Conceptual Design answers the question, "If these new materials can be made to work, what value do they add to our product?" CFCC Phase 1 was a Conceptual Design effort and provided a first approximation of the benefits of substituting shroud and combustor liners made from ceramic composites. These studies were conducted using available measured or estimated material properties. Examples of the engineering compromises often made during Conceptual Design are the assumptions that 1) properties in a complex shaped part will be the same and as uniform as properties from a flat test panel coupon, and 2) properties and microstructure of a part in service are well represented by a short duration test specimen. No attempt is made to predict life or address durability changes associated with the new materials. Assumptions and missing data add risk to this phase of the design process.

Preliminary Design is also a paper study that answers the questions, "Can we use the new material in our existing and new hardware, and if so, how will this change affect manufacturing operations, the rest of the assembly (including total cost), and customer operations and maintenance?" Additional data representing real parts made in real manufacturing facilities and operating under real service conditions are required to increase the validity of preliminary design studies. The data are used to establish design limits and provide material property curves that can be used for additional preliminary design studies. Success depends strongly on teamwork and communications between design engineering, materials engineering, internal manufacturing, and supplier manufacturing.

Detailed Design involves designing a part which can be produced reliably and economically from the new material, optimizing its use for a specific, well defined application. Here, too, risks to the users and customers are inversely proportional to the quality, quantity, and consistency of materials property and manufacturing process control data.

Engineers use three major analyses in each of the design phases. The first step predicts temperatures and stresses, and data inputs are fundamental material properties like Young's modulus (E), shear modulus (G), Poisson's ratio (μ), thermal expansion coefficient (a), and thermal conductivity (k) in all directions. Stress analyses can be performed with finite element modeling and other conventional design tools. The second analysis predicts whether a part will survive for a short period of time, requiring the engineer to evaluate the calculated stresses and temperatures against strength data, again measured or estimated in all directions and at appropriate temperatures. Micromechanical models to estimate behavior of complex parts may be used here. The third analysis focuses on durability, a life prediction based on low and high cycle fatigue properties, crack growth behavior, and compositional, microstructural, and property changes resulting from the service environment. Life prediction is the least studied design methodology, requiring extensive simulated component testing in rigs that closely approximate real service conditions.

We have shown that design engineers need a variety of data to complete their job. Confidence in the results increases with the quantity and quality of data, but these data have been limited by time and financial resources and the lack of standardized test methods for ceramic composites. Quantity depends on cost and number of individual tests that can be done with available resources. The simple fact that ceramic composites are anisotropic means that the number of tests required to characterize a batch of material may be three or four times greater than that required to evaluate a new, but isotropic, material. Quality, especially of data measured on coupons cut from panels, depends on how closely the panels represent complex shapes with varying section thicknesses and other dimensions. Composition, microstructure, and properties depend on manufacturing process history of a part, and these correlations are still being developed for CFCCs. Ceramic composites are engineered materials whose behavior can be predicted and tailored using micromechanical models, but these tools still need refinement, calibration, and validation with experimental results. The lack of data to support hardware design limits the rate at which ceramic composites will be applied in real products. Phase 2 of the CFCC program will provide some of the data required for additional Conceptual and Preliminary Design work on potential gas turbine applications.

CFCC Phase 2 Test Plans

Various material testing activities are planned for Phase 2 of the CFCC program. In the case of Toughened Silcomp these activities include both generic material property testing and tests specific to the shroud component. Primary emphasis will be on generating data needed for future component design optimization, such as high temperature tensile, compressive and shear strengths and elastic moduli. Initial evaluations of time-dependent mechanical behavior will be performed using tests such as low cycle and high cycle fatigue, creep and creep rupture, stressed thermal cycling and unstressed thermal aging. Such testing will constitute a first attempt at identifying the probable long-term failure modes of the CFCC materials; however, the results of these tests are not expected to be sufficient to allow for detailed mechanical modeling or component life prediction.

Various tests of representative component parts will also be needed to ensure that the components are behaving as expected based on the mechanical and thermal analyses. These tests will include rig testing under static and thermal cycling conditions, mechanical fatigue testing and static load testing, all performed on representative shroud components.

SUMMARY

Conceptual design evaluations of CFCC materials for use as gas turbine first stage shrouds and combustor liners are very promising. The potential economic benefit of using CFCC materials for these components, relative to current TBC-coated superalloy technology, were estimated to be over $0.8M per year in reduced fuel costs for a 160MW machine. Additional reductions in NOx and UHC emissions are expected. Initial design analyses indicate that several CFCC materials are close to meeting the short-term mechanical property requirements for these components. For instance, the mechanical properties of Toughened Silcomp were shown to exceed the expected stresses at the predicted temperatures of the shroud even under reduced cooling conditions. However, additional design optimization and material improvements are needed for all of the CFCC candidates to increase the margins between the material properties and the expected component stresses. A major obstacle to further design optimization and eventual utilization of these materials is the lack of materials property data, particularly following long-term thermal exposure under stress.

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TABLE 1. MATERIAL AND PROCESS CHANGES IMPLEMENTED IN THE PHASE I CFCC PROGRAM.

Characteristic	Pre-CFCC Silcomp	Phase I Modifications
Fiber	SCS-6	SCS-6 and SCS-9
Matrix	60%SiC, 25% Si, 15%C	60%SiC, 25% Si, 15%C or 75%SiC, 15%Si, 10%C
Fiber Coating	BN-based, batch CVD process	BN-based by batch or continuous CVD, alternate and layered BN-alternate coatings by batch CVD
Preform Fabrication Techniques	Tape casting and lamination; slurry casting	Tape casting and lamination; drum winding of tapes and lamination; drum winding of multilayer cylinders
Shapes Demonstrated	Flat panels	Flat panels and cylinders

TABLE 2. PROJECTED MAXIMUM SURFACE TEMPERATURES FOR A GAS TURBINE SHROUD AND COMBUSTOR LINER UNDER REDUCED COOLING CONDITIONS

System	Through Thickness Thermal Conductivity* ($W\,m^{-1}\,K^{-1}$)	Shroud Maximum Surface Temperature (°C)	Combustor Maximum Surface Temperature (°C)
Toughened Silcomp Si/SiC-SiC	18.9	1132	1026
CFCC Material A	3.4	1301	1121
CFCC Material B	7.3	1182	1057
CFCC Material C	4.2	1258	-

* Reported values at 1204°C.

TABLE 3. RESULTS OF ANSYS FEM ANALYSIS OF A TOUGHENED SILCOMP CFCC SHROUD UNDER FULL COOLING AND REDUCED COOLING AIR FLOW CONDITIONS.

				Based on Pre-CFCC Properties		Based on Improved Properties from the CFCC Program	
Location	Temp. °C	Type of Loading*	Calculated Stress ksi (MPa)	Allowable† Stress ksi (MPa)	Margin Safety %	Allowable† Stress ksi (MPa)	Margin of Safety %
Full Cooling Flow Condition							
1	1085	IPC	-29.0 (-200)	-74.0 (-510)	+155		
2	565	IPT	11.6 (80)	14.0 (97)	+20.7	20.3 (140)	+75.0
3	760	IPT	12.0 (83)	13.0 (90)	+8.3	19.9 (137)	+65.8
4	890	IPC	-14.4 (-99)	-74.0 (-510)	+413		
5	695	IPT	10.4 (72)	11.5 (79)	+10.6	20.0 (138)	+92.3
6	650	IPS	9.8 (68)	15.2 (105)	+55.1		
7	870	IPS	12.0 (83)	15.5 (107)	+29.2		
8	760	ILT	5.0 (34)	8.0 (55)	+60.0		
9	705	ILS	7.0 (48)	7.8 (54)	+11.4		
Reduced (33%) Cooling Flow Condition							
1	1095	IPC	-22.0 (-152)	-74.0 (-510)	+236		
2	1130	IPT	14.1 (97)	13.0 (90)	-7.8	17.7 (122)	+25.5
3	760	IPT	16.0 (110)	13.6 (94)	-14.5	19.9 (137)	+24.4
4	900	IPC	-13.0 (-90)	-74.0 (-510)	+469		
5	705	IPT	10.9 (75)	11.5 (79)	+5.5	20.0 (138)	+83.5
6	650	IPS	11.1 (77)	15.2 (105)	+36.9		
7	900	IPS	13.8 (83)	15.5 (107)	+12.3		
8	925	ILT	5.0 (34)	8.0 (55)	+60.0		
9	875	ILS	3.0 (21)	7.8 (54)	+160		

* IPT – in-plane tension; IPC – in-plane compression; ILT – interlaminar tension; ILS – interlaminar shear; IPS – in-plane shear

† Average material cracking stress for the appropriate loading condition.

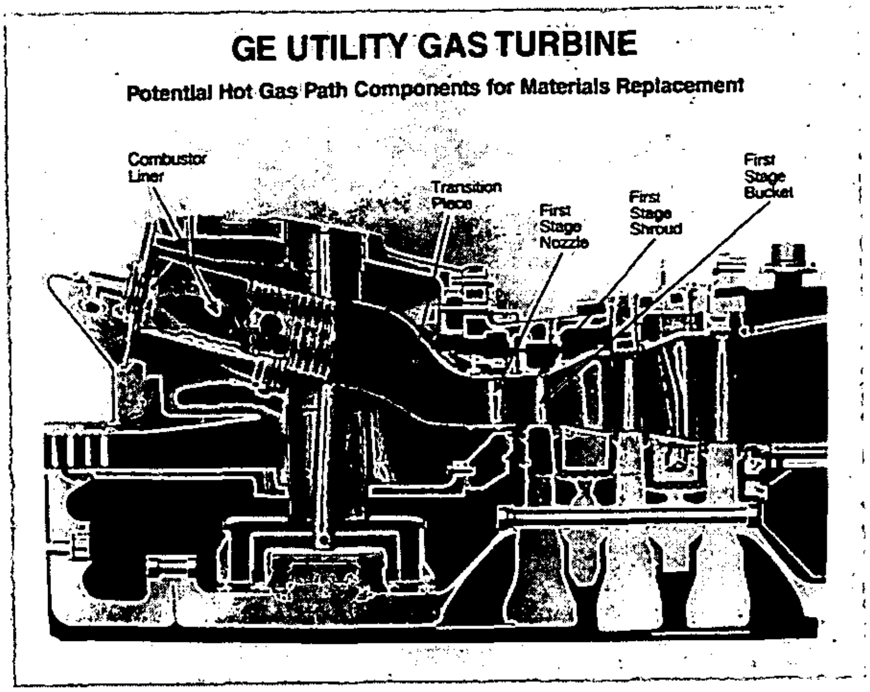

FIGURE 1. CROSS SECTION OF THE HOT GAS COMPONENTS OF AN MS7001FA INDUSTRIAL GAS TURBINE SHOWING THE POSITIONS OF THE COMBUSTOR LINER AND 1ST STAGE SHROUD.

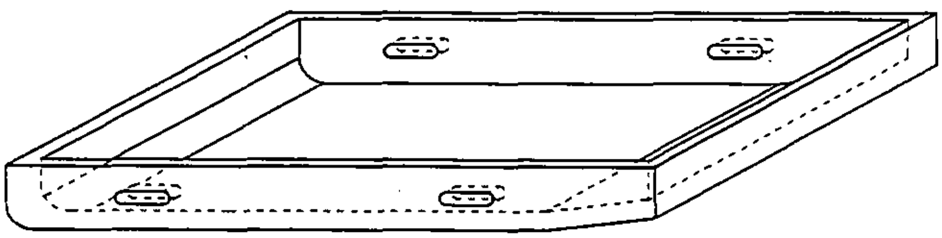

FIGURE 2. SCHEMATIC OF A CONCEPTUAL CFCC SHROUD SEGMENT DESIGN.

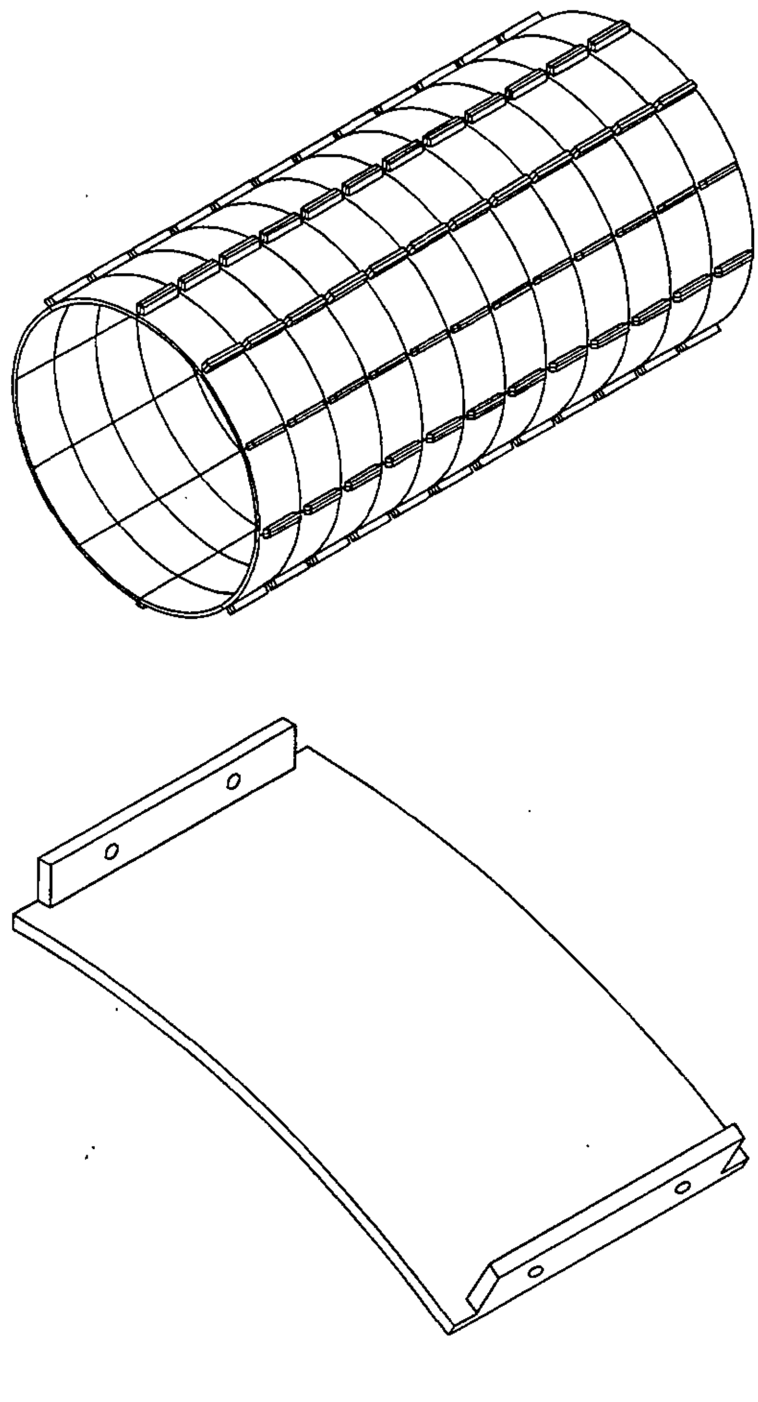

FIGURE 3. SCHEMATIC OF THE CFCC COMBUSTOR LINER DESIGN.
TOP: FULL COMBUSTOR LINER
BOTTOM: INDIVIDUAL TILE