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CONTINUOUS FIBER CERAMIC COMPOSITE (CFCC) PROGRAM

Inventory of Federally Funded CFCC R&D Projects

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INTRODUCTION

Continuous Fiber Ceramic Composites (CFCC) are a new class of materials that are lighter, stronger, more corrosion resistant, and capable of performing at elevated temperatures. This new type of material offers the potential to meet the demands of a variety of industrial, military, and aerospace applications. The Department of Energy Office of Industrial Technologies (OIT) has a new program on CFCCs for industrial applications and this program has requested an inventory of all federal projects on CFCCs that relate to their new program. The purpose of this project is to identify all other ongoing CFCC research to avoid redundancy in the OIT Program. The inventory will be used as a basis for coordinating with the other ongoing ceramic composite projects.

The National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), the U.S. Bureau of Mines, the National Institute of Standards and Technology (NIST), and the National Science Foundation (NSF) are all active in the development of advanced ceramics.¹⁻⁶ More recently, NASA and DOD have begun broad programs to develop materials for military and aerospace applications which include a continuous fiber ceramic composite development component.

The activities conducted in these programs are both complementary and important to the successful development of CFCCs for industrial applications. The three main efforts that relate to OIT's Program are the NASA-Advanced High Temperature Engine Materials Technology Program (HITEMP) and the DOD-Integrated High Performance Turbine Engine Technology (IHPTET), and the National Aerospace Plane (NASP) Program.

The HITEMP Program is targeted at aerospace applications for both airframe materials and propulsion components.⁷⁻⁸ The objectives of the program include feasibility demonstrations of advanced composite materials, validation of new structural analysis models, and testing methods. The program encompasses the metal, intermetallic, ceramic, and polymeric composite materials for both military and civilian aircraft. The objective of the work being conducted on continuous fiber composites is the identification of materials and processing approaches for reliable and durable composite microstructures. Research is focused on the selection, development, and integration of the prime constituents for these microstructures: fibers, matrix, and interfaces. Once this goal is achieved, efforts will move into developing reliable macrostructures as required by specific structural environmental conditions of airplane engines.

The other major programs that include continuous fiber ceramic composites are the DOD-IHPTET and NASP Programs. The main emphasis of these programs are developing materials to be used in components for ultrahigh temperature applications. However, there is an area of the IHPTET Program with a different perspective. Ceramic composites are expected to have a major role at temperatures less than 1650°C, and an additional program investment in composite development of intermediate temperature systems is anticipated. DOE's CFCC Program is not targeted at the ultrahigh temperatures, but would benefit from ongoing work of the intermediate temperature IHPTET Program.

Although the CFCC Program intends to identify and incorporate the relevant activities conducted under the existing military and aerospace programs, it does have a different focus and technology agenda. Military and aerospace applications are performance driven as opposed to cost driven.

Inventory of Federal Funded CFCC R&D Projects

Materials and processes are selected on the basis of their ability to deliver specialized properties, often in limited quantities. Industrial applications on the other hand, are highly sensitive to cost. The processing technologies must focus on techniques that can meet demanding economic targets and high production rates. The performance requirements of industrial applications are also considerably different and the interrelationships among processing, microstructure, and performance drive the selection of different processing routes. However, it is important that the activities under the DOE's CFCC Program be coordinated and complement those of related federally funded military and aerospace programs. Much of the specialized material analysis techniques that have been developed, which are necessary to provide chemical, microstructural, and property information, are expensive and exist primarily at government laboratories and selected universities. The government, by actively coordinating these activities and ensuring an effective relationship with other federal military and aerospace programs, can realize the most cost-effective and efficient development of CFCC technologies. This project inventory is one step in the process of coordinating federal activities to the CFCC Programs.

ORGANIZATION OF INVENTORY

The Inventory of Continuous Fiber Ceramic Composite (CFCC) Projects is a collection of descriptions of federally funded research and development projects concerned with CFCCs. Project descriptions are arranged in the inventory by category. Within each category the project descriptions are ordered alphabetically by the sponsor and then by the research organization.

The inventory is divided into two main parts. The first part is concerned with CFCC supporting technologies projects and is organized by the categories listed below.

Composite Design	Mechanical Properties
Materials Characterization	Database Life Prediction
Test Methods	Fracture/Damage
Non-Destructive Evaluation	Joining
Environmental Effects	

The second part has information on component development, fabrication, and fiber-related projects and is arranged by:

Application Assessment	Fibers Development
Component Development	Fiber Coatings
Fabrication & Processing Technology	

Each of these sections contains project descriptions (See Fig. 1), indexes, and a summary table of additional projects where only limited information such as title and research organization are available. The questionnaire that was used to solicit project information is listed in the appendix.

The Inventory of CFCC Projects is stored on a microcomputer database management system. The information can be searched and summarized in a variety of ways to meet different needs.

Inventory of Federal Funded CFCC R&D Projects

Individual Project Descriptions

Each research project description is identified by its own record identification number, which appears immediately above the project title. A project description may contain the information listed in Fig. 1. This information is included in the inventory whenever it is available.

<p style="text-align: right;">**CFCC CATEGORY**</p> <p><RECORD NUMBER: 13> A record identification number that is listed sequentially.</p> <p>TITLE: The title of the research project.</p> <p>PROJECT DURATION: Time during which research is conducted.</p> <p>PRINCIPAL INVESTIGATOR(s): Name, phone number of person in charge of research project.</p> <p>RESEARCH ORGANIZATION(s): The affiliation and address of the principal investigator.</p> <p>SPONSOR: Source of the federal dollars supporting the research project.</p> <p>OBJECTIVE: The goals or purpose of this research project.</p> <p>DESCRIPTION: The outline and direction of the project.</p> <p>TECHNICAL PROGRESS: The knowledge gained to date from the research project.</p> <p>MILESTONE SCHEDULE (TASKS): Description of key steps or products in research project.</p>
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Fig. 1. Information contained in a research project description.

Indexes

Indexes use the sequential record numbers for identification purposes. Indexes included in this inventory are:

- INDEX OF RESEARCH ORGANIZATIONS AND PRINCIPAL INVESTIGATORS.
Under the name of each research organization, listed in alphabetical order, appear the names of the principal investigators and record identification numbers.

Inventory of Federal Funded CFCC R&D Projects

- INDEX OF SPONSORS AND RESEARCH PROJECT TITLES.

Under each sponsor listed in alphabetical order, are the titles of the research projects funded by that sponsor and the corresponding record identification number.

- INDEX OF KEYWORDS.

This lists the keywords describing each project and the corresponding record identification numbers.

- INDEX OF MATERIALS.

This lists the materials used/described by each project and the corresponding record identification number.

REFERENCES

1. R. Rensbergen, "Advanced Ceramics: The NBS Research Effort," *Ceramic Bulletin*, **67**(8), 1302-4, 1988.
2. J. W. McCauley and D. J. Viechnicki, "Ceramics R&D at the U.S. Army Materials Technology Lab," *Ceramic Bulletin*, **67**(8), 1340-4, 1988.
3. H. Heystek, "Ceramic Research at the U.S. Bureau of Mines," *Ceramic Bulletin*, **67**(8), 1345-8, 1988.
4. D. Lewis, III, "Research in Ceramics at the U.S. Naval Research Lab," *Ceramic Bulletin*, **67**(8), 1349-56, 1988.
5. P. C. Maxwell, "Congressional Perspective on Advanced Materials," *Ceramic Bulletin*, **67**(8), 1357-9, 1988.
6. A. P. Katz and R. J. Kerans, "Structural Ceramics Program at AFWAL Materials Lab," *Ceramic Bulletin*, **67**(8), 1360-6, 1988.
7. *Ceramic Technology for Advanced heat Engines Program Plan*, **ORNL/TM-8896**, ORNL, June 1984.
8. *HITEMP Review 1988, Advanced High Temperature Engine Materials Technology Program*, NASA Conference Publication **10025**, November 1988.

CFCC Supporting Technologies Projects

**** COMPOSITE DESIGN ****

<RECCRD NUMBER: 1>

TITLE: Macromechanics

PROJECT DURATION: Start FY 1992

PRINCIPAL INVESTIGATOR(s): B. Walter Rosen (215-542-8400)

RESEARCH ORGANIZATION(s): Material Science Corporation, 930 Harvest Drive, Bleu Bell, PA 19422

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Macromechanics subtask is to develop the necessary modeling capability at the macrostructural level for CFCCs. The project will focus on understanding the relationship between fiber architecture and mechanical behavior in two- and three-dimensional CFCC material systems.

DESCRIPTION

This project will include modeling of two-dimensional laminated composites, in which individual layers (plies) of different fiber orientations are stacked to produce a laminated plate with the required properties. The modeling of three-dimensionally woven composites will also be studied in this program using a "unit-cell" approach. The modeling to be performed in this subtask will be closely coordinated with the thermomechanical testing portion of the program (Subtask 2.3.1) since test data will be required in order to guide the modeling effort and to verify the models when they are completed. This subtask will utilize structural analysis techniques, including finite element methods, to enable the analysis of CFCC components. The goal of this subtask is to support Task 3 (Materials and Process Development) by developing suitable structural design methodologies for components composed of CFCCs.

TECHNICAL PROGRESS

FY 1992 - Modeling of the macromechanical behavior of two-dimensional CFCC laminates will be initiated in FY 1992. Existing macromechanical models for composite laminates will be studied to determine their suitability for CFCC materials.

FY 1993 - Validation of the two-dimensional models for CFCC materials will be completed in the early portion of FY 1993. Macromechanical models for three-dimensional woven and braided CFCC materials will also be developed in FY 1993.

MILESTONE SCHEDULE (TASKS)

Complete technical assessment of macromechanical models and structural representations. TBD
Complete macromechanical modeling of two-dimensionally reinforced CFCC laminates. TBD
Complete experimental validation and refinement of macromechanical laminate models. TBD
Complete macromechanical modeling of three-dimensionally reinforced CFCC structures. TBD
Complete experimental validation and refinement of three-dimensional structural models. TBD

**** COMPOSITE DESIGN ****

<RECORD NUMBER: 2>

TITLE: Micromechanical Modeling

PROJECT DURATION: February 1991 through September 1993

PRINCIPAL INVESTIGATOR(s): H. Thomas Hahn (814-863-0997)

RESEARCH ORGANIZATION(s): Pennsylvania State University, 227 Hammond Building,
University Park, PA 16802

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Micromechanical Modeling subtask is to develop necessary modeling capability at the microstructural level. This effort will include modeling of the interaction among composite constituents--the fibers, the matrix, and the fiber-matrix interface region.

DESCRIPTION

This modeling effort will support the materials development of CFCCs by providing insight into the effect of constituent properties on the mechanical behavior of the final composite material. This subtask will utilize various micromechanical modeling techniques, including finite element methods, to enable the analysis of CFCC material behavior. The goal of this subtask is to support Task 3 (Materials and Process Development) by developing suitable design methodologies for CFCCs.

TECHNICAL PROGRESS

FY 1992 - Existing micromechanical models for composite material systems will be studied to determine their suitability for CFCC materials.

FY 1993 - It is expected that this work will include further study of the fiber-matrix interface and the development of constitutive models for three-dimensionally reinforced CFCC systems. Experimental validation of appropriate models may also take place in FY 1993.

MILESTONE SCHEDULE (TASKS)

Complete state-of-the-art survey and technical assessment of existing micromechanical models.
10/91

Develop study plan for micromechanical modeling of CFCC systems. 11/91

Complete initial development of improved micromechanical models for CFCC systems. 8/92

**** COMPOSITE DESIGN ****

<RECORD NUMBER: 3>

TITLE: Finite Element Models for 3D Ceramic Matrix Composites

PROJECT DURATION: 1991 through present

PRINCIPAL INVESTIGATOR(s): A. Starlinger (216-433-6510)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center (Aero Base Funding)

OBJECTIVE

To develop a pre-processor algorithm for finite element codes that determines stiffness properties of 3D woven or braided CMCs. The algorithm will account for temperature dependence. Effects of matrix and/or fiber failure on local stiffness terms will also be evaluated.

DESCRIPTION

The project includes the following tasks--1) formulation of various models to describe temperature dependent stiffness properties of 3D CMCs; 2) implementation of these models into a pre-processor program; 3) formulation of macroscopic failure models; 4) introduction of stiffness update procedures to account for failure effects; 5) comparison of finite element predictions to experimental data.

TECHNICAL PROGRESS

Literature survey underway on 3D woven and braided CMCs; stiffness models being formulated.

MILESTONE SCHEDULE (TASKS)

Models to be implemented into a pre-processor program. Finite element results will be compared to experimental data. Failure criteria for 3D woven and braided CMCs will be investigated and selected for code implementation. FY 1993

Appropriate failure criteria will be implemented into selected finite element programs. In case of local failure, the stiffness terms will be updated. The program predictions will be compared to benchmark experimental data. FY 1994

<RECORD NUMBER: 4>

TITLE: Modeling of Fracture Processes in Fiber Reinforced Ceramics

PROJECT DURATION: 1989 through present

PRINCIPAL INVESTIGATOR(s): Asher A. Rubinstein (504-865-5771)

RESEARCH ORGANIZATION(s): Tulane University, Mechanical Engineering Department,
New Orleans, LA 70118

SPONSOR: NASA-Lewis Research Center (Aero Base Funding)

OBJECTIVE

To develop theoretical models capable of analyzing failure processes in CMCs.

DESCRIPTION

The model will use linear and nonlinear fiber/matrix interface friction, and process zone formation by fiber intersection with crack surfaces near crack tips to relate initial matrix cracking stress to composite parameters such as fiber/matrix aspect ratio and interface friction.

TECHNICAL PROGRESS

A model was developed representing a crack growing transverse to the fibers, reflecting fiber bridging effects near the crack tip. Both linear and nonlinear interface friction effects were included.

MILESTONE SCHEDULE (TASKS)

Extension of the developed model to initial matrix cracking case and relate applied stress and fiber spacing to composite strength. Examine cases of pre-existing long cracks bridged by fibers that fail randomly, and evaluate effects on consequently matrix cracking. Additional studies of effects associated with nonlinear fiber/matrix interface friction.

**** COMPOSITE DESIGN ****

<RECORD NUMBER: 5>

TITLE: Structural Modeling of a Continuous Fiber Ceramic Matrix Composite Combustor

PROJECT DURATION: 24 months

PRINCIPAL INVESTIGATOR(s): Chris C. Chamis (216-433-3252)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (EPM)

OBJECTIVE

Develop software programs to computationally simulate the structural performance of a CMC component.

DESCRIPTION

Modify existing computer codes and other pertinent methods into an integrated system capable of modeling CMC components. Technical tasks will include geometric modeling, structural/thermal analysis and parametric design studies. This independent research activity is conducted as an alternate concept to EPM critical path research.

TECHNICAL PROGRESS

Team responsibilities assigned, potential problem area identification begun, preliminary material properties and component geometries selected.

MILESTONE SCHEDULE (TASKS)

Complete modeling studies. 1/93

Trade studies completed. 5/93

**** COMPOSITE DESIGN ****

<RECORD NUMBER: 6>

TITLE: Fracture Mechanics of Ceramic Matrix Composites

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): Roberto Ballerini (216-368-2963)

RESEARCH ORGANIZATION(s): Case Western Reserve University, Civil Engineering
Department, Cleveland, OH 44106

SPONSOR: NASA-Lewis Research Center (Generic Hypersonics Program)

OBJECTIVE

To develop an analytical model of the fracture characteristics of laminated fiber reinforced CMC test specimens and components.

DESCRIPTION

Analytical models will be developed that provide information about the effects of several microstructural variables, including fiber diameter, fiber spacing, and ply thickness on the structural integrity of laminated composite structures.

TECHNICAL PROGRESS

Techniques were developed for solving elastostatic problems involving cracks at or near bimaterial interfaces of unidirectionally fiber reinforced CMCs. The method can be generalized to treat cracks at or near the interface between anisotropic materials.

MILESTONE SCHEDULE (TASKS)

Crack growth, crack stability, and structural response in laminated CMC components will be addressed. Components containing delamination and intralaminar cracks will be investigated. FY 1992

A micromechanical model of the delamination problem will be used to investigate the response of a unit cell consisting of fibers embedded in a matrix bonded to a unit cell of anisotropic material subjected to various load conditions. The effects of fiber diameter and spacing on a delamination will be determined. FY 1993

Extend the finite element and integral equation method to calculate stiffness, stress intensity factors, and energy release rates. FY 1993

**** COMPOSITE DESIGN ****

<RECORD NUMBER: 7>

TITLE: Development of Boundary Element Methods for Ceramic Composites

PROJECT DURATION: 1988 through 1993

PRINCIPAL INVESTIGATOR(s): Prasanta K. Banerjee (716-636-2332)

RESEARCH ORGANIZATION(s): State University of New York at Buffalo

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To provide more effective thermostructural analyses for advanced high temperature composite materials of interest for propulsion applications. Particular emphasis is on accurate representations of constituent variables governing composite behavior, and to enable practical and efficient representations of engine scale variables governing realistic component structural performance.

DESCRIPTION

The behavior of advanced composites and structures made from them in the engine systems environment can only be understood when that behavior is interpreted using micromechanical analyses. The overall approach is to develop specialized boundary integral equations and associated boundary element method implementations.

TECHNICAL PROGRESS

Formulations and implementations have been completed for analysis capabilities in: elastostatic, steady heat conduction; uncoupled thermoelastic, transient heat conduction; and uncoupled thermoelastic and nonlinear interface behavior. Analysis capabilities are embodied in the BEST-CMS (Boundary Element Solution Technology--Composite Modeling System) computational tool.

MILESTONE SCHEDULE (TASKS)

Elastoplastic fiber and elastoplastic-creep matrix constitutive behavior and fracture representation to be completed. Enhanced nonlinear analysis algorithms to be incorporated. FY 1992

Steady and transient elastodynamic and free vibration analysis capability to be completed.

Thermoplastic-creep constitutive behavior to be incorporated. FY 1993

**** COMPOSITE DESIGN ****

<RECORD NUMBER: 8>

TITLE: Development of CMC Analyzer (CEMCAN) Computer Code

PROJECT DURATION: Through FY 1992

PRINCIPAL INVESTIGATOR(s): Pappu L.N. Murthy
Subodh Mital

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center
University of Toledo

SPONSOR: NASA-Lewis Research Center (in-house, base R&T project))

OBJECTIVE

Develop analysis and modeling capabilities for ceramic matrix composites (CEMCAN).

DESCRIPTION

A unique fiber substructuring concept is used to develop micromechanics equations for CMCs and embedded in the Ceramic Matrix Composite Analyzer (CEMCAN) code.

TECHNICAL PROGRESS

The computer code can presently handle ply level, laminate level, and individual slice level properties and response. A behavior model accounting for nonlinear elasticity of the constituents needs to be incorporated.

MILESTONE SCHEDULE (TASKS)

Compared CEMCAN predictions for SiC/RBSN composite with experimental results.

Complete micromechanics at slice and ply levels, integrate to obtain laminate level properties.
9/92

Complete material behavior model, microstress computations. 1/93

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 9>

TITLE: Design, Analysis & Fabrication of Innovative High Temperature Structural Composites

PRINCIPAL INVESTIGATOR(s): G.J. Dvorak (518-276-6940)

RESEARCH ORGANIZATION(s): Rensselaer Polytechnic Institute, Department of Materials Science, Troy, NY 12180-3590

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

The identification of potential high temperature composite systems; development of new materials and processing routes for fibers, matrices and composites (CMCs and IMCs); understanding thermomechanical behavior of these composites at both macro-and micro-mechanical levels using combined theoretical and experimental approaches.

DESCRIPTION

Evaluations of the high temperature chemical stability, volatility and reactivity were to be developed, as were lifetime prediction models for IMCs, MMCs. Examination of CMCs reinforced with coated C fibers possessing varying morphologies.

TECHNICAL PROGRESS

Thermodynamic calculations made of compatibility of C, SiC, and Si_3N_4 with several oxides and diborides. New chemical precursors to SiC and AlN were under study.

New fiber creep testing facility outline.

Microlaminated matrix ceramic composites (SiC/C on Nicalon preforms) under study.
Micromodeling of stresses in CMCs underway.

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 10>

TITLE: Interfaces and Mechanical Properties of Continuous Fiber-Reinforced Ceramic Composites

PROJECT DURATION: 1987 through present

PRINCIPAL INVESTIGATOR(s): Richard A. Lowden (615-574-6918)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6063

SPONSOR: DOE/Fossil Energy AR&TD Materials Program

OBJECTIVE

The objective of this task is to examine fiber-matrix interfaces and optimize the mechanical behavior of continuous fiber-reinforced ceramic composites fabricated utilizing a forced-flow, thermal-gradient chemical vapor infiltration and deposition technique.

DESCRIPTION

This project will demonstrate that the interfacial bond between Nicalon fibers and various ceramic matrices can be measured and controlled for optimization of mechanical properties such as strength and toughness. The technical approach to be followed during this project includes four tasks: (1) develop interface characterization techniques, (2) develop bond strength measurement techniques, (3) determine candidate overcoat compositions and develop or contract for overcoating of fibers, and (4) characterize composites and correlate fiber-matrix interfacial forces with mechanical properties and fracture behavior.

TECHNICAL PROGRESS

FY 1992 - The investigation of alternate interlayers and the oxidation behavior of composites fabricated using the same will continue. The effects of oxidation on the interface and mechanical properties will be examined.

FY 1993 - The investigation of influence of carbon coating modulus and structure on the properties of the interface and Nicalon fiber-reinforced SiC will continue. Interfaces in composites with alternate fiber and matrix combinations will also be examined. (eg. Nicalon/silicon nitride, Nicalon/TiB₂, Altex/mullite, etc.)

MILESTONE SCHEDULE (TASKS)

Examine alternate interlayers with improved oxidation/corrosion resistance for fossil fuel applications. 12/91

Submit a paper for open literature publication summarizing the investigation of alternate interlayer compositions for Nicalon/SiC composites. 5/92

Complete study of the fundamental issues concerning interlayers and composite mechanical properties. 12/92

Initiate characterization of interfaces in alternate composite systems. 4/93

Submit a paper for open literature publication summarizing the fundamental aspects of fiber coatings and composite mechanical properties. 8/93

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 11>

TITLE: Thermal Models

PROJECT DURATION: October 1991 through September 1993

PRINCIPAL INVESTIGATOR(s): R.B. Jr. Dinwiddie (615-574-7594)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Thermal Models subtask is to develop the necessary modeling capability for thermal property (conductivity) prediction and design. This effort will involve modeling the thermal behavior of ceramic fibers, ceramic matrix materials, and ceramic composites of many different architectures.

DESCRIPTION

This project will develop and evaluate modeling algorithms and techniques which describe and predict the thermal conductivity and/or thermal diffusivity of 1D and 2D CFCC systems as a function of constituent properties. The technical approach to be followed includes three tasks: (1) literature search/retrieval/review of existing thermal models for 1D and 2D CFCC systems with and without interfacial layers; (2) design/acquire/measure a test matrix of a representative set of CFCC material systems; and (3) evaluate and refine existing thermal models, and if necessary, develop new or hybrid models which will describe and predict the thermal conductivity and/or thermal diffusivity as a function of constituent properties, composite architecture, and interfacial properties.

TECHNICAL PROGRESS

FY 1992 - Emphasis will be placed on the literature survey to determine the state of the art in the understanding of thermal transport mechanisms in CFCCs. From this foundation, a test matrix of CFCC material systems will be designed in order to evaluate existing thermal models.

FY 1993 - Thermal diffusivity/conductivity measurements will be completed on the test matrix. These measurements will be used to evaluate the ability of existing thermal models to predict/describe the thermal conductivity of CFCC material systems. Modifications to these existing models will be recommended if necessary.

MILESTONE SCHEDULE (TASKS)

Complete literature survey/review of existing thermal models for 1D and 2D CFCC systems with and without interfacial layers. 2/92

Complete design of a test matrix of a representative set of CFCC material systems. 5/92

Obtain preliminary test data on available materials from the test matrix. 9/92

Complete draft report on performance/validity of models which describe/predict thermal conductivity and/or thermal diffusivity. 4/93

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 12>

TITLE: Interface Studies

PROJECT DURATION: June 1991 through September 1994

PRINCIPAL INVESTIGATOR(s): Richard A. Lowden (615-574-7714)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6063

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Interface Studies subtask is to examine, understand, and control fiber-matrix interfaces in CFCCs for the optimization of mechanical properties and fracture behavior.

DESCRIPTION

This task involves a collaborative effort which seeks to systematically define the role of interfacial properties on the mechanical behavior of CFCCs. The fundamental factors, such as constituent and interlayer properties, residual stresses, and frictional forces, which control the forces at the fiber-matrix interface, and thus have a significant effect on the overall properties of the composite, will be investigated. The results of this task can subsequently be used to optimize the mechanical properties of a composite system for a given application.

TECHNICAL PROGRESS

FY 1992 - A survey of the issues concerning the fiber-matrix interface in ceramic matrix composites will be conducted. Aspects such as micromechanics, testing and measurement techniques, and modification and control of interfacial forces will be considered.

FY 1993 - The effects of varying the properties of an interlayer on interfacial stresses and the fracture behavior of a representative composite system will continue. Emphasis in this period will be placed on evaluating the basic issues with regard to interfaces and composite properties.

FY 1994 - The investigation of the influence of interlayer properties and processing conditions on interfacial forces and properties for a representative composite system (Nicalon/SiC) will continue. Interfaces in other composites with alternate fiber and matrix combinations, as indicated by the industrial programs in Task 3, will also be examined.

MILESTONE SCHEDULE (TASKS)

Complete state-of-the-art survey and technical assessment of the basic issues concerning interfaces and composite mechanical properties. 12/91

Design and construct mechanical properties microprobe, Interfacial Test Facility (ITF). 4/92

Complete theoretical and experimental studies of fundamental interlayer properties and their effects on interfacial forces and composite mechanical behavior. 8/92

Complete processing/interface/composite property relationships in representative composite system(s). 2/93

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 13>

TITLE: Matrix Characterization

PROJECT DURATION: June 1991 through September 1994

PRINCIPAL INVESTIGATOR(s): Karren L. More (615-574-7788)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6064

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Matrix Characterization subtask is to characterize representative composite matrix materials in terms of processing/microstructure/property relationships.

DESCRIPTION

The characteristics of composite matrices can differ significantly from monolithic materials processed using more conventional techniques such as hot-pressing or sintering. The incorporation of fibers, which can be degraded by high temperatures and damaged or fractured during compaction, necessitates the use of temperatures, precursors, and processes that are actually quite different than the majority of typical ceramic consolidation processes. Knowledge of the mechanical and thermophysical properties are required for modeling and design of the composites. This task will ultimately address the effects of processing on the microstructure and properties of selected ceramic matrix materials.

TECHNICAL PROGRESS

FY 1992 - The processing and measurement of representative composite matrix materials properties will be initiated in FY 1992. This study will result in a complete data base of processing/microstructure/property relationships for representative matrix materials.

FY 1993 - The measurement of representative composite matrix properties will be completed and the characterization of model matrix systems will be initiated. The effects of representative service environments on the properties of the composite will be evaluated.

MILESTONE SCHEDULE (TASKS)

Complete technical assessment of processing/microstructure/property relationships for representative matrix materials - literature survey. 12/91

Initiate measurement of representative composite matrix properties. 4/92

Characterize processing/microstructure/property relationships in model matrix systems. 12/92

Evaluate the effects of representative processing and service environments on matrix properties. 7/93

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 14>

TITLE: Polymers and Composites from Alkenylsilanes and Related Compounds

PROJECT DURATION: 1986 through present

PRINCIPAL INVESTIGATOR(s): John Masnovi (216-687-2469)

RESEARCH ORGANIZATION(s): Cleveland State University, Cleveland, OH 44115

SPONSOR: NASA-Lewis Research Center

OBJECTIVE

The development of new preceramic polymers that can be converted to SiC for composite matrices or coatings.

DESCRIPTION

Focus is on the synthesis of new organometallic polymers which can be converted to SiC on pyrolysis. The technical approach is to synthesize a family of copolymers in which composition and molecular structure are used to control pyrolytic conversion and ceramic stoichiometry.

TECHNICAL PROGRESS

Polycarbosilanes, or polymers with some polycarbosilane structure, were found more suitable as preceramic polymers than polysilanes. The introduction of alkenylsilane monomers favors polycarbosilane formation. A copolymer composition has been found that converts to stoichiometric SiC. Small amounts of a disilane in the copolymer improves rheological behavior for composite fabrication. The polymerization mechanism has been determined and being applied to tailoring polymer properties. Alternate polymerization solvents under study. Reaction scaleup for composite fabrication underway, along with an industrial partner search for polymer synthesis and scaleup.

MILESTONE SCHEDULE (TASKS)

Techniques for composite processing using alkenylsilanes will be determined. New polymer systems to be explored. FY 1993

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 15>

TITLE: Hot Pressing of BAS Glass

PROJECT DURATION: September 1990 through January 1992

PRINCIPAL INVESTIGATOR(s): Alfred R. Cooper (216-368-4225)

RESEARCH ORGANIZATION(s): Case Western Reserve University

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Optimize the hot pressing conditions for BAS glass resulting in monoclinic celsian as the only crystalline phase.

DESCRIPTION

This project would optimize the temperature, pressure, and time of hot pressing the BAS glass which would result in monolithic ceramic bodies having monoclinic celsian as the only phase. The 4-point bend strengths of the resulting material will also be measured at various temperatures in order to determine the upper use temperature for this material.

TECHNICAL PROGRESS

The BAS glass powder has been hot pressed using various conditions of temperatures, pressure, and time. The resulting materials are being characterized for their densities and phases using x-ray diffraction. The four-point flexural strengths are also being measured at various temperatures between room temperature to 1400°C in air.

MILESTONE SCHEDULE (TASKS)

Optimize hot pressing conditions for BAS glass resulting in glass-ceramic monolithic bodies having monoclinic celsian as the only crystalline phase. 9/91

Measure 4-point flexural strengths of monolithic celsian (BAS) at various temperatures. 1/92

**** MATERIALS CHARACTERIZATION ****

<RECORD NUMBER: 16>

TITLE: Experimental Investigation of Pyrolytic Coatings of Materials by Chemical Vapor Deposition

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): Pirouz Pirouz (216-433-6486)

RESEARCH ORGANIZATION(s): Case Western Reserve University, Cleveland, OH 44106

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To apply state-of-the-art analytical microscopy techniques to characterize the microstructures of ceramic fibers, fiber coatings, and ceramic composites that have high potential for application in advanced aeropropulsion systems.

DESCRIPTION

These studies are in support of ongoing NASA in-house studies on high temperature composite materials. Issues to be addressed include grain size, grain boundary characterization, chemical composition, structure, and spatial distribution of ceramic and metallic phases.

TECHNICAL PROGRESS

The microstructure of as-received and annealed SCS-6 SiC fibers have been characterized and reported in the literature.

MILESTONE SCHEDULE (TASKS)

Investigations will be conducted on SCS-6 fibers with pyrolytic Si₃N₄ coatings of varying thicknesses and processing conditions. Mechanical testing will be included in screening efforts. Similar efforts will be made on reaction formed monolithic SiC, and composites made from these materials. FY 1992

**** TEST METHODS ****

<RECORD NUMBER: 17>

TITLE: Thermomechanical Testing

PROJECT DURATION: July 1991 through September 1995

PRINCIPAL INVESTIGATOR(s): Michael G. Jenkins (615-574-2588)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6064

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The goal of the Thermomechanical Testing subtask is to propose guidelines and procedures for standardized testing methodologies of the mechanical properties of CFCCs.

DESCRIPTION

The Thermomechanical Testing subtask is directed toward the evaluation and development of thermomechanical test methods for measuring the mechanical properties of CFCCs. Standardized test methods for flat and cylindrical CFCC specimen configurations are to be determined and/or developed. These tests will provide the vital engineering data for model verification and component design. The unique stress-strain response and fracture behavior of CFCCs require specialized test techniques, systems, and sensors to accurately measure the mechanical properties of CFCCs and define the important events associated with the fracture process. Existing room and elevated temperature mechanical property test methods will be evaluated and modified for application of CFCC materials. Ultimately, standardized test methodologies will be established for the characterization of the mechanical properties of CFCCs and constituent materials.

TECHNICAL PROGRESS

FY 1992 - Based upon the results of the surveys in Phase 1, the TMTF will be established for the evaluation of guidelines and procedures for testing methods of the mechanical properties of fiber monofilaments and yarns, matrix materials, and CFCCs. Specialized, elevated-temperature grips for bulk composites, matrix materials, and fibers may need to be developed.

FY 1993-1994 - The TMTF and proposed testing guidelines and procedures will be used to evaluate constituent materials in the virgin state, after extraction from the as-processed composite, and as components in the bulk, model CFCC. This model composite will be a SiC fiber-reinforced/SiC matrix material.

MILESTONE SCHEDULE (TASKS)

Complete survey of existing test methodologies for CFCCs and constituent materials. 1/92

Propose suitable thermomechanical test methodologies based on completed surveys and industrial requirements. 10/92

Establish and/or modify facilities to assess the viability of proposed thermomechanical test methodologies. 3/93

Complete studies on SiC-SiC composites and issue report on the direct application of the proposed thermomechanical test methodologies. 12/93

**** TEST METHODS ****

<RECORD NUMBER: 18>

TITLE: Standard Tensile Test Development (WBS No. 3413)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
S.M. Wiederhorn (301-975-2000)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
NIST

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Develop test equipment and procedures for measuring the strength and creep resistance of ceramic materials at elevated temperatures to assist in the development of a reliable data base for use in the structural design of heat engines for vehicular applications.

DESCRIPTION

This project is concerned with the development of test equipment and procedures for measuring the strength and creep resistance of ceramic materials at elevated temperatures to assist in the development of a reliable data base for use in the structural design of heat engines for vehicular applications.

Inexpensive techniques for tensile testing are being developed at NIST. These techniques are being used to test materials intended for heat engines. The results obtained by high temperature tensile testing will be compared with those obtained by compressive and flexural testing. Data obtained from these studies will be compared with various theories of creep and creep rupture that have been developed to date. Based on the data obtained from these studies, a methodology for high temperature design will be recommended.

**** TEST METHODS ****

<RECORD NUMBER: 19>

TITLE: International Energy Agency (IEA) Annex II management and Support (WBS No. 4115)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
Victor J. Tennery (615-574-5123)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Assist and encourage international cooperation in the development of voluntary standard methods for determining mechanical physical, and structural properties of advanced ceramic materials. Participants include the United States, Federal Republic of Germany, Sweden, and Japan.

DESCRIPTION

The purpose of this effort is to assist and encourage international cooperation in the development of voluntary standard methods for determining mechanical, physical, and structural properties of advanced ceramic materials. There were four tasks in the original Annex II agreement, "Cooperative Program on Ceramics for Advanced Heat Engines and Other Conservation Applications," 1) technical information exchange, 2) ceramic powder characterization, 3) ceramic chemistry, and 4) ceramic material property measurements. Research for subtasks 2, 3, and 4 has been completed. Participants in Annex II included the United States, the Federal Republic of Germany, and Sweden. During 1990, agreements were reached for Japan to join the Annex, and two new subtasks, Subtask 5 - Tensile and Flexural Properties of Ceramics and Subtask 6 - Advanced Ceramic Powder Characterization, were added.

**** TEST METHODS ****

<RECORD NUMBER: 20>

TITLE: Cyclic Fatigue of Toughened Ceramics (WBS No. 3214)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
K.C. Liu (615-574-5116)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Develop and demonstrate the capability of performing uniaxial tension-tension dynamic fatigue testing of structural ceramics at elevated temperatures.

DESCRIPTION

This task will develop and demonstrate the capability of performing uniaxial tension-tension dynamic fatigue testing of structural ceramics at temperatures to 1500°C. The effort includes: 1) design, fabrication, and demonstration of a load train column capable of concentric load transfer between grip and specimen at high temperature; and 2) development of the baseline information on the tensile fatigue behavior of structural ceramics at room and elevated temperature.

**** TEST METHODS ****

<RECORD NUMBER: 21>

TITLE: Tensile Stress Rupture Development (WBS No. 3215)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
K.C. Liu (615-574-5116)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Develop the test capability for performing uniaxial tensile stress-rupture tests on candidate structural ceramics.

DESCRIPTION

This task will develop the test capability for performing uniaxial tensile stress-rupture and creep tests on candidate structural ceramics at high temperature in the range where time-dependent deformation (creep) can occur. The immediate goal is to upgrade ten conventional uniaxial lever-arm creep testing machines with closed-loop control capability and to incorporate the specimen load train assembly with a self-aligning feature. Subsequently, creep and creep-rupture design data bases needed for the advanced heat engines project will be generated in the range of 1260 to 1371°C using uniaxial tensile specimens. Time-dependent strain deformation occurring in the gage section of the specimen will be measured during the test using a laser-based optical strain extensometer.

**** TEST METHODS ****

<RECORD NUMBER: 22>

TITLE: Strain Measurements via Phase Shifting Interferometry

PROJECT DURATION: 1987 through present

PRINCIPAL INVESTIGATOR(s): Ben Ovrn (216-433-3625)

RESEARCH ORGANIZATION(s): Case Western Reserve University

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Investigate the use of phase-stepping interferometry for measuring 3D strain fields of high temperature ceramics and composite materials in specimen form.

DESCRIPTION

Develop and investigate use of phase-stepping interferometry by video systems, via holographic or speckle interferometry, for the simultaneous 3D measurements of strain under high temperature test conditions. Develop necessary compensation techniques for turbulence and convection-effects.

TECHNICAL PROGRESS

1D measurement of strain in specimen at 600°C demonstrated. 2D measurements initiated with dual cameras. Compensation techniques developed and demonstrated.

MILESTONE SCHEDULE (TASKS)

Demonstrate phase-shifting interferometry concept to 1100°F. FY 1992

Demonstrate full field (3D) strain measurement using phase shifting interferometry. FY 1993

Design 3D system for hi-temp specimen test laboratory. FY 1994

**** TEST METHODS ****

<RECORD NUMBER: 23>

TITLE: High Temperature Test Methods

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): John Hemann (216-687-2190)

RESEARCH ORGANIZATION(s): Cleveland State University, Cleveland, OH 44115

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Support the development of high temperature tensile testing capability at NASA Lewis Research Center for testing CMCs.

DESCRIPTION

Develop methods to support the NASA test facility which will generate high temperature tensile strength data for continuous fiber reinforced ceramic matrix composites. Specimens to be tested in air and inert environments.

TECHNICAL PROGRESS

Optimum gripping, strain measurement, heating, and specimen geometries have been identified for testing unidirectional continuous fiber reinforced ceramic matrix composites.

MILESTONE SCHEDULE (TASKS)

Determine capabilities of various strain devices for CFCC testing. FY 1992

Develop test standards for CFCCs. 1994

**** TEST METHODS ****

<RECORD NUMBER: 24>

TITLE: Development of Methods for CMC Interface Characterization

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): Jeffery Eldridge (216-433-6074)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To characterize fiber/matrix interfaces in ceramic matrix composites to help optimize composite toughness and strength.

DESCRIPTION

Techniques are developed to evaluate fiber/coating/matrix interfaces by mechanical strength, chemical bonding, and morphology; the results are correlated to composite performance.

TECHNICAL PROGRESS

A fiber push-out test has been developed that evaluates the mechanical strength of the fiber/matrix interface over a wide range of temperatures. Auger electron spectroscopy has been applied to determine the chemical composition of the interfacial failure region.

MILESTONE SCHEDULE (TASKS)

Develop methodologies for CMC interface characterization. 1992

Develop fiber push-out test capability to 2500°F. 1994

**** TEST METHODS ****

<RECORD NUMBER: 25>

TITLE: Development of High Temperature Tensile Test Facility for CMCs

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): John Z. Gyekenyesi (216-433-8181)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Develop high temperature tensile testing capability as part of the in-house development of CMCs.

DESCRIPTION

The test facility will generate high temperature tensile strength data for CMCs. Specimens to be tested in air and inert environments.

TECHNICAL PROGRESS

Optimum gripping, strain measurement, heating, and specimen geometries were identified for testing unidirectional continuous fiber reinforced ceramic matrix composites. Tensile data has been generated for CMCs up to 1550°C in air.

MILESTONE SCHEDULE (TASKS)

Generate high temperature tensile data in air for NASA CFCCs. 1992

Generate high temperature tensile data in inert atmosphere for NASA CFCCs. 1994

**** TEST METHODS ****

<RECORD NUMBER: 26>

TITLE: Development of High Temperature (3000°F) Remote Strain Sensor for Fiber Testing

PROJECT DURATION: FY 1990 through present

PRINCIPAL INVESTIGATOR(s): Lawrence G. Oberle (216-433-3647)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

The development of a remote strain sensor for the tensile testing of small diameter fibers at high temperature.

DESCRIPTION

The remote strain sensor uses the laser speckle (Yamaguchi) technique to directly measure surface strain of samples. The technical approach involves four tasks: 1) development of the system to measure strain in small diameter wires at room temperature; 2) extension to small diameter ($<76\ \mu\text{m}$) fibers at room temperature; 3) development of data acquisition and control software; and 4) training of testing personnel.

TECHNICAL PROGRESS

Room temperature measurements of both large and small diameter wires have been made in short duration tests. The data acquisition system has been integrated into the testing system, and algorithms for data acquisition and presentation are being finalized.

MILESTONE SCHEDULE (TASKS)

Develop laser speckle strain measurement system for fibers to 2300°F. 1993

**** TEST METHODS ****

<RECORD NUMBER: 27>

TITLE: X-Ray Extensometry Technique

PROJECT DURATION: 1989 through present

PRINCIPAL INVESTIGATOR(s): Eric Jordan (203-486-2371)

RESEARCH ORGANIZATION(s): University of Connecticut

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

The objective of this task is the design and development of a high temperature non-contacting extensometer that is insensitive to environmental factors such as very bright thermal sources, thermal convection currents, obscuring flames and smoke, high velocity gas flows and higher than ambient gas pressures.

DESCRIPTION

In order to overcome the optical access and index of refraction dependency of laser-based systems, an x-ray method of measuring extension is proposed. In a previous grant (NAG3-1003) displacement measurements were made by focusing an x-ray source, and causing it to overlap preaffixed targets which fluoresce upon stimulation by the incident beam. By using two targets as fiducial markers demarcating a gage length, strain measurements can be achieved. The HITEMP sponsored work effort is to implement this technique on a testing machine and to apply it to the characterization of metal matrix and ceramic matrix composites. Application to component test rigs will also be pursued.

TECHNICAL PROGRESS

The results of the grant are summarized in the following papers: (1) "X-Ray Beam Method for Displacement Measurement in Hostile Environments" presented at the SEM High Temperature Measurements Conference in November, 1989, and (2) a NASA publication "X-Ray Based Displacement Measurements for Hostile Environments" in preparation.

MILESTONE SCHEDULE (TASKS)

Begin HITEMP sponsored effort. 4/92

Begin conducting extensometer tests on tensile machine at contractor's site. 11/92

Submit report of results. 2/93

**** NON-DESTRUCTIVE EVALUATION ****

<RECORD NUMBER: 28>

TITLE: NDE Testing - Radiography

PROJECT DURATION: October 1991 through September 1992

PRINCIPAL INVESTIGATOR(s): William A. Ellingson (708-972-5068)

RESEARCH ORGANIZATION(s): Argonne National Laboratory, Building 212, Argonne, IL 60439

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the NDE Testing subtask is to identify the issues concerning manufacture, testing including nondestructive evaluation (NDE), qualification, and usage of CFCCs in industrial applications. The focus of this specific work will be to identify process parameters which are important to be measured and identify NDE methods which hold the most promise for measuring these parameters.

DESCRIPTION

The approach to be followed in this nondestructive characterization (NDC) development program has two main parts. First, (a) conduct a thorough study to establish the status of NDE technologies which are likely to be used in CFCC technology developments, (b) verify, with appropriate ceramic processing staff, the primary parameters and characteristics to be measured, and (c) begin experimental and analytical studies on specimens. Second, (a) develop criteria for NDC laboratories necessary for the studies, (b) verify analytical modeling, (c) develop outside user potential, and (d) establish the usefulness of the efforts.

TECHNICAL PROGRESS

FY 1992 - The primary technical progress will be a survey of NDC methods for CFCCs and a survey to establish the primary processing parameters and CFCC characteristics to be measured by NDC methods.

MILESTONE SCHEDULE (TASKS)

Complete survey of status of NDE (NDC) methods for CFCC. 12/91

Submit topical report on survey. 2/92

Complete first NDE density study of special set of CFCCs. 6/92

Complete initial NDE examination of two flawed CFCC specimens with known defects. 9/92

**** NON-DESTRUCTIVE EVALUATION ****

<RECORD NUMBER: 29>

TITLE: X-ray Tomography for Ceramic Composites

PRINCIPAL INVESTIGATOR(s): John Kinney (415-243-6669)

RESEARCH ORGANIZATION(s): LLNL

SPONSOR: DOE/Office of Industrial Technologies (AIC)

OBJECTIVE

Use of high intensity monochromatic X-rays at Stanford Synchrotron Radiation Laboratory to monitor chemical vapor infiltration of fiber-reinforced ceramic composites.

DESCRIPTION

The objectives of this task are to develop the use of X-ray tomography to identify flaws, relate processing conditions to microstructure, and improve properties of crack resistant composites. The work concentrates on characterization of micro- and macrostructures of fiber reinforced composites. The results are being used to determine relationships between processing conditions, such as temperature and gas composition, on density and mechanical properties. Computer modeling of processing conditions is also being done.

**** NON-DESTRUCTIVE EVALUATION ****

<RECORD NUMBER: 30>

TITLE: NDE Testing - Ultrasonics

PROJECT DURATION: October 1991 through September 1993

PRINCIPAL INVESTIGATOR(s): Robert W. McClung (615-574-4466)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge,
TN 37831-6158

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of this subtask is to develop NDE techniques and sensors for the evaluation of CFCCs as an integrated effort in Supporting Technologies with other projects for design, development, fabrication, qualification, and life prediction. Specific emphasis is directed toward detection and evaluation of fabrication flaws such as porosity, fiber-matrix inhomogeneity, and delaminations, evaluation of bulk properties such as density and fiber-matrix bonding, and evaluation of service-induced changes or damage as a part of life-prediction studies.

DESCRIPTION

To assure full technical and cost-effective benefit from prior work, a review will be conducted for preparation of a report to renew awareness of those aspects likely to be relevant for the properties unique to CFCCs. It is anticipated that special advanced techniques such as ultrasonics, acoustics, and shearography and other relevant techniques will be studied for application at all stages of CFCC development, processing, and service performance.

TECHNICAL PROGRESS

FY 1992 - Detailed discussions will be conducted with CFCC developers and processors to establish material-evaluation needs for both process control and product evaluation. Prior NDE technology for composites and ceramics will be reviewed to establish relevancy for CFCCs.

FY 1993-1994 - Experimental development will be conducted on improved ultrasonics and acoustic techniques to measure variations such as homogeneity, porosity, and density in simple SiC/SiC specimens and to establish capability and sensitivity. Correlation evaluation will be performed with radiography and computed tomography.

MILESTONE SCHEDULE (TASKS)

Complete initial experimental studies of finished CFCC specimens to determine capabilities of existing ultrasonic technology for homogeneity, density, and porosity. 6/92

Complete initial ultrasonic examination of specimens with intentional variations in fiber-matrix bonding. 9/92

Prepare standards and procedures for ultrasonic flaw detection. 1/93

Establish system for combined studies of acoustic emission/shearography. 3/93

Establish techniques for detecting damage. 6/93

Establish techniques for evaluation of fiber-matrix bonding. 9/93

**** NON-DESTRUCTIVE EVALUATION ****

<RECORD NUMBER: 31>

TITLE: NDE of Ceramic Matrix Composites

PROJECT DURATION: Ongoing (funded annually)

PRINCIPAL INVESTIGATOR(s): Donald J. Roth (216-433-6017)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (EPM)

OBJECTIVE

Characterize flaws and microstructural factors that govern mechanical behavior of CMC samples and components in a nondestructive or noninvasive fashion.

DESCRIPTION

Use will be made of ultrasonic c-scan imaging, precision ultrasonic contact (velocity) methods and imaging, scanning laser acoustic microscopy, acousto-ultrasonic methods, acoustic emission, x-ray radiography, computed tomography, fiberoptic incorporation (smart materials) and other NDE methods both before and after environmental testing, as well as in-situ during mechanical testing. Microstructure, mechanical properties, interfacial bond properties, environmental degradation, and residual stress in fibers for coupon samples and sub-scale components are among the items to be characterized in CMCs.

TECHNICAL PROGRESS

Ultrasonic c-scan methods established for flaw characterization in CMC coupons. Established acousto-ultrasonic methods for determining fiber orientation, modulus degradation, and interface bonding in unidirectional CMC tensile coupons. X-ray and acoustic emission used during mechanical testing to characterize flaw, failure processes and interfacial shear strength. Currently examining precision ultrasonic methods to characterize volume fiber fraction and scanning laser acoustic microscopy for determining residual stress in fiber. Program initiated to develop sapphire optical waveguides for use in CMC smart materials.

MILESTONE SCHEDULE (TASKS)

Develop NDE methods for in-situ monitoring and characterization of process damage accumulation/fracture. Establish methods to incorporate fiber-optics for high temperature NDE of microstructure and damage accumulation in CMCs. 10/92

Determine sensitivity of precision ultrasonic measurements for assessing performance/life-limiting factors in CMCs. 1/95

**** NON-DESTRUCTIVE EVALUATION ****

<RECORD NUMBER: 32>

TITLE: Application of In Situ NDE Techniques to CMCs

PROJECT DURATION: 1991 through 1995

PRINCIPAL INVESTIGATOR(s): George Y. Baaklini (216-433-6016)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Nondestructively characterize and evaluate microstructural and macrostructural factors that affect the integrity, thermomechanical response, performance, and life of ceramic matrix composite (CMC) structures.

DESCRIPTION

Implement NDE technology suitable laboratory samples, benchmark specimens, and hardware. The emphasis will be on ultrasonic and radiographic NDE techniques and the development of methods for assessing defect states and property variations that affect structural integrity and life. The refinement of NDE techniques and interpretational methods will be based on their application before, during, and after thermomechanical testing and thermomechanical degradation.

TECHNICAL PROGRESS

An integrated system combining radiography and ultrasonics has been established for monitoring fracture testing of fiber toughened ceramics. Installed and applied in-situ fracture monitoring system utilizing radiography and acoustic emission. During the previous nine months, the system was applied to SiC/RBSN tensile specimens having laminated, 2D, and 3D fiber architectures.

MILESTONE SCHEDULE (TASKS)

Identify NDE techniques and interpretational methods that will be required to assess the integrity and serviceability of CMC structures beginning with laboratory test samples and benchmark specimens. FY 1993

Develop standard procedures, interrogation algorithms, and calibration prototypes for application of suitable NDE techniques to integrity and serviceability characterization of specific CMC structures. FY 1995

**** ENVIRONMENTAL EFFECTS ****

<RECORD NUMBER: 33>

TITLE: Materials for Advanced Industrial Heat Exchanger Systems

PROJECT DURATION: July 1977 through open

PRINCIPAL INVESTIGATOR(s): Michael A. Karnitz (615-574-5150)
James R. Keiser

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6065

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the ORNL project, as related to the heat exchanger program, is to provide materials technology support to DOE contractors. The objective of this task is to ensure that materials selected for critical components will meet the design and performance requirements.

DESCRIPTION

This project provides materials technology support to the Industrial Energy Efficiency Division of the Office of Industrial Technologies, and their contractors in two general categories: (1) heat exchanger project support and (2) materials technology development. Heat exchanger project support involves assistance to DOE contractors in the development of high pressure and other advanced heat exchanger systems to improve the efficiencies of industrial processes. The materials technology development portion of this project is focused on materials and processes that enhance industrial acceptance of ceramic heat exchangers.

TECHNICAL PROGRESS

A laboratory corrosion test of candidate materials, followed by flexure tests to show the effects of corrosion, was completed for Stone & Webster. A plan for leak testing ceramic tubes for SWEC was prepared, including design and identification of equipment. A laboratory corrosion test of continuous filament wound ceramic composites was completed for the Babcock & Wilcox project.

FY 1992 - The previously mentioned activities focus on selection of existing materials for specific applications, development of improved materials and fabrication processes, and determination of critical materials properties.

MILESTONE SCHEDULE (TASKS)

Stone & Webster: Conduct leak testing of ceramic tubes. Prepare draft report. 9/92

Solar Turbines: Analyze tube materials, joints, and seals from full scale heat exchanger tube verification test in STI furnace. 7/93

Develop test protocol for debris from continuous fibers. (R. J. Lee Group). 12/91

**** ENVIRONMENTAL EFFECTS ****

<RECORD NUMBER: 34>

TITLE: Environmental Effects

PROJECT DURATION: July 1991 through September 1996

PRINCIPAL INVESTIGATOR(s): Peter F. Tortorelli (615-574-5119)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6156

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The objective of the Environmental Effects subtask is to examine the trends and mechanisms of high-temperature degradation and their effects on the properties and life of CFCCs.

DESCRIPTION

This work is not focused on simple characterization of the corrosion or erosion processes, but rather on the determination of the effects of representative high-temperature environments on all properties that influence the effective lifetime of the composites. This will be accomplished by an understanding of the environmental reactions insofar as they ultimately affect composite stability, damage tolerance, failure mode, etc.

TECHNICAL PROGRESS

FY 1992 - Corrosion reactions of the separate constituents of the representative composite, as well as that of the CFCC itself, in high-temperature oxidizing environments will be characterized. Specifications for an environmental chamber for the study of specific in situ effects on mechanical properties of CFCCs will be developed.

FY 1993 - The effects of exposure on subsequently measured mechanical properties of representative composites will be measured, initial in situ measurements of mechanical properties in a specially developed or modified environmental chamber and applicable thermomechanical calculations will be completed, and testing of applicable revised models will begin.

MILESTONE SCHEDULE (TASKS)

Initiate oxidation testing of a representative CFCC material. 10/91

Critical review of approaches to evaluation of environmental effects on CFCCs. 12/91

Finalize specifications for in situ environmental experiments. 9/92

Complete analysis from initial experimental exposures of constituents and composite. 3/93

Complete thermochemical calculations on effects of a range of service and processing environments. 3/93

Complete first set of in situ experiments using environmental chamber. 9/93

**** ENVIRONMENTAL EFFECTS ****

<RECORD NUMBER: 35>

TITLE: Development of Oxidation Protection Methods for Si-Based CMCs

PROJECT DURATION: 1990 through present

PRINCIPAL INVESTIGATOR(s): Ramakrishna T. Bhatt (216-433-5513)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Improve oxidative stability of Si-based CMCs containing carbon-rich fiber/matrix interfaces.

DESCRIPTION

Protect the carbon-rich coating on the SCS-6 fiber with SiC coating. Surface coat composite with a layer of Si_3N_4 or SiC by PVD or CVD techniques. Infiltrate porous composites with Si_3N_4 yielding polymers or with glass.

TECHNICAL PROGRESS

Oxidative stability of SiC/RBSN composite was improved by coating SCS-6 fibers with an overlayer of SiC. Black glass infiltration is a viable method of improving oxidative stability of SiC/RBSN at low temperatures, but beyond 1200°C glass becomes unstable.

MILESTONE SCHEDULE (TASKS)

Evaluate oxidative stability of CVD and PVD coated, and black glass-infiltrated SiC/RBSN composites. 1990

Down select and optimize the best coating approach. 1992

**** ENVIRONMENTAL EFFECTS ****

<RECORD NUMBER: 36>

TITLE: Determination of Environmental Durability Limits for CMCs

PRINCIPAL INVESTIGATOR(s): Dennis S. Fox (216-433-3295)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To study the effect of environments (primarily oxidation kinetics, reaction mechanisms, and effects on material strength) on CMCs and their constituents.

DESCRIPTION

The oxidation kinetics of CMCs and monolithic Si-based materials are studied using thermogravimetry. The effect of long term exposure and thermal cycling on oxidation and material strength will be determined. Oxygen, H_2O/O_2 and burner rig atmospheres will be used.

TECHNICAL PROGRESS

The effects of 100-hour oxidation on SiC/RBSN has been determined.

MILESTONE SCHEDULE (TASKS)

Complete study on long term oxidation of CVD SiC and Si_3N_4 , and effect of burner rig oxidation of C/SiC composites. 1992

Initiate study of effect of H_2O/O_2 atmospheres on CVD SiC and Si_3N_4 oxidation kinetics, and initiate study of effect of cyclic exposure on oxidation kinetics of HITEMP SiC and Si_3N_4 composites. 1993

**** MECHANICAL PROPERTIES ****

<RECORD NUMBER: 37>

TITLE: Rotor Materials Data Base (WBS No. 3216)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
M.K. Ferber (615-576-0818)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Systematically study the tensile strengths of silicon nitride ceramics as a function of temperature and time in an air environment.

DESCRIPTION

This research program will systematically study the tensile strengths of silicon nitride ceramics as a function of temperature and time in an air environment. The research involves both test development and the measurement of creep/fatigue properties. The test development phase will focus upon the establishment of procedures required for accurate measurement of specimen displacement using existing mechanical extensometers. Factors responsible for non-gage section failures will also be examined using both numerical modeling and empirical testing.

In the second phase, stress rupture data will be generated by measuring fatigue lives at constant stresses. The time-dependent deformation will also be monitored during testing to ascertain the extent of high temperature creep. Tested samples will be thoroughly characterized using established ceramographic, SEM, and TEM techniques. A major goal of this phase will be to better understand the microstructural aspects of high-temperature failure including: extent of slow crack growth, evolution of cavitation-induced damage and fracture, transition between brittle crack extension and cavitation-induced growth, and crack blunting.

**** MECHANICAL PROPERTIES ****

<RECORD NUMBER: 38>

TITLE: High Temperature Tensile Testing (WBS No. 3412)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
V.S. Avva (919-334-7620)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
North Carolina A&T State University

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Test and evaluate advanced ceramic materials at temperatures up to 1200°C in uniaxial tension.

DESCRIPTION

This task will test and evaluate advanced ceramic materials at temperatures up to 1200°C in uniaxial tension. Testing may include fast fracture strengths and stepped static fatigue strength along with analysis of fracture surfaces by scanning electron microscopy.

**** MECHANICAL PROPERTIES ****

<RECORD NUMBER: 39>

TITLE: Modeling and Characterization of Multidimensionally Reinforced CMCs

PROJECT DURATION: 1990 through 1992

PRINCIPAL INVESTIGATOR(s): Tsu-Wei Chou (302-451-2904)
Azar Parvizi-Majidi

RESEARCH ORGANIZATION(s): University of Delaware

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To understand the mechanical behavior of textile preform reinforced ceramic matrix composites, including modeling and measurement of stiffness, strength, work of fracture and failure.

DESCRIPTION

During 1990, UTRC SiC/LAS and C/Glass composite laminates were investigated and characterized. In 1991, DuPont SiC/SiC 2D fabric CVI composites were studied. It is hoped the 3D and braided CMCs would be researched sometime in 1992.

TECHNICAL PROGRESS

Progress has been described in 3 ASME publications; 1 prize winning ACERS publication, 3 International conference publications and 1 PhD dissertation. Focus was on stiffness, strength and toughness modeling and tests of unidirectional, 2D fabric and 3D woven CMCs (SiC/SiC) at room temperature.

MILESTONE SCHEDULE (TASKS)

Characterize interlaminar shear strength for 2D fabric CMCs. 1st qtr. 1991

Develop experimental methods and measure interlaminar response. 2nd qtr. 1991

Evaluate existing composite toughness tests and work of fracture calculations. 3rd qtr 1991

Evaluate and model nonlinear tensile stress-strain behavior of woven CMCs. 1st qtr. 1992

Analyze damage growth, failure mechanisms in 3D and braided composites. 2nd qtr. 1992

Complete microstructure-properties relations studies for 3D composites. 3rd qtr. 1992

**** MECHANICAL PROPERTIES ****

<RECORD NUMBER: 40>

TITLE: High Thermal Conductivity Ceramic Matrix Composites

PROJECT DURATION: 18 months

PRINCIPAL INVESTIGATOR(s): Andrew Szweda (513-243-1992)

RESEARCH ORGANIZATION(s): GE Aircraft Engines, Evandale, OH

SPONSOR: NASA-Lewis Research Center (pre-EPM Project)

OBJECTIVE

To develop understanding of the thermomechanical behavior and environmental stability of the SCS-6/Silcomp(tm) SiC CMC system, and to determine the sensitivity of HSCT vehicle performance to variations in the thermomechanical properties of CMC combustor liners.

DESCRIPTION

Design trade studies of RQL and lean/premixed/prevaporized (LPP) HSCT combustors are to be conducted along with determination of the influence of thermal conductivity, strength, and temperature capability of CMC combustor liners on HSCT NO(X) formation and take-off weight.

TECHNICAL PROGRESS

Design trade studies completed on RQL and LPP combustors; performance is enhanced by higher liner thermal conductivity and temperature capability combustors due to cooling path design requirements. Mechanical evaluation of SiC/Silcomp(tm) material has begun, and modeling of thermal shock behavior has been completed; thermal shock verification testing to begin.

MILESTONE SCHEDULE (TASKS)

Complete mechanical evaluation and thermal shock tests of Silcomp(tm) CMC specimens. 5/92

**** DATABASE LIFE PREDICTION ****

<RECORD NUMBER: 41>

TITLE: Life Prediction Methodology (WBS No. 3222)

PRINCIPAL INVESTIGATOR(s): C.R. Brinkman (615-574-5106)
P.K. Khandelwal (313-230-3805)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
Allison Gas Turbine Division

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Develop and demonstrate the necessary nondestructive examination (NDE) technology, materials data base, and design methodology for predicting the useful life of structural ceramic components of advanced heat engines.

DESCRIPTION

This effort will develop and demonstrate the necessary nondestructive examination (NDE) technology, material data base, and design methodology for predicting the useful life of structural ceramic components of advanced heat engines. The analytical methodology will be demonstrated through confirmatory testing of ceramic components subject to thermal-mechanical loading conditions similar to those anticipated to occur in actual vehicular service. The project address fast fracture, slow crack growth, creep, and oxidation failure modes.

**** DATABASE LIFE PREDICTION ****

<RECORD NUMBER: 42>

TITLE: Life Prediction Methodology (WBS No. 3223)

PRINCIPAL INVESTIGATOR(s): C.R. Brinkman (615-574-5106)
Carolyn McCormick (602-220-3016)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
Garrett Auxiliary Power Division

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Develop the methodology required to adequately predict the useful life of ceramic components used in advanced heat engines.

DESCRIPTION

This effort will develop the methodology required to adequately predict the useful life of ceramic components used in advanced heat engines. Various specimen geometries will undergo comprehensive testing under both uniaxial and multiaxial loads at different environmental conditions to determine the strength-controlling flaw distributions and to identify various failure mechanisms. This information will be used to develop the flaw distribution statistical model and material behavior models for fast fracture, slow crack growth, creep deformation, and oxidation. As subroutines, these models will be integrated with stress and thermal analyses into a failure risk integration analytical tool to predict the life of ceramic components. The methodology developed will be verified by analytically predicting the life of several ceramic components and testing these components under stress and temperature conditions encountered in ceramic turbine engines.

**** DATABASE LIFE PREDICTION ****

<RECORD NUMBER: 43>

TITLE: Toughened Ceramics Life Prediction (WBS No. 3217)

PRINCIPAL INVESTIGATOR(s): D. Ray Johnson (615-576-6832)
Stanley R. Levine (216-433-3276)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
NASA-Lewis Research Center

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Understand the room and high temperature ($>1370^{\circ}\text{C}$) behavior of toughened ceramics as the basis for developing a life prediction methodology.

DESCRIPTION

The purpose of this research is to understand the room and high temperature ($>1370^{\circ}\text{C}$) behavior of toughened ceramics as the basis for developing a life prediction methodology. A major objective is to understand the relationship between microstructure and the mechanical behavior within the bounds of a limited number of materials. A second objective is to determine the behavior as a function of time and temperature. Room and elevated temperature strength and reliability, fracture toughness, slow crack growth, and creep behavior will be determined for the as-manufactured material. The same properties will also be evaluated after long-time exposure to various high temperature isothermal and cyclic environments.

These results will provide input for parallel materials development and design methodology programs. Resultant design codes will be verified.

**** DATABASE LIFE PREDICTION ****

<RECORD NUMBER: 44>

TITLE: Composite Ceramics Analysis and Reliability Evaluation of Structures

PROJECT DURATION: 1991 through 1996

PRINCIPAL INVESTIGATOR(s): Stephen Duffy (216-433-5626)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Develop analytical models using probabilistic methods of structural analysis to predict the quasi-static reliability of structural components fabricated from laminated ceramic matrix composites, 2D and 3D fabric reinforced ceramic matrix composites.

DESCRIPTION

A test bed algorithm Composite Ceramic Analysis and Reliability Evaluation of Structures (C/CARES) has been developed that incorporates a noninteractive approach to reliability modeling. The program is compatible with several commercial finite element codes, which widens the availability of the program to the structural analysis community.

TECHNICAL PROGRESS

Progress has been summarized at several conferences including the ASME/IGTI conference in Orlando and HITEMP Review-1990. The current version of the C/CARES program incorporates a flexible neutral data base format and a blank common technique. A preliminary version of a Users Manual is near completion.

MILESTONE SCHEDULE (TASKS)

Implement neutral data base concept and blank common technique. April 1991

Implement interface for MARC; use the Gauss point stresses for reliability computations. July 1991

Implement interface for ABAQUS. March 1992

Develop interactive reliability models; incorporate Fast Probability Integration techniques for reliability computations. June 1992

Incorporate load sharing rules to allow for multiple ply failures. February 1993

Improve existing Weibull parameter estimation techniques. March 1993

**** DATABASE LIFE PREDICTION ****

<RECORD NUMBER: 45>

TITLE: Creep Rupture Lifetime Assessment of CMCs

PROJECT DURATION: 1991 through 1993

PRINCIPAL INVESTIGATOR(s): Tze-jeer Chuang (301-975-5773)

RESEARCH ORGANIZATION(s): National Institute of Standards and Technology

SPONSOR: NASA-Lewis Research Center (HITEMP); National Institute of Standards and Tech

OBJECTIVE

To provide a predictive methodology for creep rupture life for continuous fiber-reinforced ceramic matrix composites (CMC). This methodology will be developed for long term sustained loading conditions at elevated temperatures.

DESCRIPTION

Initially, analytical models will be developed for creep rupture lifetime and several types of crack growth believed to be present in fiber reinforced composites. In the following year, several types of tests will be conducted on model materials and SiC/SiC type composites to verify the analytical models.

TECHNICAL PROGRESS

With work beginning in May, 1991, progress has been described in two journal publications and two international conference presentations (ACERS and Fracture Mechanics of Ceramics). Work focused on crack tip morphology and creep lifetime prediction in fibrous CMCs.

MILESTONE SCHEDULE (TASKS)

Develop generic models for creep rupture lifetime; model interfacial crack growth. June 1991

Develop solutions for steady state and transient crack growth. July 1991

Process and machine materials in preparation for testing. September 1991

Conduct tensile creep testing of model materials. March 1992

Conduct creep tests for SiC/SiC system (tensile, compressive, bending). September 1992

Compare creep data to developed models. December 1992

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 46>

TITLE: Assessment of Strength Limiting Flaws in Ceramic Heat Exchangers

PRINCIPAL INVESTIGATOR(s): J. Bower (804-522-5742)
W. Reuter (208-526-1708)

RESEARCH ORGANIZATION(s): Babcox & Wilcox, Lynchburg Research Center, Lynchburg,
VA 24506
Idaho National Engineering Lab

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

Evaluate the effect of operating environments on flaw populations of ceramic heat exchange components using advanced NDE methods. Development of advanced NDE, test methods, and other key technologies to support Babcock & Wilcox studies of strength limiting flaws in ceramics.

DESCRIPTION

This project studies the flaw population and the effect of operating environments on flaw populations of ceramic heat exchanger components. Currently the project is correlating acoustic response to flaw growth. The goal of the project is to develop lifetime prediction correlations for ceramic components. Research is conducted cooperatively with the Idaho Engineering Laboratory. Currently the INEL project is studying the application of Moire Interferometry to measure stress of components under test.

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 47>

TITLE: Fracture and Damage

PROJECT DURATION: September 1991 through September 1993

PRINCIPAL INVESTIGATOR(s): Walter G. Reuter (208-526-1708)

RESEARCH ORGANIZATION(s): Idaho National Engineering Laboratory, P.O. Box 1625,
Idaho Falls, ID 83415

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Fracture and Damage subtask is to assess and review requirements for CFCC structures used in industrial applications to identify failure conditions that can limit the lifetime of these components.

DESCRIPTION

A review and assessment of design requirements for commercial structures fabricated from CFCCs will be conducted to identify failure conditions. These failure conditions will depend upon the design requirements for specific applications. Design requirements will be identified through a literature search, discussions with industrial representatives, and attending technical meetings. It is expected that a substantial portion of the failure conditions will be associated with fracture or related processes. Therefore, preliminary tests will be conducted using moire interferometry to quantify the ability of this technique to provide the data needed to verify applicability of analytical models.

TECHNICAL PROGRESS

FY 1992 - A review and assessment of design requirements for anticipated structures fabricated from CFCCs will be completed. A report will be prepared that defines failure conditions for these structures. The report will also provide suggestions as to the future direction of the research.

FY 1993 - To be based on results obtained in FY 1992.

MILESTONE SCHEDULE (TASKS)

Complete summary report describing definition of fracture correlation. 2/92

Complete status report of failure modeling. 8/92

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 48>

TITLE: Failure Models

PROJECT DURATION: December 1991 through April 1993

PRINCIPAL INVESTIGATOR(s): Claudia P. Ostertag (301-975-6102)

RESEARCH ORGANIZATION(s): National Institute of Standards and Technology, Building 223/A356, Gaithersburg, MD 20899

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

The purpose of the Failure Models subtask is to investigate the initiation and propagation of cracks in the matrix of fiber-reinforced ceramic composites.

DESCRIPTION

NIST will use custom-designed devices which enable in situ scanning electron microscopy (SEM) examination of crack tip interaction with fibers and subsequent fiber pull-out during the loading of the materials. The SEM devices enable direct qualitative observations of the crack shielding zone at the microstructural level during loading and the crack profile and the bridging/pull-out mechanisms at and behind the crack interfaces.

TECHNICAL PROGRESS

FY 1992 - Complete a survey of the state of the art in the understanding of matrix cracking and damage mechanisms in fiber-reinforced ceramic composites. Examine the influence of fiber volume fraction and fiber coating on crack initiation and crack propagation in model fiber-reinforced composites.

FY 1993 - Examine crack initiation and crack propagation of representative composites and develop theoretical models of the damage mechanisms in fiber-reinforced composites.

MILESTONE SCHEDULE (TASKS)

Complete survey of the state of the art in the understanding of matrix cracking in CFCC. 2/92

Examine the influence of fiber volume fraction and fiber coating on crack initiation. 6/92

Examine crack initiation and crack propagation of representative composites. 4/93

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 49>

TITLE: Durability and Life Assessment of a Continuous Fiber Ceramic Matrix Composite

PROJECT DURATION: 24 months

PRINCIPAL INVESTIGATOR(s): Chris C. Chamis (216-433-3252)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (EPM)

OBJECTIVE

Evaluate the durability of a CMC component and produce accurate life assessments for the component designs.

DESCRIPTION

The effects of thermomechanical fatigue, acoustic fatigue, and creep on component life and durability will be investigated. Technical tasks include life prediction modeling using existing computer codes, fracture resistance assessments, and probabilistic structural analysis to evaluate contractor design reliability. This independent research activity is conducted as an alternate concept to EPM critical path research.

TECHNICAL PROGRESS

Team responsibilities assigned, potential problem area identification begun, preliminary model selection discussed.

MILESTONE SCHEDULE (TASKS)

Complete all studies (including durability/life assessments, fracture resistance measurements, and reliability assessments using probabilistic methods). 9/93

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 50>

TITLE: Evaluation of Failure Mechanisms and Verification of Micromechanical Models for CMCs Under Tension

PROJECT DURATION: 1991 through 1995

PRINCIPAL INVESTIGATOR(s): Abhisak Chulya (216-433-8523)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Develop theoretical foundations and experimental base for assessing and predicting fracture modes, damage, and life of highly anisotropic continuous fiber reinforced brittle matrix composites.

DESCRIPTION

In situ NDE techniques will be used to monitor failure processes under tensile loading of a variety of representative CMC specimens. Details in the sequence of micro/macro-failure modes will be studied and mechanistic models will be used for describing and predicting damage accumulation and fracture. Initial work will be done at room temperature followed by tests at elevated temperatures that simulate actual propulsion systems.

TECHNICAL PROGRESS

An integrated fracture mechanics model to predict the first matrix cracking strength, ultimate strength and work of pull-out was validated on CMC laminates. The models are valid only if a multiple transverse matrix cracking occurs and fiber breakage is minimized. In-situ monitoring of 2D CMCs is progressing at room and elevated temperatures.

MILESTONE SCHEDULE (TASKS)

Develop and experimentally verify quasi-static fracture and damage models for selected laminated 2D fabric reinforced CMCs at room and elevated temperatures. FY 1993

Develop and experimentally verify quasi-static fracture and damage models for 3D, woven and braided fiber architecture ceramic composites at room and elevated temperatures. FY 1995

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 51>

TITLE: Reliability of Continuous Fiber Composite Laminates - CMCs

PROJECT DURATION: 1988 through 1992

PRINCIPAL INVESTIGATOR(s): Robert C. Wetherhold (716-636-2432)

RESEARCH ORGANIZATION(s): State University of New York at Buffalo

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Establish formal limits for laminate reliability and the effects of different load sharing rules from fractured laminae. Both interactive and independent failure criteria shall be studied.

DESCRIPTION

Orthotropic composite laminae with directional strengths as random variables were studied using various failure models under multiaxial loading. Load sharing rules have been established with loss of stiffness upon matrix cracking. Modified bundle theory was developed to study ultimate strength in fiber direction.

TECHNICAL PROGRESS

Progress has been described in 4 ASME publications, several NASA TM's, HITEMP conference proceedings, an MS Thesis, and a Ph.D. dissertation.

MILESTONE SCHEDULE (TASKS)

Evaluate models for steady state cracking in 0° plys and shear lag for load redistribution in angle plys. March 1991

Develop and evaluate improved models for matrix cracking in 0° plys. October 1992

Develop and evaluate phenomenological models for load redistribution. February 1992

Apply Fast Probability Integration techniques to reliability calculations. March 1992

Develop and evaluate average elasticity based rules for angle ply laminates; develop reliability calculations for random matrix cracking. June 1992

Determine effect of correlated strengths on laminates with stress concentrations. August 1992

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 52>

TITLE: Damage Mechanisms for MMCs/CMCs

PROJECT DURATION: 1990 through present

PRINCIPAL INVESTIGATOR(s): Wieslaw K. Binienda
H.Q. Tan

RESEARCH ORGANIZATION(s): University of Akron

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Provide an analytical framework via symbolic computation where by a link between continuum damage mechanisms (LEFM) can be established and evaluated for unidirectional high temperature composites.

DESCRIPTION

First step is to develop generic formulations, using the perturbation problem to solve for the stress intensity factors or energy release rate at each crack tip. Secondly, design and develop a computer that can derive the resulting singular integral system of equations symbolically and automatically generate the associated Fortran code required for solution of this system using the collocation technique. Finally, an attempt will be made to homogenize the effects of the interacting distributed cracks into macrodamage models which can be efficiently coupled with the finite element method in order to analyze structural problems.

TECHNICAL PROGRESS

The work is on schedule, the 6/91 and 12/91 milestones have been completed. The 2D formulation is completed. Work is continuing on the symbolic implementation of the anisotropic option into SYMFRAC (Symbolic Fracture Code). Progress on the 3D formulation is continuing. Difficulties have been encountered in the required integration step. Parametric studies utilizing version 1.0 of SYMFRAC are currently underway.

MILESTONE SCHEDULE (TASKS)

Complete 2D formulation of homogenous isotropic and anisotropic plate with a straight and/or kinked cracks. 6/91

Complete version 1.0 of SYMFRAC, the symbolic computation code valid for isotropic materials. 12/91

Complete version 1.1 of SYMFRAC, valid for anisotropic homogenous problem. 6/92

Complete 3D formulation of m-cylinder model with n-number of circumferential cracks. 12/92

Complete version 1.2 of SYMFRAC, such that it includes 3D capability. 12/93

**** FRACTURE/DAMAGE ****

<RECORD NUMBER: 53>

TITLE: Elevated Temperature Creep Fatigue of Fiber Reinforced Ceramics

PROJECT DURATION: 1991 through 1992

PRINCIPAL INVESTIGATOR(s): Rod Ellis

RESEARCH ORGANIZATION(s): University of Michigan

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Identify and model damage mechanisms in $\text{SiC}_f/\text{Si}_3\text{N}_4$ and SiC_f/SiC composites under monotonic and cyclic loading conditions.

DESCRIPTION

A series of tension, creep, and fatigue tests will be conducted on ceramic matrix composite materials at temperatures in the range 1000°C to 1300°C. Detailed microstructural studies will be conducted on material tested partially to failure and completely to failure. Analytical models will be developed which capture the key features of damage at the microstructural level.

TECHNICAL PROGRESS

Exploratory tensile and creep tests have been conducted on [o]12 NICALON/CAS II (40vol%) material at 1100°C and 1200°C. The performance of this material under creep type loadings was extremely disappointing. Exploratory creep and recovery tests have been conducted on 0° HP-SiC/SiC₃N₄ composite at 1200°C. The material was found to exhibit significant recovery in stepped creep tests.

MILESTONE SCHEDULE (TASKS)

Phase (1) study complete and final report published. 7/15/92

**** JOINING ****

<RECORD NUMBER: 54>

TITLE: Microwave Joining of SiC

PRINCIPAL INVESTIGATOR(s): R. Silbergliitt (301-261-8373)
W. Murray Black; Joel D. Katz (703-993-1571)

RESEARCH ORGANIZATION(s): Technology Assessment and Transfer, Incorporated,
George Mason University; LANL

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

Optimization of SiC-SiC joints made using microwave energy. Joints made with Si interlayer 3-20 micrometers in width, and by reaction synthesis to form a carbide interlayer in situ.

DESCRIPTION

The purpose of this work is to optimize the properties of SiC-SiC joints made using microwave energy. Previous investigations produced joints with a silicon braze interlayer of 50 micrometer width. The current focus is to narrow the width of the interlayer, and to explore methods of forming carbide interlayers in situ.

Through the use of oil-based silicon-containing slurries and plasma-sprayed silicon coatings in place of the silicon powder used in prior work, the width of the joining interlayer was reduced from 50 micrometers to 3-20 micrometers. Microhardness evaluation of the joints made from samples with the plasma-sprayed silicon coating displayed no substantial variation in Knoop hardness across the joint interlayer.

With a cold pressed disk of titanium and carbon powder in stoichiometric ratio placed at the interface, microwave heating was used to induce a reaction leading to the formation of a titanium carbide (TiC) joint interlayer. In addition, joints were made by reacting Si and C powder in stoichiometric ratio, with the powder pressed between the samples to be joined. These joints were sectioned and sent to Los Alamos National Laboratory for evaluation.

**** JOINING ****

<RECORD NUMBER: 55>

TITLE: Metal-Ceramic Joints AGT (WBS No. 1412)

PRINCIPAL INVESTIGATOR(s): M.L. Santella (615-574-4805)
S. Kang (617-890-8460)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
GTE

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Demonstrate analytical tools for use in designing ceramic-to-metal joints including the strain response of joints as a function of the mechanical and physical properties of the ceramic and metal, the materials used in producing the joint, the geometry of the joint, externally imposed stresses both mechanical and thermal in nature, temperature, and the effects on joints exposed for long times at high temperature in an oxidizing (heat engine) atmosphere.

DESCRIPTION

This work will demonstrate analytical tools for use in designing ceramic-to-metal joints including the strain response of joints as a function of the mechanical and physical properties of the ceramic and metal, the materials used in producing the joint, the geometry of the joint, externally imposed stresses with mechanical and thermal in nature, temperature, and the effects on joints exposed for long times at high temperature in an oxidizing (heat engine) atmosphere. The technical work involves both analytical and experimental tasks. The goal of the analytical work is a predictive model that can be used in engineering design of ceramic joints. The experimental work will involve the fabrication and testing of first small scale and later scale-up sized joints.

**** JOINING ****

<RECORD NUMBER: 56>

TITLE: Metal-Ceramic Joints AGT (WBS No. 1413)

PRINCIPAL INVESTIGATOR(s): M.L. Santella (615-574-4805)
A.T. Hopper (614-424-4567)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
Battelle

SPONSOR: DOE/Office of Transportation Technologies

OBJECTIVE

Develop analytical tools necessary to design reliable high strength ceramic oxide-to-ceramic oxide and ceramic oxide-to-metal joints.

DESCRIPTION

The objective of this project was to develop the analytical tools necessary to design reliable high strength ceramic oxide-to-ceramic oxide and ceramic oxide-to-metal joints. The technical work involved both analytical and experimental tasks. The goal of the analytical work was a predictive model that can be used in engineering design of ceramic joints. A PC-based computer program for ceramic-ceramic and ceramic-metal joint design and assessment has been completed. The user friendly computer code allows quick analysis of joints between various materials. Experimental verification tests confirmed excellent agreement between predictions and experimental data.

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Summary of Additional Projects

CFCC Supporting Technologies Projects

**CONTINUOUS FIBER CERAMIC COMPOSITE PROGRAM
CFCC SUPPORTING TECHNOLOGIES - SUMMARY OF ADDITIONAL PROJECTS**

Prin. Investigator	Research Organization	Title	Sponsor
COMPOSITE DESIGN			
A. Evans	University of California, Santa Barbara	Micromechanical Modeling, Characterization of Composite Properties	DOD/Defense Advanced Research Projects Agency
	University of California, Santa Barbara	Finite Element Mechanics Homogenization and Damage Mechanisms	NASA (HITEMP)
MATERIALS CHARACTERIZATION			
A. Heuer	Case Western Reserve University	Composite Systems Interface Studies	DOD/Defense Advanced Research Projects Agency
	Naval Air Development Center	Tailored Fiber/Matrix Interfaces via Pre-Ceramic Polymers	DOD/Naval Air Development Center
77 Steven R. Nutt	Brown University	Structure of Interfaces	DOD/Office of Naval Research
D. Lewis III	Naval Research Laboratory	Chemical and Physical Characterization of Model Ceramic Matrix Composites Interfaces	DOD/Office of Naval Research
K.K. Chawla	New Mexico Institute of Mining and Technology	Interface Engineering in Alumina/Glass Composites	DOD/Office of Naval Research
Carlo G. Pantano	Pennsylvania State University	Interface Chemistry in Ceramic Matrix Composites	DOD/Office of Naval Research
A.G. Ludwick	Tuskegee University	Reinforcement-Matrix Interfaces in Ceramic Composites	DOD/Office of Naval Research
J. Brennan	UTRC	Interfacial Studies of Chemical Vapor Infiltrated Ceramic Composites	DOD/Office of Naval Research
		Design, Fabrication, and Interface Characterization of Ceramic Fiber-Ceramic Matrix Composites	DOE/Office of Energy Research

**CONTINUOUS FIBER CERAMIC COMPOSITE PROGRAM
CFCC SUPPORTING TECHNOLOGIES - SUMMARY OF ADDITIONAL PROJECTS**

Prin. Investigator	Research Organization	Title	Sponsor
NON-DESTRUCTIVE EVALUATION			
	Naval Air Development Center	Nondestructive Testing of IHPTET Materials--Ceramic Matrix Composites	DOD/Naval Air Development Center
W.A. Ellingson J.P. Singh	Argonne National Laboratory	Development of Nondestructive Evaluation Techniques and the Effect of Flaws on the Fracture Behavior of Structural Ceramics	DOE/Office of Fossil Energy
J.B. Walter	Idaho National Engineering Laboratory	Nondestructive Evaluation of Advanced Ceramic Composite Materials	DOE/Office of Fossil Energy
ENVIRONMENTAL EFFECTS			
	Naval Air Development Center	Environmental Effects on Ceramic Matrix Composites	DOD/Naval Air Development Center
	Naval Air Development Center	Influence of Glass-Ceramic Matrix on the Oxidation Behavior of Nicalon Fibers	DOD/Naval Air Development Center
R.O. Ritchie	University of California at Berkeley	Micromechanisms of Cyclic and Environmentally-Assisted Subcritical Crack-Growth in Ceramics and Ceramic Matrix Composites	DOD/Office of Naval Research
Wayne Worrell	University of Pennsylvania	Oxidation Behavior of Advanced Coating Materials at T>1300°C	DOD/Office of Naval Research
MECHANICAL PROPERTIES			
	In-house effort with Cornell, DuPont, Drexel University North Carolina A & T	High Temperature Mechanical Characterization of CMCs	DOD/Naval Air Development Center
K. Prewo J. Brennan	UTRC as part of IHPTET program	Evaluation and Testing of SiC Fiber Reinforced Glass-Ceramic Matrix Composites	DOD/Naval Air Development Center

**CONTINUOUS FIBER CERAMIC COMPOSITE PROGRAM
CFCC SUPPORTING TECHNOLOGIES - SUMMARY OF ADDITIONAL PROJECTS**

Prin. Investigator	Research Organization	Title	Sponsor
A.G. Evans	University of California at Santa Barbara	Structure and Mechanical Properties of Metal/Ceramic Interfaces	DOD/Office of Naval Research
J. Sankar	North Carolina A&T State University	Mechanical Properties of Ceramic Fiber-Ceramic Matrix Composites	DOE/Office of Fossil Energy
K.L. Reifsnider W.W. Stinchcomb	Virginia Polytechnic Institute and State University	Investigation of the Mechanical Properties of CVD Infiltrated Ceramic Composite Tubular Components	DOE/Office of Fossil Energy
FRACTURE/DAMAGE			
J. Lankford	Southwest Research Institute	Characterization of Damage Mechanisms in Ceramic Matrix Composites Materials at High Strain Rates	DOD/Office of Naval Research
79 D.E. Hasson	U.S. Naval Academy	Effect of Temperature on the Impact Behavior of Ceramic Matrix Composites	DOD/Office of Naval Research
E.R. Fuller	National Institute of Standards and Technology	Structural Reliability and Damage Tolerance of Ceramic Composites	DOE/Office of Fossil Energy
JOINING			
B.H. Rabin	Idaho National Engineering Laboratory	Joining of Silicon Carbide Reinforced Ceramics	DOE/Office of Fossil Energy

***Component Development,
Fabrication, and Fiber-related Projects***

**** APPLICATION ASSESSMENT ****

<RECORD NUMBER: 57>

TITLE: HSCT Combustor Materials

PROJECT DURATION: 1991 through 1992

PRINCIPAL INVESTIGATOR(s): Robin T. Lemke (407-796-6286)
Andy Szweda (513-243-1992)

RESEARCH ORGANIZATION(s): Pratt & Whitney/GE Aircraft Engines HSCT Team

SPONSOR: NASA-Lewis Research Center

OBJECTIVE

To continue to develop more thorough understanding of the behavior and durability of CMCs in the high temperature, long operational lifetime HSCT combustor environment by further evaluation of baseline Silcomp- and Si_3N_4 -based composites selected by GEAE and P&W, respectively. Property/processing enhancement assessments for the baseline systems, and potential alternate material system evaluations will be made.

DESCRIPTION

This pre-EPM contract to the joint P&W/GEAE team is a follow-on to previous individual contracts awarded to each team member. Further mechanical, physical, and environmental characterization will be made for database development. Matrix enhancements and smaller diameter SiC fibers will be used in baseline materials with emphasis on high thermal conductivity. Alternate materials systems will be chosen for potential thermal conductivity attributes; initial studies of their environmental stability and basic mechanical properties will be made.

TECHNICAL PROGRESS

None (new start).

MILESTONE SCHEDULE (TASKS)

Complete fiber/coating technology assessment. 7/92

Complete mechanical evaluation of baseline CMCs. 9/92

Complete mechanical evaluation of enhanced baseline CMCs. 10/92

Complete mechanical evaluation of alternate CMC systems. 10/92

**** APPLICATION ASSESSMENT ****

<RECORD NUMBER: 58>

TITLE: Materials for High Speed Transports

PROJECT DURATION: One year with extension

PRINCIPAL INVESTIGATOR(s): Robin T. Lemke (407-796-6286)

RESEARCH ORGANIZATION(s): Pratt & Whitney, West Palm Beach, FL

SPONSOR: NASA-Lewis Research Center (pre-EPM Project)

OBJECTIVE

To address the major materials issues affecting the viability of the HSCT through assessments of current capabilities and shortcomings of current materials, and to analyze the benefits resulting from their development and use.

DESCRIPTION

Activities will 1) quantify system benefits versus development costs for various advanced materials candidates being considered for HSCT applications; 2) establish an approach and provide initial data for life prediction of CMC materials needed for HSCT engine hot section components; 3) establish a preliminary database on some of the material candidates (baseline is a hot-pressed SiC/Si₃N₄ composite) for the rich-burn/quick-quench/lean-burn (RQL) HSCT combustor, including mechanical/physical properties at high temperatures and the effects of combustion environments; 4) assess the feasibility of enhancing the transverse thermal conductivity of CMCs to reduce their operating temperatures. Carbon fiber-reinforced Si₃N₄ will be the object of study.

TECHNICAL PROGRESS

Design trade studies for RQL combustor, turbine and compressor sections completed. Heat transfer analysis of combustor configurations performed. Baseline SiC/ material and C fiber preforms received and awaiting final Si₃N₄ CVI.

MILESTONE SCHEDULE (TASKS)

Publish "Goal Book" properties established during design trade studies. 1/92

Compare P&W combustor design trade studies results with those produced under similar tasking at GEAE. 2/92

Additional milestones under anticipated extension TBD.

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 59>

TITLE: Nozzle Development

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): J. Halada

RESEARCH ORGANIZATION(s): DuPont
Pratt & Whitney, West Palm Beach, FL

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate and Propulsion Directorate

OBJECTIVE

To develop SiC matrix composite nozzle flaps for F-100 engine upgrade program. Capability to 2500°F a goal.

DESCRIPTION

Materials evaluation to include effect of key material and process parameters on component performance. Evaluations will include measurements of tensile, compressive and interlaminar shear strengths, and creep, all as a function of temperature.

TECHNICAL PROGRESS

Test coupons fabricated for evaluation.

MILESTONE SCHEDULE (TASKS)

Initial material evaluation and material system downselect. FY 1992

Sub-element component fabrication and evaluation. FY 1993

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 60>

TITLE: Rotor Development

PROJECT DURATION: FY 1992 through FY 1993

PRINCIPAL INVESTIGATOR(s): R. Klacka

RESEARCH ORGANIZATION(s): DuPont
Williams International

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate and Propulsion Directorate

OBJECTIVE

To determine effects of key material and process variables on component behavior and performance.

DESCRIPTION

Rotors made of C-fiber reinforced, CVI-processed SiC are under development for application in limited life (2500°F) turbine engines. Project is a follow-on to joint Williams International/SEP (Societe Europeenne de Propulsion) project.

TECHNICAL PROGRESS

Initial batch of specimens have been fabricated for evaluation.

MILESTONE SCHEDULE (TASKS)

Coupon and sub-element fabrication. FY 1992

Rotor evaluation. FY 1993

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 61>

TITLE: Ceramic Fiber-Ceramic Matrix Hot Gas Filters

PROJECT DURATION: January 29, 1988 through September 1991

PRINCIPAL INVESTIGATOR(s): David P. Stinton (615-574-4556)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bldg. 4515, MS 6063, Oak Ridge, TN 37831-6063

SPONSOR: DOE/Office of Fossil Energy

OBJECTIVE

The purpose of this project is to develop a ceramic fiber-ceramic matrix composite that will be suitable as a high temperature particulate filter for use in hot-gas cleanup systems. The goal is to produce a composite that has the requisite strength, toughness, and corrosion resistance, but which also has sufficient porosity to be permeable to the gas stream and the size and distribution of porosity to be an effective filter.

DESCRIPTION

This task developed ceramic fiber-ceramic matrix materials and fabrication techniques suitable for production of hot-gas cleanup filters. The technology developed was transferred to industry via a research subcontract with the 3M Company. By collaboration between ORNL and 3M full size candle filters will be produced. Currently materials that are more resistant to sodium corrosion are being investigated.

TECHNICAL PROGRESS

Fabrication technique for fiber-reinforced filters was developed.

Full size candle filters were produced in subcontract with 3M.

More corrosion resistant oxide materials were identified.

MILESTONE SCHEDULE (TASKS)

Identify oxide materials that demonstrate improved corrosion resistance than SiC in laboratory testing.

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 62>

TITLE: Ceramic Composite Heat Exchanger for the Chemical Industry

PRINCIPAL INVESTIGATOR(s): D. Hindman (804-522-5825)

RESEARCH ORGANIZATION(s): Babcock & Wilcox

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

Design and field test of heat exchanger for the chemical industry. Evaluation of composite systems in industry environment.

DESCRIPTION

The third phase of this project has been initiated to design and build a prototype module heat exchanger using ceramic composite tubes to determine their performance under industrial conditions. Currently, a lab proof test of a ceramic composite tube is in preparation.

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 63>

TITLE: HIPHES System Design Study for Energy Production From Hazardous Wastes

PRINCIPAL INVESTIGATOR(s): B. Harkins (619-544-5398)

RESEARCH ORGANIZATION(s): Solar Turbines Incorporated

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

Development of preliminary design for high pressure heat exchange systems (HIPHES) to produce heated pressurized air to a turbine. Resolution of a critical material and design problem.

DESCRIPTION

This project is in the second phase of a three-phase effort to develop high pressure heat exchange systems for recovery of energy from hazardous wastes. A preliminary design of an advanced heat exchange process based on the use of ceramic composites has been developed. Research on critical material and design needs has begun.

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 64>

TITLE: HiPHES System Design Study for an Advanced Reformer

PRINCIPAL INVESTIGATOR(s): J. Williams (617-589-7147)

RESEARCH ORGANIZATION(s): Stone & Webster Engineering Corporation

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

Development of preliminary design for high pressure heat exchange system (HiPHES) for an advanced convective reformer. Resolution of critical material and design problems.

DESCRIPTION

This project is in the second phase of a three-phase effort to develop high pressure heat exchange systems for an advanced convective reformer. A preliminary design of an advanced heat exchange process based on the use of ceramics has been developed. Research on critical material and design needs has begun.

**** COMPONENT DEVELOPMENT ****

<RECORD NUMBER: 65>

TITLE: Enabling Propulsion Materials for High Speed Civil Transports (HSCT)

PROJECT DURATION: 1992 through 1997

PRINCIPAL INVESTIGATOR(s): Waldo A. Acosta (216-433-3393)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center
GE Aircraft Engines, GE Aircraft Engines/Pratt & Whitney
HSCT Team

SPONSOR: NASA-Lewis Research Center (EPM)

OBJECTIVE

Develop high temperature ceramic matrix composite (CMCs) materials for the combustor liner of the high speed civil transport engine.

DESCRIPTION

The high speed civil transport of the 21st century must be environmentally acceptable and economically feasible. Combustion gas temperatures approaching 3400°F are anticipated, which translates into a combustor material temperature of up to 3000°F. Additional requirements limit or do not allow the use of cooling air. Advanced CMCs with high temperature capability, strength, and long term durability for the combustor liner are enabling to the success of the HSCT engine. This research program will address the issues related to the combustor design and material development, ceramic fiber development, coatings development, composite material development, material screening and characterization, and the development of design methods. A broad cross section of U.S. engine companies, materials suppliers and fabricators, and academia will be part of this program.

MILESTONE SCHEDULE (TASKS)

Develop technology development plan. 4/92
Select alternate materials and designs. 4/93
Select primary and secondary fibers. 3/92
Develop testing and characterization plan. 6/92
Establish scale-up viability. 9/94
Demonstrate primary fiber technology readiness. 4/95
Select initial material for fabrication. 3/92
Develop fabrication scale-up plan. 10/94
Develop NDE plan. 3/92
Develop characterization test methods. 7/92

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 66>

TITLE: Thermally Durable Ceramic Matrix Composites

PROJECT DURATION: Through FY 1994

PRINCIPAL INVESTIGATOR(s): David Larsen (607-974-3882)

RESEARCH ORGANIZATION(s): Corning Incorporated, Advanced Materials Research, SP-FR-51, Corning, NY 14831
Pratt & Whitney, 400 Main Street, East Hartford, CT 06108

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate and Propulsion Directorate

OBJECTIVE

To develop glass ceramic matrix composites that are oxidatively resistant under load at high temperatures (2200°F).

DESCRIPTION

Two approaches will be examined. The first is development of Nicalon fiber reinforced materials with borosilicate glass and SiC-whisker doped magnesium aluminosilicate (MAS) glass-ceramics as the matrix. The second is development of sheet silicate interphase-coated Nicalon fibers in a calcium aluminosilicate (CAS) matrix, which will commence later in FY 92 so as to build upon present DARPA/ONR exploratory program. Pratt & Whitney will focus materials testing/evaluation toward end-user application needs.

TECHNICAL PROGRESS

Have fabricated and tested (> 1000°C) specimens using approach #1 (see Description). Downselects taking place to determine preferred compositions for more extensive testing.

MILESTONE SCHEDULE (TASKS)

(a) Begin sheet silicate coatings development effort; (b) complete assessment of approach #1. FY 1992

Preliminary evaluation of materials fabricated using approach #2 (with sheet silicate interphase coatings). FY 1993

Complete evaluation of approach #2. FY 1994

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 67>

TITLE: Processing Science for Chemical Vapor Infiltration

PROJECT DURATION: November 1988 through September 1992

PRINCIPAL INVESTIGATOR(s): Theodore M. Besmann (615-574-6852)
R.A. Lowden; D.P. Stinton; T.L. Starr; L.F. Alla

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, P.O. Box 2008, MS 6063,
Oak Ridge, TN 37831-6063
GTRI

SPONSOR: DOD/Air Force Wright Laboratory

OBJECTIVE

Develop and verify predictive computer-based model of both isothermal and forced chemical vapor infiltration.

DESCRIPTION

The two CVI processes selected to be modeled span the range of the unassisted CVI concepts: conventional CVI (CCVI) and forced CVI (FCVI). CCVI was selected because it represents the foremost commercial technology; FCVI was selected because it represents a developing technology with substantial promise for producing otherwise unavailable materials.

The materials to be used in the proposed effort are SiC matrices and Nicalon fibers. The investigation will focus on continuous fibers in the form of unidirectional tape lay-ups, 2D cloth lay-ups fabricated from plain-weave fabric, and 3D orthonogonal woven structures. The preform architectures have been chosen to follow a logical sequence to support the analytical model, beginning with the simple one-dimensional unidirectional case and then adding fibers to each direction.

The approach to modeling CVI processes is based on conservation equations for mass, energy, and momentum. These differential equations express, in mathematical form, the physical requirement that the total mass, energy, and momentum of a system is constant. This approach is widely used for modeling physical systems involving material and energy flow and was recently used by GTRI to model forced flow/thermal gradient CVI processing with excellent results.

TECHNICAL PROGRESS

FY 1992 - Complete demonstration of scale-up system.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 68>

TITLE: Advanced Ceramic Matrix Composite for Ceramic Composite Component Demonstration (C3D)

PROJECT DURATION: September 1991 through March 1993

PRINCIPAL INVESTIGATOR(s): T. Schmid

RESEARCH ORGANIZATION(s): Pratt & Whitney, West Palm Beach, FL
Dow Corning; Corning, Inc.

SPONSOR: DOD/Air Force Wright Laboratory Flight Dynamics and Materials Directorate

OBJECTIVE

This program will carry out a basic evaluation of two materials systems for potential use in engine nozzle sidewalls.

DESCRIPTION

Subcontracts to Dow-Corning to evaluate HPZ reinforced SiCN matrix (polymer derived) composites; Corning for HPZ/CAS (calcium aluminosilicate glass-ceramic) composites. Emphasis is on coupon specimen geometries.

TECHNICAL PROGRESS

New start.

MILESTONE SCHEDULE (TASKS)

Coupon fabrication and preliminary evaluation. FY 1992

Completion of feasibility assessment. FY 1993

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 69>

TITLE: Thermal Gradient Chemical Vapor Infiltration with Microwave Radiation

PRINCIPAL INVESTIGATOR(s): D. Lynn Johnson (708-491-3584)

RESEARCH ORGANIZATION(s): Northwestern University, 2145 Sheridan Road, Evanston, IL
60208-3108

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To prove the concept of microwave assisted chemical vapor infiltration (MACVI) as a composite processing method; to characterize the mechanical and elastic properties at ambient and elevated temperatures of ceramic composites produced by this method; to develop fiber coatings compatible for use with the MACVI process; and to explore the limits of applicability for MACVI to CMC systems.

DESCRIPTION

A CVD/CVI system is to be assembled and characterized, then used to initially prove the concept on $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3$; eventually fabrication of SiC/SiC composites will be attempted. Downselect of up to three interface systems for $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3$ will be made. Characterization of MACVI composites and coatings will be performed. Collaborator/subcontractor Allied Signal will develop coatings for $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3$, $\text{Al}_2\text{O}_3\text{-SiO}_2/\text{SiC}$, and SiC/SiC.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 70>

TITLE: Innovative Processing of Composites for High Temperature Applications

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): Michael D. Sacks (904-392-6676)
Reza Abbaschian (904-392-6609)

RESEARCH ORGANIZATION(s): University of Florida, Department of Materials Engineering,
Gainesville, FL 32611

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

A fundamental understanding of the processing science and technology necessary for fabrication of CMCs, IMCs and MMCs with superior mechanical properties at high temperatures (> 1200°C).

DESCRIPTION

Among the efforts to be carried out under this project are: (1) determination of fundamental approaches to microscale design of composites with tailored properties; (2) development and understanding of processes for improved fibers; (3) development/understanding of processes for interface control, mechanical and chemical integrity of interfaces; (4) development of innovative methods for making dense fiber and whisker reinforced CMCs and IMCs.

TECHNICAL PROGRESS

Produced sol-gel derived, dense short fibers of tetragonal Y_2O_3 - ZrO_2 with Al_2O_3 dispersions and of glass-free mullite; as well as sols from which to spin them. Development of low O_2 SiC fibers in progress; transient viscous sintering process under development for mullite based composites. Mechanical testing capability up to 1500°C established.

MILESTONE SCHEDULE (TASKS)

Develop fiber spinning techniques, evaluate effects on fiber properties and production of sufficient fiber for composite fabrication, with emphasis on mullite fibers containing grain growth inhibitors.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 71>

TITLE: Development of Leading Edge Materials for Ramjet Combustors

PROJECT DURATION: Through FY 1992

PRINCIPAL INVESTIGATOR(s): Kevin Stuffle (602-323-6881)

RESEARCH ORGANIZATION(s): Advanced Ceramics Research, Inc., 4541 East Fort Lowell Road, Tucson, AZ 85712

SPONSOR: DOD/Naval Surface Warfare Center

OBJECTIVE

The development of SiC fiber-reinforced ZrB₂ matrix composites requiring lower processing (hot pressing) temperatures.

DESCRIPTION

A reactive densification method is used for in-situ formation of ZrB₂ matrices. Si&C powders are combined with ZrB₂ in the desired proportions, then made with filament wound SCS-6 fibers into "prepregged" tape for final hot pressing.

TECHNICAL PROGRESS

The reactive densification process has been studied, with optimization of matrix composition and fiber volume fraction a key goal. Preliminary mechanical property measurements give 3-point bend strengths near 800 MPa. A filament winding apparatus was constructed and the process scaled up from the Phase I (hand layup) methods used previously.

MILESTONE SCHEDULE (TASKS)

Examine possibility for multifilament tow impregnation. Complete materials optimization and characterization.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 72>

TITLE: SiC-Fiber Reinforced Glass-Ceramic Matrix Composite Development

PROJECT DURATION: October 1988 through May 1991

PRINCIPAL INVESTIGATOR(s): Karl M. Prewo (203-727-7237)

RESEARCH ORGANIZATION(s): United Technologies Research Center, Silver Lane, East
Hartford, CT 06108

SPONSOR: DOD/Navy Air Systems Command (IHPTET)

OBJECTIVE

Development of high temperature fiber-reinforced glass-ceramic matrix composites for IHPTET applications.

DESCRIPTION

The Integrated High Performance Turbine Engine Technology program has as its main goal the doubling of thrust-to-weight performance found in current turbine engines. New composite materials with enhanced mechanical properties at higher temperatures than currently possible are being developed. Desired properties are high fracture toughness, strength, and elevated temperature stability ($>2600^{\circ}\text{F}$) for prolonged periods.

TECHNICAL PROGRESS

Fabrication of 2D and 3D composite panels successfully demonstrated.

Laboratory testing demonstrated at temperatures up to 1700°F .

Strength-500 MPa; $K(\text{Ic}) \approx 20\text{MPa}/\text{m}$.

MILESTONE SCHEDULE (TASKS)

Engine testing of panels awaiting start.

Major manufacturing technology initiative planned for late FY 91 start, possibly to address ATF engine requirements.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 73>

TITLE: Carbon-Fiber Reinforced Glass Matrix Composites for Space-Based Applications

PROJECT DURATION: May 1985 through FY 1993

PRINCIPAL INVESTIGATOR(s): Karl M. Prewo (203-727-7237)

RESEARCH ORGANIZATION(s): United Technologies Research Center, Silver Lane, East Hartford, CT 06108

SPONSOR: DOD/Strategic Defense Initiative Organization -Innovative Science & Technology

OBJECTIVE

Development of glass and glass-ceramic matrix composites for use in space based systems.

DESCRIPTION

Improvement of composite performance through studies of mechanisms governing composite properties, and improvements to mechanical properties and environmental stability. Routes to these goals include study of matrix chemistry and fiber/matrix reactions.

TECHNICAL PROGRESS

Composite stiffness doubled (versus beginning of project); near-zero CTEs demonstrated over temperature range of spacecraft; environmental durability in low earth orbit verified.

FY 1992 - Extend high temperature capability and study techniques for enhanced producibility.

MILESTONE SCHEDULE (TASKS)

Truss tubes delivered for mechanical testing by independent laboratory.

Investigate SiC-coated carbon fibers to improve oxidation resistance at high temperatures.

Investigate tailored thermal conductivity composites, using new high conductivity carbon fibers.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 74>

TITLE: Fabrication of Fiber-Reinforced Composites by Chemical Vapor Infiltration (CVI)

PROJECT DURATION: 1984 through open

PRINCIPAL INVESTIGATOR(s): David P. Stinton (615-574-4556)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge,
TN 37831-6063

SPONSOR: DOE/Office of Fossil Energy

OBJECTIVE

The purpose of this task is to develop a ceramic composite having higher than normal toughness and strength yet retaining the typical ceramic attributes of refractoriness and high resistance to abrasion and corrosion. In addition, a practical process capable of fabricating simple or complex shapes in reasonable times (48 hrs.) is desired.

DESCRIPTION

Develop a process for rapidly fabricating fiber-reinforced composites using Nicalon fibers and an SiC matrix (plates & tubes). Develop a coating to protect composites from sodium corrosion. Develop a process for infiltrating with an oxide matrix.

TECHNICAL PROGRESS

Potential forced CVI process.

IR-100 award for process.

Characterization showed isothermal and forced CVI composites to be equal.

Fabrication of dense tubular composites.

FY 1992 - Optimize process for fabricating tubular composites.

FY 1993 - Develop process for depositing an oxide overcoat for corrosion protection.

FY 1994 - Develop CVI process for oxide matrix.

MILESTONE SCHEDULE (TASKS)

Open literature publication describing matrix characterization of fiber reinforced SiC composites fabricated by CVI.

Demonstrate efficient fabrication of tubular composites.

Identify a CVI process capable of depositing a corrosion resistant oxide coating onto SiC matrix composites.

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**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 75>

TITLE: Chemical Vapor Deposition of Ceramic Composites

PRINCIPAL INVESTIGATOR(s): Ted Besmann (615-574-6852)
Mark Allendorf; Peter Reagan (675-574-4565)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831
SNLL; Thermoelectron Tech.

SPONSOR: DOE/Office of Industrial Technologies (AIC)

OBJECTIVE

Explore novel ceramic matrix composites produced by chemical vapor deposition (CVD) of a dispersed phase and a matrix phase. Develop a single step process for fabrication of ceramic composites which are stable in air at high temperatures.

DESCRIPTION

The objective of this effort is to explore novel ceramic matrix composites produced by simultaneous chemical vapor deposition (CVD) of a dispersoid phase and a matrix phase. The basic mechanisms which control the toughness, strength, thermal expansion, and thermal conductivity of the composite coatings are investigated by varying the quantity, composition, and morphologies of the two phases. The work at SNLL includes computer modeling of the process.

The ultimate objective is to utilize the CVD process to fabricate ceramic matrix composites, stable in air at 2500°F, with 30 ksi fracture strength and 10 MPa $\sqrt{m}$ fracture toughness, and to develop a single step process for fabrication of ceramic composites that are stable in air at high temperatures for numerous applications in automotive and gas turbine engines, chemical processing, and waste heat energy recuperation.

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 76>

TITLE: Polymeric Precursors to Ceramics

PROJECT DURATION: 1986 through present

PRINCIPAL INVESTIGATOR(s): Francis Hurwitz (216-433-5503)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center

OBJECTIVE

The development of ceramic composite matrices, as well as infiltrants for porous ceramics and composite coatings from organometallic polymers.

DESCRIPTION

The program is focused on the development of polymer-derived ceramic composite matrices and on the environmental protection of ceramic composites.

TECHNICAL PROGRESS

Fabrication, densification and pyrolysis techniques for polymer-derived CMCs were developed. Ply lay-up was optimized to improve mechanical behavior and eliminate warping. The conversion of polysilsequioxanes to silicon oxycarbides (1200°C), and at higher temperatures (1400°C), SiC and amorphous silica, has been characterized.

The influence of fillers and interface coatings on composite behavior for the Nicalon/Si-C-O composites will be determined. Polymers not containing oxygen are being synthesized under a cooperative agreement with Cleveland State University and procedures for composite fabrication using these as matrix precursors will be developed in-house. Polysilazanes (Si-C-N polymers) are being purchased for study as candidate matrix precursors. The first Si-C-N composites have been fabricated successfully.

MILESTONE SCHEDULE (TASKS)

Determine influence of fillers and fiber interface coatings on mechanical properties of Nicalon/Si-C-O composites. 5/93

Determine feasibility of CVD SiC coatings as oxidation protection system for Si-C-O composites. 9/93

Develop polymer-derived coating system for protection of SiC/RBSN composites. 1/94

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 77>

TITLE: Fiber Reinforced Ceramics Processing

PROJECT DURATION: Ongoing

PRINCIPAL INVESTIGATOR(s): Stanley R. Levine (216-433-3276)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center

OBJECTIVE

Optimize the strength and toughness of FRC matrix materials.

DESCRIPTION

Fundamental studies of liquid phase sintering of Si_3N_4 and SiC to yield materials that are optimized with respect to strength, toughness and capability for use as FRC matrix materials.

TECHNICAL PROGRESS

Si_3N_4 - Sc_2O_3 with high strength and toughness identified. Schemes for optimum liquid-phase sintering/toughening of Si_3N_4 and approaches for toughening of SiC identified. The results are being applied to HiP densification of SiC/RBSN.

MILESTONE SCHEDULE (TASKS)

Complete creep studies of Si_3N_4 - Sc_2O_3 . 12/92

Complete creep studies of reaction bonded silicon nitride and reaction formed silicon carbide matrix materials. 12/93

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 78>

TITLE: Si₃N₄ Processing

PROJECT DURATION: 1989 through present

PRINCIPAL INVESTIGATOR(s): Donald Feke (216-368-2750)

RESEARCH ORGANIZATION(s): Case Western Reserve University, Chemical Engineering
Department, Cleveland, OH 44106

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Develop colloidal processing strategies for the fabrication of strong, tough and oxidation resistant 3D RBSN composites reinforced by SiC fibers.

DESCRIPTION

Study the effectiveness of depletion stabilization strategies to improve the processing of RBSN composites. Identify candidate binder systems for the depletion stabilizing additives and solvent. Infiltrate slip into 3-D preform, prepare green bodies and densify preform.

TECHNICAL PROGRESS

A stable colloid has been developed using silicon, steryl alcohol and polystyrene. Preliminary coating studies on small diameter SiC fibers have been performed. The coating is adherent to fibers.

MILESTONE SCHEDULE (TASKS)

Select polymer binders and solvents for colloidal processing. 1990

Develop a colloidal slurry system to coat SiC fibers and infiltrate SiC preforms. 1991

Fabricate 1-D SiC/RBSN composite and measure physical and mechanical properties. 1992

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 79>

TITLE: Multidirectional Weave CMCs

PROJECT DURATION: November 1991 through November 1992

PRINCIPAL INVESTIGATOR(s): Mary Marshall (207-282-5911)

RESEARCH ORGANIZATION(s): Fiber Materials, Incorporated, Biddeford Industrial Park,
Biddeford, ME 04005

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

The development of low void content multidirectionally woven continuous fiber ceramic matrix composites.

DESCRIPTION

Both theoretical and experimental studies involving model systems will provide results that can be applied to alternate high temperature composites systems in the future. The project involves three tasks: 1) establish new multidirectional fiber weave design that should facilitate both matrix impregnation and subsequent composite densification during hot pressing; 2) evaluate both analytically and experimentally the designs with what new fiber structures can be processed to fabricate dense, high fiber-content CMCs; and 3) provide NASA-Lewis with both these preforms and densified CMCs.

TECHNICAL PROGRESS

New start November 1991.

MILESTONE SCHEDULE (TASKS)

Task 1--Four weave design selected from preliminary design study for experimental evaluation in Task 2. 3/92

Task 2--Different processing approaches (mullite matrix/Nextel fiber or glass matrix/Nextel) evaluated by FMI. 7/92

Task 3--Multidirectionally woven, continuous fiber preforms and densified CMCs delivered to NASA. 11/92

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 80>

TITLE: Nitridation Kinetics and Interface Properties in SiC-Reinforced RBSN Composites

PROJECT DURATION: 1989 through 1992

PRINCIPAL INVESTIGATOR(s): John Haggerty (617-253-2129)

RESEARCH ORGANIZATION(s): Massachusetts Institute of Technology, Dept. of Materials
Science & Engineering, Cambridge, MA 02139

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To develop strong, tough and oxidation resistant SiC/RBSN composites using high purity, submicron Si powder produced at MIT.

DESCRIPTION

Study nitridation kinetics of MIT Si powder in presence of carbon-rich and silicon-rich SiC particles. Determine influence of polymeric binders typically used for CMC fabrication on the nitridation kinetics.

TECHNICAL PROGRESS

SiC particles - both carbon-and silicon-rich and polymeric binders used for SiC/RBSN composites at NASA Lewis were found to retard nitridation kinetics of high purity silicon powder.

MILESTONE SCHEDULE (TASKS)

Fabricate and measure mechanical properties of SiC particle-reinforced RBSN. FY 1990

Study the influence of polymer fugitive binders on the nitridation kinetics of RBSN composites. FY 1991

Fabricate SiC/RBSN composite using MIT powder. FY 1992

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 81>

TITLE: Processing Optimization for Celsian Matrix CMCs

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): Narottam P. Bansal (216-433-3855)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To develop and optimize processing parameters resulting in strong and tough continuous fiber-reinforced BAS/SAS (barium/strontium aluminosilicate) glass-ceramic matrix composites.

DESCRIPTION

This project involves processing development for continuous fiber-reinforced BAS/SAS glass-ceramic matrix composites. Composite samples will be fabricated by hot pressing under different temperature, pressure, and time profiles. The resulting composites will be characterized for their mechanical and fiber/matrix properties at various temperatures and in different environments.

TECHNICAL PROGRESS

SiC/BAS glass-ceramic matrix composites were prepared using tape layup methods. Three point flexure strengths (room temperature) were ≈ 250 -300 MPa for initial matrix cracking and ultimate failure strengths of up to 900 MPa. Optimum processing occurs at ≈ 1350 -1450°C for about two hours. No fiber/matrix chemical interaction was seen during processing; fiber push-out testing gave interfacial shear strengths of about 6 MPa.

MILESTONE SCHEDULE (TASKS)

Optimize processing for SiC/SAS composites. 1992

Determine factors limiting temperature/life use of SiC/BAS and SiC/SAS. Optimize processing for 3D fiber reinforced composites. 1994

Determine feasibility of improved glass-ceramic matrix composites. 1995

Determine structural properties for optimized glass-ceramic matrix composites. 1996

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 82>

TITLE: Development of Si_3N_4 Matrices and Associated Processing

PROJECT DURATION: 1987 through present

PRINCIPAL INVESTIGATOR(s): Ramakrishna T. Bhatt (216-433-5513)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Determine and optimize the performance of $\text{SiC}/\text{Si}_3\text{N}_4$ composites for strength, toughness, thermoxidative stability and fabrication capability.

DESCRIPTION

Fabricate $\text{SiC}/\text{Si}_3\text{N}_4$ composites. Alter composite microstructure by varying fiber, interface and matrix. Correlate microstructure with performance and theory.

TECHNICAL PROGRESS

Strong and tough SiC/RBSN composite developed. Influence of microstructure on composite performance determined. Upper temperature limit in inert and oxidizing environment studied.

MILESTONE SCHEDULE (TASKS)

Optimized fabrication variables. 1987

Measured laminate properties. 1988

Determined oxidative stability. 1989

Fabricated fully dense $\text{SiC}/\text{Si}_3\text{N}_4$ by HIPing. 1990

Determine upper temperature limit for SiC/RBSN . 1991

Develop oxidation protection approaches. 1992

Fabricate with small diameter fibers. 1993

**** FABRICATION & PROCESSING TECHNOLOGY ****

<RECORD NUMBER: 83>

TITLE: Development of Tough Al_2O_3 Matrix Ceramic Matrix Composites

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): Martha H. Jaskowiak (216-433-5515)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To develop strong, tough oxide/oxide composite for use above 2500°F.

DESCRIPTION

Alumina matrix composites reinforced with single crystal sapphire fibers are being developed for high temperature aerospace applications. Presently, this project involves concurrent efforts in three areas: optimizing composite fabrication conditions, tailoring interfacial properties through the use of fiber coatings, and determining effects of fiber coatings and processing on fiber properties.

TECHNICAL PROGRESS

Porous ZrO_2 coatings proven to be effective in lowering interfacial shear strength between sapphire fibers and polycrystalline alumina when processed at 1400°C or lower. Pt fiber coatings also lower interfacial shear between alumina and sapphire; however, processing and use temperature is limited to less than 1400°C because of Pt migration on fiber surfaces at these temperatures. Above 1200°C, fiber strength degradation was observed for coated fibers.

MILESTONE SCHEDULE (TASKS)

Demonstrate strong, tough sapphire/ Al_2O_3 . 1992

Determine factors limiting use temperature/life of sapphire/ Al_2O_3 . 1993

Develop processing methods for 3D-reinforced oxide/oxide CMC. 1994

Determine feasibility of improved oxide/oxide CMC. 1995

Determine structural properties for optimum oxide/oxide CMC. 1996

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 84>

TITLE: Polycrystalline YAG Fiber

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): K.S. Mazdiasni (619-455-4268)

RESEARCH ORGANIZATION(s): General Atomics, P.O. Box 85608, San Diego, CA 92138

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate

OBJECTIVE

To determine the feasibility of producing a YAG fiber with desired microstructural control and stability.

DESCRIPTION

Sol-gel techniques will be explored as methods for creating polycrystalline YAG fibers. The fibers will be doped to attempt the desired level of control over grain growth, high temperature microstructural stability and mechanical properties.

TECHNICAL PROGRESS

Green state fibers successfully spun; pyrolysis study underway.

MILESTONE SCHEDULE (TASKS)

Definition of relevant fiber processing parameters. FY 1992

Completion of process and fiber feasibility assessment. FY 1993

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 85>

TITLE: SiC/Si₃N₄ CVD Fibers

PROJECT DURATION: Through FY 1992 (15 month duration)

PRINCIPAL INVESTIGATOR(s): W.J. Lackey (404-853-0573)

RESEARCH ORGANIZATION(s): Georgia Institute of Technology, Georgia Tech Research Institute, Atlanta, GA 30332

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate

OBJECTIVE

To determine the feasibility of forming SiC, Si₃N₄, or mixed SiC/Si₃N₄ fibers by CVD processes onto multifilament carbon fiber tows.

DESCRIPTION

This study will examine whether commercially available, multifilament carbon yarns can be CVD-coated, with SiC or Si₃N₄. Spreading of the yarns and applicability of microns thick coatings to produce the duplex fibers are among the processing issues to be resolved.

TECHNICAL PROGRESS

Processing studies initiated for SiC fibers. Three μ m thick coatings successfully applied, but with considerable fiber bridging. Additional spreading of yarns being pursued.

MILESTONE SCHEDULE (TASKS)

Definition of CVD process parameters. FY 1992

Completion of feasibility assessment. 12/31/92

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 86>

TITLE: Laser Heated Pedestal Grown YAG Fiber

PROJECT DURATION: FY 1991 (Six month duration)

PRINCIPAL INVESTIGATOR(s): R. Schlecht

RESEARCH ORGANIZATION(s): Laser Genics Corp., San Jose, CA 95161-1330

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate (SBIR)

OBJECTIVE

Demonstrate the feasibility of using the laser heated pedestal growth (LHPG) technique to grow single crystal YAG and zircon fibers.

DESCRIPTION

The LHPG technique uses lasers to grow single crystal fibers, usually starting from pre-extruded rods made from powders of the desired composition. The laser heats and melts the rods, while the crystal orientation is controlled through the use of a seed crystal that is made to contact the melt zone and withdrawn at a controlled rate.

TECHNICAL PROGRESS

Materials grown and being characterized.

MILESTONE SCHEDULE (TASKS)

Completion of Phase I Small Business Innovative Research (SBIR) feasibility study. FY 1992

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 87>

TITLE: Oxide Fiber Feasibility Studies

PROJECT DURATION: July 1991 through FY 1992

PRINCIPAL INVESTIGATOR(s): Ed Courtright (509-375-6926)

RESEARCH ORGANIZATION(s): Pacific Northwest Laboratories, Battelle Boulevard,
Richland, VA 99352
GE Corporate R&D, Schenectady, NY 12301

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate

OBJECTIVE

To assess the potential for use of certain oxide compositions as single crystal fibers for very high temperatures.

DESCRIPTION

This study is a follow-on to prior work identifying candidate materials for ultra high (> 3000°F) temperature composites, especially as single crystal fiber reinforcements. Both laser heated and melt extracted processes are being considered for fiber growth. Very high temperature creep measurements will be a part of the study.

TECHNICAL PROGRESS

Promising high temperature creep data for MgAl_2O_4 observed.

MILESTONE SCHEDULE (TASKS)

Fabrication of fibers and assessment of properties at high temperatures. FY 1992

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 88>

TITLE: EFG YAG Fiber

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): J. Fitzgibbon (603-673-5831)

RESEARCH ORGANIZATION(s): Saphikon, Inc., 51 Powers Street, Milford, NH 03055
GE Corporate R&D Laboratory, GE Corporate R&D
Laboratory Schenectady, NY 12301

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate

OBJECTIVE

To determine the feasibility of producing YAG single crystal fibers by edge defined film growth (EFG).

DESCRIPTION

Saphikon uses EFG to manufacture sapphire fibers and other products; adaptation of this process will be made to the growth of YAG fibers. The EFG process uses melts of the composition of interest to grow fibers, films (ribbons) or other shapes by the insertion and controlled withdrawal of seed crystals from the melts.

TECHNICAL PROGRESS

Initial fibers successfully fabricated. Characterization underway.

MILESTONE SCHEDULE (TASKS)

Process parameters to be defined and initial fibers evaluated. FY 1992

Fiber feasibility assessment completed. FY 1993

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 89>

TITLE: YAG-Alumina Fiber

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): T.I. Mah (513-426-6900)

RESEARCH ORGANIZATION(s): Universal Energy Systems, Inc., 4401 Dayton-Xenia Road,
Dayton, OH 45432
Advanced Crystal Products, Advanced Crystal Products,
Woburn, MA 01801

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate

OBJECTIVE

To determine the feasibility of producing fibers from YAG-Al₂O₃ eutectic melts.

DESCRIPTION

Continuation of Phase I SBIR: fibers to be produced by edge defined film growth (EFG) process.

TECHNICAL PROGRESS

Filaments successfully grown over a range of pulling rates at Advance Crystal Products; property determination and process optimization underway. Fabrication of new EFG apparatus underway.

MILESTONE SCHEDULE (TASKS)

Complete fabrication of EFG apparatus. FY 1992

Assessment of fiber growth feasibility. FY 1993

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 90>

TITLE: Creep Resistant YAG Fiber

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): John W. Halloran (313-763-1051)

RESEARCH ORGANIZATION(s): University of Michigan, Dept of Materials Science & Engineering, Ann Arbor, MI 48104-2136

SPONSOR: DOD/Air Force Wright Laboratory Materials Directorate

OBJECTIVE

To determine the feasibility of producing a YAG fiber with desired high temperature creep resistance.

DESCRIPTION

Polymer precursor based techniques will be explored as methods for creating creep resistant fibers. Selective placement of dopants will be used as a means to create fabricated fibers with elongated grains parallel to fiber axes. These elongated grains are thought to increase creep resistance without large sacrifices in tensile strength.

TECHNICAL PROGRESS

Green state YAG filaments successfully spun. Pyrolysis conditions being determined.

MILESTONE SCHEDULE (TASKS)

FY 1992 - Definition of fiber processing parameters.

FY 1993 - Completion of feasibility assessment.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 91>

TITLE: Alpha-Alumina Fiber Development (Nextel 610)

PROJECT DURATION: Through 1994

PRINCIPAL INVESTIGATOR(s): David M. Wilson (612-736-5936)

RESEARCH ORGANIZATION(s): 3M Company, Metal Matrix Composites Program, St. Paul, MN 55144

SPONSOR: DOD/Defense Advanced Research Projects Agency (Part of MMC Factory Program)

OBJECTIVE

Development of a continuous multifilament alumina fiber for use in advanced metal matrix composites.

DESCRIPTION

Alumina fibers are produced using a spinning process from sol-gel precursors, then pyrolyzed and fired. Automated process for continuous production of fiber tows to use feedback control and NDE monitoring techniques now under development.

TECHNICAL PROGRESS

Automated fiber production line has been installed; process optimization now underway to consistently match the 400 ksi tensile strengths previously obtained in laboratory produced fibers. Further high temperature property evaluation now taking place, and new efforts to increase final fiber diameters ($\approx 50\mu\text{m}$) are beginning.

MILESTONE SCHEDULE (TASKS)

Increase production rate with improved fiber consistency on automated spinning line.

Increase fiber content in tows from 112 to 420 filaments.

Continue efforts to develop larger diameter fibers (proposed).

Continue mechanical property evaluation/testing efforts at ambient elevated temperatures.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 92>

TITLE: Ceramic Fiber Testing and Characterization

PRINCIPAL INVESTIGATOR(s): Thomas L. Starr (404-853-0579)
(404-894-3678)

RESEARCH ORGANIZATION(s): Georgia Tech Research Institute, Materials Science and
Technology Lab, Atlanta, GA 30332

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To characterize commercial fibers for their composition, physical, mechanical, and dielectric properties.

DESCRIPTION

Measurements planned include fiber density, filament counts and diameter; composition/phase analysis and stability; tensile strength, modulus and thermal expansion; dielectric constants and loss factor. Mechanical, dielectric, and stability testing will be done at elevated temperatures in addition to ambient temperature.

TECHNICAL PROGRESS

Composition analyses performed on HPZ, Tyranno, and 3M alumina fibers.

Diameters compiled on Astroquartz II, Tonern and HPZ fibers. Room temperature strength and modulus testing underway, high temperature tests to follow.

Complex permittivity measurements begun.

MILESTONE SCHEDULE (TASKS)

Begin property measurements at elevated temperature. FY 1992

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 93>

TITLE: Ceramic Fibers by Flux Melting/Directional Solidification

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): Lawrence P. Cook (301-975-6114)

RESEARCH ORGANIZATION(s): National Institute of Standards and Technology, Building 223 Room A315, Gaithersburg, MD 20899

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To demonstrate the feasibility of growing single crystal oxide (alumina) fibers by directional solidification of flux melted eutectic solutions.

DESCRIPTION

Eutectic solutions of alumina and cryolite (Na_3AlF_6) are under study to determine cooling parameters for controlled precipitation of alumina crystals. Processing effects on relative c/a axis growth rates, crystal morphology and size are being examined by various crystallographic and microscopic techniques.

TECHNICAL PROGRESS

Initial efforts have yielded tabular c-axis platelets approximately 1-10 μm thick x 1 mm wide. Minimum cooling rates have been established and crystallographic morphology determined. A controllable gradient furnace for directional solidification studies has been constructed.

MILESTONE SCHEDULE (TASKS)

Determine optimum operating conditions of gradient furnace for crystal growth with desired morphology/orientation. Investigate use of additives to promote rodlike crystal growth. Investigate adaption to a continuous process using floating zone/Czochralski techniques.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 94>

TITLE: Seeded Secondary Grain Growth in Alumina Fibers

PROJECT DURATION: Through FY 1993

PRINCIPAL INVESTIGATOR(s): Carol A. Handwerker (301-975-6158)

RESEARCH ORGANIZATION(s): National Institute of Standards and Technology,
Gaithersburg, MD 20899

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To produce alumina fibers with large oriented grains ("bambo" microstructure). Enhanced creep resistance and other mechanical property advantages normally associated with single crystal sapphire fibers are desired.

DESCRIPTION

Attempts will be made to induce controlled secondary grain growth in polycrystalline alumina tapes via three approaches:

- 1) seeding with platelets of various size ranges (5-10 μm , 15-25 μm)
- 2) additives for anisotropic grain growth (eg., CaO)
- 3) inhomogeneous doping to obtain secondary grain growth

If successfully demonstrated, fiber fabrication will be transitioned to Ceramic Process Systems and/or University of Michigan.

TECHNICAL PROGRESS

Determining appropriate additive/dopant levels for seeding.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 95>

TITLE: Tough Ceramics from Fibrous Monoliths

PROJECT DURATION: Through March 1993

PRINCIPAL INVESTIGATOR(s): John W. Halloran (313-763-4970)

RESEARCH ORGANIZATION(s): University of Michigan, Dept. of Materials Science & Engineering, Ann Arbor, MI

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

Demonstration of a new class of tough, inexpensive ceramic composites consisting of fibrous monoliths.

DESCRIPTION

The feasibility of a process of forming structural ceramic fibers will be investigated, employing dry spinning methods on melt-spun ceramic particle-organic slurries. After binder burnout, fibers will be pressureless-sintered into billets, their mechanical properties evaluated and fracture mechanisms identified.

TECHNICAL PROGRESS

New start.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 96>

TITLE: High Modulus Oxynitride Glass Fibers

PROJECT DURATION: Through FY 1994

PRINCIPAL INVESTIGATOR(s): Richard M. Laine (313-764-6203)

RESEARCH ORGANIZATION(s): University of Michigan, Dept. of Materials Science and Engineer., Ann Arbor, MI 48104-2136

SPONSOR: DOD/U.S. Army Materials Technology Laboratory

OBJECTIVE

To develop high modulus oxynitride fibers for lightweight structures.

DESCRIPTION

This project follows exploratory work at MTL in oxynitride fibers; emphasis is on examining non-melt processing routes to obtain Mg-oxynitride glass fibers.

TECHNICAL PROGRESS

Precursor chemistries under evaluation.

MILESTONE SCHEDULE (TASKS)

Phase I: Evaluate sol-gel versus preceramic precursor routes to glass formation. Phase II: Downselect route; defect elimination; non-melt fiberization process explored. Phase III: Scale-up of process and fiber characterization; new compositions explored.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 97>

TITLE: Stoichiometric Nanocrystalline SiC Fibers

PROJECT DURATION: Through FY 1994

PRINCIPAL INVESTIGATOR(s): Richard M. Laine (313-764-6203)

RESEARCH ORGANIZATION(s): University of Michigan, Dept. of Materials Science and Engineer., Ann Arbor, MI 48104-2136

SPONSOR: DOD/U.S. Army Materials Technology Laboratory

OBJECTIVE

To establish a domestic production capability in low cost, high quality SiC fiber for ceramic matrix composite reinforcement. (Domestic Fiber Production Center)

DESCRIPTION

Nanocrystalline SiC fibers are to be demonstrated via melt spinning of commercial polymethylsilane polymer precursor.

TECHNICAL PROGRESS

Precursor chemicals being evaluated; initial fiber spinning underway.

MILESTONE SCHEDULE (TASKS)

Phase I: Bench scale fiber production of up to 100 g batches; fiber characterization studies.

Phase II: Scaleup (500 g batches); single tow fiber production.

Phase III: Pilot production (1 kg batches); multi-tow spinning and measurement of high temperature properties.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 98>

TITLE: Ceramic Fiber Residue Measurement

PRINCIPAL INVESTIGATOR(s): Michael A. Karnitz (615-574-5150)

RESEARCH ORGANIZATION(s): Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831

SPONSOR: DOE/Office of Industrial Technologies

OBJECTIVE

Determination if health hazards could be caused by the handling, processing, or machining of continuous ceramic fiber components.

DESCRIPTION

This project determines whether whisker-like particles can be generated during the handling, processing, or machining of continuous ceramic fiber ceramic matrix composites. Currently a test protocol is being written.

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 99>

TITLE: Advanced High Temperature Composite Materials for Engine Applications

PROJECT DURATION: 1988 through 1993

PRINCIPAL INVESTIGATOR(s): Richard E. Tressler (814-865-7961)
John R. Hellmann (814-865-0163)

RESEARCH ORGANIZATION(s): Pennsylvania State University, University Park, PA 16802

SPONSOR: NASA

OBJECTIVE

To develop ceramic fibers with improved high temperature creep and creep-rupture properties, to make accurate measurements of fiber mechanical properties, and determine the property/microstructure relationships. Design, fabricate, and characterize interfaces in metal, intermetallic, and ceramic matrix composites to maximize high temperature creep resistance while maintaining adequate fracture resistance for gas turbine engine applications.

DESCRIPTION

The database on creep and creep-rupture behavior of SiC, sapphire and polycrystalline Al_2O_3 fibers will be augmented. Interface efforts will be concentrated on development of test and analysis methods for evaluation of fiber/matrix interface mechanical behavior, and micromechanical analysis procedures for study of interphase evolution and fiber surface modification in high temperature composites.

TECHNICAL PROGRESS

The creep and rupture behavior and their mechanisms in c-axis sapphire have been characterized. Methods to increase creep resistance of polycrystalline alumina-based fibers have been investigated. Tin oxide interface systems in sapphire/alumina ceramic composites have been examined. Fiber pushout tests and SIMS methods were developed for analyses for fibers, interfaces, and interfacial shear behavior in composites.

MILESTONE SCHEDULE (TASKS)

Continue fiber property characterizations of various oxide and SiC fibers at elevated temperatures. Continue development work of Fe_2O_3 -seeded Al_2O_3 fibers and tin oxide interface coatings. Evaluate other candidate interface systems for ceramic fiber reinforced metal and ceramic matrix composites. FY 1992

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 100>

TITLE: Development of Doped Single Crystal Oxide Fibers

PROJECT DURATION: 1992 through 1994

PRINCIPAL INVESTIGATOR(s): Peter Lagerlof (216-368-6488)

RESEARCH ORGANIZATION(s): Case Western Reserve University

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

The growth and characterization of doped sapphire fibers and identification of creep resistant compositions.

DESCRIPTION

Sapphire fibers doped with Mg^{2+} and Ti^{4+} are grown using laser float zone techniques to achieve solution and precipitation hardening.

TECHNICAL PROGRESS

High strength (8 GPa) sapphire fibers are produced either with 500 ppm each of MgO , TiO_2 , or 500 ppm each of MgO and TiO_2 , and showed superior high temperature strength retention compared to undoped fibers.

MILESTONE SCHEDULE (TASKS)

Determine effects of different dopant concentrations and their effect on microstructure. FY 1992

Perform in-depth TEM characterization. FY 1993

Determine high temperature creep resistance. FY 1994

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 101>

TITLE: Development of Small Diameter 3000°F SiC Fibers

PROJECT DURATION: 12 months through January 1992

PRINCIPAL INVESTIGATOR(s): Jonathan Lipowitz (517-496-4435)

RESEARCH ORGANIZATION(s): Dow Corning Corporation, Midland, MI 48640

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

Development of strong, thermally stable, small diameter polycrystalline continuous SiC fibers derived from polymer precursors.

DESCRIPTION

Under this contract, development will begin of continuous online processing of the highly successful batch processed fibers developed under a previous Hitemp contract.

TECHNICAL PROGRESS

Polycarbosilane derived fibers have been produced with $\approx 10 \mu\text{m}$ diameter and in lengths of up to 100 mm. Tensile strengths of 2.6 GPa and moduli of 450 GPa have been obtained.

MILESTONE SCHEDULE (TASKS)

Development of fibers in fully continuous form. Downselect to preferred polymer precursor and optimize processing for best fiber properties. FY 1992

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 102>

TITLE: High Temperature Performance of Current Fibers

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): James A. DiCarlo (216-433-5514)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To evaluate the performance of commercial developmental fibers for application in high temperature structural CFCCs, and to develop approaches for fibers with improved microstructures.

DESCRIPTION

SiC and Al₂O₃-based fibers are obtained commercially or on a proprietary basis or from in-house laser growth facilities. Key physical and mechanical tests are performed to elucidate fiber deficiencies. Data and microstructural analyses are performed to understand controlling mechanisms. Approaches are developed and demonstrated to minimize or eliminate limiting mechanisms.

TECHNICAL PROGRESS

Simple creep and modeling approaches have been developed to understand and rank thermomechanical stability of polycrystalline ceramic fibers. Processing/microstructure approaches have been identified for improved high temperature performance of polycrystalline SiC and single crystal Al₂O₃-based fibers.

MILESTONE SCHEDULE (TASKS)

Develop models for fracture strength and creep of sapphire fibers; develop rankings for current ceramic fibers. 1992

Demonstrate model accuracy and underlying mechanisms for tensile creep and strength of polycrystalline fibers at high temperature. Determine feasibility of improved strength retention for CVD SiC fibers. 1993

Demonstrate continuous single crystal SiC fibers. 1995

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 103>

TITLE: Development of Single Crystal Oxide Fibers

PROJECT DURATION: 1990 through present

PRINCIPAL INVESTIGATOR(s): Ali Sayir (216-433-6254)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

The growth and characterization of directionally solidified $\text{Al}_2\text{O}_3/\text{Y}_3\text{Al}_5\text{O}_{12}$ -eutectic fibers.

DESCRIPTION

The alumina/yttrium-aluminum garnet eutectic system is chemically, microstructurally, and mechanically stable at high temperatures (1750°C). The present work was undertaken to produce continuous fiber forms using high thermal gradient processes such as laser float zone methods.

TECHNICAL PROGRESS

Alumina/YAG eutectic fibers were successfully produced. Microstructure and crystallographic phase relations have been identified. Room temperature tensile strength is approximately 1.7 GPa; the temperature dependence of the strength has been determined.

MILESTONE SCHEDULE (TASKS)

Perform microscopic characterization and determine fracture mechanisms. FY 1992

Determine high temperature creep and slow crack growth rates. FY 1993

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 104>

TITLE: Improvement of High Temperature Strength and Coating Retention in CVD Fibers

PROJECT DURATION: 1992 through 1993

PRINCIPAL INVESTIGATOR(s): R. Suplinskas

RESEARCH ORGANIZATION(s): Textron Specialty Materials

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To identify the factors affecting the high temperature strength and coating retention of CVD SiC fibers of the SCS type.

DESCRIPTION

This project is in two parts. In part I, the CVD processing parameters will be varied in order to produce an uncoated CVD SiC fiber with a microstructure having better high temperature strength retention than SCS-6 fiber. In Part II, a 0.5 μ m CVD SiC coating will be applied to single or double pass SCS-6 fibers which have or have not been annealed to produce a stable protective layer for the existing SCS-6 carbon rich coating.

TECHNICAL PROGRESS

Start 12/91.

MILESTONE SCHEDULE (TASKS)

Delivery of three 1k ft. fiber samples with improved high temperature strength. 3/92

Delivery of four 2k ft. SiC coated fibers. 7/92

Delivery of two 1k ft. fibers optimized for high temperature strength; two coating variations selected and samples delivered; final report. 12/92

**** FIBERS DEVELOPMENT ****

<RECORD NUMBER: 105>

TITLE: Advanced Ceramic Fibers for Hypersonic Applications

PROJECT DURATION: 1988 through present

PRINCIPAL INVESTIGATOR(s): James A. DiCarlo (216-433-5514)
Peter Lagerlof (216-368-6488)

RESEARCH ORGANIZATION(s): Case Western Reserve University, Dept. of Materials
Science & Engineering, Cleveland, OH 44106

SPONSOR: NASA-Lewis Research Center (Hypersonic Research Program)

OBJECTIVE

To develop processing and test method approaches for producing and evaluating single crystal oxide fibers with potential for high temperature composite reinforcement.

DESCRIPTION

Using primarily processing based on laser-heated melt growth, single crystal oxide fibers are grown with various compositions and microstructures. These fibers are evaluated by innovative test methods to determine temperature-dependent strength, creep, and creep rupture and their underlying mechanistic sources.

TECHNICAL PROGRESS

Single crystal mullite fibers successfully grown. Three point fiber bend test demonstrated.

MILESTONE SCHEDULE (TASKS)

Enhance processing and properties of mullite fibers. FY 1992

Mechanistic understanding of thermomechanical properties. FY 1993

**** FIBER COATINGS ****

<RECORD NUMBER: 106>

TITLE: Sheet Silicate-Coated Fiber Glass-Ceramic Matrix Composites

PROJECT DURATION: Through FY 1992

PRINCIPAL INVESTIGATOR(s): Kenneth Chyung (607-974-3361)

RESEARCH ORGANIZATION(s): Corning Incorporated, Sullivan Park, Corning, NY 14830

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To develop sol-gel synthesized coatings that are oxidatively stable and provide debond behavior appropriate for high temperature structural ceramic matrix composites.

DESCRIPTION

Alkoxide precursors are being used to develop sheet silicate interface coatings as alternatives to carbon and BN. Feasibility studies are to be done on calcium aluminosilicate (CAS) substrates, with further work to be done using Nicalon fibers in CAS matrices. Three coating compositions to be selected for fabrication and evaluation.

TECHNICAL PROGRESS

First year efforts were concentrated on synthesis of potassium fluorophlogopite (KFP) mica, thermochemical compatibility studies with CAS, and fabrication/characterization of K-phlogopite coated Nicalon/CAS composites. While high temperature air embrittlement resistance is claimed, the degree of reactivity found indicates that more compatible coating systems need to be found.

MILESTONE SCHEDULE (TASKS)

Four new sheet silicate compounds to be fabricated and evaluated for thermochemical stability.
FY 1991

Micromechanical measurement of coating-properties to be made.

Further efforts to optimize KFP coatings.

Continued composite fabrication/characterization studies.

**** FIBER COATINGS ****

<RECORD NUMBER: 107>

TITLE: Ceramic Fiber Coating Development

PROJECT DURATION: Through FY 1992

PRINCIPAL INVESTIGATOR(s): Hal Streckert (619-455-2911)

RESEARCH ORGANIZATION(s): General Atomics, P.O. Box 85608, San Diego, CA
92138-5608

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To develop fiber coating techniques for continuous application using both gas and liquid phase processes.

DESCRIPTION

Coatings are to be demonstrated on both monofilaments and multifilament tows. Scaleup efforts are to demonstrate continuous capability of processes, including dip coating in aqueous sols, in situ curing (to form hydroxide cure products after dipping but before drying), and reaction bonding (a multidip process in succeeding solutions followed by curing and drying). Fabrication of Si_3N_4 composites by CVI to be characterized for coating efficacy assessment.

TECHNICAL PROGRESS

Demonstrated plasma-assisted CVD coating system with continuous capability up to 50 m/hr of BN on Nicalon tows.

Liquid phase system demonstrated for BN, TiB_2 , Y_2O_3 , and ZrO_2 on Nicalon tows, Y_2O_3 and HfO_2 on Saphikon. Assessments have been made on the advantages and disadvantages of each liquid phase process on coating quality and versatility.

Mechanical testing on BN-coated Nicalon/ Si_3N_4 composites showed CVD coatings worked to greatest advantage.

Preliminary economic analyses of both CVD and liquid phase processes performed; indicated feasibility of both types of processes.

MILESTONE SCHEDULE (TASKS)

Complete coating studies and scaleup efforts. Weaving of coated fibers to be demonstrated. Continue composite fabrication/evaluation. FY 1992

**** FIBER COATINGS ****

<RECORD NUMBER: 108>

TITLE: Fiber Coatings by Sputtering for High Temperature Composites

PRINCIPAL INVESTIGATOR(s): M.L. Emiliani (407-796-6716)

RESEARCH ORGANIZATION(s): Pratt & Whitney Aircraft, Government Engines Business,
W. Palm Beach, FL 33140-9600

SPONSOR: DOD/Defense Advanced Research Projects Agency

OBJECTIVE

To identify fiber coatings that promote interfacial debonding and improved fracture toughness in intermetallic and ceramic matrix composites.

To learn what coating/deposition parameters control debond behavior in composites.

DESCRIPTION

Magnetron sputter coated fibers and substrates have been supplied to collaborative team at UC-Santa Barbara for characterization studies by TEM, XPS, SIMS, XRD, and indentation techniques. Coated fibers will be incorporated into composites to validate micromechanical models.

TECHNICAL PROGRESS

Y_2O_3 has been shown to be an effective debond and protective coating for Nb reinforced TiAl. Both Mo and porous ZrO_2 coatings show debond behavior in Al_2O_3/Al_2O_3 composites.

**** FIBER COATINGS ****

<RECORD NUMBER: 109>

TITLE: Ceramic Processing

PROJECT DURATION: 1991 through 1994

PRINCIPAL INVESTIGATOR(s): Stanley R. Levine (216-433-3276)
James Cawley

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center
Case Western Reserve University

SPONSOR: NASA-Lewis Research Center

OBJECTIVE

Investigate the ultimate potential of SiC/SiC composites by studies of model systems.

DESCRIPTION

Study SiC single crystal fibers (LANL whiskers) in dense α and β SiC matrices. Identify and characterize coating materials and structures to isolate the whiskers from the matrix.

TECHNICAL PROGRESS

New start Fall 1991.

MILESTONE SCHEDULE (TASKS)

Complete initial fiber matrix compatibility studies. 1992

Determine feasibility of durable coating systems. 1994

**** FIBER COATINGS ****

<RECORD NUMBER: 110>

TITLE: Reaction-Formed SiC/SiC Composites

PROJECT DURATION: Ongoing

PRINCIPAL INVESTIGATOR(s): Donald R. Behrendt (216-433-5512)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center
General Elec. Aircraft Engines

SPONSOR: NASA-Lewis Research Center (EPM)

OBJECTIVE

To examine and investigate the processing variables and to optimize these variables in the processing of SiC/SiC composites by the reaction-formed silicon carbide method.

DESCRIPTION

The approach is divided into processing development and characterization. Processing development contain the five tasks: 1) optimize the char yield of the carbon source resin, 2) use of a Si-base alloy during infiltration to produce a low free-Si matrix, 3) fiber coating development for fiber matrix interface control, 4) fabricate 2-dimensional SCS-6 fiber composites, and 5) fabricate 3-dimensional, small diameter fiber composites.

TECHNICAL PROGRESS

Interface coatings have been identified and some coated SCS-6 fibers have been evaluated. Infiltration of an unreinforced matrix with Si-base alloy has begun, in an effort to reduce the free silicon remaining after melt infiltration. Modeling of liquid silicon infiltration of a porous carbon precursor has been completed.

MILESTONE SCHEDULE (TASKS)

Optimize resin char yield. 9/92

Optimize precursor for high density and infiltration process for low free-Si. 9/94

Identify coatings for SCS-6 and small diameter fibers. 9/93

Strong, tough composite fabricated. 9/93

3-dimensional small diameter fiber composites fabricated (if suitable fibers are available) 9/94

**** FIBER COATINGS ****

<RECORD NUMBER: 111>

TITLE: Development of Interface Coatings for SiC Fibers

PROJECT DURATION: 1990 through present

PRINCIPAL INVESTIGATOR(s): Gregory N. Morscher (216-433-8675)

RESEARCH ORGANIZATION(s): NASA-Lewis Research Center, 21000 Brookpark Road,
Cleveland, OH 44135

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To develop non-oxide ceramic matrix composite fiber/matrix interfaces via coatings for SiC fibers which provide load transfer between fiber and matrix and promote fiber/matrix debonding and are stable under CMC use conditions for long lifetimes.

DESCRIPTION

This program will determine and develop likely fiber coatings consisting of different materials and morphologies on CVD SiC fibers and demonstrate the feasibility of such coating approaches for meeting CMC fiber/matrix interface requirements. Test methods will be developed to evaluate coatings. The coatings developed will have both carbon and non-carbon (and non-BN) containing morphologies. Several coating techniques will be utilized including CVD and sol-gel.

TECHNICAL PROGRESS

The ability to use CVD SiC overcoatings on SiC fibers to protect existing carbon coatings has been demonstrated. This ability will be used to simulate the matrix for a single filament/coating "minicomposite." Several approaches for non-carbon containing interfaces have been identified which will be further investigated. Two contracts will be the key to providing commercially fabricated interfacial coatings.

MILESTONE SCHEDULE (TASKS)

Demonstrate minicomposite tensile test for coating evaluation. FY 1992

Demonstrate approaches for interface coatings, including unbonded multilayer (Northrop), protection of carbon (Textron) and in-house efforts. FY 1993

Determine feasibility of oxidatively stable, carbon-containing interface coatings for SiC fibers. FY 1994

Determine feasibility of >2500°F non-carbon interface coatings for SiC fibers. FY 1995

**** FIBER COATINGS ****

<RECORD NUMBER: 112>

TITLE: Ceramic Fiber Coating

PROJECT DURATION: One year

PRINCIPAL INVESTIGATOR(s): Harry Carpenter

RESEARCH ORGANIZATION(s): Northrop Corporation

SPONSOR: NASA-Lewis Research Center (HITEMP)

OBJECTIVE

To demonstrate the performance of a potentially oxidation resistant fiber coating process consisting of multiple, ultrathin ($<0.1\mu\text{m}$) unbonded layers.

DESCRIPTION

Unbonded multilayers of SiC will be deposited onto SiC fibers via CVD. Seven different systems will be examined to determine the effect of coating design features on interfacial shear strength. The two best systems will be evaluated after exposure to oxidizing conditions.

TECHNICAL PROGRESS

Contract not yet awarded.

MILESTONE SCHEDULE (TASKS)

Evaluate fiber/coating process (assuming start date of 4/92). 7/92

Optimize coating design and deposition process. 10/92

Demonstrate oxidation resistance. 5/93

Final report. 6/93

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Summary of Additional Projects

Component Development, Fabrication, and Fiber-related Projects

CONTINUOUS FIBER CERAMIC COMPOSITE PROGRAM
COMPONENT DEVELOPMENT, FABRICATION, AND FIBER-RELATED PROJECTS - SUMMARY OF ADDITIONAL PROJECTS

Prin. Investigator	Research Organization	Title	Sponsor
COMPONENT DEVELOPMENT			
W. Fohey	Williams International	Combustor Evaluation	DOD/Air Force Materials Directorate
T. Kafka	3M Company	Fabrication of Commercial-Scale Fiber-Reinforced Hot-Gas Filters by Chemical Vapor Deposition	DOE/Office of Fossil Energy
FABRICATION & PROCESSING TECHNOLOGY			
D. Lewis	Naval Research Laboratory	Fiber Composite Surface Laminates	DOD/Defense Advanced Research Projects Agency
Y.M. Chiang	Massachusetts Institute of Technology	Liquid Phase Reaction Bonding of Structural Ceramics and Composites	DOD/Office of Naval Research
Y.M. Chiang	Massachusetts Institute of Technology	Processing of Reaction-Bonded Silicon Carbide Structural Ceramics	DOD/Office of Naval Research
J.A. Cornie	Massachusetts Institute of Technology	Composites Research	DOD/Office of Naval Research
J.C. Schneider	San Juan Technologies	Low Cost Structural Ceramic Composites	DOD/Office of Naval Research
Mark Allendorf Nancy Scoville	SNLL Thermoelectron	Chemical Vapor Deposition of Ceramic Composites	DOE/OIP-Advanced Industrial Concepts
T.L. Starr	Georgia Institute of Technology	Development of Fiber Reinforced Ceramics	DOE/Office of Fossil Energy
T.L. Starr	Georgia Institute of Technology	Modeling of Fibrous Preforms for CVD Infiltration	DOE/Office of Fossil Energy
	Allied Signal/Garrett Components Division	Development of Ceramic Fiber Reinforced Si ₃ N ₄ Matrix Composites	NASA (HITEMP)

CONTINUOUS FIBER CERAMIC COMPOSITE PROGRAM
COMPONENT DEVELOPMENT, FABRICATION, AND FIBER-RELATED PROJECTS - SUMMARY OF ADDITIONAL PROJECTS

Prin. Investigator	Research Organization	Title	Sponsor
FIBERS DEVELOPMENT			
A. Heuer	Case Western Reserve University	Investigation of Single Crystal Sapphire	DOD/Defense Advanced Research Projects Agency
	Saphikon, Inc. GE Aircraft Engines	Intelligent Processing of Sapphire Fibers	DOD/Defense Advanced Research Projects Agency
A.G. Evans	University of California, Santa Barbara	Fugitive Phases for Oxide/Oxide Systems	DOD/Defense Advanced Research Projects Agency
J. Economy	University of Illinois	Low Cost BN Fibers by Nitridation of Boria Fibers	DOD/Defense Advanced Research Projects Agency

Appendix

CFCC Federally-Funded Research & Development Questionnaire

CFCC Federally-Funded Research & Development Questionnaire

INTERNAL PROJECT ID:

1. Title of Research/Development Project/Effort:
2. Work Element Description and Number (e.g., '2.2.1, Fiber', unique project identification):
3. Principal Investigator(s) (list first name, middle initial, last name):
4. Research Organization (Affiliation of PI):
5. Complete Mailing Address of PI (Street, P.O. Box, City, State, Zip):
6. PI's Phone Number:
Commercial: () - ; FTS: () -
7. PI's FAX Number:
Commercial: () - ; FTS: () -
8. Project Duration:
Project starting date _____ through project expiration date _____
9. Objective of the Project (short statement):
10. Description of Project (Briefly describe the project and its proposed direction):
11. Milestones (list few major ones-less than 10):

CFCC Federally-Funded Research & Development Questionnaire - cont'd

12. List major accomplishments (if applicable):
13. Briefly Describe Future Plans for FY92, FY93, FY94 (one sentence per year):
14. Funding History (list funding in units of thousands, \$65,000 is 65k; FY92 is from Oct 1 1991 to Sept 30, 1992)
FY92_____ FY93_____ FY94_____
15. Name of Sponsoring Organization (also list the office, e.g., DOE-Off. of Industrial Technologies):
16. Please define the materials system(s) used for the fiber and the ceramic composite (list both the chemical name and trade name (if applicable)):
17. List keywords or terms that describe your project, e.g., the properties studied, applications, testing, etc.):

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