Final Report for
NASA Glenn Cooperative Agreement NCC3-776
"Elevated Temperature Testing and Modeling of Advanced Toughened Ceramic Materials"

The purpose of this report is to provide a final report for the period of 12/1/03 through 11/30/04 for NASA Cooperative Agreement NCC3-776, entitled "Elevated Temperature Testing and Modeling of Advanced Toughened Ceramic Materials."

During this final period, major efforts were focused on both the determination of mechanical properties of advanced ceramic materials and the development of mechanical test methodologies under several different programs of the NASA-Glenn. The important research activities made during this period are summarized as follows:

1. Mechanical properties evaluation of two gas-turbine grade silicon nitrides
   Mechanical testing to determine strength, fracture toughness, slow crack growth, and creep of two gas-turbine grade silicon nitrides (AS800 and SN282) was initiated. Strength testing at RT, 1315 and 1371°C was completed using a large number of test specimens. Also slow crack growth testing to generate life prediction parameters was initiated at 1315 and 1371°C and some results at the two test temperatures were obtained. These results will be used CARES/life code to predict gas-turbine components' lives. Creep testing for AS800 and SN282 in compression, tension, and flexure was also initiated and is in progress. The work is under the Ultra-Efficient Engine Technology (UEET) Program, NASA Glenn.

2. Mechanical testing for fuel-cell seal materials
   Major mechanical properties of fuel-cell seal materials (glass/zirconia and glass/alumina composites), including strength, fracture toughness and elastic modulus fuel-cell seal materials were completed at ambient temperature. This work was conducted to develop new seal materials with long-term durability and life under solid oxide fuel cell (SOFC) operating conditions.

3. Mechanical properties evaluation of thermal barrier coatings and CFCCs.
   Effect of sintering on mechanical and physical properties of plasma-sprayed thermal barrier coatings was determined as a function of annealing temperature. The properties included strength, modes I and II fracture toughnesses, elastic modulus, constitutive relations (deformation), density, and microhardness. Annealing times were 5, 10, 20, 100, and 500 hours, annealed at 1316oC in air.
   Double notch shear testing for SiC/SiC and C/SiC with different test rates at elevated temperatures was conducted to determine a relationship between shear strength and test rate to better understand governing failure mechanisms and to develop a life prediction methodology of the composite materials. This work was performed under the UEET Program.

4. Foreign object damage (FOD) testing
   Extensive FOD testing for AS800 and SN282 silicon nitrides and SiC/SiC composite was carried out at both ambient and elevated temperatures. This testing was for the evaluation of the gas turbine-grade ceramics in terms of resistance to foreign object damage.

Detailed descriptions of the work performed during thc final period can be found from the publications as listed below.

Publications (12/03-11/04)

1. "Foreign Object Damage in Disks of Gas-turbine Grade Silicon Nitrides by Steel Ball Projectiles at Ambient Temperature," S. R. Choi, J. M. Perreira, L. A. Janosik, and R. T. Bhatt, *J. Mater. Sci.*, **39** 6173-6182 (2004).

2. "Foreign Object Damage in Flexure bars of Two Gas-Turbine Grade Silicon Nitrides," S. R. Choi, J. M. Pereira, L. A. Janosik, and R. T. Bhatt, *Mat. Sci. Eng.*, **A379** 411-419 (2004).

3. "Foreign Object Damage Behavior of a SiC/SiC Composite at Ambient and Elevated Temperatures," S. R. Choi, R. T. Bhatt, J. M. Pcrcira, and J. P. Gyekenyesi, *ASME Paper No.* **GT 2004-53910**; presented at the ASME Turbo Expo 2004, Vienna, Austria, June 2004.

4. "Shear Strength as a Function of Test Rate for SiC/BSAS Ceramic Matrix Composite at Elevated Temperature," S. R. Choi and N. P. Bansal, *J. Am. Ceram. Soc.*, **87**[10] 1912-1918 (2004).

5. "Load-Rate Dependency of Ultimate Tensile Strength in Ceramic Matrix Composites at Elevated Temperatures," S. R. Choi and J. P. Gyekenyesi, in print, *Int. J. Fatigue* (2004).

6. "Slow Crack Growth of Brittle Materials with Exponential Crack-Velocity Formulation – Static Fatigue," S. R. Choi, N. N. Nemeth, and J. P. Gyekenyesi, accepted in *J. Mater. Sci* (04).

7. "Delayed Failure of Ceramic Matrix Composites in Tension at Elevated Temperatures," S. R. Choi, N. P. Bansal, and M. J. Verrilli, in print in *J. Euro. Ceram. Soc.*, (2004).

8. "Shear Strength Behavior of Ceramic Matrix Composites at Elevated Temperatures," in print *Ceramic Transactions*, Vol 165 (2004).

9. "Mechanical Properties/Database of Plasma-Sprayed ZrO_2-8wt% Y_2O_3 Thermal Barrier Coatings," S. R. Choi, D. Zhu, and R. A. Miller, in print in *Int. Journal of Applied Ceramic Technology*, 1[4] (2004).

10. "Development and Fatigue Testing of Ceramic Thermal Barrier Coatings," Dongming Zhu, Sung R. Choi, and Robert A. Miller, *Surface & Coating Technology*, **188-189** 146-152 (2004); also in **NASA/TM-2004-213083**, National Aeronautics & Space Administration, Glenn Research Center, Cleveland, OH (2004).

11. "Mechanical Properties of Plasma-Sprayed Thermal Barrier Coatings," S. R. Choi, D. Zhu,

and R. A. Miller, **NASA/TM-2004-213216**, National Aeronautics & Space Administration, Glenn Research Center, Cleveland, OH (2004).

12. "Solid Oxide Fuel Cell Seal Development at NASA Glenn Research Center," B. M. Steinetz, N. P. Bansal, F. W. Dynys, J, Lang, C. C. Daniels, J. L. Palko, and S. R. Choi, presented at the 2004 Fuel Cell Seminar, San Antonio, TX, November 1-5, 2004; to be published in the Proceedings (2004).