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FOREIGN TRIP REPORT

ORNL/FTR-2954

DATE: July 11, 1988

SUBJECT: Report of Foreign Travel of V. J. Tennery, Head, High Temperature Materials Section, and V. R. Bullington, Conservation Program Office, Metals and Ceramics Division

TO: Alexander Zucker

FROM: V. J. Tennery and V. R. Bullington

PURPOSE: The travelers attended the 33rd ASME International Gas Turbine and Aeroengine Congress and Exposition, held in Amsterdam, The Netherlands, on June 5-9, 1988, and participated as follows. **V. J. Tennery**: to present a technical paper, entitled "Application of Electron Microscopy for the Analysis of the Mechanical Behavior of Advanced Ceramics," and to make a presentation at the Executive Committee Meeting of the IEA Annex II Agreement between the United States, Federal Republic of Germany, and Sweden on June 8 regarding status of U.S. research on Annex II and present the proposed U.S. Annex III research plan. Dr. Tennery had planned to visit The Netherlands Energy Research Foundation in Petten, and the DFVLR in Cologne, Federal Republic of Germany, for discussions on ceramic research, but those visits were cancelled. **V. R. Bullington**: To staff the exhibits for the Ceramic Technology for Advanced Heat Engines Project.

SITES VISITED:	6/05-6/09/88	33rd ASME International Gas Turbine and Aeroengine Congress and Exposition	Amsterdam, The Netherlands	R. Th. Praaning

ABSTRACT: The travelers attended the 33rd ASME International Gas Turbine and Aeroengine Congress and Exposition. V. R. Bullington staffed the exhibits for the Ceramic Technology for Advanced Heat Engines Project and distributed informational materials to the attendees. V. J. Tennery presented a paper; in addition, he organized and presented the U.S. portion of a technical status review for the Executive Committee, IEA Annex II (including U.S. research being conducted within the IEA Annex II agreement on advanced structural ceramics). Finally, Dr. Tennery made a technical presentation on the proposed research plan for an Annex III agreement on structural ceramics.

COMPREHENSIVE TRIP REPORT

33rd ASME INTERNATIONAL GAS TURBINE AND AEROENGINE CONGRESS AND EXPOSITION

International Exhibition and Congress Center RAI
Amsterdam, The Netherlands

There is growing worldwide recognition of the importance of microscopic analyses techniques in determining high-temperature failure mechanisms in advanced structural ceramics. The world gas turbine community has also realized that critical materials issues for advanced gas turbines can now only be solved using state-of-the-art instruments such as high resolution analytical electron microscopes, for example, to determine how presently available experimental materials such as structural ceramics can be systematically improved to the point where they can realistically be considered as candidate engineering materials. The Ceramics Committee of the ASME, therefore, organized a number of technical sessions focussed on structural ceramics for gas turbine application for the 33rd Congress.

V. J. Tennery spent most of the time in the ceramic sessions, and the following summarizes results reported. Two technical sessions were specifically oriented to structural ceramic properties and characterization, and five sessions (including two panel sessions) were oriented to ceramic components and their application in gas turbine engines. Reprints of many of the papers from the technical sessions were obtained by the traveler and are available. No papers were published from the two panel sessions, which covered ceramic component specifications and emerging ceramic composites.

The first session was on use of microscopy for characterizing structural ceramics. Two papers in the first session clearly showed the critical importance of very high resolution electron microscopy and state-of-the-art scanning electron microscopy in identifying the origin of critical flaws in silicon nitride ceramics. The scanning transmission electron microscope was shown to be particularly useful for characterizing the composition of the matrix phase in silicon nitride materials. The topic of the second session was on mechanical design and properties of structural ceramics. A particularly interesting paper on ceramic reliability concerned statistical analysis of multiaxial failure using Weibull statistics and the multiaxial elemental strength (Muest) model. The author proposed a model in which it is assumed that pre-existing flaws in the material can be characterized by a flaw extension stress or strength, and that the flaw distributions can then be described by the distribution in this strength. A variant of the Muest model, which includes multiaxial elemental stress modes combined with fracture mechanics, was also discussed. In this model, the statistical parameters are introduced at the microscopic flaw level in the determination of the flaw density function. They characterize the equivalent stress operating at each flaw, whereas in the Weibull model, they characterize the strength of the bulk specimen, expressed as a maximum stress. The model was tested using reaction-bonded silicon nitride, and the Weibull, the Barnett-Freudentahl approximation, and the Muest models were compared. The former two gave highly conservative predictions relative to the experimental data, while the Muest model gave excellent agreement.

The panel session on ceramic component specifications clearly showed that we are very far away at the present time in reaching agreement on a set of rigorous material specifications for various ceramic components in advanced gas turbine engines. In many cases, the engine manufacturers do not yet know exactly what value of a given property is critical as a function of temperature and time, and in essentially all cases, the suppliers are not prepared to make components to such a specification set. High-temperature mechanical properties including long-term tensile fatigue as well as tensile fast fracture behavior are critically lacking for all structural ceramics, including composites currently considered for use in uncooled gas turbine engines.

The session on thermal barrier coatings for metallic turbine components contained some noteworthy presentations. One discussed the merits of ceramic thermal barrier coatings on superalloy hot flow path components, and showed that a coating 0.25 mm thick can reduce metal temperature about 170°C, depending upon the local heat flux. This amount of metal temperature reduction is greater than the cumulative gains made in temperature capability of airfoil alloys over the past 20 years. Unfortunately, the science and technology of developing stable adherent ceramic coatings has been very slow. Recent advances in electron beam-physical vapor deposition offer promise of providing ceramic coating microstructures providing the required reliability and economics. Another paper included a model having a life prediction algorithm that includes both cyclic and time-dependent damage. Correlation between the predicted and actual spallation lives of coatings applied to B1900 alloy, which were stress and temperature cycled up to about 1170°C was within a factor of 3, which is considered very good at this time.

The panel session on emerging ceramic composites included a very interesting paper by a representative of Societe Europenne de Propulsion (SEP) in France. The SiC/SiC composite studied and manufactured for some time by SEP is very similar to the CVD SiC infiltrated matrix composites investigated for the past few years in the Metals and Ceramics Division at ORNL. SEP has carried out extensive work in fabricating actual gas turbine components of this continuous or long fiber reinforced composite material. An axial flow turbine rotor having a diameter of about 15 cm was shown to the audience and circulated for examination. The paper also included indication that SEP is conducting extensive high-temperature tensile testing of these materials. It was stated that flexure testing of these materials is relatively useless for determining useful mechanical properties of interest to gas turbine applications. SEP studied the tensile behavior of their composite using a specimen having a total length of 120 mm, with a gage section 40 mm long and a cross section 8 mm wide by 3 mm thick. Tensile strength measurements using these specimens show that irreversible nonlinearity in the stress-strain relation occurs in the range of 100+ to 80 MPa, which is the stress at which matrix cracking commences. The design implications of this permanent deformation were discussed, but no clear conclusions were reached by the panel members or the audience. R-curve measurements using compact tensile specimens were also reported for both 2D carbon and 2D SiC fiber reinforced SiC matrix composites. At 25°C, the carbon reinforced composite exhibited a fracture energy of 15,000 J/m^2 for a crack propagation length of only 1 mm, while 2D SiC/SiC composites reached a maximum J value of about 10,000 J/m^2 at a crack length of 3 mm. These recent data were felt to be very important in eventually understanding the high-temperature mechanical behavior of this class of composites.

The session on small ceramic gas turbine engines was well attended: all three papers were from the United States. One paper predicted that the first real commercial use of structural ceramics in gas turbines may be in the next generation of auxiliary power units (APU) in aircraft and mobile power applications. Design compromises were discussed between a metal and ceramic version of an APU delivering 100 shaft horsepower. Hot rig tests of the silicon nitride rotors showed that foreign object damage from carbon deposits in the combustor frequently caused rotor disintegration. Design, reliability, and cost analyses showed that the ceramic design could be very competitive if available materials had fracture strengths and Weibull moduli about 30% and 100% better than currently available. Review papers of the AGT 100 and AGT 101 programs demonstrated the significant progress made in the past 5 years in fabricating complex ceramic gas turbine components. The 85-h test of the AGT 101 all-ceramic hot section to 1200°C was particularly noteworthy.

V. R. Bullington staffed the exhibits for the Ceramic Technology for Advanced Heat Engines Project throughout the Exposition. Mr. Bullington coordinated the shipment of three Department of Energy exhibits to Amsterdam, supervised the setup, and the subsequent dismantling and return shipment of these exhibits. During the Exhibition, an estimated 4800 people visited the exhibits. In addition to interacting with people at the exhibits, Mr. Bullington distributed the following materials: (1) brochures covering the Ceramic Technology for Advanced Heat Engines Project, (2) brochures on the High Temperature Materials Laboratory and The High Temperature Materials Laboratory User Program, and (3) brochures on "The Outlook for Ceramics in Heat Engines 1990-2010, Results of a World Wide Delphi Survey." Other material distributed included a bibliography of publications in the Ceramic Technology for Advanced Heat Engines Project, a data sheet on the International Energy Agency Annex II, a facts sheet of the High Temperature Materials Laboratory, and the ORNL Ceramic Technology for Advanced Heat Engines Project newsletter.

IEA ANNEX II EXECUTIVE COMMITTEE MEETING

International Exhibition and Congress Center RAI
Amsterdam, The Netherlands

The IEA Executive Committee meeting was initially attended by representatives of the United States (including Dr. Tennery), the Federal Republic of Germany, and Japan. The meeting was organized into two parts. The first part was attended by Dr. Kiichiro Yamagishi, Director of the R&D Program for the Moonlight Project in the Agency of Industrial Science and Technology of MITI in Tokyo, Japan. Dr. Yamagishi described the new ceramic gas turbine programs in Japan, which he has initiated. The new R&D program is planned to start in September 1988. An assessment is currently being conducted for Dr. Yamagishi by the Japan Fine Ceramics Association.

This assessment includes two turbines having outputs of 100 and 300 kW. The total project is planned for 9 years at an approximate total cost of $130M, assuming the small turbine project is not carried to completion. The 100-kW turbine (CGT-100) for automobile use will include a 2-year critical decision point. If the decision is to proceed at that time, then an additional $80M will be added to the budget to bring the total to about $210M to be spent in the 9-year period. If the small gas turbine enters this latter stage, three Japanese auto companies will be selected as prime contractors. The 300-kW turbine (CGT-300) project will be managed for MITI by NEDO, which is a new energy development organization in Japan. NEDO will in turn provide 100% contract funds to three groups who will work on the project. Dr. Yamagishi is advised as to who to select for contractors by a Japanese federal laboratory, such as NIRIM. It appeared that competitive bidding may not be used in Japan for selecting contractors for these types of projects.

The group then discussed the possibility of organizing an Annex III agreement on structural ceramics, and Dr. Yamagishi stated that Japan definitely wants to be a member of any Annex III, and that he regrets that Japan did not join Annex II, which is now nearing completion. Dr. Tennery then made a presentation outlining the latest U.S. proposal for Annex III based upon recent meetings at Cocoa Beach and Cincinnati plus considerable feedback received from U.S. companies. This proposal includes cooperative international tensile strength research, and Dr. Yamagishi was very receptive to the need for this type of international work. Also provided was a brief description of the German proposal discussed at the Dearborn meeting last October. Dr. Yamagishi then left the meeting to catch a plane to return to Japan.

The Executive Committee meeting then entered the second part, including a detailed review of the status of research results for Annex II. Dr. Tennery presented the status of Subtask 2 on powder characterization and the overall results of Subtask 4, and in particular the fractography analyses. Included was the latest draft of the report being prepared at ORNL on fractography results from the three member countries. Ms. Bruckner-Foit of the KFK, University of Karlsruhe, then presented a summary of the statistical analysis done in the FRG on the fracture strength data. Particular attention was given to the Kolmogorov-Smirnov statistical analyses of the data sets as a means to identify flexure strength data sets which do not belong to the general population of each of the three ceramics provided by each of the three participating countries. There was some confusion concerning statistical rejection criteria for the data sets, and Dr. Tennery agreed to provide a final summary of U.S. review comments for the draft report to the FRG no later than mid-August. He also agreed to provide Ms. Bruckner-Foit with data describing all of the specimens used in both Subtasks 3 and 4. Dr. Michael Hatcher of KemaNord in Sweden then summarized the results provided to him from all three countries for the chemical analysis results of Subtask 3. He also reviewed the status of his draft report.

The meeting adjourned with agreements to finalize the review process for both the fracture statistics and fractography reports as soon as possible so that we can proceed with their publication.

APPENDIX A

ITINERARY

V. J. Tennery

1988

06/03-04	Travel from Oak Ridge, TN, to Amsterdam, The Netherlands, via plane
06/05-09	Conference site at the International Exhibition and Congress Center RAI
06/10	Travel from Amsterdam, The Netherlands, to Oak Ridge, TN, via plane

V. R. Bullington

06/01	Travel from Oak Ridge, TN, to Amsterdam, The Netherlands, via plane
06/05-09	Conference site at the International Exhibition and Congress Center RAI
06/10-12	Dismantle and prepare exhibits for shipment, and arrange for returning the exhibits to Oak Ridge
06/13	Travel from Amsterdam, The Netherlands, to Knoxville, TN, via plane

APPENDIX B

LITERATURE ACQUIRED BY V. J. TENNERY

1. "Electron Microscopy Techniques for the Microstructural Characterization of Silicon Nitride," K. N. Siebein and R. L. Yeckley, ASME Paper 88-GT-184.

2. "Whisker Orientation Measurements in Injection Molded Silicon Nitride-Silicon Carbide Composites," J. T. Neil and D. A. Norris, ASME Paper 88-GT-193.

3. "Ceramic Reliability: Statistical Analysis of Multiaxial Failure Using the Weibull Approach and the Multiaxial Elemental Strength Model," J. Lamon, ASME Paper 88-GT-147.

4. "Design and Test of Non-Rotating Ceramic Gas Turbine Components," A. L. Neuberger and G. Carrier, ASME Paper 88-GT-146.

5. "Ceramic Bearings for Use in Gas Turbine Engines," E. V. Zaretsky, ASME Paper 88-GT-138.

6. "Current Status and Future Trends in Turbine Application of Thermal Barrier Coatings," K. D. Sheffler and D. K. Gupta, ASME Paper 88-GT-286.

7. "Processing Aspects of Plasma Sprayed Ceramic Coatings," R. C. Novak, ASME Paper 88-GT-289.

8. "Porosity Determination of Thermal Barrier Coatings," M. V. Roode and B. Beardsley, ASME Paper 88-GT-278.

9. "Thermal Barrier Coating Life Prediction Model Development," T. A. Cruise, S. E. Stewart, and M. Ortiz, ASME Paper 88-GT-284.

10. "Comparison of Ceramic Vs. Advanced Superalloy Options for a Small Gas Turbine Technology Demonstrator," T. Bornemisza and J. Napier, ASME Paper 88-GT-228.

11. "AGT 101/ATTAP Ceramic Technology Development," G. L. Boyd and D. M. Kreiner, ASME Paper 88-GT-243.

12. "AGT 100 Project Summary," H. E. Helms, ASME Paper 88-GT-223.

13. "Development of Ceramic Turbine Rotors," K. Katayama, M. Sasaki, and T. Itoh, ASME Paper 88-GT-282.

APPENDIX C

DISTRIBUTION

1. Assistant Secretary for International Affairs, DOE, Washington
2. M. H. Chiogioji, Director, Office of Transportation Systems, Conservation and Renewable Energy, DOE, Washington
3. A. A. Chesnes, Director, Heat Engine Propulsion Division, Office of Transportation Systems, Conservation and Renewable Energy, DOE, Washington
4. D. J. Cook, DOE/ORO
5. J. A. Lenhard, DOE/ORO
6. M. J. Rohr, DOE/ORO

7-8. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831

9. B. R. Appleton
10. R. A. Bradley

11-16. V. R. Bullington

17. D. R. Johnson
18. R. R. Judkins
19. M. W. Rosenthal
20. G. M. Slaughter
21. J. O. Stiegler

22-27. V. J. Tennery

28. J. R. Weir
29. A. Zucker

30-31. ORNL Laboratory Records Department

32. ORNL Laboratory Records Department-RC
33. Laboratory Protection Division
34. ORNL Patent Section
35. ORNL Public Relations Office