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NASA/CARES Dual-Use Ceramic Technology Spinoff Applications

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Abstract

NASA has developed software that enables American industry to establish the reliability and life of ceramic structures in a wide variety of 21st Century applications. Designing ceramic components to survive at higher temperatures than the capability of most metals and in severe loading environments involves the disciplines of statistics and fracture mechanics. Successful application of advanced ceramics depends on proper characterization of material properties and the use of a probabilistic brittle material design methodology. The NASA program, known as CARES (Ceramics Analysis and Reliability Evaluation of Structures), is a comprehensive general-purpose design tool that predicts the probability of failure of a ceramic component as a function of its time in service. The latest version of this software, CARES/LIFE, is coupled to several commercially available finite element analysis programs (ANSYS, MSC/NASTRAN, ABAQUS, COSMOS/M, MARC), resulting in an advanced integrated design tool which is adapted to the computing environment of the user. The NASA-developed CARES software has been successfully used by industrial, government, and academic organizations to design and optimize ceramic components for many demanding applications. Industrial sectors impacted by this program include aerospace, automotive, electronic, medical, and energy applications. Dual-use applications include the design of automotive engine components, graphite and ceramic high temperature valves, TV picture tubes, ceramic bearings, electronic chips, glass building panels, infrared windows, radiant heater tubes, heat exchangers, and artificial hips, knee caps, and teeth.

Introduction

Transferring technological innovations beyond their primary aerospace applications into products with a much wider range of impact continues to be an integral part of the space program. The National Aeronautics and Space Administration (NASA) strives to ensure that its technological advances are readily accessible to industrial and academic organizations as well as to other government laboratories. At the NASA Lewis Research Center, a major effort has been dedicated to understanding and predicting the complex behavior of advanced, high-temperature ceramic materials for aerospace and terrestrial propulsion systems. Successful utilization of advanced ceramics for these applications depends on proper characterization of material properties and the use of a probabilistic brittle material structural design methodology. NASA has developed the CARES[1-3] (Ceramics Analysis and Reliability Evaluation of Structures) software, a comprehensive general-purpose design tool that predicts the probability of failure of a ceramic component as a function of its time in service. Although created primarily to foster the introduction of ceramic materials in demanding space and aeronautics propulsion systems, this series of ceramic life prediction software and associated technology are being implemented for numerous other "dual-use" applications. The NASA/CARES software is used worldwide by more than 250 organizations representing industries such as aerospace, automotive, electronics, medical, and power generation. This paper describes the probabilistic ceramic component design procedure and the life prediction capabilities incorporated into the CARES design software. In addition, several typical "dual-use" ceramic technology spinoff applications designed using this software are presented.

Probabilistic Component Design

Significant improvements in aerospace and terrestrial propulsion, as well as in power generation for the next century require revolutionary advances in high temperature materials and structural design. Advanced ceramics offer the unique combination of being abundant materials that have a lighter weight and a greater capacity to sustain load at a higher use temperature than metals. In addition, substitution of structural ceramics for traditional metals will reduce costs by increasing durability and efficiency. The increasing importance of ceramics as structural materials places high demand on assuring component integrity while simultaneously optimizing performance and cost. Designing ceramic components for durability requires that all potential failure modes are identified and accounted for in a comprehensive design methodology.

Ceramic properties have progressively improved due to advances in both processing and composition. This has reduced the number and size of strength-controlling defects, led to the development of tougher materials that better tolerate the presence of flaws, and improved understanding and control of microstructural composition. However, ceramics are inherently brittle, and the lack of ductility leads to low strain tolerance, low fracture toughness, and large variations in observed fracture strength caused by the variable severity (size) and random distribution of flaws. Ceramic structures that appear to be identical can vary greatly in their fracture behavior and designers must take this into account. Variations in apparently identical structures arise from invisible imperfections throughout the material that weaken the structure and can be sources of unexpected catastrophic failure. In addition, the ability of a ceramic component to sustain load degrades over time as a result of oxidation, creep, stress corrosion cracking, cyclic fatigue, and elevated-temperature use.

Stress corrosion cracking, cyclic fatigue, and elevated- temperature sustained load response are different aspects of the phenomenon called subcritical crack growth (SCG). SCG refers to the progressive extension of a crack over time. An existing flaw extends until it reaches a critical length, causing catastrophic crack propagation. Under the same conditions of temperature and load, ceramic components display large variations in rupture times from SCG. Unfortunately, the small critical flaw size and large number of flaws make it difficult to detect beforehand the particular flaw that will initiate component failure. Probabilistic brittle material design techniques are therefore necessary to predict the probability of a ceramic component's failure as a function of service time.

Traditional material failure analyses employing a deterministic approach, where failure is assumed to occur when some allowable stress level or equivalent stress is exceeded, are not adequate for monolithic ceramic component design. Such phenomenological failure theories are reasonably successful when applied to ductile materials such as metals. However, since analysis of failure in components fabricated from ceramics is governed by the observed scatter in strength, statistical design approaches must be used to accurately reflect the stochastic physical phenomena that determine material fracture response. Reliability analysis is essential for accurate failure prediction and efficient structural utilization of brittle materials subjected to arbitrary stress states.

In the United States, development of brittle material design technology has been actively pursued during the past two decades. In the late 1970s, NASA initiated development of the SCARE[4,5] (Structural Ceramics Analysis and Reliability Evaluation) computerized design program under the Ceramic Applications in Turbine Engines (CATE) program sponsored by the Department of Energy (DOE) and NASA. The goal of this project was to create public domain ceramics design software to support projects for the DOE, other government agencies, and industry. SCARE has since evolved into the CARES and, most recently, CARES/LIFE[6-9] (Ceramics Analysis and Reliability Evaluation of Structures Life Prediction Program) integrated design programs.

Probabilistic component design involves predicting the probability of failure for a thermomechanically loaded component from specimen rupture data. Typically these experiments are performed using many simple geometry flexural or tensile test specimens. A static, dynamic, or cyclic load is applied to each specimen until fracture. Statistical strength and SCG (fatigue) parameters are then determined from these data. Using these parameters and the results (i.e., stress and temperature distributions) obtained from a finite element analysis, the time-dependent reliability for a complex component geometry and loading is then predicted. Appropriate design modifications are made until an acceptable probability of failure is achieved, or until the design has been optimized with respect to some variable design parameter. This design methodology combines the statistical nature of strength-controlling flaws with the mechanics of crack growth to allow for multiaxial stress states, concurrent (simultaneously occurring) flaw populations, subcritical crack growth, and component size effect. These issues are addressed within the CARES/LIFE program.

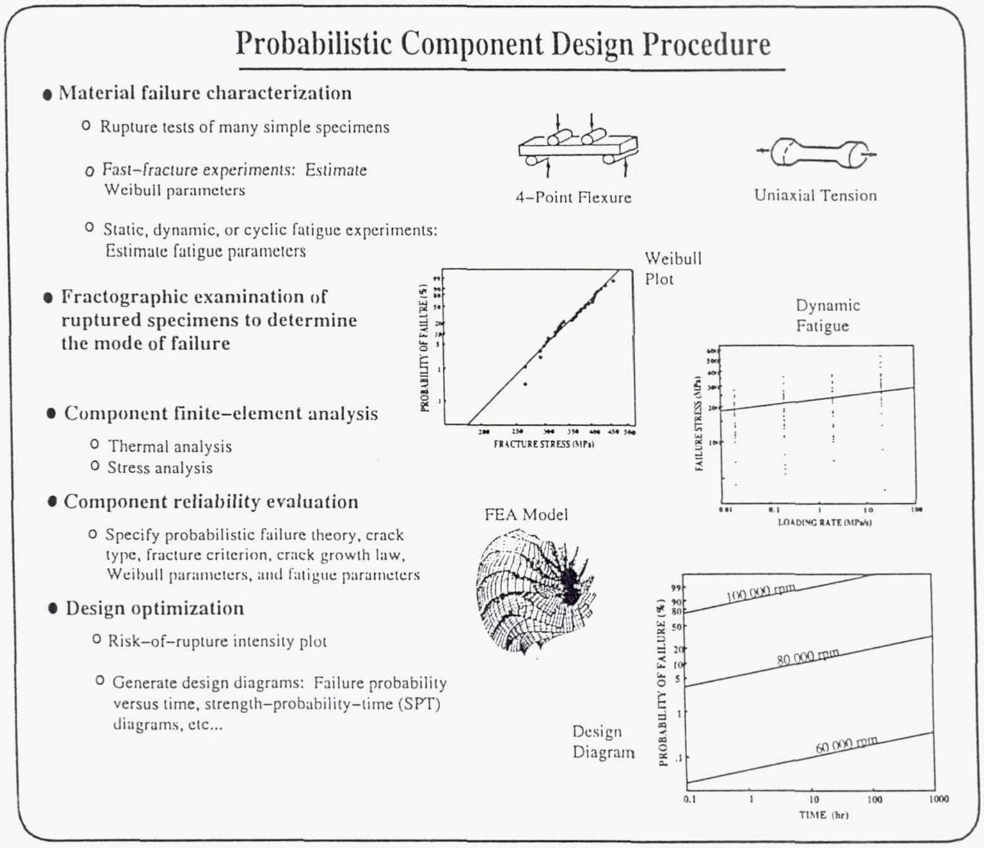

Figure 1. Outline of the probabilistic component design procedure utilized in the NASA/CARES series of integrated design software.

Life Prediction Capabilities

The CARES design software combines multidisciplinary research—in the areas of fracture analysis, probabilistic modeling, model validation, and brittle structure design—to determine the reliability of monolithic ceramic components. Compiling the diverse elements of this technology into one package provides industry, government, and academia with a powerful, innovative design program for engineers to simply select and use. CARES/LIFE, the latest version of this software, is coupled to several commercially available finite-element programs (e.g., ANSYS, ABAQUS, MSC/NASTRAN, COSMOS/M, and MARC), resulting in an advanced integrated design tool adapted to the computing environment of the user. CARES/LIFE incorporates the capability to account for material failure from SCG of pre-existing flaws, and also considers the effect of proof testing components prior to service. This version also retains all of the capabilities of the previous CARES code, which include fast-fracture component reliability evaluation and Weibull parameter estimation from inert strength (without SCG contributing to failure) specimen data. CARES/LIFE can estimate parameters that characterize SCG from specimen data as well.

Input for the CARES/LIFE program includes material data from simple experiments and results from a finite element analysis of a complex component. Finite-element heat transfer and linear-elastic stress analyses are used to determine the component's temperature and stress distributions. The reliability at each element (a very small subunit of the component) is calculated assuming that randomly distributed volume flaws and/or surface flaws control the failure response. The overall component reliability is the product of all the element survival probabilities. CARES/LIFE generates a data file containing element risk-of-rupture intensities (a local measure of reliability) for graphical rendering of the structure's critical regions.

CARES/LIFE describes the probabilistic nature of material strength, using the Weibull cumulative distribution function[10]. The Weibull equation is based on the weakest-link theory (WLT). WLT assumes that the structure is analogous to a chain with many links. Each link may have a different limiting strength. When a load is applied to the structure such that the weakest link fails, then the structure fails.

The effect of multiaxial stresses on reliability is predicted by using the principle of independent action (PIA),[11,12] the Weibull normal stress averaging method (NSA),[13] or the Batdorf theory.[14,15] For the PIA model the reliability of a component under multiaxial stresses is the product of the reliability of the individual principal stresses acting independently. The NSA method involves the integration and averaging of tensile normal stress components evaluated about all possible orientations and locations. This approach is a special case of the more general Batdorf theory and assumes the material to be shear insensitive.

The Batdorf theory combines the weakest link theory and linear elastic fracture mechanics (LEFM). Conventional fracture mechanics analysis requires that both the size of the critical crack and its orientation relative to the applied loads determine the fracture stress. The Batdorf theory includes the calculation of the combined probability of the critical flaw being within a certain size range and being located and oriented so that it may cause fracture. A user-selected flaw geometry and a mixed-mode fracture criterion are required to model volume- or surface-strength-limiting defects. Mixed-mode fracture refers to the ability of a crack to grow under the combined actions of a normal load (opening mode) and shear load (sliding and tearing modes) on the crack face. CARES/LIFE includes the total strain energy release rate fracture criterion, which assumes a crack will extend in its own plane (coplanar).[15] Out-of-plane crack extension criteria are approximated by a simple semiempirical equation.[16,17] Available flaw geometries include the Griffith crack, penny-shaped crack, semicircular crack, and notched crack. The Batdorf theory is equivalent to the probabilistic multiaxial theories proposed by Evans[18] and Matsuo.[19]

Subcritical crack growth is difficult to model, because it is a complex phenomenon often involving a combination of failure mechanisms. Existing models usually employ empirically derived crack propagation laws that describe the crack growth in terms of the stress intensity factor at the crack tip plus additional parameters obtained from experimental data. The stress intensity factor in LEFM is proportional to the remote applied stress and the crack configuration.

In CARES/LIFE, the relations describing subcritical crack growth are directly incorporated into the PIA, NSA, and Batdorf theories. Subcritical crack growth is modeled with the power law,[20,21] the Paris law,[22] and the Walker law[23,24] for static and constant-amplitude cyclic loading. These laws use experimentally determined parameters which are material- and environment-sensitive. The power law is an exponential relationship between the crack velocity and the stress intensity factor. It is used to model stress corrosion cracking in materials such as glasses and alumina exposed to H_2O. Elevated-temperature slow crack growth of silicon nitrides, silicon carbides, and alumina also follows power law behavior.

Some polycrystalline ceramics are prone to strength degradation due to mechanical damage induced by cyclic loading. The Paris and Walker laws have been suggested as models to account for this behavior.[24] The Paris law is an exponential relationship between the incremental crack growth per load cycle and the range of the stress intensity factor. The Walker equation is functionally similar to the Paris equation with additional terms to account for the effect of the R-ratio (minimum cycle stress to maximum cycle stress) on lifetime.

CARES/LIFE is capable of predicting the change in a surviving component's reliability after proof testing is performed. Proof testing is the loading of all components prior to service to eliminate those which may fail prematurely. The components that survive the proof test will have a lower (attenuated) risk of failure in service. In CARES/LIFE the attenuated failure probability is calculated using the PIA, the NSA, and the Batdorf theories. The Batdorf model is used to calculate the attenuated failure probability when the proof test load and the service load are not in line or have different multiaxial stress states. This feature is useful when the proof test does not identically simulate the actual service conditions on the component. The durations of the proof test and the service load are also considered in the analysis.

Predicted lifetime reliability of structural ceramic components depends on Weibull and fatigue parameters estimated from widely used tests involving flexural or tensile specimens. CARES/LIFE estimates fatigue parameters from naturally flawed specimens ruptured under static, cyclic, or dynamic (constant stress rate) loading. Fatigue and Weibull parameters are calculated from rupture data of three-point and four-point flexure bars, as well as tensile specimens. For other specimen geometries, a finite element model of the specimen is also required when estimating these parameters.

Activities regarding validation of CARES/LIFE software include example problems obtained from the technical literature, in-house experimental work, Monte Carlo simulations (computer-generated data sets), beta-testing by users, and participation in a round robin study of probabilistic design methodology and corresponding numerical algorithms.[25]

Ceramic Technology Spinoff Applications

In addition to their primary space and aeronautics propulsion applications, CARES and CARES/LIFE software are used to design ceramic parts for an extensive range of other demanding applications. These include parts for turbine and internal combustion engines, bearings, laser windows on test rigs, radomes, radiant heater tubes, spacecraft activation valves, cathode ray tubes (CRTs), rocket launcher tubes, electronic chips, heat exchangers, and artificial hips, knee caps, and teeth. Engineers and material scientists also use these programs to reduce data from specimen tests to obtain statistical parameters for material characterization. The following are some typical examples illustrating how this software and associated technology are being implemented for several diverse applications, including "dual-use" spinoff applications.

The DOE and Oak Ridge National Laboratory (ORNL) have several ongoing programs such as the Advanced Turbine Technology Applications Project (ATTAP)[26,27] for automotive gas turbine development, the Heavy Duty Transport Program for low-heat-rejection heavy duty diesel engine development, and the Ceramic Stationary Gas Turbine (CSGT) program for electric power cogeneration. CARES and CARES/LIFE are used in these projects to design stationary and rotating equipment, including turbine rotors, vanes, scrolls, combustors, insulating rings, and seals. These programs are also integrated with the DOE/ORNL Ceramic Technology Project[28] (CTP) characterization and life prediction efforts.[29,30]

Solar Turbines Incorporated is using CARES/LIFE to design hot-section turbine parts for the CSGT development program[31,32] sponsored by the DOE Office of Industrial Technology. This project seeks to replace metallic hot section parts with uncooled ceramic components in an existing design for a natural-gas-fired industrial turbine engine operating at a turbine rotor inlet temperature of 1120°C. At least one stage of blades and vanes, as well as the combustor liner, will be replaced with ceramic parts. Ultimately, demonstration of the technology will be proved with a 4000-hour engine field test.

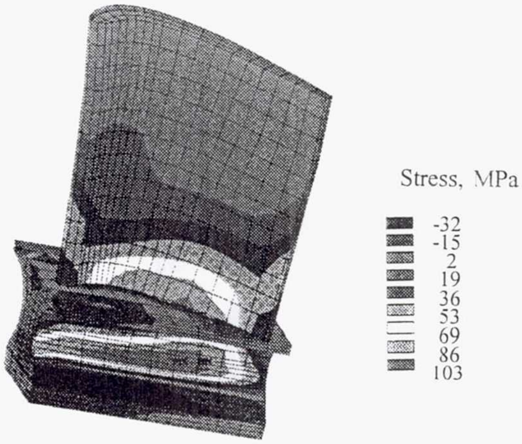

Figure 2. Stress contour plot of first-stage silicon nitride turbine rotor blade for a natural-gas-fired industrial turbine engine for cogeneration. The blade is rotating at 14,950 rpm. (Picture provided courtesy of Solar Turbines Incorporated.)

A monolithic graphite spacecraft activation valve was designed by the Aerospace and Electronics Division of Boeing Space Defense Group.[33] The valve directs reaction control gases for fine-tuning a high-performance kinetic energy kill vehicle's trajectory during the last 9 seconds of flight. The valve was designed to withstand a gas pressure of 11.4 MPa at 1930°C.

Extensive work has been performed at the Fluid Systems Division of AlliedSignal Aerospace to analyze graphite and ceramic structural components such as high-temperature valves, test fixtures, and turbine wheels. A silicon nitride turbine wheel has been designed as a retrofit for Waspalloy in a military cartridge-mode air turbine starter.[34] The substituted part reduces cost and weight while increasing resistance to temperature, erosion, and corrosion.

Ceramic automotive turbocharger wheels are being developed at AlliedSignal's Turbocharging and Truck Brake Systems.[35] AlliedSignal has designed the CTV7301 silicon nitride turbocharger rotor for the Caterpillar 3406E diesel engine. The reduced rotational inertia of the silicon nitride ceramic compared to a metallic rotor significantly enhances the turbocharger transient performance and reduces emissions. AlliedSignal's effort represents the first design and large-scale deployment of ceramic turbochargers in the United States. Over 1700 units have been supplied to Caterpillar Tractor Company for on-highway truck engines, and these units together have accumulated a total of over 120 million miles of service.

Ceramic poppet valves for spark ignition engines have been designed by TRW's Automotive Valve Division[36] as well as by General Motors. These parts have been field tested in passenger cars, with excellent results. Potential advantages offered by these valves include reduced seat insert and valve guide wear, improved valve train dynamics, increased engine output, and reduced friction loss using lower spring loads.

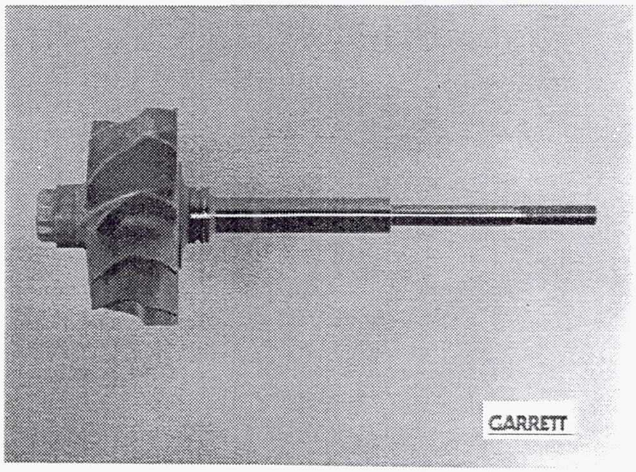

Figure 3. AlliedSignal's CTV7301 silicon nitride turbocharger rotor is featured in the Caterpillar Tractor Company 3406E diesel engine. (Photograph courtesy of AlliedSignal Turbocharging and Truck Brake Systems.)

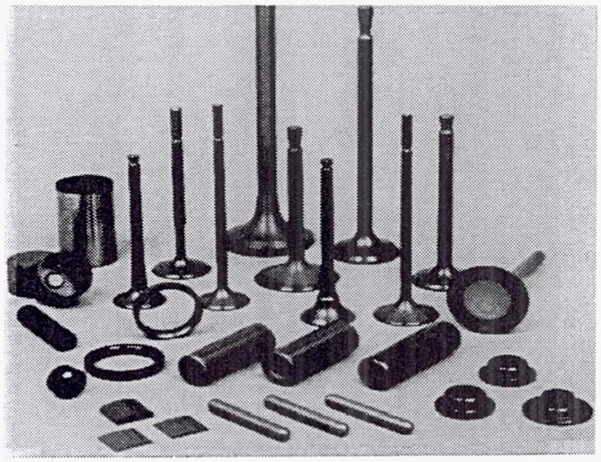

Figure 4. Ceramic poppet valves and engine components designed and field tested by TRW's Automotive Valve Division. (Photograph courtesy of TRW Automotive Valve Division.)

Ceramic pistons for a constant-speed drive are being developed at Sundstrand Corporation's Aerospace Division. Constant-speed drives are used to convert variable engine speed to a constant output speed for aircraft electrical generators. The calculated probability of failure of the piston is less than 0.2×10^{-8} under the most severe limit-load condition. This program is sponsored by the U.S. Navy and ARPA (Advanced Research Projects Agency, formerly DARPA - Defense Advanced Research Projects Agency). Sundstrand has designed ceramic components for a number of other applications, most notably for aircraft auxiliary power units.

GTE Laboratories analyzed and designed a ceramic-to-metal brazed joint for automotive gas turbine engines.[37-39] The thermal expansion mismatch between the two different materials in ceramic-to-metal joining results in high residual stresses that increase the likelihood of ceramic failure. One of the goals of this work was to improve the capability of the metal shaft to transmit power by reducing concentrated tensile stresses. Their results confirmed the importance of probabilistic failure analysis for assessing the performance of various brazed joint designs.

Glass components behave in a similar manner as ceramics and must also be designed using reliability evaluation techniques. Phillips Display Components Company has analyzed the possibility of alkali strontium silicate glass CRTs spontaneously imploding.[40] CRTs are under a constant static load due to the pressure forces placed on the outside of the evacuated tube. A 68-cm diagonal tube was analyzed with and without an implosion protection band. The implosion protection band reduces the overall stresses in the tube and, in the event of an implosion, also contains the glass particles within the enclosure. Stress analysis showed compressive stresses on the front face and tensile stresses on the sides of the tube. The implosion band reduced the maximum principal stress by 20%. Reliability analysis showed that the implosion protection band significantly reduced the probability of failure to about $5x10^{-5}$.

The largest known zinc-selenide (ZnSe) window has been designed by Hughes Danbury Optical Systems (formerly Perkin-Elmer). The window formed a pressure barrier between a cryogenic vacuum chamber containing optical equipment and a sensor chamber. The window measured 79 cm in diameter by 2.5 cm thick and was used in a test facility at Boeing for long-range infrared sensors.

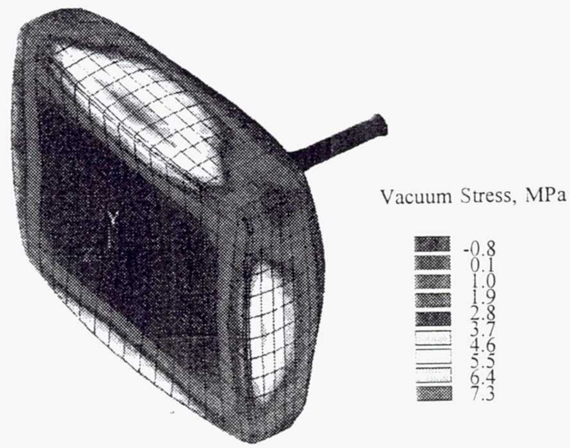

Figure 5. Stress plot of an evacuated 68-cm-diagonal cathode ray tube (CRT). The probability of failure was less than $5.0x10^{-5}$. (Picture provided courtesy of Philips Display Components Company.)

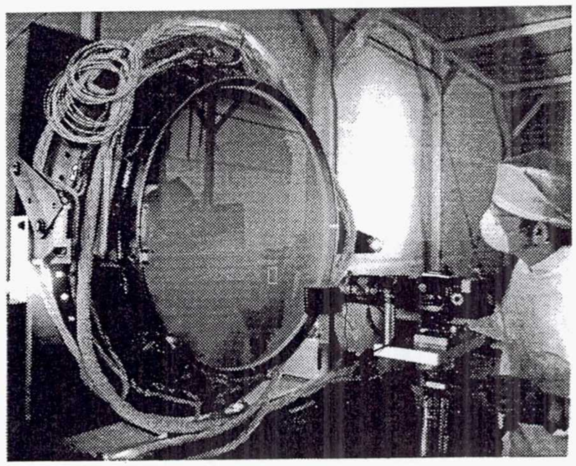

Figure 6. The largest known ZnSe window manufactured for a cryo-vacuum chamber. (Photograph provided courtesy of Hughes Danbury Optical Systems.)

At the NASA-Lewis Research Center, a design study demonstrated the viability of an uncooled silicon nitride combustor for commercial application in a 300-kW engine with a turbine inlet temperature of 1370°C.[41] The analysis was performed for the worst transient thermal stress in an emergency shutdown. The most critical area was found to be around the dilution port.

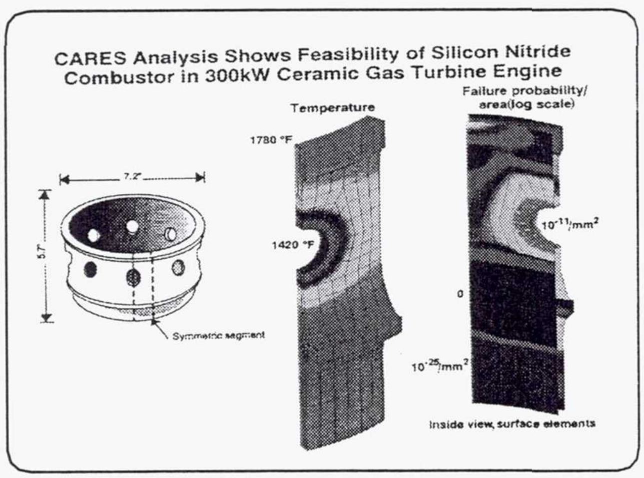

Figure 7. Schematic, temperature, and probability of failure plots of a silicon nitride combustor section for a 300-kW ceramic gas turbine engine. This analysis simulates an emergency stop condition. (Picture courtesy of NASA Lewis Research Center.)

The structural integrity of a silicon carbide convective air-heater for use in an advanced power generation system has been assessed by ORNL and the NASA-Lewis Research Center. The design used a finned tube arrangement 1.8 m in length with 2.5-cm diameter tubes. Incoming air was to be heated from 390° to 700°C. The hot gas flow across the tubes was at 980°C. Heat transfer and stress analyses revealed that maximum stress gradients across the tube wall nearest the incoming air would be the most likely source of failure.

At the University of Florida College of Dentistry, probabilistic design techniques are being applied to dental ceramic crowns. Frequent failure of some ceramic crowns (e.g., 35% failure of molar crowns after three years), which occurs because of residual and functional stresses, necessitates design modifications and improvement of these restorations. The University of Florida is investigating thermal tempering treatment as a means of introducing compressive stresses on the surface of dental ceramics to improve the resistance to failure.[42] Evaluation of the risk of material failure must be considered not only for the service environment but also from the tempering process.

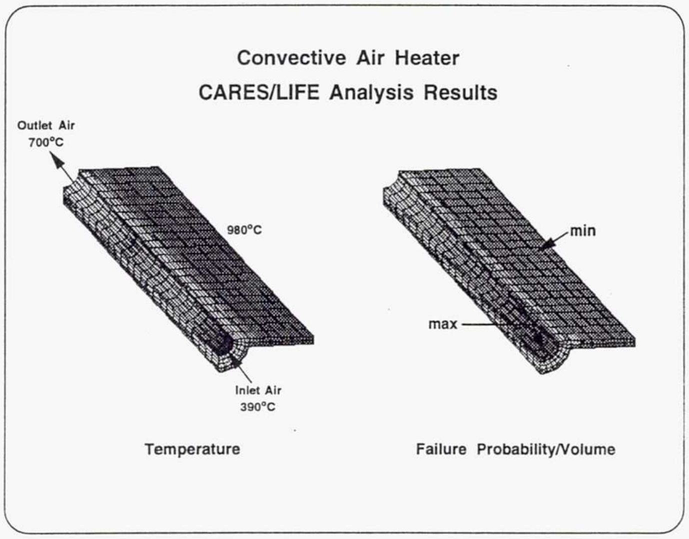

Figure 8. Temperature distribution (left) for a silicon carbide convective air heater. Incoming air is heated from 390° to 700°C. The corresponding risk-of-rupture intensity plot (right) obtained using CARES/LIFE indicates where failure is most likely to occur.

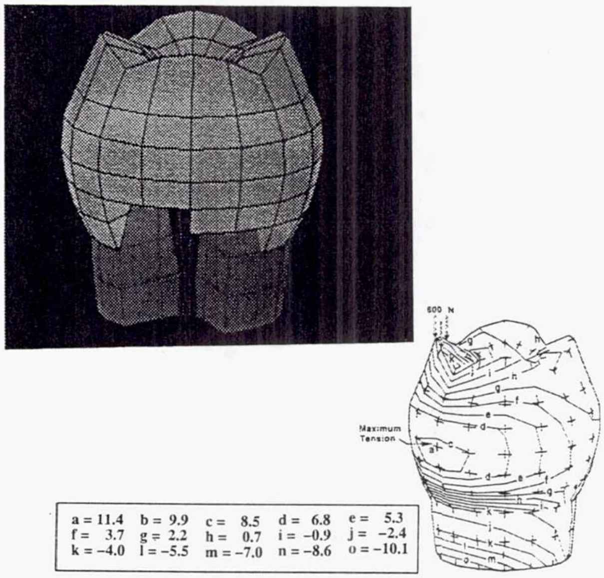

Figure 9. Finite element model (left) of a dental crown. Stress contour plot (right) resulting from a 600-N biting force. (Figures courtesy of University of Florida College of Dentistry.)

Conclusion

Showing the customer that the government is a partner and is interested in a successful transfer of technology involves cultivation of interest in the technology as well as cooperation with both existing and potential customers. The technology transfer activities associated with the NASA/CARES project have generated considerable good will and enthusiasm among customers. The impact of the technology transfer effort associated with this project is evident from the extensive customer base that has been developed. Numerous essential contacts with industry, government laboratories, and the university community provide valuable exchange of information on current structural ceramics research activities. In addition, a number of cooperative efforts have been initiated as a result of this willingness to consult with and accommodate customers. As improved ceramics emerge for structural applications, the importance of this work to industry, government agencies, and academia will undoubtedly continue to grow and gain further recognition.

The NASA/CARES software has been successfully used to design ceramic components for a wide range of demanding applications. The latest version of this program, CARES/LIFE, allows the engineer to design against premature failure from progressive cracking due to subcritical crack growth. Potential enhancements include transient creep analysis, three-parameter Weibull statistics, oxidation modeling, flaw anisotropy, threshold stress behavior, and crack-resistance curve modeling. Inquiries regarding CARES/LIFE should be forwarded to the authors. In addition to being available from the authors themselves, the NASA/CARES series of software is distributed through the NASA Computer Software Management and Information Center (COSMIC), at the University of Georgia.

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