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CERAMICS FOR ATS INDUSTRIAL TURBINES

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ABSTRACT

The U.S. Department of Energy and most U.S. manufacturers of stationary gas turbines are participating in a major national effort to develop advanced turbine systems (ATS). The ATS program will achieve ultra-high efficiencies, environmental superiority, and cost competitiveness compared with current combustion turbine systems. A major factor in the improved efficiencies of simple cycle ATS gas turbines will be higher operating temperatures than current engines. These temperatures strain the limits of metallic alloy and flow-path cooling technologies.

Ceramics materials offer a potential alternative to cooled turbine alloys for ATS turbines due to higher melting points than metallics. This paper evaluates ceramics technology and plant economic issues for ATS industrial turbine systems. A program with the objective of demonstrating first-stage ceramic vanes in a commercial industrial turbine is also described.

INTRODUCTION

The development of ceramics for gas turbines has been pursued for about 20 years. Much of the work to date has been directed to small automotive gas turbines (Khandelwal, 1991, and Rettler, et al., 1995). Some recent efforts have been directed to ceramics for industrial turbines. Work is in progress to develop and demonstrate ceramic combustor liners, ceramic first-stage vanes, and ceramic first-stage blades in an industrial turbine (van Roode, et al., 1994 and 1995).

A major national effort has recently been initiated to develop Advanced Turbine Systems (ATS) designed for ultra-high efficiencies, environmental superiority, and cost competitiveness compared with current industrial and power plant gas turbine systems (U.S. Department of Energy, 1994). If metallics are to be used for turbine expander airfoils, advancements in cooling methods and alloys will be needed for the extreme temperatures (rotor inlet temperatures up to 1427°C [2600°F]) necessary to achieve the ultra-high ATS efficiency goals for simple cycle systems. An alternate approach is to develop structural ceramics for ATS turbine vanes and blades, which alleviates cooling requirements.

This paper describes systems performance and economic benefits of using structural ceramics for expander vanes and blades of industrial ATS turbines. A recently initiated effort is also described that has objectives to design, evaluate, and demonstrate first-stage ceramic vanes in an industrial turbine.

POTENTIAL BENEFITS OF CERAMIC VANES AND BLADES

Turbine Performance

The primary incentive for using ceramics rather than metallics for vanes and blades is improvement in turbine engine cycle efficiency and output that produce economic benefits for the end user of the engine. These improvements in turbine performance for ceramics are due to a reduction in the amount of compressor discharge air that bypasses the combustion process for purposes of cooling the expander components downstream of the first-stage vanes.

Figure 1 illustrates the benefits of reducing chargeable cooling air (that air which decreases efficiency) and leakage from a value determined for a 14,700 hp (11 MW) turbine with a rotor inlet temperature of 1427°C (2600°F). Each reduction of 25% in cooling air requirements increases the overall engine efficiency by about 0.80 percentage points and increases the engine output power by more than 900 hp (0.67 MW). Furthermore, the turbine exhaust temperature increases by about 10°C (18°F) for each 25% decrease in chargeable cooling flow to enable slightly higher steam outputs for the

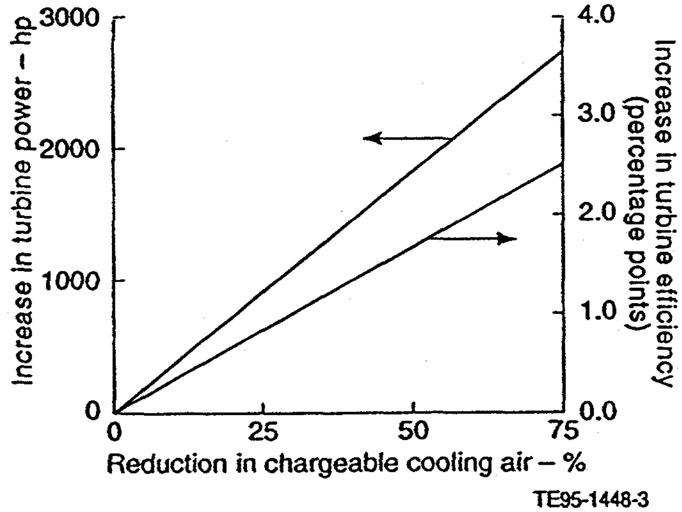

Figure 1. Performance Improvement for 14,700 hp Turbine Due to Reduction in Expander Cooling Requirements.

turbine operated in a cogeneration plant. As a reference, elimination of first rotor blade cooling would increase the engine efficiency by about 1.2 percentage points, the power output by 1280 hp (0.95 MW), and the turbine exhaust temperature by 14°C (25°F).

Plant Economics

Economics were compared for plants using an 11 MW turbine using advanced cooling of metallic vanes and blades and the same engine using uncooled ceramics for the second-stage vanes and blades of the expander. The objective of the analysis was to obtain an understanding of the economic benefits to a turbine end user of the improved efficiency and power output associated with a ceramic second stage. Both engines operate at a rotor inlet temperature of 1427°C (2600°F). The ceramic turbine was assumed to use the same compressor as the all-metallic turbine and therefore its pressure ratio was not optimized for reduced cooling flows. Since accurate costs are not available for these future engine designs, both turbine costs were assumed at $100/hp which resulted in about $85,000 higher cost, because of higher output, for the engine with the ceramic second-stage compared with the all-metallic engine. Estimated future costs (in the year 2002) of natural gas fuel at $3.81/MMBtu and value of electricity of $0.066/kW-h, both in 1993 dollars, were used in the economic analyses.

Table 1 gives the calculated improvement in percentage points of internal rate of return (IRR) to the owner/operator of electrical generation plants and cogeneration plants using the turbine with a ceramic second-stage compared with IRRs for plants using the all-metallic turbine. The IRRs for all the plants using either engine are economically attractive and the engine with ceramic vanes and blades improves the IRRs over values for the all-metallic engine by 1.0 percentage points for the generation plants and by 0.6 percentage points for the cogeneration plants. Additional evaluations showed that the

Table 1.
Plant IRR Improvements for Turbine with Ceramic Second-Stage Compared with Turbine with All-Metallic Stages.

Ceramic turbine price ($)	Plant type	IRR improvement for ceramic turbine (% points)
1,560,000*	Generation	1.0
1,560,000*	Cogeneration	0.6
1,474,300**	Cogeneration	1.0

* $100/hp
** Same as metallic turbine price at $100/hp for metallic turbine

congeneration plant using the ceramic turbine provides a higher IRR than the cogeneration plant using the second stage metallic turbine at a cost of $100/hp when the cost of the second stage ceramic turbine is less than or equal to $108/hp. Consequently, the use of ceramics for expander vanes and blades can improve economic benefits to the end user of the turbine, even if there is some resulting cost increase for the engine.

However, there are benefits for decreased costs of the ceramic vanes and blades. For example, if the ceramic engine in the example above could be produced and priced the same as the metallic engine, the improvement in IRR would nearly double to 1.0 percentage point for the cogeneration plant using the turbine with ceramic second-stage vanes and blades compared with the cogeneration plant using the turbine with all-metallic vanes and blades (see Table 1).

ISSUES FOR INDUSTRIAL TURBINE CERAMIC VANES/BLADES

As mentioned earlier, much of the ceramic effort for gas turbines has been directed to automobile engine applications. Although some issues concerning development of ceramics for industrial turbines are common to those for automobile turbines (e.g., prevention of excessive contact stresses at ceramic/metallic interfaces), there are some issues for industrial turbines that result in different design constraints.

The design life for vane and blades of industrial turbines is on the order of 30,000 hr, compared to a few thousand hours design life for automobile engines. Consequently, long-term ceramic material degradation (e.g., slow crack growth and creep) will be of greater issue for industrial turbines.

The thermal shock environment will probably be more severe in an industrial ceramic turbine than a ceramic automobile turbine. To prevent overspinning, fuel is immediately shut off to an industrial turbine that experiences a loss of generator load. The expander vanes and blades experience an instantaneous drop in gas temperature from values corresponding to full load combustor outlet to a temperature corresponding to no combustion. The maximum deceleration thermal shock of vanes and blades of an automobile turbine corresponds to a gas temperature drop from full load combustor outlet to an idle speed combustor outlet temperature. In addition to a more severe thermal shock environment in a ceramic industrial turbine compared to a ceramic automobile turbine, the ceramic materials in an industrial turbine might less likely be capable of withstanding the thermal shocks. This is because of the greater degradation of ceramic material properties, mentioned earlier, over the longer lifetimes of industrial turbine vanes and blades. Finally, the larger sizes of vanes and blades of an industrial turbine compared to an automobile turbine results in larger volumes and surface areas of ceramic materials subjected to thermal shock stresses. Weibull theory, used to calculate ceramic component reliability, indicates an increasing probability of failure with increasing volume and surface areas experiencing a given level of stress.

Yearly production quantities of a industrial turbine model are typically less than a few hundred per year while production quantities for an automobile engine model can be over 10,000 per year. Consequently, costs of ceramic parts might be a greater issue for the lower production volumes of ceramic industrial turbines compared to ceramic automobile turbines.

A technology issue is whether the best available structural ceramics will be capable of providing typical industrial turbine design lifetimes (order of 30,000 hr) at the very high gas temperatures of the upstream expander rows in ATS industrial turbines. As indicated earlier, ATS turbine rotor inlet average temperatures might be 1427°C (2600°F) with the combustor pattern producing hot spots over 100°C (180°F) higher in temperature. Consequently, some cooling might be necessary for ceramic airfoils in the upstream rows in ATS turbines. This decreases some of the advantages of ceramics, even though the amount of cooling airflow would be less than for metallic airfoils.

Although cooled ceramic vanes have been produced and evaluated in cascade experiments (Tsuchiya, et al., 1995), the eventual commercial cost of ceramic vanes with internal cooling passages is expected to be significantly greater than for solid ceramic vanes. The cooled ceramic vanes that have been produced to date have been significantly larger than required for the 11MW industrial ATS turbine described in an earlier section. Since the technology might not be available to manufacture smaller vanes with internal cooling passages at acceptable production yields, the economic analyses described earlier considered uncooled ceramic vanes and blades in the lower temperature second stage of the 11MW turbine evaluated.

CERAMIC VANE DEVELOPMENT PROJECT

As discussed earlier, high temperature ATS industrial turbines designed with ceramic vanes and blades would provide improved performance and better plant economics compared with turbines using advanced cooling and alloys, for the assumptions presented. Since ceramic airfoils have not yet been used commercially in industrial turbines, it would be beneficial to prove this technology first at current turbine inlet temperatures as a stepping stone to introduction at higher ATS turbine temperatures. Accordingly, a U.S. Department of Energy/Allison Engine Company project has been initiated to retrofit and demonstrate ceramic first-stage vanes in a commercial industrial turbine. This project consists of several activities:

- design of first-stage ceramic vanes and mounting hardware
- ceramic vane procurement
- thermal shock proof tests of the ceramic vanes
- proof test of the vanes and mounting hardware in an engine
- demonstration of the ceramic vanes and mounting hardware in a long term Allison 501K turbine run in the field

Design/Analyses of Ceramic Vanes and Mounting Hardware

Ceramic vanes and mounting hardware will be specified and designed for retrofit into an Allison 501K turbine. For that engine, the first-stage vanes are exposed to an average combustor outlet temperature up to the vicinity of 1100°C (2000°F) with hot spots several hundred degrees higher. The intended vane life is 30,000 hr, comparable to the current design life of metallic vanes.

Computerized heat transfer and stress analyses will be used to evaluate an initial design and refine it, as needed. Ceramic properties of the vendor materials will be used in the analyses.

A probabilistic design methodology has been developed by Allison that addresses the statistical nature of a ceramic's strength distribution and the reliability requirement for the component in service. The engine operating environment will be input to the finite element modeling of the component to analytically assess the fast fracture reliability and long life probability of survival. Both steady-state and transient (startup and shut down) thermal and mechanical loads for engine operation will be considered in design analyses.

The probabilistic design methodology is described in detail by Khandelwal, et al., 1995. Probability of survival (POS) is calculated for damage mechanisms of fast fracture, slow crack growth, and creep. Fast fracture is characterized by a two parameter Weibull model, which is an industry standard. Separate durability models were developed for slow crack growth and creep, using data from tests of a variety of specimens. The durability models were incorporated into the NASA software CARES (Gyekenyesi and Nemeth, 1987).

The results of the design and analyses activities will be used to specify the ceramic vane configuration to ceramic vendors. These activities will also be used to produce mounting hardware drawings for fabrication or procurement.

Procurement of Ceramic Vanes

The ceramics suppliers will be involved in the definition of vane and mount designs. As indicated earlier, limiting the cost of ceramic components to about the same cost as the metallic components they replace can result in IRR benefits to the end user of the turbine. The purpose of interaction with the ceramics suppliers is to assure that the vane design is engineered not only for long life but also for acceptable production costs. Procurement of the ceramic vanes will be based on the specifications and drawings resulting from the iterative design, analyses, and supplier interactions.

Thermal Shock Proof Tests

Proof tests will be conducted for all ceramic vanes that are expected to operate in later engine tests. The proof tests will simulate temperatures corresponding to at least one engine startup from room temperature to full load (vicinity of 1100°C [2000°F]), a period of exposure at that temperature, and an abrupt drop in temperature to represent a generator trip in service which results in an immediate shutdown of fuel to the turbine. The purpose of this test is to subject the vanes to the expected highest stress condition due to thermal shock before installation in an operating turbine. After the proof test, each vane will be visually inspected and analyzed by nondestructive techniques such as fluorescent penetrant and microfocus X-ray.

Vane/Mount Proof Test in Engine

A full set of first-stage ceramic vanes and their mounting hardware will be operated in a 501K turbine at Allison. The purpose is a proof test of both ceramic vanes and metallic mounting components in an operating test engine prior to installation at a commercial site. The test will verify that the metallic mounting hardware does not transmit excessive contact stresses or excessive mechanical loads to the ceramic vanes due to distortions caused by the combustor temperature patterns. The test will probably consist of a normal startup of the turbine, operation for up to 50 hr at load, and a normal shutdown.

Ceramic Vane Field Demonstration

Since the field demonstration depends on a final agreement with the end-user, the following test plans are preliminary.

Vanes that had been screened in the thermal shock proof test and the engine proof test will be installed with mounting hardware in an Allison 501 turbine that has been taken out of commercial service for maintenance.

The turbine will reenter service at its commercial site for up to 8000 hr under its normal operating conditions. The commercial site will most likely be a cogeneration plant, at which operation is essentially continuous at full load, except for unanticipated shutdowns (such as generator trips) and scheduled maintenance (probably 6 month intervals). Inspection frequency for the ceramic vanes and their mounts will depend on the agreement with the end-user, since any additional inspection outages result in loss of plant revenues. At the end of the test, ceramic vanes will be removed from the engine and analyzed to assess their condition and expected additional life.

RESULTS

Screening analyses were conducted to evaluate whether a ceramic vane profile shape could be used that is the same as the metallic vane shape in the 501K turbine. Ceramic vanes with the current shape in the 501K turbine and with alternate shapes were analyzed for the conditions anticipated to produce the highest stresses in the turbine.

The highest stresses for the ceramic vanes in service are expected to result from emergency shutdowns due to loss of generator load at industrial generation and cogeneration plants. To prevent the turbine from overspinning, fuel flow to the combustors is immediately shut off. This results in a very rapid drop in the gas temperature at the first vanes from the full continuous load value to the compressor discharge air temperature (a drop of more than 720°C [1300°F]). The turbine airfoils experience high thermally induced stresses during emergency shutdowns because the thin trailing edges cool much faster than the thick noses of the airfoils.

Analyses were conducted to calculate the probability of survival (POS) under emergency shutdown thermal shock conditions for a ceramic airfoil with the same shape as the current metallic first-stage vane airfoil in the 501K turbine. The current first vane profile (Figure 2) has a ratio of maximum thickness to minimum (trailing edge) thickness of about 6. The trailing edge thickness is about 0.89 mm. The axial chord of the airfoil is about 25 mm and the height is about 30 mm. Properties of three candidate ceramic materials were used in the POS analyses. Two Si_3N_4 materials and a composite of SiC particulates in a matrix of alumina were evaluated. The initial screening analyses did not consider the effects of the vane platforms. The calculated POS for all 60 first-stage ceramic vanes exposed to a single emergency shutdown was 98.7% for the best (AS800, Si_3N_4) material. To improve the POS, hollow ceramic vanes with the same airfoil shape were evaluated. The hollow vane would experience lower thermal shock stresses than the solid vane, due to less variation in thermal mass along the chord. Although the hollow design does reduce thermal shock stresses, information from the ceramic suppliers has shown that the vane cost increases for increasing dimensions of the hollow region such that only a small hollow cavity can be produced for ceramic vanes at a competitive cost in production quantities. Consequently, little thermal shock benefits can be realized for competitively priced hollow vanes (with a small hollow region) of the scale for the 501K turbine.

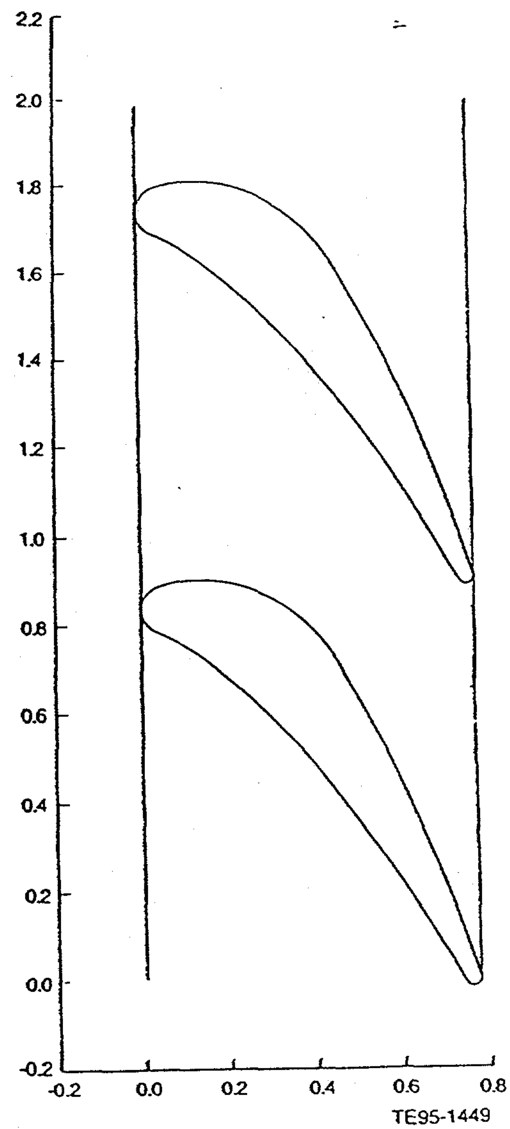

Figure 2. First-Vane Metal Airfoil Profile for 501K Turbine.

Another option evaluated to alleviate thermal shock stresses was to increase the vane trailing edge thickness and restagger the first stator airfoils. However, this reduces the minimum flow area of the engine and decreases turbine performance by an unacceptable degree.

Solid vanes with modified airfoil shapes were then evaluated. The trailing edge thickness was not changed from that of the current production engine, but the dimension of the thickest part of the airfoil was reduced. The Allison aerodynamics group designed a new airfoil with a ratio of maximum thickness to trailing edge thickness of 3.6 compared with a value of 6 for the original vane. However, discussions with a ceramics supplier revealed that the thinner airfoil was beyond their experience for economical production and process development would be needed to produce that ceramic vane in commercial quantities at a competitive price.

Consequently, a second vane shape with a somewhat thicker nose region was generated by the Allison aerodynamics design group. The shape was reviewed with all the prospective ceramic suppliers for the program and was judged to be acceptable for economics of production.

The ratio of maximum thickness to trailing edge thickness of the second vane is 4.3 compared with 6 for the original 501K turbine first-stage vane. The profiles stacked radially are shown in Figure 3 for the second redesigned vane. As for the thinnest vane, this airfoil provides somewhat lower aerodynamic losses than the original 501 turbine vane that was designed years ago before advances in computer aerodynamic design procedures. Furthermore, the stress levels due to thermal shock for the vane with a thickness ratio of 4.3 are only slightly higher than for the thinnest vane (with a ratio of 3.6). For a Si_3N_4 (AS800) material, the calculated emergency shutdown thermal stress levels in the 4.3 ratio vane are 24% lower than for a vane of the shape currently used in the 501K turbine, and the probability of thermal shock survival of a single emergency shutdown predicted by the POS analysis for the full set of 60 vanes now exceeds 99.9%.

As a result of the above vane shape evaluations, the airfoil with a 4.3 thickness ratio (shown in Figure 3) has been selected as the new baseline design for further 3-D analyses for thermal shock and the steady-state environment in the engine. The thinnest vane is retained as a backup should the upcoming 3-D stress analyses indicate that a thinner vane is needed.

Various vane platform and mount design alternatives have been discussed with ceramic suppliers for inputs on design features that affect production costs. An initial design has been chosen for 3-D thermal and stress analyses. The ceramic vane is not hard mounted in this design and the contact area at metallic interfaces is minimal. Brush seal mounting is used to provide ceramic interface compliance. These design features reduce contact stresses and the extent of expensive diamond machining needed for ceramic surfaces in contact with metallic mounts.

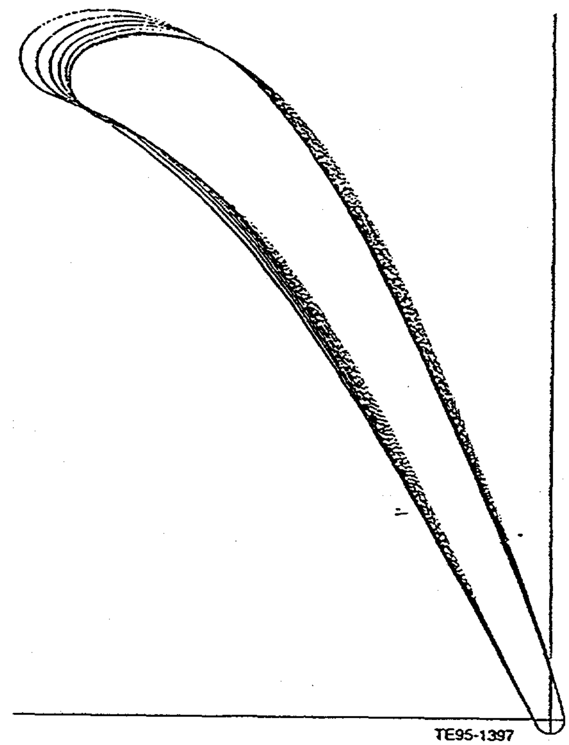

Figure 3. Redesigned Ceramic Vane for Improved Thermal Shock Performance.

SUMMARY AND CONCLUSIONS

The successful development of ceramics to replace metallics for the vanes and blades in the hot section of ATS industrial turbines could reduce chargeable cooling air requirements and thereby increase engine power and efficiency. The turbine performance improvements can increase the economic benefits to end users of ATS turbines in generation and cogeneration plants, even should the incorporation of ceramics result in some increase in turbine cost.

Rotor inlet average temperatures of up to 1427°C (2600°F) are being considered for ATS turbines. The combustor temperature pattern can result in local gas stream hot spots over 100°C (180°F) higher than the average temperature. A technology issue for ceramics in the highest temperature rows of ATS turbines is whether, without cooling, the best available ceramics will be capable of providing typical industrial turbine vane and blade design lifetimes on the order of 30,000 hr. Although cooling flow requirements would be less than for metallics, the advantage in engine performance over metallics is decreased. Furthermore, the eventual commercial cost of ceramic vanes and blades with internal cooling passages is expected to be significantly greater than for uncooled ceramic vanes and blades. The lesser engine performance improvement at a greater engine cost for cooled ceramics decreases the relative economic benefits to the end user of the turbine in generation and cogeneration plants. Considering both economics and risks, promising locations to introduce ceramic vanes and blades in ATS turbines might be the lower temperature downstream rows of the hot section where metallic cooling would be required but ceramic cooling would not be required.

An Allison/DOE program has been initiated to incorporate and demonstrate ceramic first stage vanes in an industrial turbine. This program will evaluate the aerodynamic and structural integrity of the ceramic component in an industrial turbine application. A successful demonstration could provide increased confidence and a starting point from which to launch similar evaluations for second stage static vanes and rotating blades of ATS turbines at a later time.

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REFERENCES

Gyekenyesi, J. P., Nemeth, N. N., 1987, "Surface Flaw Reliability Analysis of Ceramic Components with the SCARE Finite Element Postprocessor Program," Journal of Engineering for Gas Turbines and Power, Vol. 109, No. 3, pp. 274-281.

Khandelwal, P., 1991, "Development and Testing of CMC Components for Automotive Gas Turbine Engines," AIAA paper AIAA-91-189, presented at 27th Joint Propulsion Conference, June 24-26, Sacramento, CA.

Khandelwal, P. K., Provenzano, N. J., and Schneider, W. E., 1995, "The Development of Life Prediction Techniques for Structural Ceramics," ASME Paper 95-GT-30.

Rettler, M. W., Easley, M. L., and Smyth, J. R., 1995, "Ceramic Gas Turbine Technology Development," ASME paper 95-GT-207.

van Roode, M., Brentnall, W. D., Norton, P. F., and Boyd, G. L., 1994, "Ceramic Stationary Gas Turbine Development Program - First Annual Summary," ASME paper 94-GT-313.

van Roode, M., Brentnall, W. D., Norton, P. F., and Edwards, B. D., 1995, "Ceramic Stationary Gas Turbine Development Program - Second Annual Summary," ASME paper 95-GT-459.

Tsuchiya, T., et al., 1995, "Development of Air-Cooled Ceramic Nozzles for a Power Generating Gas Turbine," ASME Paper 95-GT-105.

U.S. Department of Energy, 1994, February, "Report to Congress - Comprehensive Program Plan for Advanced Turbine Systems."