HIGH TEMPERATURE CMC NOZZLES FOR 65% EFFICIENCY

Final Technical Report

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ABSTRACT

GE Gas Power has executed a development project that targeted cooled high-temperature ceramic matrix composite (CMC) nozzles as an innovative turbomachinery component that contributes toward the DOE's goal for advanced gas turbines that are capable of at least 65% efficiency in combined cycle application. This technology advancement has potential to also benefit gas turbines used in coal-based IGCC applications with pre-combustion carbon capture and hydrogen as the resulting fuel. The development of this technology built upon CMC capability advancements made under earlier DOE programs. The objective for this project was to develop the application of ceramic matrix composite for nozzle application in an industrial gas turbine hot gas path.

The CMC component development activity done in this project facilitates high firing temperatures through improved cooling designs and concepts, better sealing, reduced leakage, advanced manufacturing processes to facilitate high performing turbomachinery, and revolutionary component architecture to improve the gas turbine performance in a combined cycle application.

The objectives for this project were to develop the application of the CMC material system for nozzles in an industrial gas turbine hot gas path. The objectives for the two phases of the Project were:

Phase I – To leverage existing design know-how and analytical techniques for CMC materials; and to utilize extensive analytical evaluations to develop and refine designs for a CMC nozzle. The design(s) will be the basis for development and testing in Phase II.

Phase II – Starting with the best design(s) selected from Phase I, detailed design, fabrication and testing will be performed with the goal of delivering a prototype CMC nozzle design that is ready for application in an operating gas turbine. Detailed assessments will also be performed on sealing effectiveness and cooling flow reduction.

The benefit of a CMC material system over state-of-the-art high temperature metal alloys is the temperature capability. CMCs can withstand operating temperatures that are hundreds of degrees (°F) higher than the most robust metallic materials. In a gas turbine, airflow is extracted from the compressor and utilized to cool the components in the hot turbine section. This extraction of compressed air results a performance penalty in gas turbine efficiency. With CMC components operating at higher temperatures and with less cooling required, gas turbine performance can be improved.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMW	Advanced Manufacturing Works, a GE Gas Power facility
APS	Air Plasma Spray
CMC	Ceramic Matrix Composite
CT	Computed Tomography
CTQ	Critical to Quality (attribute)
DIC	Digital Imaging Correlation
EBC	Environmental Barrier Coating
EDM	Electrical Discharge Machining
FEA	Finite Element Analysis
FEM	Finite Element Model
GEGP	General Electric Gas Power
GEGR	General Electric Global Research
GT	Gas Turbine
GTCC	Gas Turbine Combined Cycle
GTOS	Gas Turbine Outage Simulator
GTTL	Gas Turbine Technology Laboratory, a GE Gas Power facility
ISW	Inner Side Wall
IGCC	Integrated Gasification Combined Cycle
LOI	Lack of Infiltration
MI	Melt Infiltration
MRL	Manufacturing Readiness Level
NPI	New Product Introduction
OSW	Outer Side Wall
PDC	Polymer-Derived Ceramic
S1N	Turbine Stage 1 Nozzle (stationary vane)
S2N	Turbine Stage 2 Nozzle (stationary vane)
TRL	Technology Readiness Level

Phase I TECHNICAL PROGRESS

Phase 1 approach: The concept design began with a search into patents, relevant literature and prior CMC nozzle designs developed at GE Aviation. Then, the engineering team identified fit, form and function requirements for application of CMC technology in a heavy-duty gas turbine with a follow-on brainstorming session to identify viable new concepts. A stage 2 nozzle (S2N) of the HA class of turbines was selected for the design focus. The boundary conditions from the existing metal nozzle were then applied to evaluate each concept design. This specific nozzle stage was selected based on risk and cost benefit with a maturation time suitable for Phase II.

Phase I findings included: The traditional nozzle concept ranked highest based largely on cooling flow savings, repair-ability and manufacturing risk, which made it more attractive than competing concepts. The efficiency improvement of the CMC S2N has been estimated to be 0.2 points of combined cycle efficiency. For a 65% efficient plant, the CO_2 reduction would be approximately 0.31%. An additional benefit in gas turbine power output of 1.3% would also be realized. Phase II work completed the detailed design of the traditional concept.

Task 1.1 - Program Management and Planning

The team completed regular program review meetings at prescribed intervals. Milestone memos were delivered for each formal milestone, as shown below in Table 1.

Milestone	Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
1.1	Updated Project Management Plan	10/30/2014	10/27/2014	PMP submitted to Project Officer	Submitted to DOE via email
2.1	Complete Traditional-style Design Concept	6/30/2015	6/26/2015	Milestone Memo	Submitted to DOE via email
2.2	Complete Bayonet-style Design Concept	12/31/2015	12/18/2015	Milestone Memo	Submitted to DOE via email
3.2	Complete Film Cooling Definition	9/30/2015	9/30/2015	Milestone Memo	Submitted to DOE via email
4.1	Define Top Sealing Concepts	3/31/2015	3/23/2015	Milestone Memo	Submitted to DOE via email
4.2	Complete Sealing Effectiveness Assessment	9/30/2015	9/30/2015	Milestone Memo	Submitted to DOE via email
5.1	Submit Phase II Application	3/31/2016	3/30/2016	Phase II Applicatoin Submittal	Phase II Application Submittal

Table 1 – Phase I Formal Program Milestones

Task 1.2 – Design and analyze CMC nozzle configurations

Traditional style nozzle design

A nozzle assembly with a CMC fairing and metal support structure was defined based on the existing metal nozzle. In such a design (shown in Figure 1), mechanically induced stresses are carried by the support spars, while thermally induced stresses are carried by the CMC fairing around the metal by locally warming or cooling of the part.

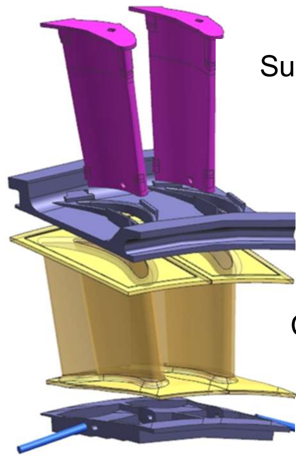

Figure 1 – Traditional Style Nozzle Assembly

The metal support structure was mechanically sound; however, the support spar was thermally limiting. The relatively low cooling air flow and high radiation load from the CMC airfoil could exceed the capability of the metal spar. Thermal barrier coatings on the spar and/or the inside of the CMC airfoil would reduce the amount of heat radiated from the CMC airfoil to the spar.

Bayonet style nozzle design

The bayonet style nozzle concept (shown in Figure 2) consisted of metal inner and outer sidewalls (ISW, OSW) connected by two metal airfoils. In this design, CMC airfoils are inserted through the outer sidewall between the metal airfoils. The cooling flow savings of the bayonet concept was limited by the number of CMC airfoils in the assembly and by the metal inner and outer flowpath surfaces. The larger nozzle segments would challenge current investment casting infrastructure capability and would need special features in the outer sidewall to reduce stresses driven by thermal chording of the larger segment.

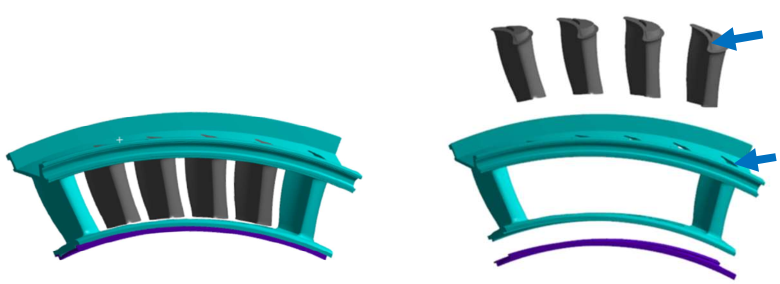

Figure 2 – Bayonet Style Nozzle Concept

A second bayonet concept was defined that consisted of all CMC airfoils inserted into a metal outer sidewall. The inner sidewall was part of the rotor structure. This concept was limited in cooling flow savings by the metal inner and outer flowpath surfaces.

A final, hybrid concept (shown in Figure 5) was defined that combined features from both the traditional and bayonet style nozzle concepts. The hybrid nozzle concept consisted of a metal outer support structure with a self-supporting CMC fairing pinned to the outer sidewall. A metal rotor seal structure was pinned to the CMC fairings. This concept had flow savings similar to the traditional style nozzle design but required more CMC material since it was self-supporting.

Task 1.3 – Investigate cooling concepts for high temperature locations

Impingement cooling concepts

The goal of the cooling design was to effectively cool the assembly while minimizing thermal gradients through the CMC fairing. The support spar was used to deliver impingement cooling to the CMC airfoil with the same cooling flow also being reused to cool the trailing edge (TE) of the CMC airfoil. The cooling effectiveness of the impingement air flow was locally tailored through jet size or jet spacing to reduce thermal gradients in the airfoil. Serpentine passages were configured to minimize cooling flow while maximizing the overall cooled area. Manufacturing trials were performed to demonstrate that serpentine channels in CMC could be created.

It was learned that the CMC fairing endwalls could be cooled with a small amount of purge flow ducted between the CMC and metal support structure and that the metal support endwalls, as proposed, did not require dedicated cooling flow.

Task 1.4 – Define sealing approach concepts

Sealing configuration concepts

Sealing concepts were created and evaluated based on capability under various alignment and offset conditions that commonly occur between adjacent parts as they undergo thermal growth throughout the gas turbine operating cycle. The metal seals used in today’s engines do not possess the required temperature and oxidation capability. Cooled metal seals with low risk and known capability have been produced that can run at the needed engine conditions. These seals can be employed with low risk in higher temperature applications; however, to reduce cooling flow, seals with higher temperature capability are needed. Seals with thermal barrier coatings and ceramic seals are possible solutions. These seals have been tested to understand their leakage under various slot alignment conditions.

Task 1.5 – Phase I Results for Phase II Downselect

The two traditional style nozzle concepts are similar except for the inner seal and attachment structure, as shown in Figure 3.

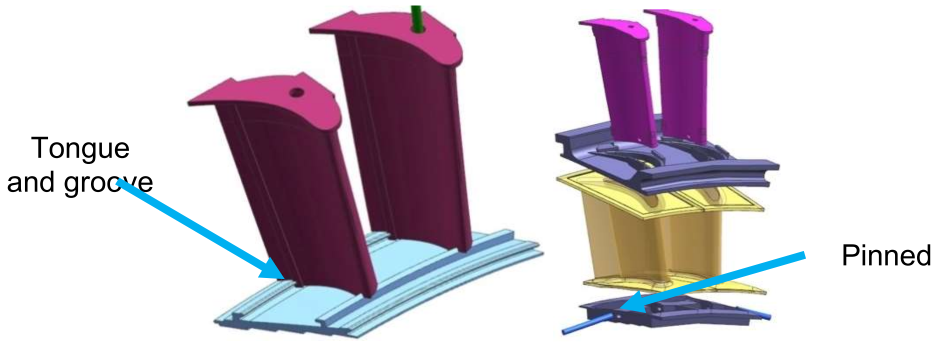

Figure 3 – Inner Sealing and Attachment Structure

The bayonet style nozzle was broken down into 3 concepts: Bayonet 1, Bayonet 2A and Bayonet 2B. Bayonet 1 has cantilevered CMC airfoils between metal support airfoils that attach the ISW to the OSW. Bayonet 2 has cantilevered CMC airfoils with a rotating ISW. Bayonet 2A has an inner flowpath made of CMC, while Bayonet 2B has an inner flowpath made of a suitable metal.

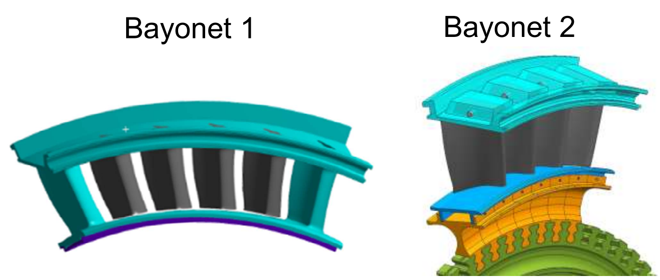

Figure 4 – Bayonet Style Nozzle Concepts

An additional concept was developed to take advantage of the positive attributes from the traditional style and bayonet style nozzle concepts. The hybrid design has full CMC flowpath coverage, is cantilevered from the OD attachment, and is pinned to the inner seal structure.

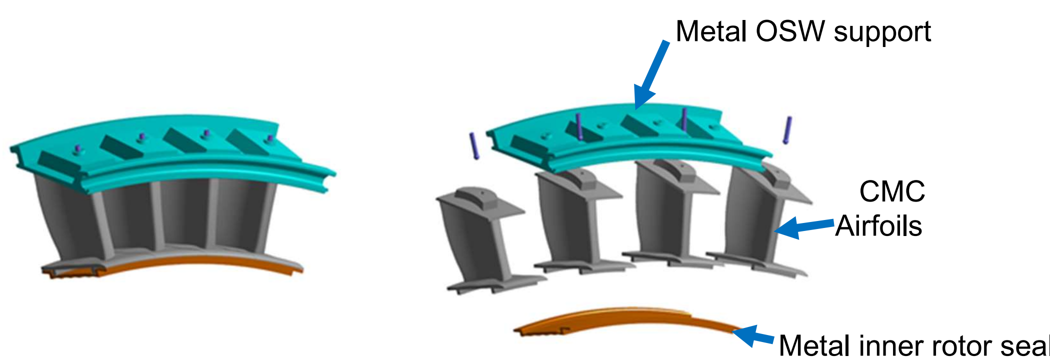

Figure 5 – Hybrid Nozzle Concept

Data used to rank these concepts was developed as follows. The cost of the CMC was estimated by creating and arranging the flat ply shapes to determine the amount of raw material required. The flow savings was estimated using a through-thickness heat transfer model. Leakage was estimated using the total sealing length and sealing test data gathered under this program. Manufacturing difficulty was based on the design features and the assumed tooling and steps needed to complete the part. Growth potential, or the ability for the concept to adapt to typical engine uprates such as increased Tfire, was assumed to be greater for CMC than metal due to the higher use temperature of CMCs. Scalability is a measure of the ability to make the features smaller or larger while maintaining the capability to manufacture with current equipment. The performance impact was estimated for changes other than those caused by flow savings or sealing improvements as compared to a metal nozzle. Risk level was determined based on analysis and prior experience with similar designs.

A 1-9 ranking system was used to compare the concepts with 1 being the lowest score and 9 being the highest (best) score. A relative weighting factor of 1-9 was used to emphasize the more important CTQs, attributes that are "critical to quality." See Table 2 for the CTQs and their descriptions. Table 3 shows the nozzle concept per CTQ and the sum score.

Critical-To-Quality Attribute (CTQ)	Description
Retrofitability	Ability to insert into existing engine without changing surrounding hardware
CMC Cost	Raw material - Based on nested plies, delta from baseline metal design
Other Costs	Support hardware, other affected parts
Flow Savings	Calculated, delta from baseline metal design
Leakage	Calculated, delta from baseline metal design
Performance	Performance impacts other than flow savings or leakage
Repairability	Designs requiring repairs in load carrying areas (self-supporting designs) are less repairable
Growth	Does design support typical engine up-rates?
Scalability	Ease of scaling features to smaller/larger engines
Manufacturing (CMC)	Level of difficulty of manufacturing CMC parts
Manufacturing (Metal)	Level of difficulty of manufacturing metal parts
Risk	Design - stress, Unknown, Outage risk, damage to other hardware

Table 2 – Nozzle Concept CTQ's

CTQ	Relative Weight	Traditional 1	Traditional 2	Bayonet 1	Bayonet 2a (CMC ISW)	Bayonet 2b (Metal ISW)	Hybrid
Retrofitability	5	9	9	9	5	1	9
CMC Cost	9	3	3	9	5	9	1
Other Costs	6	7	8	5	7	1	9
Flow Savings	9	8	8	1	4	3	9
Leakage	9	1	2	8	9	8	2
Performance	9	9	9	1	5	5	9
Repairability	3	9	9	1	1	1	1
Growth	3	9	9	1	3	1	8
Scalability	1	9	9	1	9	9	9
Manufacturing (CMC)	5	3	3	9	5	9	1
Manufacturing (Metal)	5	8	8	1	7	6	9
Risk	3	7	9	2	1	3	6
Sum		**415**	**436**	**309**	**358**	**335**	**392**

Table 3 – Nozzle Concept Ranking

Learning and the impact on the path taken

Mechanical analysis of the traditional nozzle showed that supporting the CMC fairing along the interior of the airfoil would require thicker walls. An additional model was created to find the required wall thickness. Then, another model was created that moved the support pads closer to the end-walls to take advantage of the additional structure with good results.

Analysis of the airfoil cooling concept for the traditional nozzle showed that the temperature limit of the metal spar was reached prior to that of the CMC fairing. It was recognized that use of thermal barrier coatings would reduce the radiant heat transfer from the CMC to the spar. Additionally, the project team learned that cooling methods used in the metal nozzle generally overcooled the CMC fairing. This led to the development of methods and features to reduce the cooling effectiveness where required.

Conceptual design of the bayonet style nozzle resulted in several variations as the project team gained a better understanding of how it could be configured and also the limitations of those configurations. A CMC airfoil with CMC rotating inner sidewall was finally selected.

Review of the traditional and bayonet concepts led to development of the hybrid concept that combined the CMC fairing from the traditional nozzle concept with the self-supporting attachment of the bayonet concept. In terms of identified CTQs for this project, this concept ranked below the traditional concept (Table 3).

Manufacturing trials showed large cooling features can be cut in the plies and laid up into a pre-form while smaller features are better created by machining them into the pre-form. Maintaining cooling feature shape during part forming can be difficult and may require additional tooling and processing steps.

Conclusions

The traditional nozzle concept ranked highest based largely on cooling flow savings, repair-ability and manufacturing risk, which made it more attractive than competing concepts. The efficiency improvement of the CMC S2N has been estimated to be 0.2 points of combined cycle efficiency. For a 65% efficient plant, the CO_2 reduction would be approximately 0.31%. An additional benefit in gas turbine power output of 1.3% would also be realized. Phase II work completed the detailed design of the traditional concept, then fabricated and assembled the CMC nozzle design.

Phase II

GE Gas Power developed a cooled high-temperature Ceramic Matrix Composite (CMC) nozzle as an innovative turbomachinery component that contributes towards the DOE's goal for advanced gas turbine efficiencies that are greater than 65% in combined cycle applications. This technology advancement will also benefit gas turbines used in coal-based Integrated Gasification Combined Cycle (IGCC) applications with pre-combustion carbon capture and hydrogen as the resulting fuel. The objective for this project is to develop and test ceramic matrix composites (CMC) to the point that CMC components could be designed and deployed for nozzle applications in an industrial gas turbine hot gas path. The project completed extensive analytical evaluations to develop a CMC nozzle for application in an industrial gas turbine hot gas path, leveraging existing design knowledge and analytical techniques for CMC materials.

The scope of work included all key efforts necessary to support the objectives of this project. The key technical challenges for incorporating CMC nozzles within an industrial gas turbine are associated with managing thermal growth mismatches that exist between CMC and metal hardware at joints and interfaces. Adequate sealing strategies for these critical locations needed development. Finally, determination of how a CMC vane with the complexity of three curved interwoven surfaces could be fabricated and meet design requirements was accomplished.

Phase II efforts focused on three major activities: 1) design and fabrication of CMC nozzles for industrial gas turbines 2) the design and fabrication of appropriate CMC/EBC test rigs, and 3) test execution for performance assessments of EBC durability, CMC strength and cooling flows. The end goal was to deliver a full-scale full-featured CMC nozzle segment. The HA class engine was selected as the target GT. The Stage 2 Nozzle (S2N) was selected as the target application.

2018 Change Request (2018 pivot): the DOE approved a change request from testing in a high temperature nozzle test rig to fabricating and assembling a full-scale prototype nozzle segment.

Task 2.1 - Project Management and Planning

The GEGP team completed regular program review meetings at prescribed intervals. Milestone memos or other control documents were delivered for each formal milestone. Public presentations were given at the annual UTSR workshop. A formal Peer Review was completed at NETL's Pittsburgh, PA, site in April 2019.

Milestone	Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
2.1.0.1	Update Project Management Plan	10/21/2016	12/16/2016	PMP file	Submitted to DOE via e-mail 12/17/21
2.1.0.2	Kickoff meeting with DOE/NETL	11/29/2016	11/29/2016	Presentation file	EPACT marked & clean versions provided.
2.2.1.1	CMC preform definition	6/30/2017	6/29/2017	Milestone Memo	Submitted to DOE via e-mail 6/29/17
2.4.1.1	Define design changes needed for manufacturab	9/30/2017	9/29/2017	Milestone Memo	Submitted to DOE via e-mail 10/9/17
2.2.3.1	Model definition for fabrication	12/31/2017	12/29/2017	Milestone Memo	Submitted to DOE via e-mail 1/25/18
2.3.2.1	Model release for fab – test cell definition	12/31/2017	1/12/2018	Milestone Memo	Submitted to DOE via e-mail 1/25/18
2.7.1.1	Demonstrated durability of EBC/CMC	6/30/2019	7/16/2019	Milestone Memo	Submitted to DOE via e-mail 7/17/19
2.11.1.1	Preform definition complete	6/30/2019	5/17/2019	Milestone Memo	Submitted to DOE via e-mail 7/17/19
2.8.1.1	Identify results that drive design change	9/30/2019	12/31/2020	Milestone Memo	Submitted to DOE via e-mail
2.8.3.1	Demonstrate margin to design loads	6/30/2021	6/30/2021	Milestone Memo	Documented in Q2 2021 report
2.13.1.1	CMC nozzle complete	9/30/2021	9/30/2021	Milestone Memo	Submitted to DOE via e-mail
2.16.1.1	Instrumentation definition of nozzle complete.	9/30/2021	9/30/2021	Milestone Memo	Submitted to DOE via e-mail
2.10.0.1	Conclusions and documentation	9/30/2021	12/30/2021	Final Report	12/30/21 submittal

Table 4 – Phase II Formal Program Milestones

The following are the documented success criteria.

- ☑ CMC nozzle design will be reviewed and approved for release to manufacturing.
- ☑ Initial CMC nozzle fabrication trials will be completed and recommended design changes for manufacturability identified.
- ☑ The nozzle metal-support structure will be defined.
- ☑ The high-temperature nozzle test rig will be defined.
- ☑ Feature test of initial CMC nozzles fabrication pieces and recommended design changes will be completed.
- ☑ Prototype CMC nozzle fabrication will be completed.
- ☑ High temperature testing of the environmental barrier coating (EBC) will begin.
- ☑ High temperature seal material tests will be completed.
- ☑ Flow testing of high temperature sealing materials will begin.
- ☑ Nozzle feature tests with demonstrated margin to design loads will be completed.
- ☑ Detailed design of CMC nozzle will be completed.
- ☑ Fabrication of CMC nozzles will be completed.
- ☑ Flow testing of seals and nozzle components will be completed.
- ☑ Instrumentation definition of CMC nozzles will be completed.
- ☑ Cooling and sealing schemes for the CMC nozzle will be sufficient for the application.
- ☑ The Phase II program will be executed on-schedule and within budget. This includes on-time delivery of required reports.

All milestones were successfully completed, culminating with the fabrication and assembly of the full CMC nozzle segment.

Task 2.2 – Complete design definition of CMC nozzle

A detailed design study on the down-selected nozzle concept created in Phase I of this program was performed. This design was analyzed with loads typical of a power generation gas turbine nozzle. Due to the complexity of the stage 2 nozzle shape, consideration was given to bonding fabricated CMC sub-elements to make an assembled nozzle. Attention to the seal design and the metal-to-CMC interfaces was given. Also included was small-scale bench testing to assist seal configuration selection.

Subtask 2.2.1 - Design Details of the CMC

The preliminary design of the Phase I concept was evaluated and defined so that consideration of required tooling and ply definition could begin. Critical CMC tooling included an autoclave compaction tool, which was found to be vitally important. This tool forms the flow-path surface of the vane such that no machining is required except at the TE, thereby reducing machining effort and cost.

Ply definition was selected so that the laminate produces sufficient strength for the CMC vane Laminate architectures that enable the 3D curved surfaces of the vane were considered next. Then definition of seal slots and load pads was added. Manufacturing trials of these early laminate designs followed with many lessons learned, particularly at the intersection of the airfoil and end-walls. This learning fed back to the design process to drive changes that facilitated the successful fabrication of vanes from which feature test pieces were cut. The final step was to optimize the CMC design and define special features and tolerances to ensure fit, form, and function objectives could be met.

Subtask 2.2.2 - Design bonded joint

Bonding technology development efforts indicated promising results for simplifying manufacturing, facilitating repair, and lowering cost of ceramic matrix material components. This task explored where this technology could be applied on the CMC nozzle and identified design improvements needed for application of bonded CMC sub-elements. As the fabrication of very large and complex components is still limited, joining of small and simple components into large and complex components is potentially an effective, time- and cost-saving method. Multiple bonding methods were developed with varying viability for these applications. Some applications required processing at high pressures and temperatures while other cases contained a joint material that is significantly different from the silicon carbide (SiC) material used for the CMC nozzle. This task defined the best processes for a bonded joint application on the CMC nozzle.

Clemson University completed this work, as a program subrecipient, with GE Gas Power providing CMC substrate material and technical consultation. Bond shear strength of 10 MPa at 1800°F was set as these conditions provided sufficient strength for proposed load pad application in the CMC vane. Two commercially available bond agents and two Clemson-formulated polymer-derived ceramic (PDC) bond agents were tested. The Clemson formulations used Si-based polymeric precursors with active and passive fillers and showed that the shear strength significantly better than the commercially available systems. The test setup and results are shown in Figure 6. Unfortunately, the best bond agent, PDV with 12% Al, failed to meet the shear strength goal of 10 MPa.

Figure 6 – Bond test fixture, bond microsection, test summary

Subtask 2.2.3 - Design of all integrated metal structures

Design of metal support spars, in contact with or near the CMC, were designed simultaneously with the CMC design described in section 2.2.1 to ensure that the metal structure could meet life or strength requirements of the nozzle design. Detailed design of the inner metal carrier and outer metal carrier was completed. This subtask included definition of special features and complete tolerance stacks prior to the final integrated design definition. Because the metal hardware is affected by the radiant thermal energy emanating from the CMC in proximity, it must react to the aerodynamic turning loads from the CMC airfoil. Thermal and mechanical loads were applied to finite element models (FEM) of the metal hardware. Stress of the metal hardware was calculated by finite element analysis (FEA). The stress values were then used to calculate part cyclic life. All metal hardware, except the inner carrier, exceeded the low cycle fatigue (LCF) requirement for production parts. But it was determined this part had sufficient LCF capability margin. Once complete metal forgings were ordered, machining of all metal parts was completed in task 2.13.

Subtask 2.2.4 - Design integration of nozzle

Sealing joints between CMC and metal hardware are a significant technology attribute that must be designed for a CMC nozzle to provide the desired turbine efficiency improvement. Because of the thermal growth mismatch between CMC and metal, the two components must not be rigidly constrained to ensure thermal stresses will not exceed the material capability of the joint. Joints that allow relative motion between CMC and metal will profusely leak cooling flow without sealing, thus the need to focus on effective sealing of the joints. During this task, the integrated CMC vane and metal hardware of the nozzle design were analytically assessed to verify that the performance benefit of the nozzle assembly satisfies the target flow reduction predicted to increase for target combined-cycle gas-turbine efficiency.

Conceptual nozzle assembly architecture that satisfied the target flow reduction was identified as a nozzle assembled of two CMC vain airfoils captured by metal carriers and spars. This arrangement (shown in Figure 7) allowed the CMC vane to carry the high thermal loads while the metal carried the mechanical load from turning the flow. All mechanical loads react through the metal to the gas turbine casing and finally to the gas turbine foundation. This hardware arrangement allowed CMC to do what it does best: operate at the very high flow-path temperatures of the S2N. Bulk surface temperatures can be 500°F higher for a typical metal nozzle. Therefore, less cooling is required, as much as two-thirds less than an all-metal nozzle assembly.

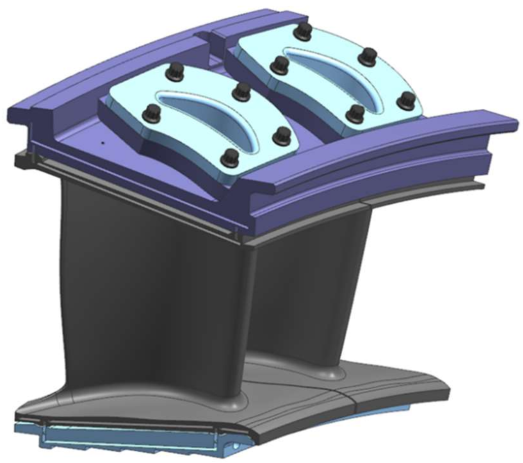

Figure 7 – Nozzle segment assembly

Subtask 2.2.5 - Seal Development Testing

Bench flow tests were performed to identify the best options for seal material and style for application as the perimeter seals. Cold flow tests were used to make this assessment. As these seals are positioned between the metal carriers and the CMC vane, the seals were predicted to operate above 1800°F. As shown in Figure 8, two styles of seal were tested: 1) a compressible W-seal and 2) a vertical segment seal. GEGP has good experience with compressible W-seals (sometimes called E-seals) with convolutions that allow expansion and contraction between the sealing surfaces. Properly designed, good sealing effectiveness is available through the range of motion. At operating temperatures, compression may be limited, or creep of the seal material would affect sealing effectiveness. The tested W-seal demonstrated excellent sealing effectiveness exceeding our goal of less than 2 mils.

Because of creep concerns with the W-seal, an alternate approach to the perimeter seal was considered. These vertical spline seals, like intersegment seals, have the advantage of little to no stress during operation. They are flat, thin, and loaded against the seal surface by pressure alone. There is no mechanical compressive load as compared to the W-seal. This seal is easy to fabricate with a variety of commercially available high temperature seal materials making it less expensive that the W-seal.

In most test conditions, they met the sealing effectiveness requirement. However, this vertical spline seal was less effective than the W-seal and more sensitive to seal surface offsets. Therefore, the W-seal became the preferred perimeter seal configuration. To reduce the temperature of the W-seal, an Ox-Ox insulator plate was designed built to fit between the W-seal and the CMC vane.

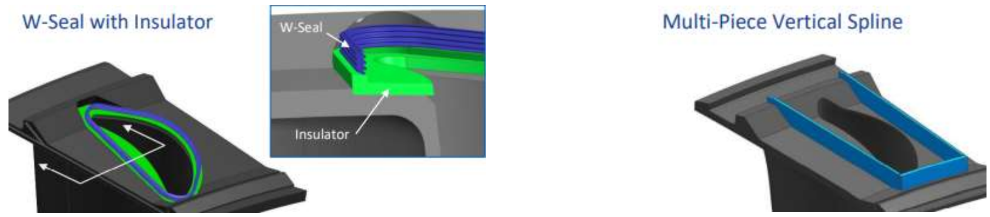

Figure 8 – Perimeter seals: W-seal and Spline Seal

Metal nozzles use intersegment seals to provide sealing between opposing nozzle surfaces at the flow-path slash face. These seals are the closest of all seals to the hot gases in the flow path so they must withstand high temperature. Typically, in traditional metal nozzles, these seals will operate below 1750°F. To reduce as much cooling flow as possible in the CMC nozzle design, the seals are predicted to run above 2000°F. This temperature is too high for traditional intersegment seal materials like Haynes 188.

Other metallic and non-metallic seals were evaluated. Cold flow tests were performed on four seal architectures with seal performance from best to worst as follows: 1) laminated metal, 2) thin solid metal, 3) Ox-Ox ceramic composite, and 4) thick solid metal. Though all met the effective gap target, this became less important to flow savings as that was driven by the perimeter seal effectiveness. The intersegment sealing effectiveness was important in preventing hot flow-path gas injection into the nozzle assembly at locations where backflow margin is low. High temperature specimen tests began during this task to evaluate material capability against key durability risk. This effort was completed in Task 2.14.

Task 2.3 – Design high-temperature nozzle test rig

A high temperature rig was designed for testing the nozzle concept design of Task 2. Key features of the rig were the ability to run the CMC at representative temperatures and temperature gradients and to measure flow around the seals with representative delta-pressures across the seals in order to verify sealing performance for seal design selection. These objectives were achieved with multiple design iterations on the duct and CMC vane box flow path, as shown in Figure 9.

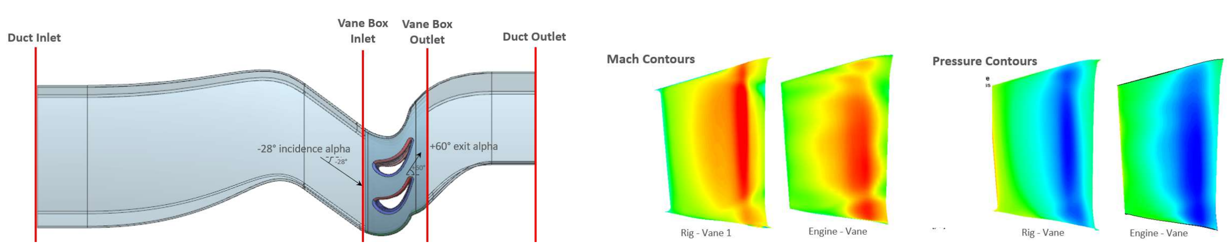

Figure 9 – Duct and CMC vane box flow path, Mach No. and pressure contours

Subtask 2.3.1 - Facility requirement and mods

The GEGP GTTL facility in Greenville, SC, is capable of providing the required temperatures, pressures, and flow across the CMC nozzle sector test to produce the proper temperature, temperature gradients, and pressure gradients across the seals. Therefore, this facility was selected to perform the CMC vane and seal test. Required modifications included piping for air flow from facility compressors to the modular test stand to achieve sufficient high temperature flow across the CMC vanes and provide representative cooling flows through the CMC vane and across the vane assembly seals, as shown in Figure 10. This task delivered drawings, models, and specifications of all required hardware.

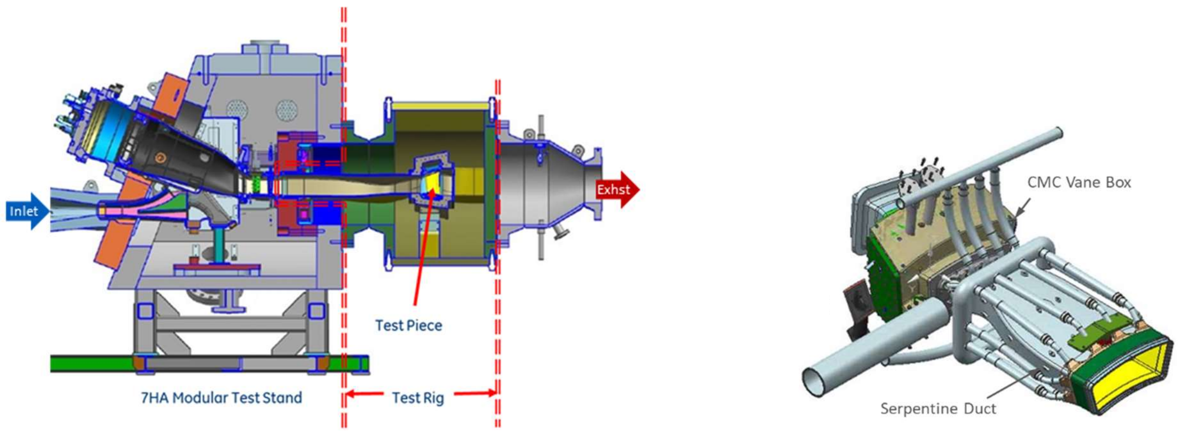

Figure 10 – Modular test stand and piping modification definition

Subtask 2.3.2 - Test cell definition

This task identified the cell design that satisfied the test requirements. Key hardware defined was the serpentine duct, CMC vane box, and instrumentation. One key feature to design was a quick access port to the CMC nozzle arrangement being tested. This facilitated hardware inspection and hardware changes like seals and flow circuits structures. A second key feature was the design of the upstream and downstream test stand interface structures. Since the cell is essentially a pressure vessel, structural analysis was performed to demonstrate that the test rig and stand satisfied strength and safety requirements. The instrumentation requirements for the CMC vane box and the CMC vane test articles were defined, as shown in Figure 11.

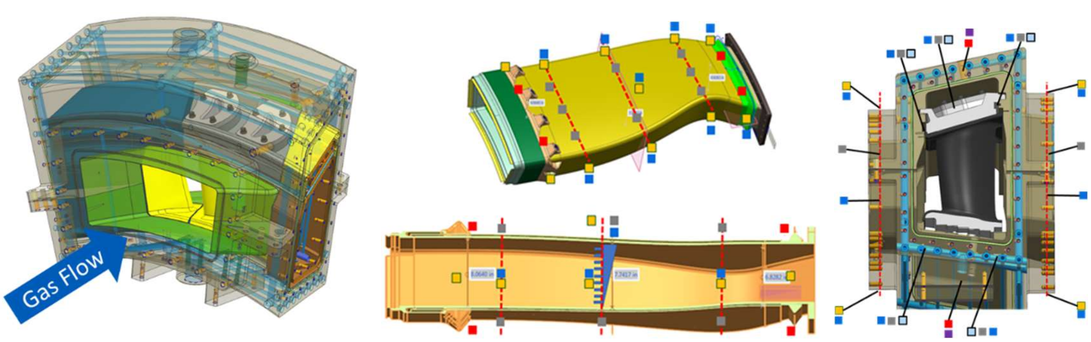

Figure 11 – CMC vane test section and instrumentation callout

Task 2.4 – Fabrication of nozzles, end-walls, seals

Subtask 2.4.1 - Initial fab trials

This task identified key attributes to manufacturing a successful CMC vane. Since the vane has many surfaces, airfoil, end wall, cooling passages, etc., several manufacturing iterations were required to define a process that delivered a finished part. This task identified the manufacturing process needed to successfully fabricate the CMC vane.

The first effort in the build trial was to demonstrate that the CMC vane laminate architecture could be fabricated. The effort was not a trivial one as the design required three thick, curved laminate structures (airfoil, OSW and ISW end-walls) to be formed together as one integral laminate. To do this, the three structures were fabricated separately as sub-elements and then combined together with a series of interlocking and overlapping laminates for the flow-path surface. Dedicated tools were used for the sub-element section and to create CMC fillers, as shown in Figure 12. Then, another special tool was used to assemble the sub-element sections, fillers, and flow-path laminates. Once built, this same tool was used to hold the laminate build in position through the autoclave step to achieve proper compaction and shape. A key improvement was made by machining the end-wall airfoil cut out before attaching it to the airfoil, which produced a better structural fit between airfoil and end-wall and a more dimensionally accurate final CMC vane laminate.

Figure 12 – CMC airfoil ply architecture with airfoil, end-wall, and tooling

Furnace cycles were optimized during this task. The autoclave consolidated and cured the laminate. Pyrolysis eliminated all organic substances in preparation for melt infiltration. Silicon was then melted into the laminate to densify the structure. Changes were made to all three furnace cycles to accommodate the CMC vane due to its large size and laminate thickness. In all cases, the temperature schedules were adjusted to reduce ramp rates and to extend hold times to properly process the CMC vane. These changes improved silicon infiltration and dimensional quality for the entire CMC laminate.

Figure 13 – CMC as machined seal surface, coated CMC, and cross-sections

Initial fabrication trials demonstrated that the basic shape of the CMC vane could be fabricated and successfully complete all furnace cycles. The final product demonstrated that dimensional quality was sufficient with modest dimensional non-conformance of the airfoil and end-walls. This was corrected in Task 2.13 with autoclave tool design and ply laminate changes. As shown in Figure 14, the end-wall edges were successfully machine-ground with diamond machining bits, and the TE cooling holes, and seal slots were successfully created by electrical discharge machining (EDM). Computed Tomography (CT) was used to inspect the internal laminate sections for infiltration quality of silicon. All airfoil sections, even the thickest areas, were satisfactory with some lack of infiltration (LOI), due to incomplete of compaction. This issue was addressed in task 2.13 with toll changes and the addition of compaction intensifiers. Because end-walls showed considerable LOI, more manufacturing development was performed in Task 2.13.

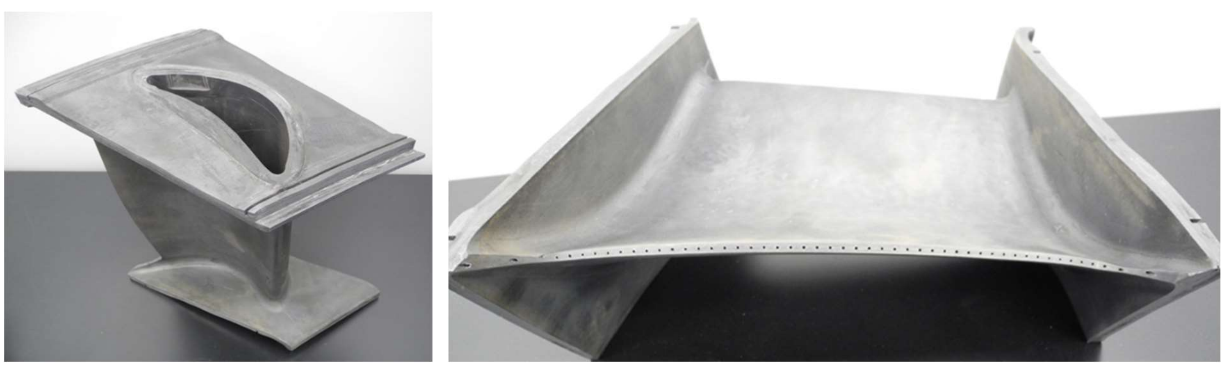

Figure 14 – Initial CMC vane fab trial with machined surfaces and cooling holes

Subtask 2.4.2 - Seal Surface Finish Improvements for CMC’s

Surface finish can significantly affect sealing effectiveness which directly impacts cooling flow savings. This task developed a coating system that would produce sealing surface finishes of no more than 150 Ra (roughness average) on CMCs. A polymer-derived ceramic (PDC) was developed that can be easily applied to a finished CMC sealing surface, then cured and machined, if necessary, without substrate degradation. Key attributes included good wetting with SiC, material compatibility at operating temperatures, and ability to coat with traditional application techniques. This task consists of three key steps: 1) coating composition optimization, 2) wetting characterization, and 3) application process definition. Clemson University, program subrecipient, completed all this work, with GE Gas Power providing CMC substrate material and technical consultation.

A good ceramic coating for SiC/SiC CMC must have several desirable properties including a compatible coefficient of thermal expansion (CTE), wettability, and chemical compatibility with the CMC. In addition, the processing temperature should be lower than 1350°C, and the use temperature should be higher than 1200°C. It was a challenge to find suitable glass-ceramic materials that can fulfill the above set of properties. GEGP proposed and focused on glass ceramics containing $BaO\text{-}Al_2O_3\text{-}SiO_2$ and $SiO_2\text{-}Al_2O_3\text{-}Y_2O_3$ to make the coatings and investigated their physical properties (including microstructure, phase composition, thermal expansion, and softening temperature).

Specifically, the physical properties of fifteen compositions containing $BaO\text{-}Al_2O_3\text{-}SiO_2$, BAS, $SiO_2\text{-}Al_2O_3\text{-}Y_2O_3$, or SAY glass ceramics were investigated. Glass ceramic coatings with compositions of SAY:BAS ratios of 70:30 and 80:20 were successfully applied on SiC/SiC composites (see Figure 15). After furnace heat-treat, the resulting coating compositions delivered surface finish values of 50 Ra or less, exceeding the initial goal of less than 150 Ra. Furnace thermal cyclic testing to 2200°F was performed with limited degradation observed in the coating. It was unclear what that means for the surface finish under extended use on a GT or more importantly the impact on sealing effectiveness. That would need to be explored further but it is possible the long-term sealing effectiveness would be improved with the tested coatings compared to the as-machined CMC surface.

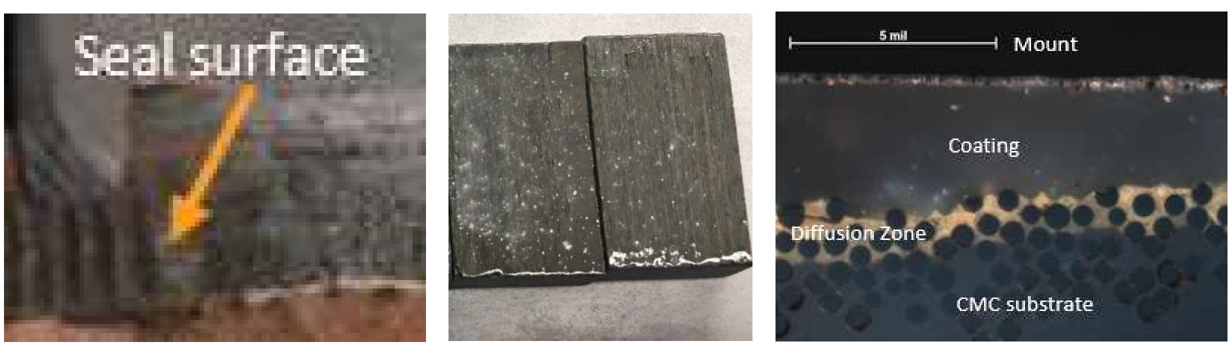

Figure 15 – CMC as machined seal surface, coated CMC and cross-section

To complete their work under the program and to support future production needs for application on various CMC surface geometries, Clemson considered alternate ways to apply the coating. Three approaches were successfully demonstrated: 1) cold spray, 2) brush on, and 3) tape.

Subtask 2.4.3 - Fabricate and test (structural) specimens

This task fabricated CMC nozzle structures for the sole purpose of testing to structural failure to demonstrate design margins. Special tensile test frames were used to evaluate regions of the CMC vane that were predicted to experience high stress. The tested parts then underwent evaluation to determine if the failure occurred as predicted.

Structural analysis identified two areas of interest: 1) the TE to end-wall fillet; and 2) the airfoil wishbone section. The TE fillet stress was believed to be due to thermal strain in the CMC fillet from the thermal growth mismatch between the TE and the end-wall. Evaluation of this section was begun before the 2018 pivot (i.e., change request) and was completed after the pivot, so the results are discussed further in Task 2.8.

The wishbone section is formed when the airfoil hollow cavity transitions to the solid TE section. High stresses occur in the laminate wraps that form the airfoil cavity when the cavity is pressurized with compressor extraction air for cooling purposes. This cavity pressurization creates a mechanical load that tries to separate the TE-to-cavity plies, similar to pulling a wishbone apart. A fixture was designed and fabricated to mechanically create similar loads on airfoil wishbone section, as shown in Figure 16.

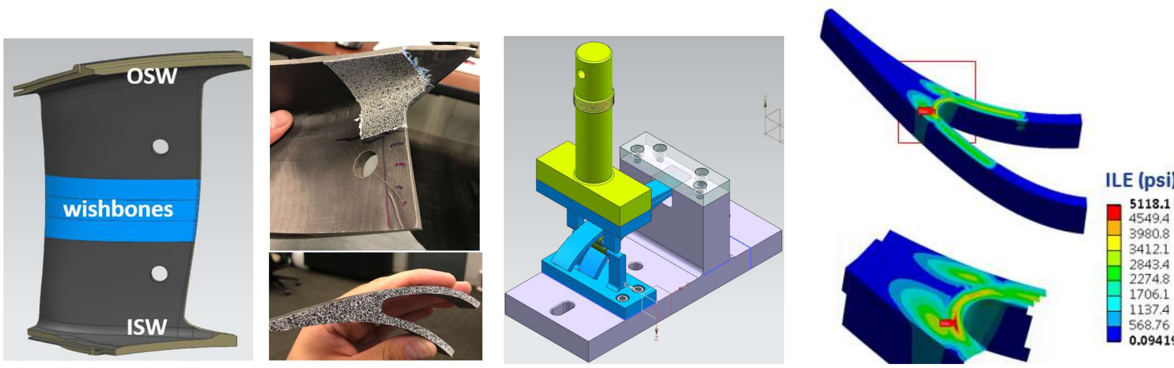

Figure 16 – CMC vane specimens, wish-bone test rig, predicted stress

Wishbone specimens were cut from early CMC vane fabrication trials and tested to failure in the fixture. The failures occurred at the anticipated location in the laminate but at a lower load level than expected. DIC, digital imaging correlation, was used to determine stress in the wishbone test section and to identify the initial failure location, as shown in Figure 17. Testing demonstrated that the stiffness of the specimens was significantly below the design intent (Figure 17 load vs. deflection chart). This data was key in driving design improvements to achieve acceptable structural integrity. Changes were made to the laminate architecture and autoclave furnace cycle to achieve the desired strength.

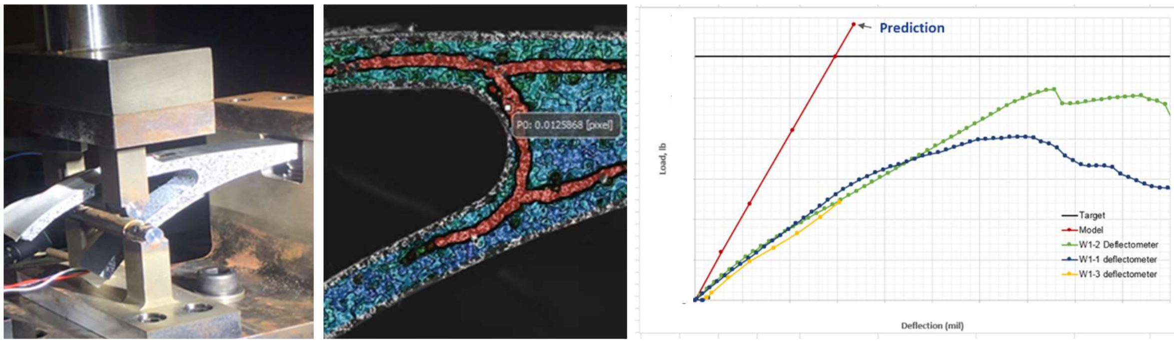

Figure 17 – CMC wishbone specimens, DIC of failure, load vs. deflection

Structural analysis identified that the initial CMC vane design concept had high stresses in the TE fillet and the airfoil wishbone sections. Early manufactured parts were tested for strength and cyclic capability. Neither the TE fillet nor the airfoil wishbone had satisfactory load and durability capability initially. Design changes were made to reduce the stress and to increase the load-carrying capability. This required ply architecture changes, which were incorporated into the larger vane of the 2018 design pivot. The design changes made in Task 2.11 successfully addressed the TE fillet and airfoil wishbone structural inadequacies by improving the CMC ply architecture and lowering stress levels.

Subtask 2.4.4 - Fabricate prototype nozzles for test (this subtask is deleted from program scope)

This task was to fabricate CMC nozzles used for the test of Task 2.6. The initial scope of this task was to include the application of the Environmental Barrier Coating (EBC) over the flow path surfaces of the CMC structure. Seals and all metal supporting structure were also to be included so that a nozzle arrangement could be assembled for testing.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

Task 2.5 – Fabricate nozzle test rig

The high temperature rig designed under Task 2.3 for testing of full-scale nozzles was to be fabricated. All key features were to be assembled with required instrumentation. Interface joints, thermal loading apparatus and pressurized air supply would be installed. The rig would be energized for the prescribed number of cycles, pressures and temperatures in the tests performed in Task 2.6. Appropriate facility modifications would also be performed meet test needs.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

Subtask 2.5.1 - Facility mods and interface fabrication (this subtask is eliminated from program scope at the 2018 pivot)

Use of an existing facility would require modifications. The modifications would focus on the interface surfaces between the facility and the test cell and between cooling flow supply to the nozzle and test cell internal structures. All hardware required for the facility changes and interface connections were to be fabricated during this task. Additionally, any installation required for facility changes was to be completed during this task.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

Subtask 2.5.2 - Test cell fabrication and commissioning (this subtask is eliminated from program scope at the 2018 pivot)

There would have been many pieces to be fabricated and assembled for the test cell including the casing, flow path, nozzle mounting structures, and air supply for cooling the nozzle in the cell. All hardware required for the test cell was to be fabricated during this task. Assembly and installation of the test cell into the facility would be completed. Once the facility and test cell hardware was fabricated and assembled, then a cold flow sealing check would validate flow, seals, and instrumentation were functioning properly.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

Task 2.6 – Test nozzles and seals to demonstrate fit, form, function, and flow savings potential

A full-scale nozzle incorporating key elements of the design including sealing and cooling features and loaded joints from Task 2.4 were to be fabricated for assembly and tested in a high temperature rig fabricated under Task 2.5. The purpose of the test was to validate the sealing effectiveness and cooling capabilities under steady state and cyclic conditions. The measured sealing effectiveness would substantiate the flow saving benefit of a CMC nozzle. The test would also demonstrate the thermal and aerodynamic load-carrying capability of the nozzle design where the test rig is energized to subject the test article to a prescribed number of cycles, pressures, and temperatures. Temperatures and flows would be measured with high temperature thermocouples and pressure-induced flow meters.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

Subtask 2.6.1 - Configuration 1 – Seals (this subtask is eliminated from program scope at the 2018 pivot)

Sealing effectiveness is a key attribute for an effective CMC nozzle design. The performance benefit achieved with CMC would largely be dependent on the how well the seals perform. Sealing effectiveness would be demonstrated in the test cell with a prototypical nozzle arrangement. The test activities were to include up to five seal configurations for assessment. Configurations would be defined by seal material, seal type, and seal interface joint design. Seal material options were metal and ceramic based. Seal configurations were defined by shape and whether or not the seal was internally cooled. The seal interface joint was defined by the geometry on either side of the seal. The purpose of these tests was to identify the best measured sealing approach. It was intended to perform these tests at nominal nozzle operation temperature to assess how well the seals would perform once the CMC and metal structures reached operating temperature and thermally grew to their operating dimensions. Since CMC grows at one-third the amount of metal, this test would verify that seals do not unseat from their installed position, thereby producing gaps, or get crushed during operation, thereby producing damaged, ineffective seals.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

Subtask 2.6.2 - Configuration 2 – Cooling (this subtask is eliminated from program scope at the 2018 pivot)

Cooling effectiveness is an important attribute to verify because of its effect on durability of both the CMC and metal structure and, to a lesser degree, the effect on flow savings of the CMC nozzle design. Most of the design's cooling flow is made up of the required leakage flow, defined by the sealing effectiveness, to cool the metal and CMC structures. If cooling efficacy could be demonstrated, then there would be no need for additional dedicated cooling flow, which enhances the performance benefit of the CMC nozzle. This subtask was to assess the cooling flow in the test cell with an arrangement of prototypical nozzles. The test activities would include up to three cooling configurations defined by impingement plate geometries and cooling circuits. The best measured cooling approach was to be identified by comparing the best temperature distribution obtained with the least amount of flow.

As agreed, no work was performed under this task due to the 2018 program pivot to fabricating a prototype CMC vane segment.

<u>Task 2.7 – High temp EBC/CMC durability test</u>

The Environmental Barrier Coating (EBC) is important to protect the CMC material from damage by water and oxygen at high temperature over a part's entire service interval, which may be many thousands of hours in harsh conditions. The EBC must remain structurally attached and hermetic to prevent volatilization and a loss of CMC material, as shown in Figure 18. EBC chemistry was defined prior to this program, but the application architecture was improved and evaluated in this task. The EBC applied to the CMC substrate, which represented a coated CMC vane, underwent high temperature tests with thermal gradients. These tests determined a suitable EBC architecture for application to the CMC prototype nozzle.

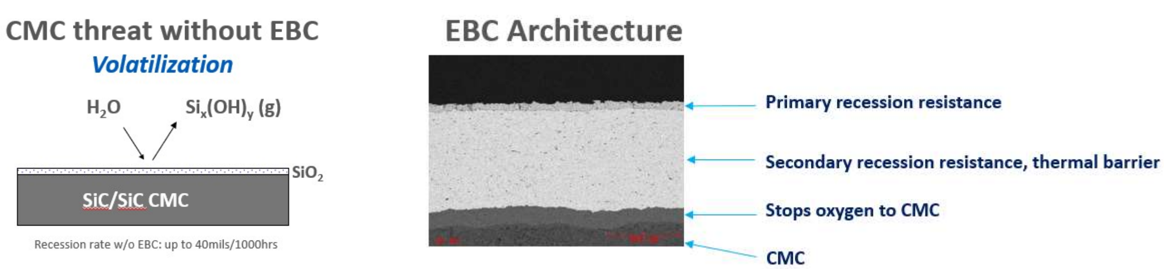

Figure 18 – CMC volatilization without EBC; CMC with EBC architecture

Subtask 2.7.1 - Interval Evaluation

As shown in Figure 19, EBC-coated CMC specimens were tested in natural gas rigs to assess durability and hermeticity of the EBC. The specimens were inspected periodically to determine if the EBC quality was deteriorating over time. Initial specimens showed significant coating cracks and bond coat oxidation before the 8000-hour test finished, an indicator of poor durability. Changes were made to how the primary recession layer was applied, particularly creating a loosely interconnected outer layer. This approach yielded excellent results. The loosely interconnected outer layer has the advantage of lowering the temperature of the hermetic layers underneath. This reduced the thermal stresses in the hermetic layers thereby eliminating the previously observed cracks and bond coat oxidation.

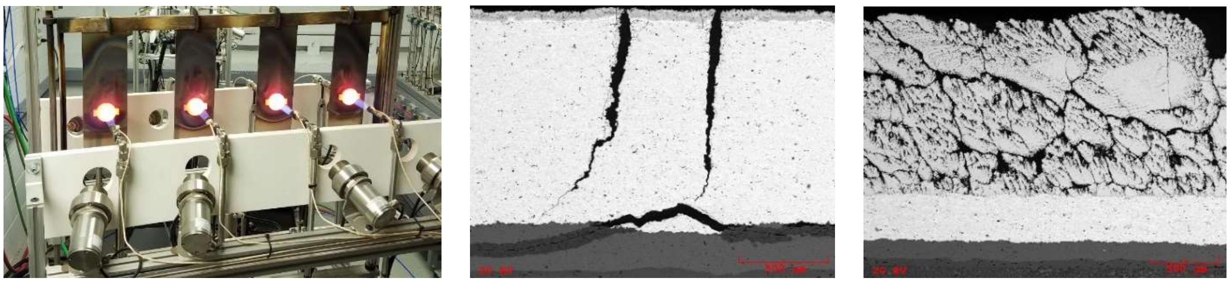

Figure 19 – EBC durability test, Initial application, Improved approach

Hermeticity is an important attribute of the coating because water and oxygen will deteriorate the CMC substrate as they react at elevated temperatures with SiC CMC to produce silicon hydroxide and carbon dioxide gases. This causes the CMC to recess slowly, or sublimate, resulting in a loss of CMC material. There are areas on the CMC nozzle where recession of the CMC would be of concern if an EBC spall occurred. With enough time, the CMC section thickness would be compromised causing either structural failure or a cooling flow leak.

Task 2.8 – Feature test for strength and durability

Specimens were tested by simulating the loading of a full-scale nozzle to assess key CMC nozzle design attributes and features. The specimens were sub-elements derived from a full-scale nozzle to match capabilities of the load testing equipment and to create representative magnitude and direction of stress/strain. Areas of the nozzle design that are strength or durability challenged were tested for capability using these specimens. These specimens utilized electro-mechanical loading frames.

Subtask 2.8.1 - Test early designs and fabricated nozzles

The CMC composite material is a highly orthotropic material system, meaning that the strength capability varies depending on the direction of the stress through the composite structure. The capability can also vary significantly with the quality of the manufacturing process. The nozzle having a highly curved airfoil and two integrated end-walls adds complexity to the fabrication process resulting in variation in material strength. Early structural testing identified opportunities for improvement, which resulted in changes in the manufacturing process including layup and furnace cycle modification.

Structural analysis identified that the initial CMC vane design concept had high stresses in the TE fillet and the airfoil wishbone sections, as discussed above and as shown in Figure 20. Early manufactured parts were tested for strength and cyclic capability. Neither the TE fillet nor the airfoil wishbone had satisfactory load and durability capability. Design changes were made to lower the stress and to increase the load-carrying capability. This required ply architecture changes that were incorporated into the larger vane of the 2018 design pivot. The design changes made in Task 2.11 successfully addressed the TE fillet and airfoil wishbone structural inadequacies by improving the CMC ply architecture and lowering stress levels.

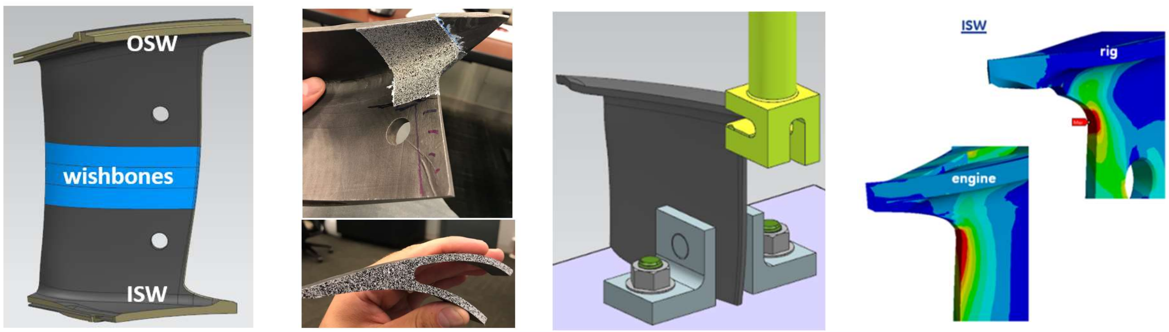

Figure 20 – CMC vane specimens, TE fillet load rig, predicted stress

Subtask 2.8.2 - Effect of Defects

Based on cost and schedule, the program was limited to manufacturing a few full-scale, full-featured CMC nozzles which constrained the number of design and manufacturing changes that could be made to address defects. The changes were limited to laminate architecture, ply shape, and furnace cycle protocols. Therefore, structural testing determined which defects were acceptable and which would require design/manufacturing modifications. It has been observed in past CMC development activities that the material system is quite damage-tolerant and capable of shedding load around defective laminate regions. Therefore, a limited number of changes to the design and manufacturing process were anticipated to address defects.

Analysis of the final DoE CMC S2N design indicated life-limiting local strains in the seal slot region of the OD slash face of the CMC vane. A feature test of the existing two feature specimens was designed and performed in the GTTL small component test lab. The purpose of the test was to simulate the local strains in the feature-based geometry in such a way that a direct verification of life capability could be determined. The test plan was designed to accomplish the comparison at the same local strain level. The test also undertook a stretch goal of additional actual life verification via cyclic testing.

Feature test specimens, shown in Figure 21, were designed and built from an existing CMC S2N sample of CMC end-wall structure and subjected to a 3-point bend test. The test geometry was then separately analyzed to provide the appropriate test loads to apply to generate high local strains in the test part matching the actual part. Parts were loaded, and a determination made on the effects of the local strain levels and life capability.

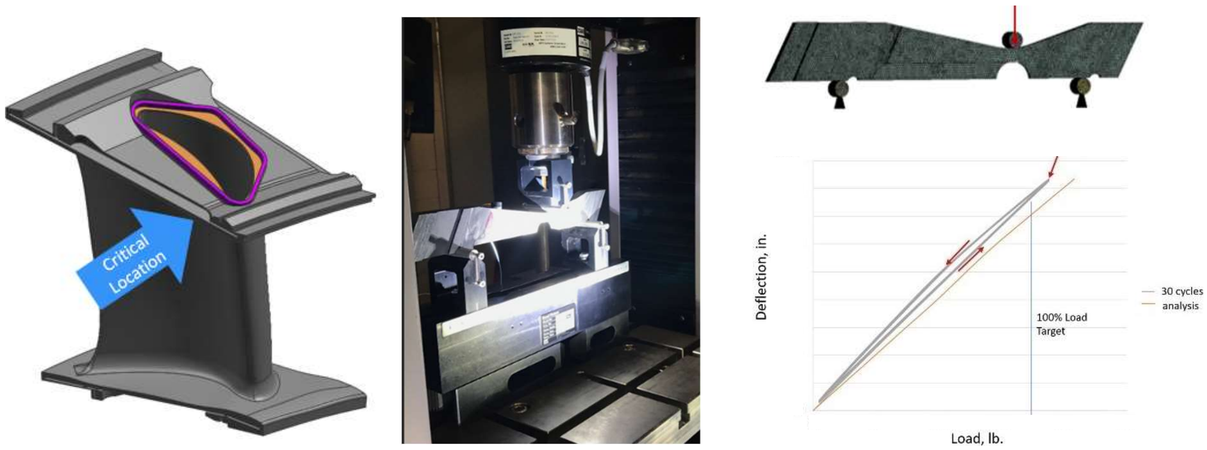

Figure 21 – Critical location, specimen in load frame, cyclic demonstration

Subtask 2.8.3 - Test final design

A structural test of the final design included ultimate and cyclic capability valuation on specimens derived from a full-scale prototype nozzle to determine that the design and manufacturing processes yielded parts suitable for operational use in an industrial gas turbine. The testing determined the design margins to mechanical and thermal loads based on the most structurally limiting, analytically determined locations of the nozzle. Digital Image Correlation (DIC), a 3D, full-field, non-contact optical technique to measure contour, deformation, and strain, measured the amount and type of stress during the test. Strain gages and displacement measurements supplemented the DIC measurements. The conclusion of these tests demonstrated that the CMC vane is structurally suitable for in-engine field testing. This potential field engine test was not included in this project.

The feature test for CMC results required rigorous control of as-modeled specimen geometry, ply architecture, and modeling approach to achieve the best possible results. Local strains, deflections, and accelerometer data were recorded for all tests. The local strains were measured using the Digital Image Correlation (DIC) tool used by GTTL. The CMC test specimens had all required features, including seal slots, to represent the outer end wall of the S2N. Target load was set to represent the combined thermal and mechanical load expected during engine operation. The specimens exceeded target load by a significant amount, as shown in Figure 22. These results demonstrated that the CMC nozzle, even at its most structurally limiting location (the notch), has margin to withstand engine operational loads. This result was as predicted, which demonstrated the conservatism of the intent and methods of the CMC lifing approach. Also, the specimens were quiet (i.e., did not experience vibratory excitation), as measured via accelerometer, until failure. This may have been due to loading type (3-point bend) or CMC directional properties with plies oriented parallel to load.

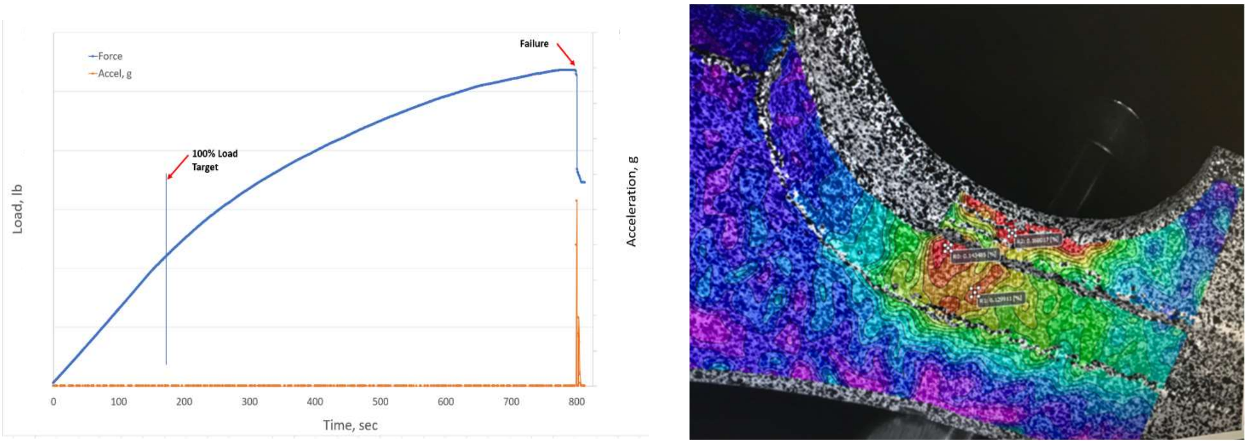

Figure 22 – Load to failure and DIC in notch just before failure

<u>Task 2.9 – Full-scaled full-featured demo field test</u>

To demonstrate that a CMC hot gas path part with applied EBC can withstand the operating environment of a power generating gas turbine, periodic borescope inspections would be needed to track the condition of the EBC and overall health of the CMC specimens. To facilitate this inspection in an efficient manner, GEGP built and demonstrated a prototype in-situ inspection system (see Figure 23). The system consisted of a small platform containing high-definition video cameras that can be inserted through a combustor and attached to a blade airfoil. The platform was rotated with the blades to video inspect the surrounding hardware, specifically the shrouds and nozzles. The high-definition video captured up to 100% of the hot gas path surface and was used to track the condition of the flow path surfaces and the EBC coating during periodic borescope inspections. The deliverables for this task were: 1) development of prototype inspection system; 2) an evaluation of the inspection technology in a gas turbine; and 3) documentation of lessons learned.

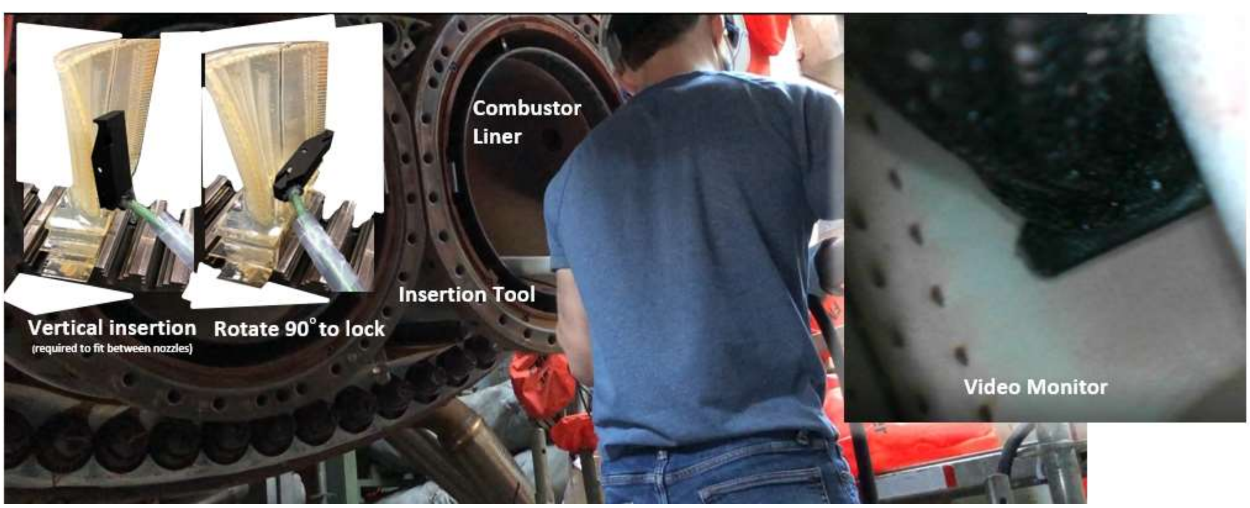

Figure 23 – Prototype inspection system and trial application

The inspection equipment was designed, built, and initially tested on the bench (Figure 23). Lessons learned inspired modifications needed for a follow-on demonstration in a gas turbine. Modifications were made to improve the camera, as well as insertion and extraction methods. The improved robot was tested in an actual turbine at GE's Gas Turbine Outage Simulator (GTOS) in Greenville, SC. Additional improvements were identified and evaluated before a test occurred in a fielded gas turbine. The inspection team successfully completed inspection process reviews with the customer operating fielded CMC shrouds. Then, the inspection team validated the approach on an open turbine unit at the customer site to obtain final clearance before the actual inspection of the CMC shrouds. Images from the in-situ inspection are shown in Figure 24.

Figure 24 – Inspection results

Task 2.10 – Conclusions and Documentation

This document serves as the final report for both the Phase I and Phase II Programs. A written summary of all tasks was created under this task and reported out in this document. Final oral report was completed under this task.

Task 2.11 – Design engine test parts

This task defined key design elements of a CMC nozzle for testing in an engine. The design was directed to an HA-class, full-scale S2N and included geometry definition of CMC and metal hardware required to create a complete nozzle segment. The task included identifying EBC application requirements. Interface surfaces with adjacent hardware were considered to ensure fit, form, and function of the entire nozzle arrangement was not compromised. The hot gas path and cooling flow conditions for design analysis were representative of an advanced high-efficiency gas turbine.

The CMC S2N was a hybrid construction, which used ceramic matrix composite (CMC) vanes and sidewalls with a metal support structure. The nozzle was constrained at the OSW, which made it cantilevered. Because of the hybrid construction and unique sealing features, special metal nozzle adapter segments were designed to interface between the CMC nozzle assembly and the adjacent NPI nozzles on either side. See Figure 25.

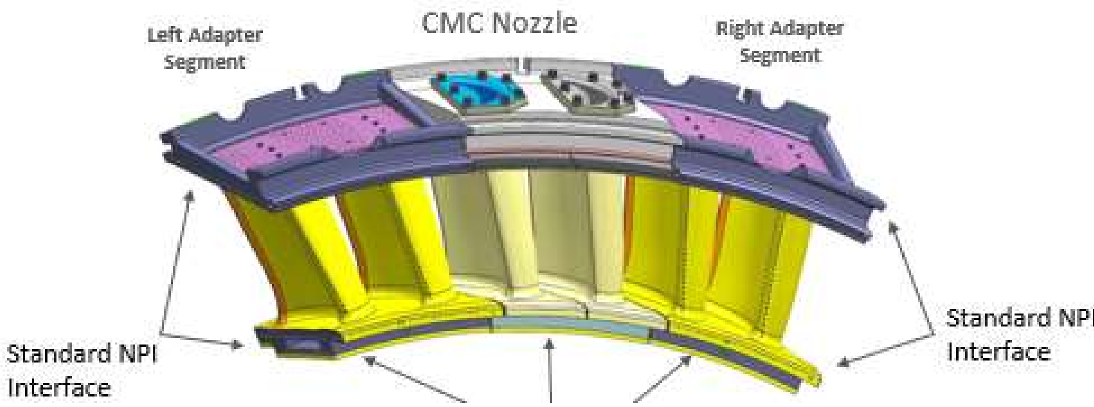

Figure 25 – CMC S2N Engine Test Arrangement Position

The metal support structure utilized a bolted and pinned design for ease of assembly. The spars attached to the OSW component using bolts. The honeycomb carrier attached to the spars via sliding pins. During final assembly, the nozzle sidewalls were clamped together to compress the 4 W-seals. Once compressed to the proper distance, the retaining pins were inserted, and the clamping force removed.

The CMC airfoil would be supplied with stage 11 compressor extraction air for cooling. The airfoils used both impingement and trailing edge convection cooling. The vane trailing edge convection cooling was accomplished using small holes fed from the airfoil hollow cavity. Each structural spar includes holes which impinge cool air upon the airfoil inner cavity. Post impingement air was then directed to the inner and outer sidewalls and was used for convective cooling. The pressure drop between the airfoil impingement and sidewall convection cooling was achieved with a custom W-seal at the OD and the ID of each CMC airfoil. High compliance and high effective sealing were needed to demonstrate the overall target flow savings. Other seal types were investigated but none had the necessary effective gap for the required compliance. To reduce the contact temperature of the W-seals at the CMC interface, a unique Ox-Ox insulator was designed. The insulator provided the necessary temperature drop while limiting additional leakage at the Ox-Ox/CMC interface. The slash face seals were typical flat spline seals. The flat spline seals were made of Ox-Ox materials. The circumferential seals were standard AO seals and were not unique to the CMC S2N.

Task 2.12 – Intentionally left blank

This section is an artifact of the proposal submitted in 2018 in support of the program pivot, and there is no defined scope or work performed.

Task 2.13 – Fabricate nozzles for engine test

A full-scale CMC nozzle segment was fabricated under this task. The nozzle segment consisted of two CMC vanes (also called fairings), two metal spars, one metal OSW, one metal HCC, two pins and seals. Key features required for operation within a gas turbine were included. Machining and coating development activities were completed. The key deliverable was one finished and assembled CMC nozzle segment.

The metal hardware was designed with a traditional approach using standard work tools and commonly used materials. Therefore, this section focused on the fabrication of the ceramic composite parts. The engineer began with the final definition and determined what unmachined shape was required to be built. This is called the preform, which was constructed of individual plies stacked to form layers of plies called a laminate. The laminate was built in a tool to form the proper shape of the nozzle. Once the laminate build was completed, the part proceeded though three furnace cycles: 1) autoclave for laminate compaction and cure; 2) pyrolysis (sometime called burn-out) for conversion of the matrix material; and 3) silicon melt infiltration for laminate densification, as shown in Figure 26.

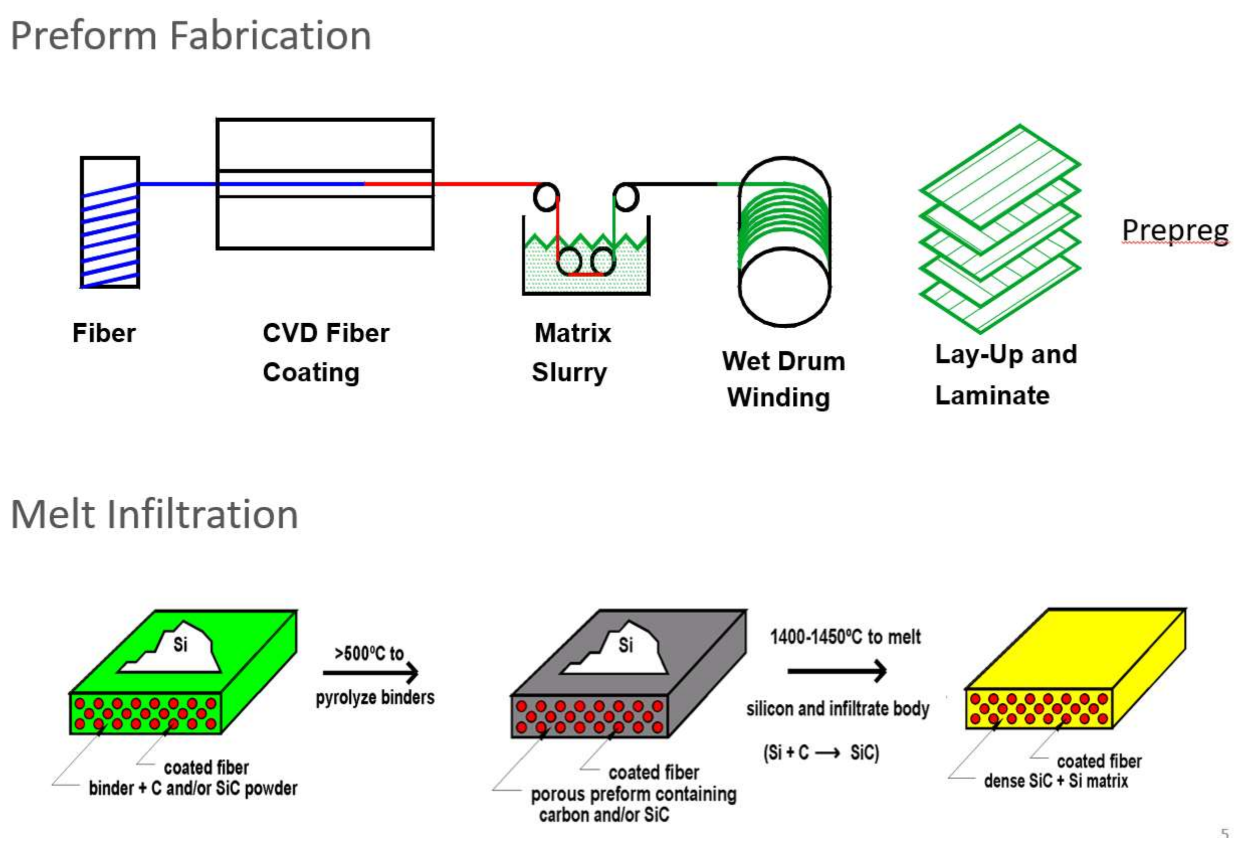

Figure 26 – Preform Fabrication and Furnace Processing

The design required that the trailing edge (TE) of the CMC airfoil section be provided with a small amount of cooling to maintain temperatures below the design limit. Early fabrication trials were made to determine the most suitable approach. Two TE cooling concepts were fabricated: 1) straight holes; and 2) stacked serpentine passages, as shown in Figure 27. Though both concepts were successfully fabricated, the straight hole design was easier to fabricate and therefore was selected to be incorporated into the CMC nozzle airfoil for engine test demonstration.

Figure 27 – Straight holes and stacked serpentine passages

Early fabrication trials demonstrated that lack of silicon infiltration during the melt infiltation (MI) process was a common occurrence in the thick sections of the inner and outer walls of the nozzle. The lack of infiltration contributed to poor ply laminate compaction during autoclave. To improve MI necessary for a sucessful compaction, five changes were made to the fabrication process: 1) ply shapes, 2) laminate architecture, 3) tooling, 4) addition of compaction intensifiers, and 5) an optimized autoclave cycle. CT scans showed these changes resulted in significant improvement in infiltration.

After autoclave, the nozzle laminate was visually inspected and found to be acceptable. The nozzle laminate proceeded through pyrolysis and melt infiltration as described in Figure 26. After the MI, two inspections were completed: 1) blue light scanning for dimensional assessment; and 2) CT for densification evaluation. The airfoil dimensional profile for the first production prototype was quite good and was considered acceptable. The blue light scan was performed before final machining, so the machining shock appears thick or dark red in color. The flow-path section does not get machined so red and blue color show as thick, +0.030”, and thin, -0.030”, areas, respectively, as shown in Figure 28. The laminate was inspected for internal lack of infiltration. CT observations showed a series of LOI indications in the airfoil to end-wall fillet. In general, the densification was good, and the fillet LOI indications suggest compaction in that area could be improved.

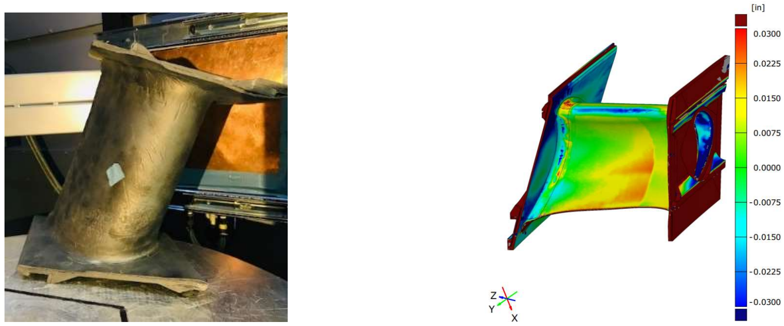

Figure 28 – Nozzle after MI and Blue light results

Two CMC fairings were fabricated. After MI, the fairing required machining for seal surfaces, load surfaces, and cooling holes. By design, the flow path surfaces were as formed and were not machined, except for the TE where cooling holes exit the airfoil. Machining was performed by diamond grind, due to the high hardness of SiC/SiC CMC, or by EDM, as SiC/SiC CMC is a semiconductor material, as shown in Figure 29. Difficulty in machining features via EDM occurred due to a non-optimized laminate compaction. With more trials, an optimized laminate architecture and autoclave furnace cycle might address this issue.

Figure 29 – Unmachined CMC fairing, grind setup, EDM setup

The application of EBC on the CMC vanes was performed after all machining operations were completed. EBC was required on all the flow path surfaces of the CMC vane to protect the CMC from volatilization during GT operation. To prepare for coating the actual CMC vanes, a SiC mock part that reproduced the dimensions of the final prototype part was printed and sintered. Dimensional inspection of the finished product showed the mock part was within 1 mm of the component model on all surfaces to be coated. Masking was also needed to prevent coating deposition in areas that must remain coating free for final assembly.

Non-contact optical dimensional inspection was performed after each iteration, and application adjustments were made to produce the required thickness uniformity on all areas, as shown in Figure 30. Difficult locations were the transitions from airfoil to fairing which tended to collect coating at a higher rate, and sharp leading and trailing edges on which the coating was deposited more slowly. The hole masking method previously tested on coupons was successful at keeping the cooling holes open. Each layer was deposited with application modifications to reach the required layer thicknesses. EBC thicknesses were satisfactory and suitable for engine tech demonstration.

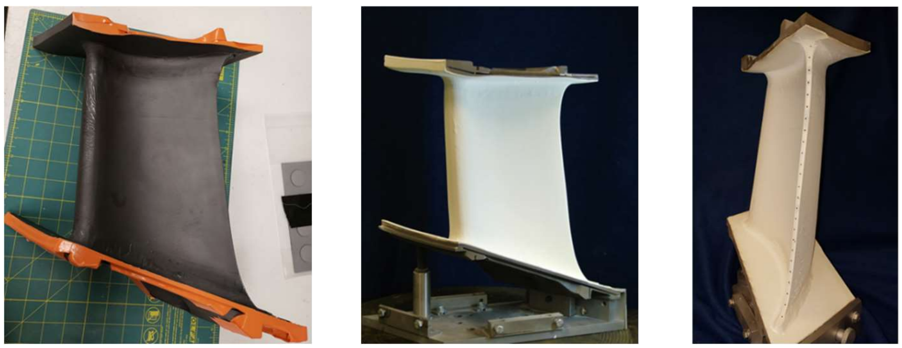

Figure 30 – CMC vane masking, Profile view, TE view

Task 2.14 – Design, build and test of high temp seals (GRC)

The sealing effectiveness of prototype seals used in the nozzle arrangement was determined in special purpose seal test rigs. Seals of representative size, shape and material were tested at various surface-finish, pressure-ratio and temperature conditions. This data quantified the sealing effectiveness of the nozzle assembly, which determined the total leakage flow, which, in turn, directly impacts thermodynamic efficiency of the gas turbine.

This section summarizes development and testing of the sealing system to support the CMC S2N development program at GE Gas Power. Sealing system performance and durability is critical to realizing the full performance of the CMC S2N, amounting to a two-thirds flow reduction when compared to the metal S2N. The CMC airfoil and its surrounding metallic structure created a need for multiple new sealing interfaces, which also needed to operate at higher temperatures than a traditional all-metal nozzle. Two key sealing developmental efforts included: (i) Intersegment (including circumferential and leaf) seals, and (ii) perimeter seals and heat shield.

The primary challenge for intersegment seals was elevated operating temperatures of 2000° F+, requiring new materials. Several metallic and non-metallic material candidates were down-selected for screening tests against various failure modes, such as oxidation, strength, chemical reaction, recession, fracture toughness, and wear, along with leakage flow performance. Based on lab results, the risk associated with those failure modes was identified as low (L), medium (M), or high (H). Once a medium or high risk was found, the test for that material was often discontinued to focus on more promising materials. Two primary material candidates for intersegment seal locations were selected for final test. At every location, duplicate seals were fabricated, one of each material. Leakage tests of these high temperature seal materials demonstrated lower sealing effectiveness than traditional production seals, but the overall cooling flow leakage rate is constrained by the perimeter seals.

The primary challenge for perimeter seals was the need to maintain a small effective gap at elevated temperatures. W-seals exhibited effective gaps at or below target values (lower is better) at simulated operating conditions. A perimeter spline seal was also designed and tested. However, it failed to meet the minimum leakage requirement at these locations.

Task 2.15 – Design, build, and test cold flow of cooling circuit

At GTTL, nozzle components were flow tested to determine flow rates through key geometries like the metal spar impingement structure and CMC TE cooling circuit. Parts were full scale and representative of components of the CMC S2N assembly.

CMC S2N cooling and sealing flow reduction is the key enabler towards realizing the DoE program goal of increasing CC efficiency beyond 65%. With a stringent goal of two-thirds less cooling flow than its HA-Class metal counterpart, the CMC S2N is expected to contribute to 0.15% efficiency gain and a 7 MW output increase.

For S2N airfoil cooling flow reduction, alternate integral cooling features such as printed cores were explored for cooling effectiveness, cost, manufacturing complexity, etc. The standard trailing edge cooling hole design ended up more desirable considering the trade-off of all the factors involved. With elevated CMC and bond coat target temperatures, the required flow reduction is achievable with a low flow TE cooling design along with limited impingement of the metal spar.

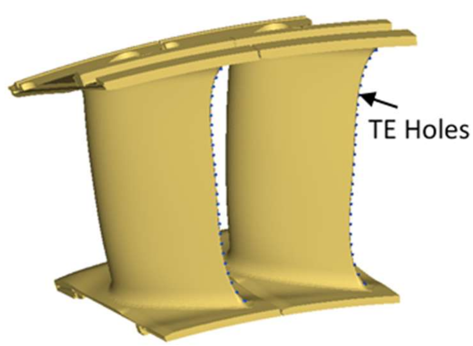

Figure 31 –TE Cooling

In addition, the CMC S2N eliminated the standard metal nozzle sidewall cooling features such as cooling holes, pin banks, serpentine cores, etc. These were replaced with a unique leakage-based sidewall cooling design as shown in Figure 37. Post-impingement air from the airfoil was reused to cool both the inner and outer sidewalls, resulting in additional flow savings. However, the total flow savings did not include any post-spall mitigation to address spall issues.

The CMC airfoil with surrounding metallic structure created two types of sealing challenges: 1) sealing the airfoil post-impingement to gas path; and 2) intersegment seals needed to operate at higher temperatures than a traditional nozzle. Various perimeter seal designs such as vertical spline seals, etc., were evaluated before arriving at the final design. Insulators or heat shields of high temperature material were used to insulate the perimeter seals from CMC material. Several metallic and non-metallic material candidates were down-selected for screening tests against various failure modes such as oxidation, strength, chemical reaction, recession, fracture toughness, and wear, along with leakage flow performance.

In general, the CMC S2N design met temperature targets in most of the regions with a two-thirds reduction in cooling flow compared to HA-class metal S2N. Also, spar, outer sidewall, and inner sidewall metal temperatures were within the allowable temperatures.

Comparing the CMC thermal temperature to that of a production metal nozzle shows why CMC temperature capability is needed to reduce cooling flow to increase efficiency and power output. On average, the CMC was designed to operate at temperatures 500°F higher than its HA-class metal counterpart that is in production.

Task 2.16 – Instrument nozzles for engine installation

This task defined the instrumentation definition for the nozzle segment. The instrumentation callout included the location for and type of thermocouple and pressure sensors.

The application of instrumentation to measure key parameters of the CMC nozzle segment during operation in an HA-class power turbine was defined. Four parameters were identified as necessary to validate that the CMC nozzle was operating as designed, at a significantly reduced cooling flow compared to its metal counterpart. Two instruments measured the cooling flow air pressure and temperature as it circulated through the assembly as defined in Task 2.15. Two other instruments measured the temperature of the metal and CMC structure. The instrumentation callout had a total of 15 air pressure taps with 14 of these post-impingement (down-stream of the spar impingement). There were 4 air temperature readings with 3 of these post-impingement. There were 16 metal temperature measurement locations and 28 CMC temperature measurement locations. Pressures to be measured with the use of static pressure tap that connected via a hypo-tube to a pressure transducer mounted external to the engine. Temperatures to be measured by use of high temperature capable thermocouples. Wire connections to run from the thermocouples to a data acquisition system external to the engine.

The final step of this program was to assemble all the metal and CMC hardware together with all the seals installed. This proved to be a bit more challenging than anticipated when the Phase II program was first conceived. This is largely due to the perimeter seals that were trapped between the metal and CMC structures. These must be compressed at assembly with approximately 500 pounds of load. This is a novel requirement for hot gas path hardware. For existing metal designs, the metal in the hot gas path thermally grows more than the cooler casing structure that surrounds the hot gas path. So seals for metal nozzle are typically loose at assembly and become tight during turbine operation. With the CMC nozzle, the opposite is true because the CMC airfoil thermally grows less in the spanwise direction than the interior metal spar. In this case, the perimeter seals must expand to maintain a seal between the CMC OSW and ISW and the metal carriers that support them.

As shown in Figure 32, a fixture was designed to facilitate the assembly of the nozzle segment with its seals installed. The fixture used the mechanical advantage of four threaded rods to apply sufficient load to properly compress the perimeter seals and to complete the assembly without damaging the nozzle hardware.

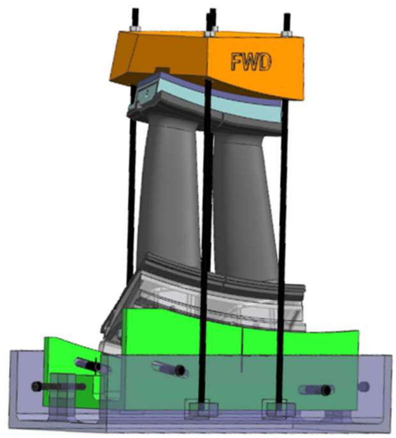

Figure 32 – Assembly fixture design, metal fit check, CMC fairing installation

Upon completion of the nozzle segment assembly fit checks, the CMC nozzle fairings received an EBC application. Then, the nozzle segment final assembly was completed with the use of the assembly fixture.

Conclusions and Impacts

The Phase I program defined the basic architecture of the CMC nozzle and initial application target. Fundamental questions of how to manage the thermal growth differences between metal and CMC while simultaneously carrying the thermal and mechanical loads were solved. Recognizing the material advantages of CMC, the design positioned the CMC to face the hot flow path gases to carry the high thermal loads. In parallel, the internal metal parts would carry the mechanical loads at a lower temperature. Several CMC/metal nozzle arrangements were considered. The one most likely to satisfy design requirements and program objectives was proposed for Phase II.

The Phase II program developed a gas turbine nozzle design that significantly reduced the cooling flow requirement compared to a metal nozzle, thereby enabling the performance benefits targeted in the program objectives. The selected target application was an HA-class stage 2 industrial gas turbine nozzle. Quantifiable benefits were predicted, and the technology development risk was determined to be manageable. With the successful development of the CMC S2N in this program, a logical next step would be the development of film cooling holes needed for high temperature applications.

The Technology Readiness Level (TRL) at the program start was level 3, as positioned by the previous successful development of CMC technology, much of that funded by the DOE. Using subscale and full-scale, full-featured component tests with prototype temperatures, pressures, and stresses in this program has moved the TRL to level 5. Fabricating and assembling the CMC nozzle segment in this program has positioned the technology to advance quickly to TRL 7 with the application of the CMC nozzle segment into GEGP's most advanced HA-class turbine, as shown in Figure 33.

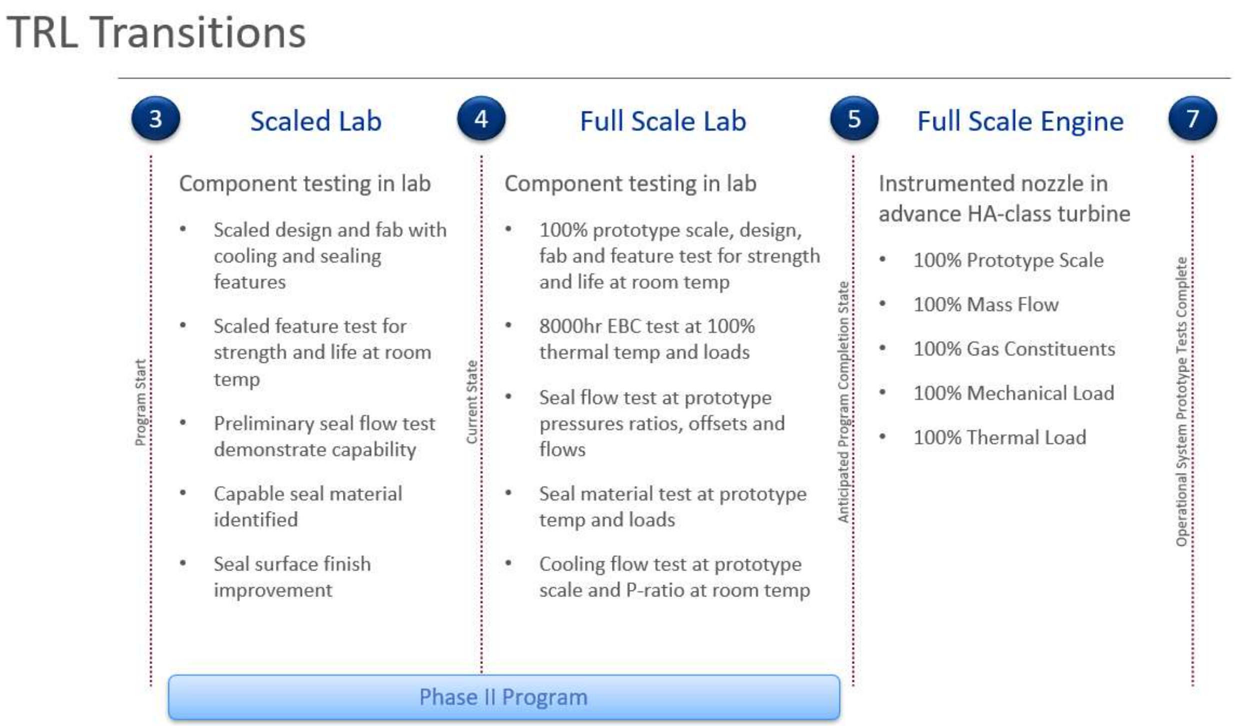

Figure 33 – Program Transition of its Technology Readiness Level

Regarding Manufacturing Readiness Level (MRL), the AMW team made great strides in improving the manufacturing readiness of the CMC nozzle. GE Gas Power leveraged learning from shroud and airfoil fabrication techniques established prior to this program to advance the MRL level for a CMC nozzle from 3 to 5. Further optimization and automation in ply cutting, kitting, ply layup, laminate assembly, auto-clave and final machining would be required to hit production cost targets. The fabrication process highlighted that the laminate assembly is labor intensive. However, once the tool and furnace cycles were properly defined, the CMC vanes had respectable densification and dimensional attributes even for first few made. Limited work would be needed to make the metal hardware fabrication production-ready as material and processes are mature for GT hardware. Minimal work is also needed to optimize the assembly of the nozzle segments as the assembly tool developed in this program worked well, but improvements for speed could be realized.

The benefits of the CMC S2N approach have not diminished throughout the duration of this project. Any high temperature nozzle design for which the lower cooling flows are important could benefit by the application of the CMC nozzle technology developed in this program. As the industry considers new fuels such as hydrogen, and new high-efficiency gas turbines are needed, the CMC nozzle may be well suited for further development. This technology might be applied in a first turbine nozzle stage (S1N) to even greater benefit. The cantilever architecture considered in Phase I would be a great starting point for a simple, lower-cost design.

As firing temperatures increase in pursuit of ever higher gas turbine efficiency, more capable materials will be needed. SiC/SiC CMCs have higher temperature capability than today's nickel superalloys. This capability can enable cooling flow savings, which improve gas turbine efficiency and power output. For the CMC S2N designed and fabricated under during Phase II, shown in Figure 34, the benefits are significant. The efficiency improvement of the CMC S2N has been calculated to be 0.15 pts. combined cycle efficiency. For a 65% efficiency plant, the CO_2 reduction would be approximately 0.23%. For an HA-class gas turbine, an additional increase in power output of 7MW per GT could also be realized. Calculated customer value is 3.5x the estimated cost of a production set of CMC S2Ns, thus demonstrating that there is commercial foundation for the CMC nozzle technology.

Figure 34 – Fabricated 2nd stage CMC nozzle segment

The GE Gas Power team would like to thank the US Department of Energy and the National Energy Technology Laboratory team. Special thanks to Patcharin (Rin) Burke, our program manager, for guiding us through this challenging program.