DE-FE0006696

Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines

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December 29, 2014

FINAL SCIENTIFIC/TECHNICAL REPORT

For Period: 8 July 2011 – 30 September 2014

Department of Energy
Office of Science (SBIR)
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Disclaimer

Abstract

In this Advanced Turbine Program-funded Phase III project, Florida Turbine Technologies, Inc. (FTT) has developed and tested, at a pre-commercial prototype-scale, spar-shell turbine airfoils in a commercial gas turbine. The airfoil development is based upon FTT’s research and development to date in Phases I and II of Small Business Innovative Research (SBIR) grants. During this program, FTT has partnered with an Original Equipment Manufacturer (OEM), Siemens Energy, to produce spar-shell turbine components for the first pre-commercial prototype test in an F-Class industrial gas turbine engine and has successfully completed validation testing. This project will further the commercialization of this new technology in F-frame and other highly cooled turbine airfoil applications. FTT, in cooperation with Siemens, intends to offer the spar-shell vane as a first-tier supplier for retrofit applications and new large frame industrial gas turbines. The market for the spar-shell vane for these machines is huge. According to Forecast International, 3,211 new gas turbines units (in the >50MW capacity size range) will be ordered in ten years from 2007 to 2016. FTT intends to enter the market in a low rate initial production. After one year of successful extended use, FTT will quickly ramp up production and sales, with a target to capture 1% of the market within the first year and 10% within 5 years (2020).

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Executive Summary

Florida Turbine Technologies' (FTT) spar-shell airfoil concept is potentially an enabling technology for future high performance gas turbine-based stationary power generation systems such as those currently being developed under the DOE Office of Fossil Energy-sponsored Advanced Turbine Program. These airfoils require significantly less cooling flow than the current state-of-the-art, thereby addressing durability concerns associated with turbine inlet pressure and temperature increases desired for higher efficiencies in future gas turbines. The successful development of this technology will significantly contribute to the achievement of the Advanced Turbine Program goals.

The potential advantages of this technology are compelling. The near-term advantage of implementing this technology in the first stage turbine vane is a reduction of turbine firing temperature of 70°C, which translates into significant durability improvement for hot gas path (combustor and turbine) components. Additional implementation of this technology into the first stage turbine blade and second stage turbine vane will enable combined cycle efficiency to be increased by 1%. If realized, this seemingly small efficiency increase would power an additional 1,800 homes for each F-class gas turbine combined cycle power unit with no additional fuel. This is equivalent to reducing carbon emissions by 9,000 tons per year.

The primary objective of this project was to develop and test - at a pre-commercial prototype scale – first-stage spar-shell turbine airfoils requiring significantly less cooling flow than the current state-of-the-art (SOTA). The scope of this project included the design, analysis, fabrication, assembly, instrumentation, installation and testing of prototype spar-shell turbine airfoils and associated hardware, culminating in the validation of performance and functionality in a commercial gas turbine engine.

1 Introduction

This Department of Energy (DOE) sponsored Agreement was focused on the development of specific gas turbine technologies to provide highly durable turbine components that require the lowest cooling flow possible. Technology advances within the turbine systems represent a direct approach for improving the overall power plant efficiency. In particular, technologies that permit turbines to operate at increased temperatures and pressures are desired to achieve the specific performance goals. Current gas turbine systems already operate at temperature and pressure levels that are sufficiently high to require the use of advanced materials systems and cooling of the turbine components. The use of cooling in the turbine, although permitting turbine components to operate within an environment of high temperature and pressure, causes an efficiency debit to the turbine subsystem and overall power plant. This is a direct result of the needs to compress the coolant to the working pressure of the turbine, and the fact that the coolant must be routed around the combustor such that heat cannot be added to provide useful work through expansion in the turbine. Cooling approaches being developed under this program are needed to address efficiency and durability concerns of future turbine systems where turbine inlet temperatures will be increased to advance output capabilities relative to the current state-of-the-art. In addition to providing higher temperature capabilities, features of these systems will accomplish a second objective of making turbine components more dependable and reliable.

This work is motivated by the engineering challenges that are posed by the design of future turbine systems. These challenges are highlighted by worldwide demands to manage energy consumption and emissions that may be harmful to the environment. One of the challenges facing engineers today is the need for turbomachinery to operate for extended periods of time in increasingly demanding environments of higher pressures and temperatures. This is needed to increase the efficiency of turbomachinery systems relative to the current state-of-the-art. These environments pose an engineering challenge because they increase the heat load on turbomachinery components that must be addressed with new cooling and materials technologies. At the same time, current turbine components are limited by the thermal-structural fight imposed by thermal gradients developed within the turbine components. These issues are exacerbated by the fact that current turbomachinery components are manufactured as single-piece, multi-wall structures. To compound these concerns, turbomachinery designers must find ways to reduce the amount of cooling flow that is required by turbomachinery components. This must be done to enable overall performance and efficiency goals to be met. This will require new thnking with regard to how to cool turbine parts, and an increased emphasis must be placed on what must be done to enable the use of high temperature material systems that reduce reliance and dependance on non-domestic strategic materials.

To meet the needs of future turbomachinery systems, Florida Turbine Technologies. Inc. has explored the feasibility of. performed conceptual and detailed designs, fabricated proptotype hardware and engine-tested an innovative cooling approach for robust design. This approach is needed to provide durable turbines while realizing the future turbine system goals of reduced cooling flow consumption and increased efficiency. Development of this approach offers several advantages relative to the current state-of-the-art. To provide for a robust design, an innovative cooling approach has been investigated to make turbine hardware capable of performing without failure over a wide range of conditions. To realize these goals, several objectives, as delineated in the following paragraphs, have been accomplished.

The historical development of turbine materials and cooling capabilities shown by Schilke, et al. [1] in Figure 1 illustrates the progression of materials development over the past several decades. Clearly, the history demonstrates the progression of both materials and cooling technologies over this time period. At the same time, the divergence of the firing temperature from the material capability highlights the fact that turbine components have become increasingly dependant on the cooling methods. Although new technologies are being developed to enable revolutionary advancement of the material capabilities, it is expected that future turbine systems will become increasingly dependant on the turbine cooling. Consequently; as the turbine inlet temperatures are increased to elevate turbine power and performance, turbine components will be exposed to increased operating risk because the temperature difference between the hot working fluid and the maximum temperature capability of the structural material systems used to form the turbine components will increase. To meet the future needs, turbine components must remain serviceable and demonstrate robust behavior under these increasingly demanding circumstances.

To provide more than a small improvement to overall turbine system capabilities, FTT understands that future turbine systems must be designed around the requirements for reduced cooling flow (increased performance) while continuing to provide high levels of durability in a part that is readily manufactured. Specifically, the flow path heat transfer properties of future turbines will be highly dependant on the thermodynamic transport properties of the specific working fluid(s), and will also be highly dependant on cycle performance characteristics (i.e.: temperature and pressure). For future clean energy industrial gas turbine applications, working fluid compositions having reduced nitrogen content and increased fractions of water (steam) and/or carbon dioxide are expected with the combustion of coal-derived syngas and high hydrogen fuels derived from syngas with oxygen separated from air.

Modern turbine components are subjected to a variety of conditions which affect the design of the cooling system. For example, as mentioned previously, many modern turbine components utilize a thermal barrier coating system as a protective thermal insulation device against the hot gases of the working fluid. However, these coatings are typically brittle and are thus subject to several forms of failure. To give a few examples, simple handling damage can cause these coatings to be distressed and broken from parts prior to or during engine installation. In addition, they are subject to a number of complex potential failure modes within the context of engine operation including simple erosion, oxidation failure of the interface bond layer between the coating and the underlying structural material, structural failure due to thermal stresses manifested by the temperature difference between the hotter coating and the cooler structural material and sintering of the coating due to elevated temperature operation of over long time periods. Over the years, extensive research has been performed to identify coating chemistries that are increasingly tolerant of these failure modes.

Additionally, research has been performed to better understand the potential failure modes and to characterize the consequences that lead to them so that suitable lifing methods could be developed.

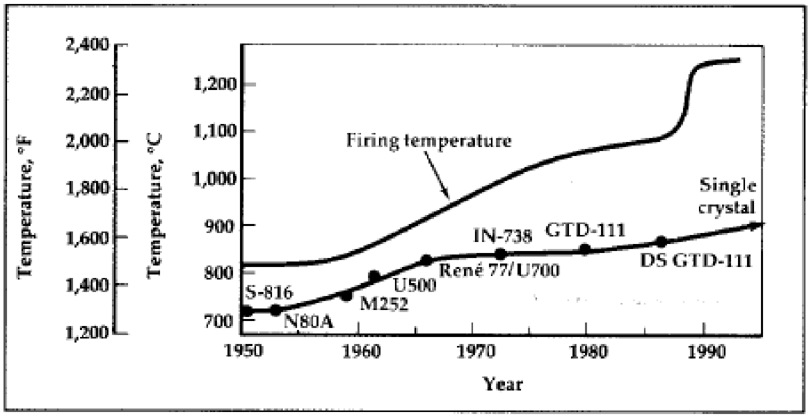


Figure 1: Trends in Turbine Firing Temperature and Alloy Development

Regardless, the durability of thermal barrier coatings continue to be a concern to cooling system designers, and the simple question remains: What happens when the thermal barrier coating is compromised? Today, this question is answered by designing parts with ample cooling flow such that the cooling is sufficient for the part to survive until the next service inspection even in the event of a TBC failure. At the time of engine overhaul, the part would be removed from the engine and, depending on its condition would either be scrapped or be reconditioned. However, this approach leads to the use of excessive amounts of cooling air, because the component could have been designed with less cooling air if only the coating could be depended upon, or otherwise be considered prime-reliant.

Realization of significant turbine cooling flow reduction requires the duty of the internal convective cooling system to be improved relative to the current state-of-the-art. Further, the requirements for film cooling flow must be reduced because reduced cooling flow will have the immediate effect of decreasing the film cooling performance. This is especially true in turbine components located in the first stages of the turbine because the recent turbine design development trend has been to add large quantities of film cooling flow to address local cooling concerns. To achieve these objectives, turbine designs must be made capable of supporting increasing flows of heat through the walls of the component to provide the desired cooling effects. The material and coating systems must be capable of supporting these increased heat flows without incurring deleterious consequences.

Under this SBIR program FTT has investigated alternative solutions to problems such as this to make the part more robust, but without the need to use excessive quantities of cooling air. To give an example, first consider a current state-of-the-art first stage turbine vane shown in Figure 2 which is typically cooled by the three methods previously described: internal cooling by convection heat transfer, ejection of spent coolant to provide a film cooling effect, and the use of TBC coating as a layer of thermal protection. In these parts, the internal cooling by convection heat transfer is typically accomplished by impingement of cooling air onto the internal surfaces of the component. To facilitate this mechanism, tubes containing a myriad of holes are inserted into the component. Coolant is allowed to flow into the tubes and impingement jets are formed as the coolant exits through the myriad of holes. These jets impinge on the inside surfaces of the part to be cooled, enhancing the internal convection heat transfer effect relative to no impingement. Once the coolant has accomplished the internal cooling by convection heat transfer, it is allowed to enter film cooling holes where it is ejected from the part to form a film cooling effect. In the meantime, the TBC coating reduces the heat load from the part and further protects it from the hot gases flowing around it. Extension of this design concept to future turbine systems having increased pressure and temperature will require cooling flow to be increased substantially.

As an alternative to designing a robust first stage turbine vane based on the use of excessive cooling flow, one approach would be to promote increased internal convection heat transfer, while using less cooling flow. However, from a cooling standpoint, the first stage turbine vane is rather unique because the pressure of cooling flow is only marginally higher than the pressure of the hot gases at the leading edge of the vane. The difference is established by the necessity for high performance, which requires the combustor to incur only a small pressure loss. Further, the pressure of coolant inside the vane must be maintained higher than that of the hot gas to make it possible for spent coolant to be ejected onto the airfoil surface to provide the desired film cooling effect, and also to prevent hot gas from inflowing into the component. The latter situation; especially, could lead to catastrophic failure of the component as the temperature of the material is increased to its melting value. Since convection heat transfer is related to the coolant system pressure loss, the ability to increase the heat transfer within the context of the present cooling system is severely limited.

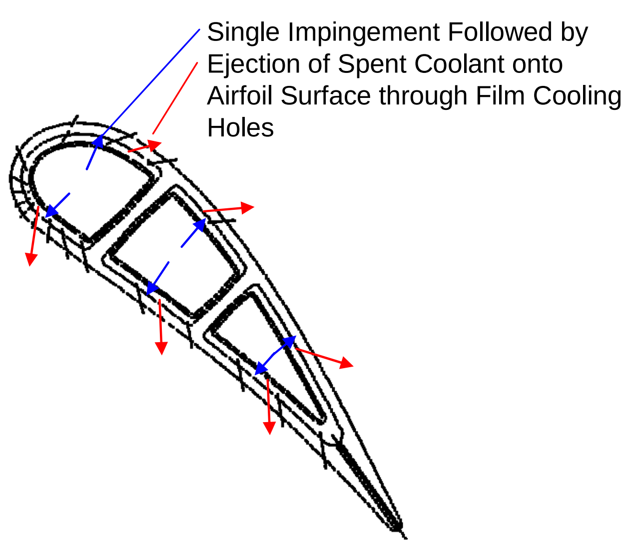


Figure 2: Current State-of-the-Art First Stage Turbine Vane Uses Single Impingement

To improve internal convection heat transfer relative to this state-of-the-art, FTT has developed a concept design approach of an innovative cooling system based on the use of sequential impingement. Although the basic concept of sequential impingement is not new, it’s utilization in the design of a cooled spar-shell turbine airfoil as described in the following paragraphs is novel. A schematic representation of such a system is illustrated in Figure 3 as presented in FTT’s patent disclosure F650R. As shown in this figure, coolant flow enters a supply cavity located centrally within the airfoil. The coolant first passes through impingement cooling holes from the supply cavity to impinge directly on a defined heat transfer surface. Second, this flow is returned to return cavities located within the inner structure to be circulated to another region of the part where it again passes through holes to impinge on a second heat transfer surface of interest. The process can be repeated several times within the range of allowable pressure conditions for the coolant. Ideally, the first impingement regions would be directed at surfaces adjoining high gaspath pressures, such as the leading edge and forward pressure side surfaces. Secondary impingement could be directed at surfaces adjacent to lower gaspath pressure regions, such as the aft pressure side and finally ending with impingement onto the low pressure regions of the airfoil, such as the suction side. Using this system, cooling flow could be leveraged by impinging on separate heat transfer surfaces in a sequential fashion. Further, this approach might be useful to reduce or eliminate the effects of impingement heat transfer degradation due to cross flows, which are prevalent in existing impingement cooling designs.

Development of this sequential impingement cooling approach represents an enabler for the use of alternative, fabricated material systems by way of the spar-shell technology. By combining these two technologies, the high value cooling technology is developed into the cooler, structural member of the spar. This part may be refurbished and reused during overhaul operations. Meanwhile, the complexity of the shell, which may be produced from alternative materials having high temperature capability such as ceramics or refractory metals, may be minimized.

In this example, the concept of sequential impingement is described within the context of the first stage turbine vane. However, it will be obvious that its utility might be extended to other turbine components to include other static (non-rotating) hardware and rotating turbine blades.

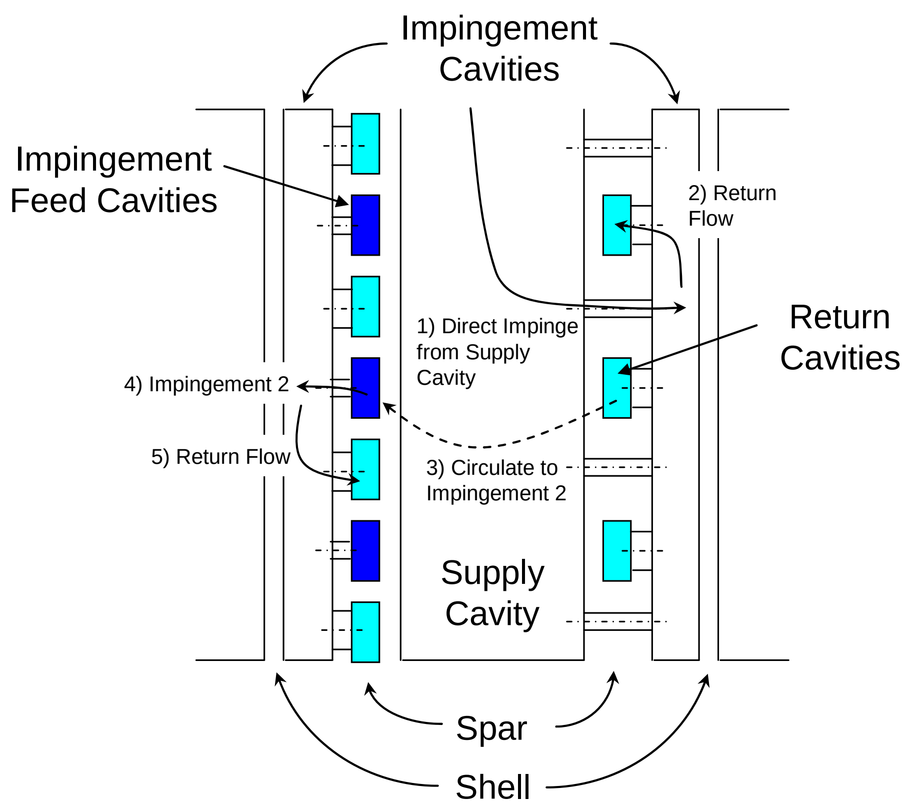


Figure 3: Sequential Impingement Using a Spent-Flow Return System

2 Milestone Log

Milestones for the subject project are summarized below. Each of these milestones built from the design, development and fabrication of actual turbine components to a conclusion with a test evaluation of the hardware in an actual engine operating environment.

Title:	Project Kick-off Meeting
Planned Date:	7/25/2011
Completed:	7/25/2011
Verification Method:	Meeting held with DOE. Presentation slides published.

Title:	Identification of Test Engine
Planned Date:	9/15/2011
Completed:	8/15/2011
Verification Method:	Letter of Commitment from partner, Siemens Energy.

Title: Concept Design Review (CDR)
Planned Date: 12/22/2011
Completed: 11/17/2011
Verification Method: Review completed.

Title: Casting Release to Manufacturing
Planned Date: 4/30/2012
Completed: 4/26/2012
Verification Method: Meeting minutes published.

Title: Final Design Review (FDR)
Planned Date: 11/20/2012
Completed: 11/26/2012
Verification Method: Review completed, Meeting minutes published.

Title: Final Detailed Design Drawings
Planned Date: 1/29/2013
Completed: 4/10/2013
Verification Method: Drawings and CAD files released.

Title: Final Assembly-Level Drawings
Planned Date: 2/26/2013
Completed: 6/10/2013
Verification Method: Drawings and CAD files released.

Title: Casting Manufacturing Complete
Planned Date: 4/10/2013
Completed: 4/10/2013
Verification Method: Receipt of casting hardware.

Title: Spar Manufacturing Complete
Planned Date: 7/31/2013
Completed: 9/1/2013
Verification Method: Receipt of spar hardware.

Title: Hardware Fabrication Complete

Planned Date: 9/20/2013
Completed: 10/31/2013
Verification Method: Receipt of Hardware.

Title: Hardware Review
Planned Date: 9/27/2013
Completed: 11/16/2013
Verification Method: Hardware shipped.

Title: Test Readiness Review
Planned Date: 11/1/2013
Completed: 11/18/2013
Verification Method: Review Completed. Pwerpoint slides published.

Title: Test Feedback Review
Planned Date: 3/21/2014
Completed: 10/22/2014
Verification Method: Review Completed.

Title: Deliver Final Report
Planned Date: 3/31/14
Completed: 12/31/2014
Verification Method: Report Delivered.

3 Extent to Which the Program Satisfied the Success Criteria and Decision Points

The overarching goal of this program was the successful demonstration of FTT’s spar-shell technology in a real gas turbine operating environment. Successful achievement of this goal is defined by the following criteria:

- Demonstrate the benefits of spar-shell technology to provide desired durability in a real gas turbine engine operating environment while cooling flow is reduced by a target of 40%.
- Demonstrate manufacturability and inspectability of the hardware as evidenced by acceptance of the hardware for installation in the defined test article.

- Verify engine efficiency, performance and operability in the presence of the new first stage turbine vane hardware.
- Demonstrate retrofitability of hardware into existing turbomachinery as defined by ease of installation, operation and maintenance.

The decision points in this program coincided with several of the key program milestones. Namely, a partner was selected for demonstration of the hardware produced under this program before work could begin in earnest to design the hardware. Further, the design passed successful conceptual and final design reviews before the program proceeded to the next steps. Once these were complete, hardware was produced of a sufficiently high quality level to support installation within an existing turbomachinery test article. Finally, this hardware passed the required engine test and evaluation before the program was deemed a success.

4 Impact

The impact of this program is projected to revolutionize the gas turbine industry with the implementation of innovative cooling approaches for robust design. These approaches are needed to provide durable turbines while realizing the future turbine system goals of reduced cooling flow consumption and increased efficiency. Development of these approaches offers several advantages relative to the current state-of-the-art. To provide these designs, innovative cooling design approaches are being developed based on FTT's Spar-Shell technology to make turbine hardware capable of performing efficiently and without failure over a wide range of conditions.

The advantages of this technology are compelling. By retrofitting this technology into the installed gas turbine-based electrical power generation capacity, development of the technology has the potential to reduce U.S. dependance on foreign sources of energy with an equivalent oil savings of 84 million barrels of oil per year, which equates to 4 days of U.S. consumption. The technology will also reduce carbon dioxide emissions by 25 million tons per year.

Development of this technology will maintain the U.S. technological leadership and competitiveness in this important field of gas turbine-based electrical power generation. The innovative nature of the technology will also forge new relationships between industry, academia and government as these organizations build a new spirit of cooperation and collaboration to understand all of the ramifications of the technology.

All of the award's budget has been spent within the United States.

5 Extent to Which the Program Has Demonstrated the Technology

The major goal of the project was to develop and test – at a pre-commercial prototype scale – first-stage spar-shell turbine airfoils requiring significantly less cooling flow than the current state-of-the-art. One of the first steps required to achieve that goal was the development of a relationship with an Original Equipment Manufacturer (OEM) or ther entity to which a partnership could be forged to carry out the engine testing needed to demonstrate the technology. While FTT has had a long-term relationship with Siemens Energy, they were solicited to provide the needed support and a partnership agreement was reached early in the program. Establishment of this partnership provided a means for the two companies to work together.The specific contributions of the partner include:

1. In-kind support – Participation as a proving ground and commercial sales partner. Following successful design, manufacturing and risk assessment/evaluation, Siemens intends to participate in marketing of Spar-Shell^{TM} turbine vanes as a performance/durability upgrade for existing equipment and continue to work with FTT to enhance other equipment within the Siemens portfolio.
2. Facilities – Identification of a suitable gas turbine test article that may be used for the initial test evaluation of Spar-Shell^{TM} vanes in Siemens’ Berlin test bed.
3. Collaborative research – Participation in the design activities as performed under the *“Demonstration of Enabling Spar-Shell^{TM} Cooling Technology in Gas Turbines”* to include, as a minimum, participation in gas turbine integration, instrumentation and validation test reviews and major decision points in the program.

5.1 Conceptual Design

Most of the conceptual design for the spar-shell vane was carried out under a pedecessor Phase I SBIR program titled: “Development of Innovative Cooling Approaches for Robust Design”, DOE contract #SC0002713-1. However, some details of the conceptual design were reviewed at the onset of this program and Specific details of the conceptual design that are applicable are summarized here. Changes that were made to the concept to facillitate the final design, fabricate hardware and to test in an existing large scale industrial gas turbine engine are also summarized here.

5.1.1 Aerodynamic Design

The aerodynamic design considered in this study is based on a typical first stage turbine vane from a large-scale industrial gas turbine engine. Although some variation in the aerodynamic shape of the airfoil has been shown to be feasible based on another Spar-Shell development program, the aerodynamic shape assumed in the original concept design study had constant cross-section from the root to the tip of the airfoil. This was to simplify the mechanical design and feasibility study of the part. The impact of using geometry of constant cross-section was studied under a previous spar-shell development program. The results from that study indicated turbine efficiency would be reduced by only ~0.1% if both the first stage turbine vane and the first stage turbine blade were made with constant cross section. Under the present program, the project team was tasked with retrofitting the sequential impingement cooling concept into the first stage turbine vane of an existing large scale industrial gas turbine engine. Siemens’ W501F first stage turbine vane was selected for this purpose, and the decision was made to use the existing casting such that external geometry was identical to existing hardware and internal modifications were limited to the changes needed to incorporate the sequential impingement cooling technology.

5.1.2 Cooling System Design

To understand the benefits of a sequential impingement cooling system in a first stage turbine vane, a comparison was made of the typical design practice with the proposed approach. In the typical design practice of the geometry illustrated in Figure 2, the impingement pressure ratio would be nearly constant, and the magnitude would be set by coolant outflow requirements at the leading edge, where the hot gas flowpath pressures are highest. Coolant outflow is required to insure that a continuous flow of coolant is maintained through all of the film cooling holes as shown in Figure 2, and to prevent any inflow of hot gases from the primary flowpath into the airfoil. This is achieved by maintaining the internal pressure at a higher level than the static flowpath pressure on the airfoil external surfaces at all locations around the airfoil, and especially where film cooling holes are present. This is illustrated in Figure 4, where the coolant supply pressure, post-impingement pressure and flowpath pressures are plotted. In this system, the coolant impinges onto the inside surfaces of the structural airfoil and is subsequently discharged from the airfoil through film cooling holes or trailing edge discharge holes. This approach obviously limits the utilization of the coolant to provide heat transfer during its limited residence within the part, and the magnitude of the impingement pressure ratio is limited to a relatively low value all around the airfoil. At the same time, the potential opportunity for improvement is clearly represented by the difference between the post-impingement pressure and the gaspath pressures over substantial regions of the surface of this airfoil.

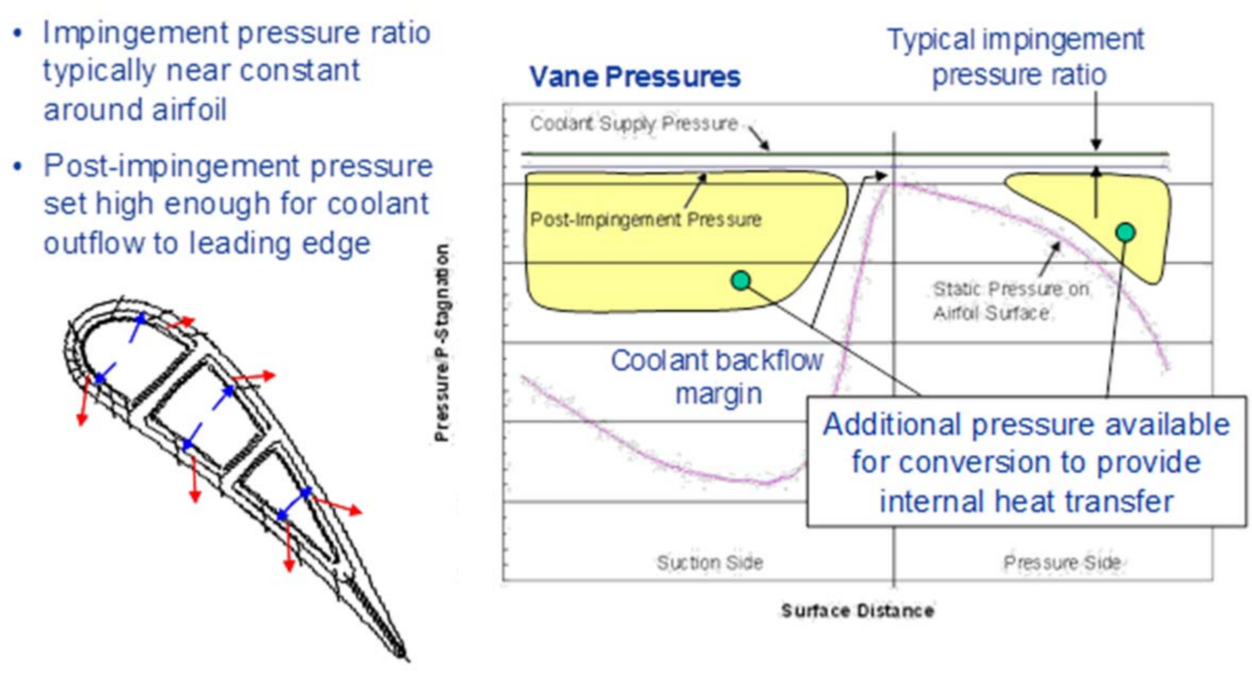


Figure 4: Typical Design Practice - Conventional Technology

Conversely, in the sequential-impingement approach shown in Figure 5, three levels of post impingement pressure can be used to optimize the system for high impingement heat transfer. To accomplish this goal, three isolated post-impingement cavities must be defined within the geometry. This is facilitated using the conceptual attachment (hook or other) arrangement for spar-shell turbine components. The regions at the ends (inner and outer flowpath extents) will require the development of a separate sealing system to maintain the independence and isolation of the the three post-impingement cavities.

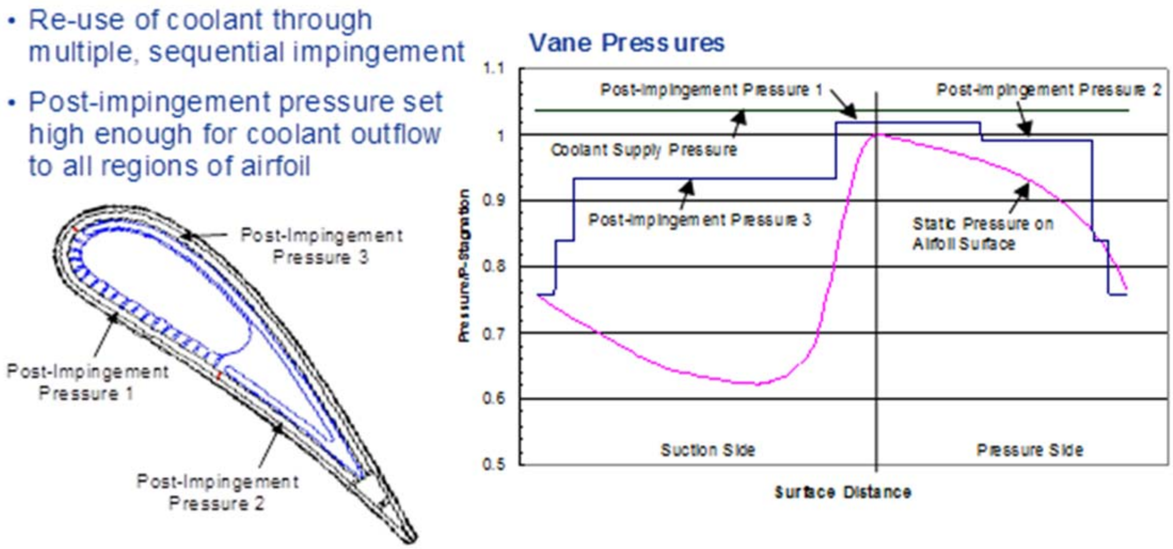


Figure 5: Utilization of Available Pressure Enables Sequential Impingement

The operation of the sequential impingement system is as follows. First, cooling flow enters the spar structure from the I.D. or the O.D., or both, and is allowed to pass through holes located in the spar to impinge into the cavity located behind the airfoil leading edge and forward pressure side. Since this region to be impinged upon is much smaller than the entire internal surface area, much less cooling flow is required to achieve the same internal convection heat transfer coefficient as the conventional technology design. Second, after the cooling flow has impinged into the first impingement cavity, it is collected into return chambers within the spar which channel it to the second impingement cavity which is located adjacent to the aft pressure side of the airfoil. This second cavity is maintained at a lower pressure than the first cavity, which facillitates the flow of coolant from the first cavity to the second. Meanwhile, the pressure in the second post-impingement cavity is maintained higher than the gaspath pressure in this region, which insures positive backflow/outflow margin from this cavity. Finally, after the cooling flow provides cooling in the second impingement cavity, it is again collected into return cavities in the spar where it is channeled to the suction side of the airfoil to be impinged a third time. Again, the pressure in the third impingement cavity is maintained at a lower pressure than the second to facillitate the flow of coolant, and the pressure inside the third cavity is maintained at a higher pressure than that on the suction side of the airfoil for positive backflow/outflow margin. In the end, coolant is ejected from the suction side cavity from cooling holes located in the forward suction side of the airfoil. Coolant ejected here will also provide an efficient film cooling effect because it covers a large amount of surface area and the acceleration effects of the primary flow on this side of the airfoil are well known to provide better film cooling retention effects relative to similar ejection from the pressure side of the airfoil. To improve the cooling, the goal is to increase the heat transfer for a given quantity of cooling flow. In the studies performed during the Phase I program, the results from calculations based on these examples indicate the heat transfer can be increased by 280% for a given cooling flow.

A conceptual design study of the sequential impingement system was performed to determine the potential benefit relative to conventional single impingement systems. The results of the analyses are shown in Figure 6. To perform this study, an impingement hole diameter and impingement distance were selected and were maintained at constant values for the three sequential impingement cavities depicted by regions 1, 2 and 3. The spacing of the holes was varied by adjusting the pitch-to-diameter ratio and the impingement pressure ratio was allowed to increase incrementally from the first impingement to the last to make full use of the available pressure. These adjustments allowed a preliminary optimization of the arrangement. The final results from the study indicated the heat transfer per unit of cooling flow, a critical driver for increased thermal efficiency, could be increased by 280% using the sequential impingement cooling system.

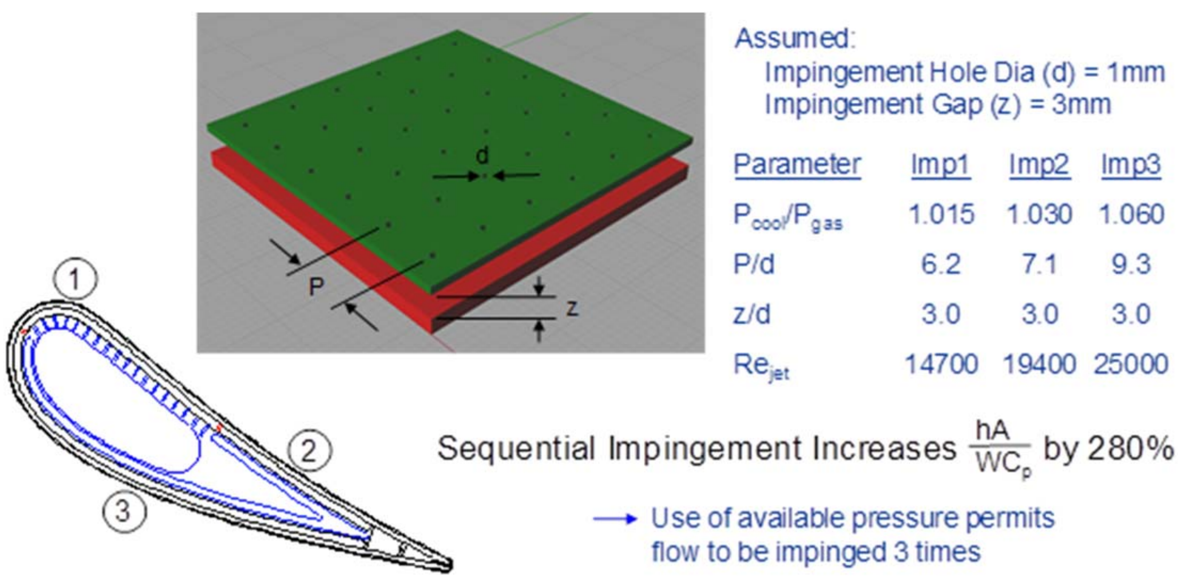


Figure 6: Analytical Assess Confirmed Benefits of Sequential Impingement

The overall performance of cooling system designs are frequently shown on a heat load parameter chart or technology plot. Such a comparison is shown in Figure 7 where a conventionally-cooled first stage turbine vane is compared with the proposed spar-shell approach. The x-axis of this chart reflects the heat load parameter which is a ratio of the capacity of the coolant to absorb heat to the heat load imposed on the part. The ordinate reflects the cooling effectiveness. The cooling technology is identified on this chart in three parts. First, the foundation of the cooling system is reflected in it's capability to provide cooling by internal convection heat transfer – through the direct transfer of heat to the coolant. This cooling method causes the coolant temperature to increase as heat is absorbed. Coolant temperature rise will be higher for designs having improved internal cooling methods. The effectiveness of the internal cooling system is measured by the thermal efficiency (η_{th}) which indicates the amount of coolant temperature rise as a function of the maximum possible. As shown in the figure, the current technology for first stage turbine vanes (square symbols) have a thermal efficiency of about 25%. For the spar-shell turbine vane, the goal is to increase the thermal efficiency to about 50% by using a sequential impingement cooling system. As shown, nearly the same cooling effectiveness can be produced by both designs even though the spar-shell uses about 40% less flow (as reflected by reduced heat load parameter). The next component that contributes to the overall cooling is the effect of film cooling which may be present on the airfoil when spent cooling flow is ejected through film cooling holes to provide a thin buffer layer of cooler air between the hot gases of the primary flowpath and the surface of the turbine component. This technology increases the cooling effectiveness (at constant heat load parameter) relative to the original foundation provided by the internal convection cooling methods. In this case, the cooling effectiveness is increased more for the conventional design simply because it has more cooling flow available to provide the film cooling effect. Finally, the influence of thermal barrier coatings are indicated by an increase of the heat load parameter as reflected by a reduction of the incident heat load due to the thermal resistance of the TBC. This causes the cooling effectiveness to move to an increased (effective) heat load parameter at nearly constant thermal efficiency and film effectiveness. In the case of the spar-shell design, increased heat flow causes the thermal barrier coating to be more effective such that the overall cooling effectiveness is equivalent to the current state-of-the-art while using 40% less cooling flow.

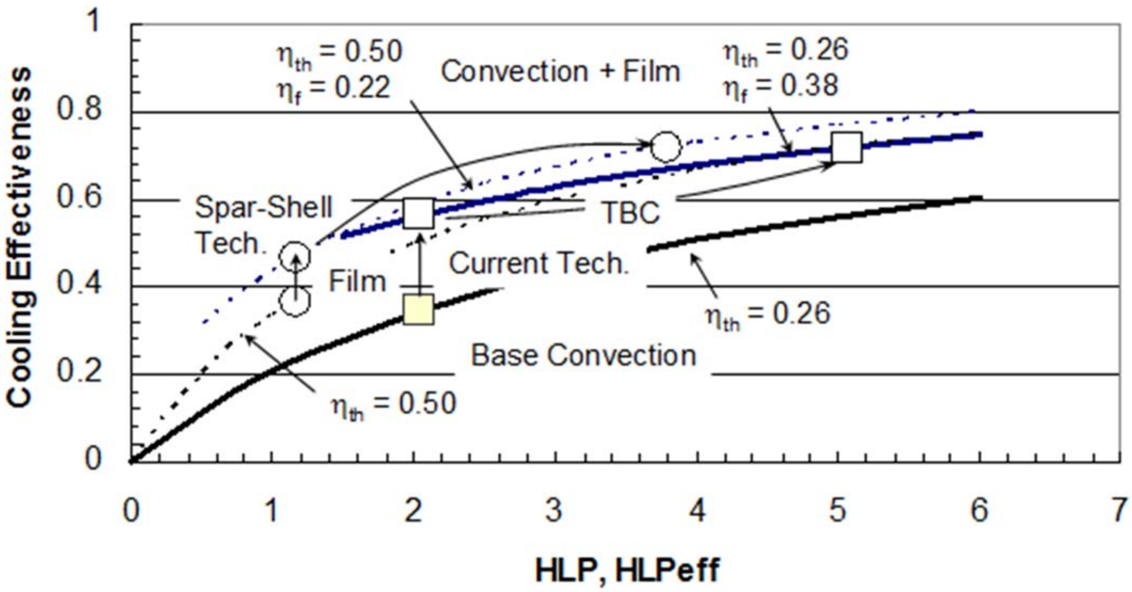


Figure 7: Spar-Shell Technology Enables 40% Cooling Flow Reduction

5.1.3 Mechanical Design

Today's current state-of-the-art turbine vane is manufactured using an investment casting process which is limited by material selection and production costs. The spar-shell vane concept is not restricted by these limitations since it can be manufactured by a number of different methods. Since the spar-shell vane component can be manufactured without casting the airfoil shape, advanced alloys, such as refractory metals, could be utilized to further increase the engine's firing temperature and subsequently the performance.

In order to integrate the sequential impingement cooling scheme, the spar-shell vane must be an assembly of multiple components. To realize the potential benefits of the spar-shell technology, a new set of engineering challenges related to the introduction of multiple components must be addressed when compared to todays' state-of-the-art monolithic vane. Since the vane is an assembly of multiple components: repair/replacement can be simplified allowing for less costly engine maintenance and overhaul, fatique issues currently seen at the airfoil–to–platform fillets will be mitigated, and higher engine operation temperatures will be realized with the use of higher temperature shell materals.

In order to realize the increased efficiency, reduced repair and maintenance costs, the vane will be required to meet all of the criterion required of today's state-of-the-art gas turbine vane.

5.1.3.1 Conceptual Spar and Shell Vane Geometry

An overall cut-away view of the spar-shell vane concept can be seen in the patent illustration shown in Figure 8. As illustrated, a number of individual parts constituting the spar, shell and I.D. and O.D. endwalls can be assembled to produce the turbine vane component.

In the FTT approach, the spar is an assembly of layers that facilitate the routing of coolant flows through the sequential impingement system. Several types of layers are required to facilitate the required distribution of flow. These are comprised primarily of two layers, "A" and "B", as illustrated in Figure 9. The spar layers mentioned would be stacked together by alternating the "A" and "B" layers, and then the entire spar would be brazed in a vacuum furnace. In the concept design, there were approximately 21 of the "A" layers and 21 of the "B" layers brazed on top of each other. The braze serves to seal the machined cavities to its adjacent layer, thus forming the internal coolant routing plenums. In one conceptual design configuration, the use of tie bolts was envisioned to sufficiently support and reinforce the structure to transmit the gas bending load from the airfoil shell to the platforms relieving the brazed joints from supporting these loads. The need for these tie bolts and/or other options that might be considered to transmit the required loads will continue to be evaluated as the detailed design progresses. The assembled spar structure is illustrated in Figure 10.

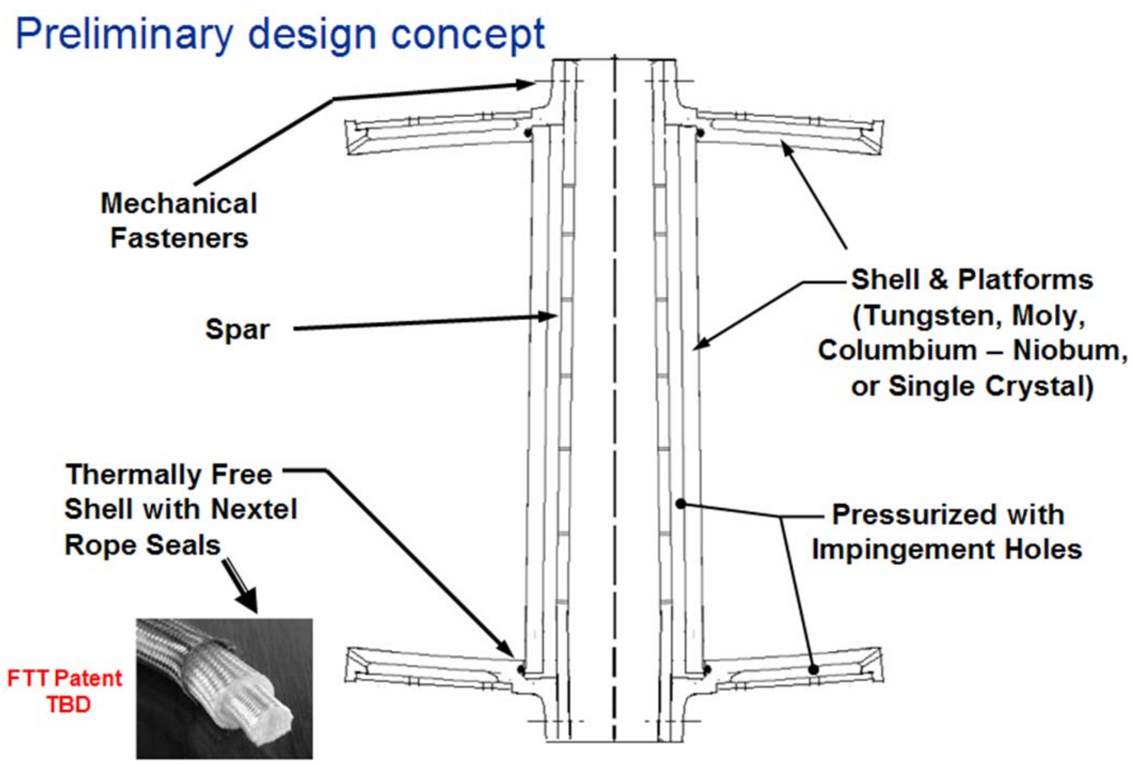


Figure 8: Patent Illustration

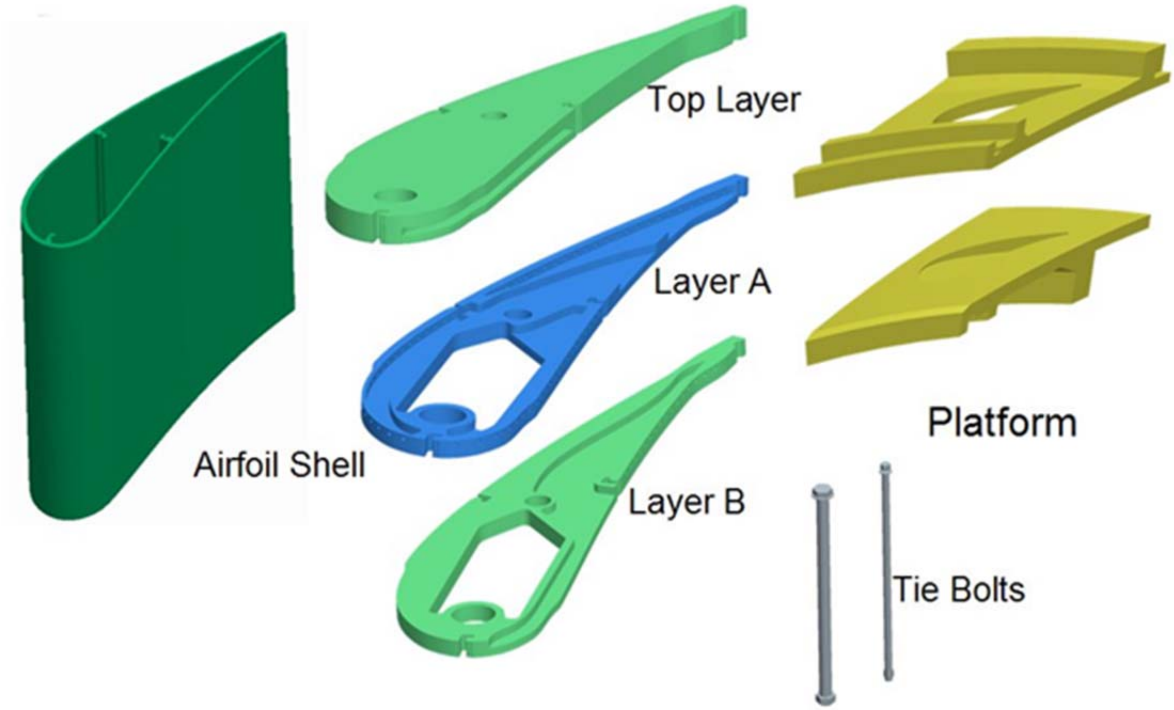


Figure 9: Spar-Shell Vane Components

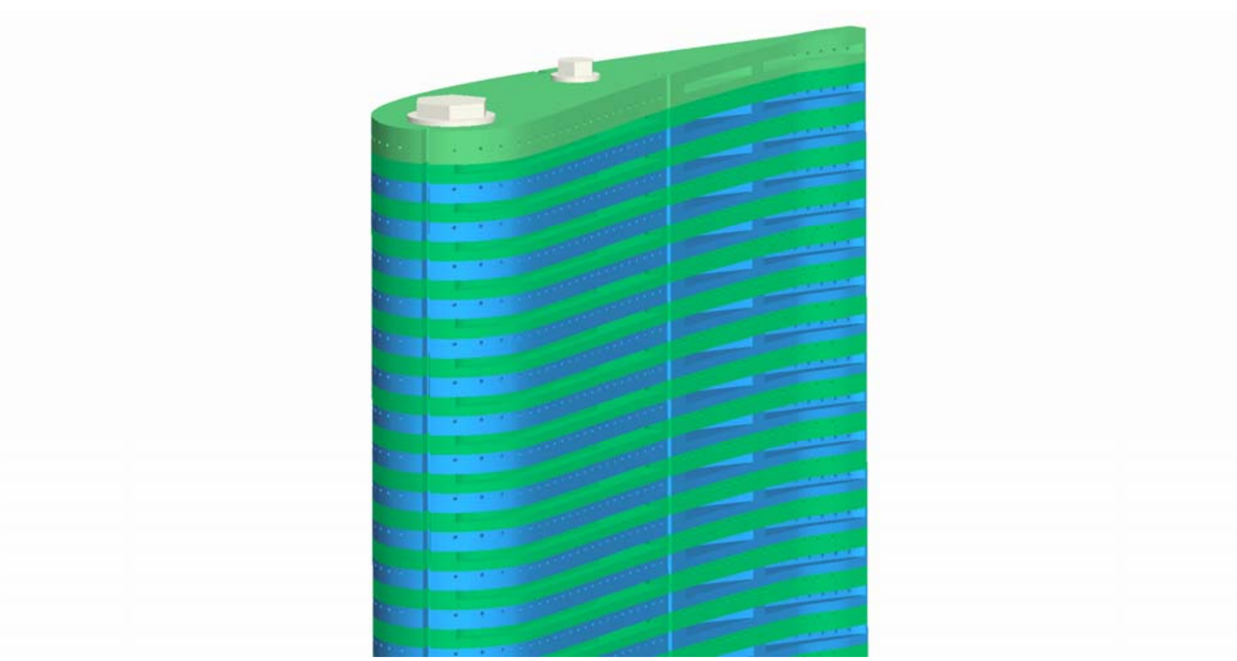


Figure 10: Spar Assembly

The assembly procedure of this vane would be as follows: First the “A” and “B” spar layers would be stacked, aligned, and then brazed together. The tie bolts would then be installed to preload the stack in compression to ensure the tensile forces are reacted through the tie bolts. The brazed spar stack is then bolted to the inner diameter platform and the airfoil shell inserted over it. The outer diameter platform would then be bolted on the top of the spar. Following final inspections, the vane assembly is now ready to be installed in to the engine. Figure 11 illustrates the assembly of the vane component via an exploded view.

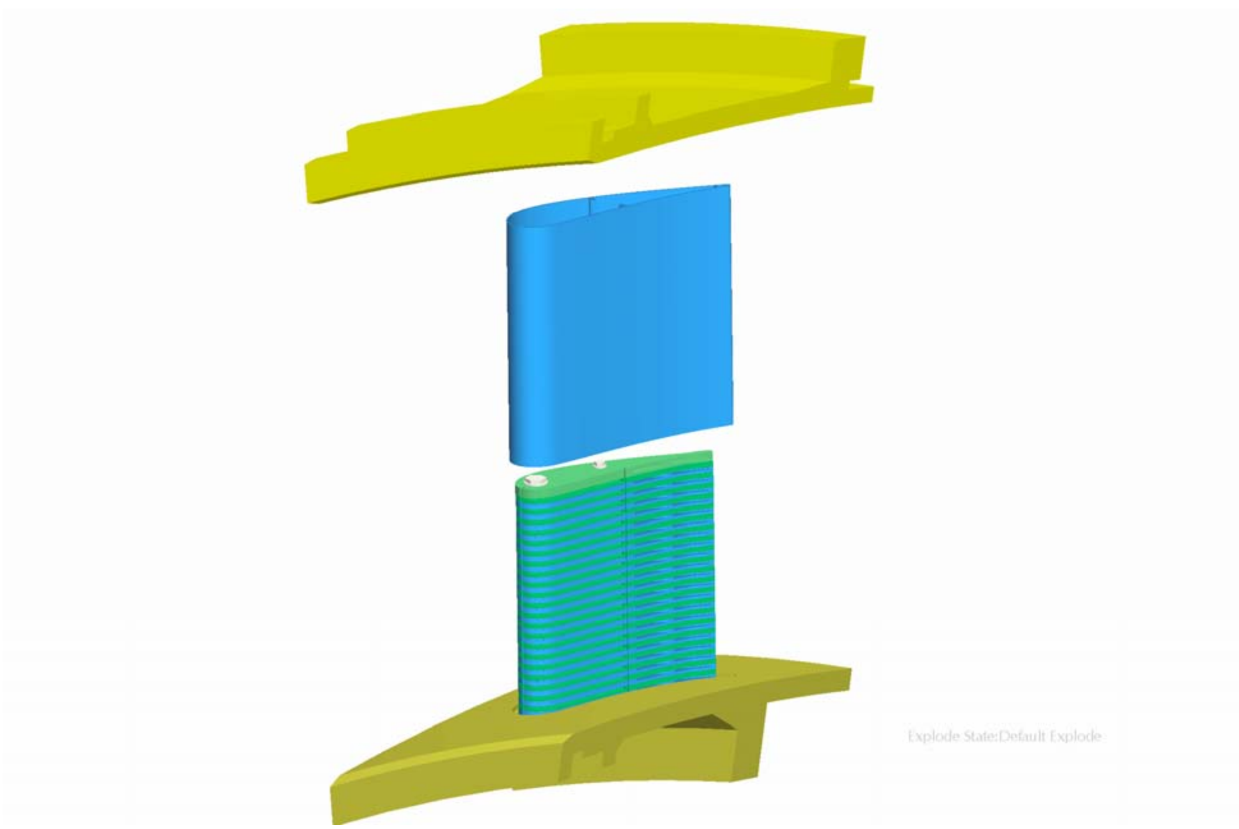


Figure 11: Vane Assembly - Exploded View

5.1.4 Risk Assessment

Risk management for this project was a continuous process that was carried out through a variety of means including weekly Integrated Product Team (IPT) meetings, regular program reviews and frequent reviews by FTT's technical experts. In the end, these risk assessments served to mold and shape the design into a product that meets all of the requirements. At the onset of the detailed design phase, additional risk assessments were performed which concluded that the previously selected concept design posed schedule and technical risks to the program that could be mitigated by changing the design from a single spar approach to one which uses two spars. Thermal, flow and structural analyses verified the design change was warranted and presented only a small trade to the benefits of the technology, manifested in a small required cooling flow increase. A Failure Modes and Effects Analysis (FMEA) was conducted June 7, 2012 in collaboration with FTT's project partner, Siemens Energy. During this review, four risk items were identified for which mitigation plans were identified to limit potential impacts. These items included: i) Interruption of cooling circuit due to seal failure, resulting in a hot spot in the cooling circuit. To mitigate this risk, the team considered, designed and tested a variety of seal arrangements. The approach selected by the team demonstrated very good sealing performance during leakage testing, was deemed relatively easy to install, and integrated a backup sealing feature in the event of failure of the primary sealing features. ii) Cracking, oxidation or erosion because of a hot spot in the cooling circuit or other causes. This risk was mitigated by performing detailed analysis of heat transfer, to identify any local cooling deficiencies. Results from these analyses indicated any local backside cooling deficiencies could be reasonably expected to be cured by conduction heat transfer within the structural material of the vane, and the risk was considered low for a short-term test. iii) Increased TBC spallation and reduced post-spallation life. This risk is largely mitigated by the short-term nature of the validation test program. This item was explored further in a thermal and oxidation/erosion life analysis to determine the liklihood of a through-wall oxidation/erosion event during the course of the validation test program. The results of the analysis, shown in Figure 12, support the risk of such an occurrence to be low.

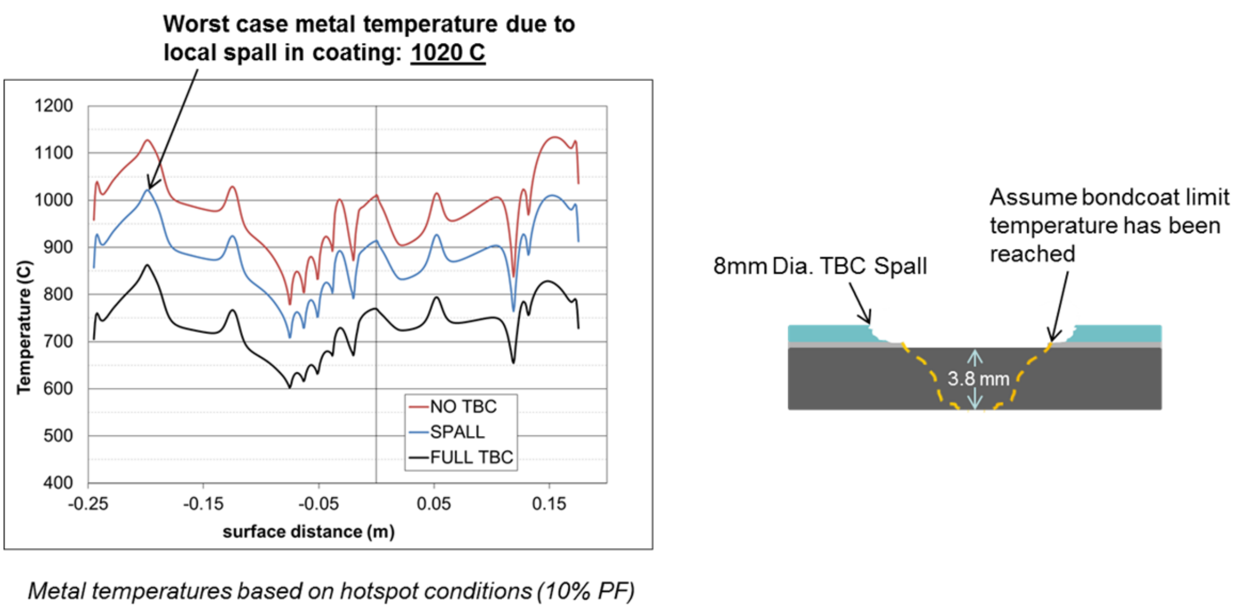


Figure 12: Shell Wall Depletion Due to TBC Spallation will not Reach 100% During Planned Test Program

iv) Hot gas ingestion. This risk was mitigated through extensive analytical and experimental test verification of the internal flow and pressure loss characteristics of the cooling system design. In conclusion, results from this FMEA activity identified no new risk items.

5.2 Detailed Design

The static airfoil components located immediately downstream from the high temperature combustion exhaust stream must be cooled with compressor discharge air in order to prevent distress caused by exposure to the high temperatures. The current state-of-the-art for cooling of these components is accomplished with a sheet metal insert that has an abundance of holes to direct the cooling flow to impinge on the inside of the structure. Another method commonly used in conjunction with the first is to allow the post-impingement cooling air to exit into the gas path through small effusion cooling holes. This method removes heat via two modes; the first being through convection heat transfer in the cooling holes, and the second is by directing this air to flow along the external surface of the airfoil, thus forming a boundary layer of “cooler” air to block the hot gases from contacting the airfoil’s surface.

While these cooling methods are effective, they are not necessarily the most efficient. The spar-shell cooling insert takes advantage by impinging the cooling air multiple times in a series, or sequential, fashion and by varying the coolant discharge pressure around the airfoil in order to more effectively use the cooling air before it is exhausted from the internal cavity.

This increase in cooling efficiency is realized by re-routing the cooling air before it exits the vane. Thus, more heat can be removed with the same amount of cooling air.

5.2.1 Concept Design Changes Facilitate Pre-Production Prototype Demonstration of Technology

Several significant changes of the concept design were made at the onset of the detailed design to facilitate the pre-production prototype demonstration of the technology. These changes were driven by an Integrated Product Team (IPT) approach to the design which considered all technical, schedule, cost, etc. aspects of the design which was driven to satisfy the goals and objectives of the program.

First, and perhaps most significantly, while the concept design incorporated a single spar insert which supported a surrounding airfoil shell using hook-type features, early in the detailed design phase, it was decided that such an architecture was too risky to implement into a full-size IGT in the near-term defined by this program. As an alternative, the IPT devised a two-insert system to demonstrate sequential impingement cooling as is shown in Figure 13. There are several advantages to reduce risk using this approach. First, this revision reduced the complexity of the airfoil casting, making it possible to use the existing casting with only minor revisions of the internal geometry to accommodate the sequential impingement spars. This revised design retains an internal rib which provides structural support for the airfoil walls. This was done in lieu of using structural hooks, an as-yet unproven technology, that would be required to support the walls in the single-insert design.

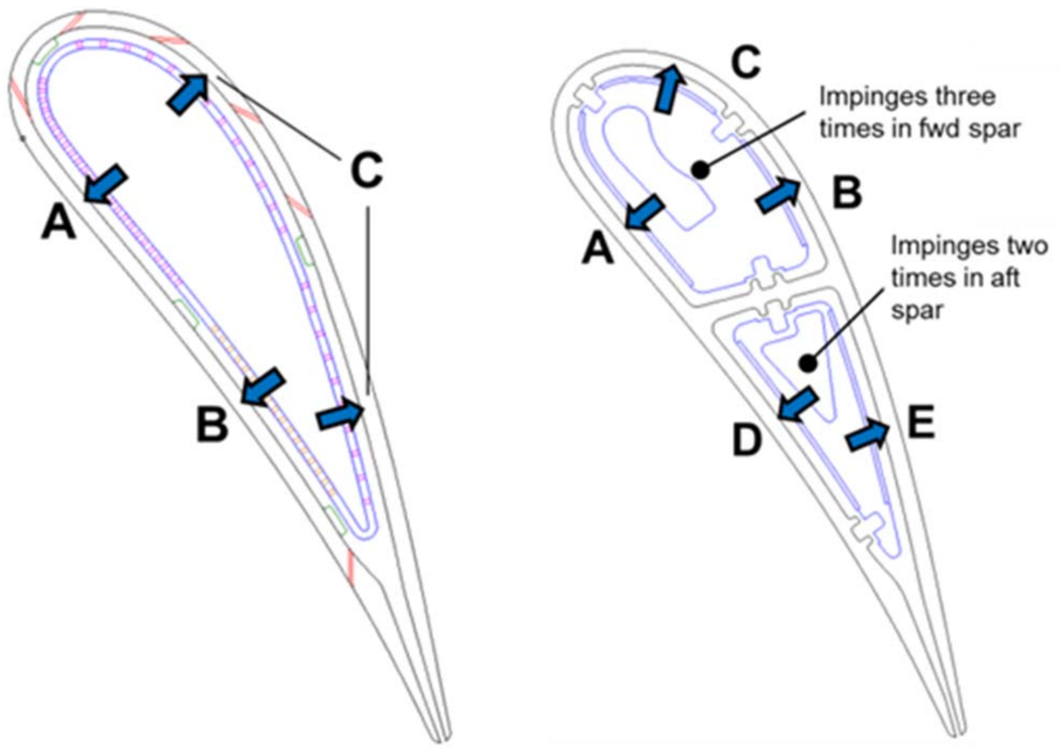


Figure 13: Overall Design Changed from One Insert to Two

Second, the fabrication method of the spar insert(s) was changed to a casting relative to the previous approach to bond individual layers. Based on the prototype casting technologies available, this represented a lower risk, and lower cost approach relative to the bonded layer fabrication. A photo of a spar model is provided in Figure 14.

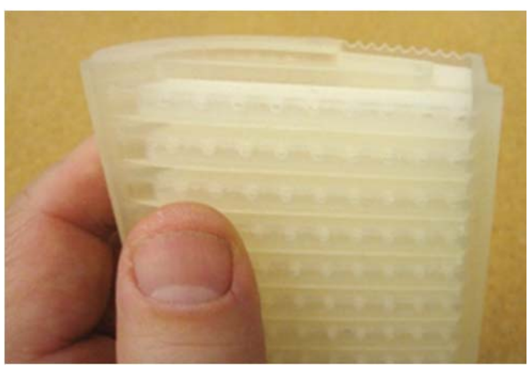


Figure 14: SLA Model of Prototype Spar

5.2.2 Bill of Materials

The static airfoil with a spar-shell type cooling scheme is comprised of the following components: a static airfoil structure (with an internal cavity suitable for a cooling insert), a cooling flow routing device called a spar, a sealing structure that divides the internal airfoil cavity in to several zones, and fixity provisions to ensure the spar stays properly located within the airfoil. In Figure 15 below a complete parts list for this prototype test endeavor is given.

Component	QTY	Description	Material
501F Vane	1	Modified First Stage Vane	IN 939
Spar - Forward	1	Cooling Insert Structure	347 SS
Forward Spar OD Mounting Cap	1	Mounting Hardware / Cooling Circuit Cap	IN 625
Forward Spar ID Mounting Cap	1	ID Spar Alignment Cooling Circuit Cap	IN 625
Forward Spar ID Alignment Rail	1	ID Spar Alignment Feature	IN 625
Spar - Aft	1	Cooling Insert Structure	347 SS
Aft Spar OD Mounting Cap	1	Mounting Hardware / Cooling Circuit Cap	IN 625
Aft Spar ID Mounting Cap	1	ID Spar Alignment Cooling Circuit Cap	IN 625
Aft Spar ID Alignment Rail	1	ID Spar Alignment Feature	IN 625
Seal	5	Radial Impingement Plenum Seal	X-750
Seal Cover Plate	5	Seal Chamber OD Cap	IN 650
Impingement Plate #1	1	Cooling Circuit - Flow Distributor	347 SS
Impingement Plate #2	1	Cooling Circuit - Flow Distributor	347 SS
Impingement Plate #3	1	Cooling Circuit - Flow Distributor	347 SS
Impingement Plate #4	1	Cooling Circuit - Flow Distributor	347 SS
Impingement Plate #5	1	Cooling Circuit - Flow Distributor	347 SS

Figure 15: Bill of Materials

The figure above itemizes each component giving a basic description, the quantity, and the material.

Figure 16 & Figure 17 identify the various parts and components and better relate how they interact with each other to realize a more efficient cooling design.

From this, it is apparent that a sequential impingement cooling scheme requires a few more components then the current state-of-the-art. Controlling the cost while additional parts or features are used to enhance internal cooling has been facilitated largely by the fact that the spar-shell design requires considerably fewer expensive film cooling holes relative to a conventional design. Further, additional cost reduction measures may be applied in a full production design relative to the present prototype demonstration hardware.

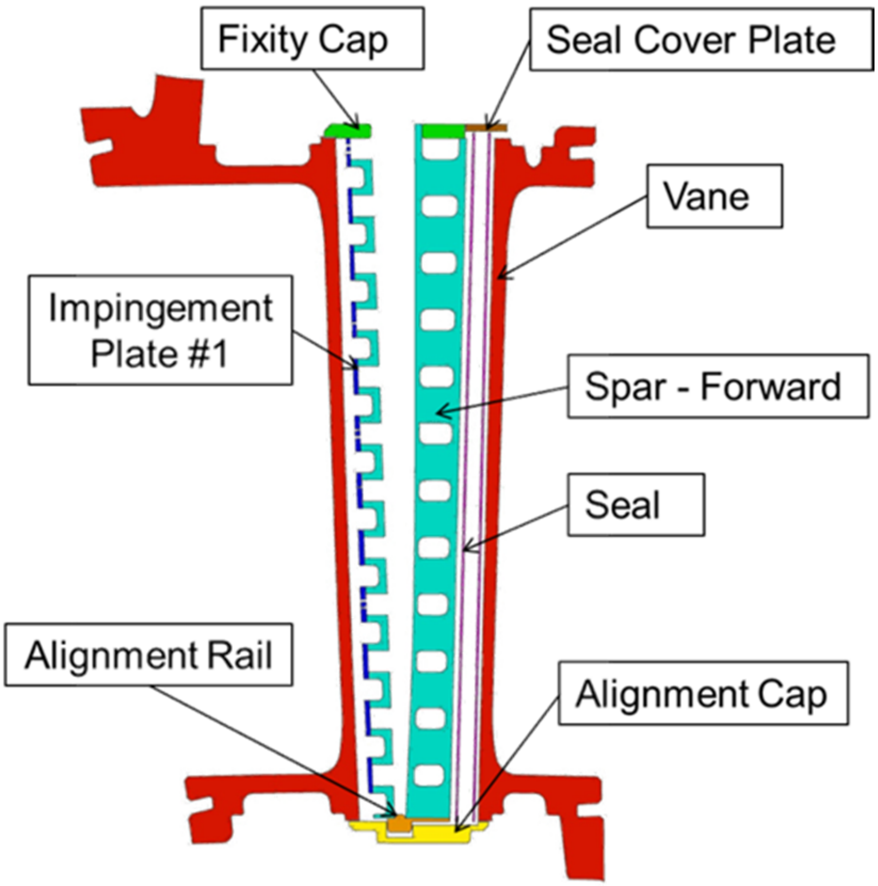


Figure 16: Component Identification – Radial

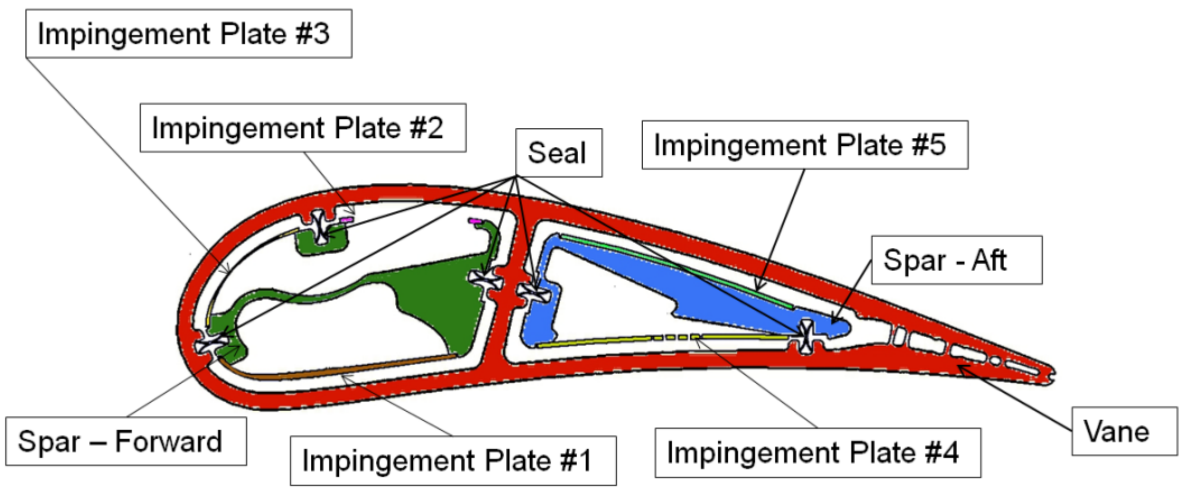


Figure 17: Component Identification - Chord wise

5.2.3 Boundary Conditions / Critical Interfaces

The boundary limitations for this prototype test are as follows:

- A current 501FD3 first stage static airfoil vane must be retrofitted to accept a spar-shell type cooling scheme. All critical interfaces are to be held constant, and the basic airfoil shape must remain unchanged.
- The cooling scheme must ensure that the internal airfoil coolant pressure is always higher than the external airfoil pressure to ensure a positive backflow margin and to prevent hot gas inflow in the event that the structuaal material might crack or other through-wall distress to occur.
- Modifications made to the 501FD3 vane may not reduce the reliability or life expectancy of the component.

5.2.4 Vane Modification Details

In order to implement a spar and shell type cooling scheme into the 501FD3 first stage vane some modification of the airfoil casting core and subsequent machining processes was required.

The internal geometry of the original equipment (location of internal ribs, specific details of internal heat transfer enhancement devices, etc.) was not compatible with the desired design for a spar-shell cooling system. The following changes to the casting core were required to properly implement out design.

- The spar-shell vane was designed using a single internal rib, and special features were designed into the geometry to facillitate FTT's unique sealing device which is used to segregate the independent impingement chambers of the spar-shell design.

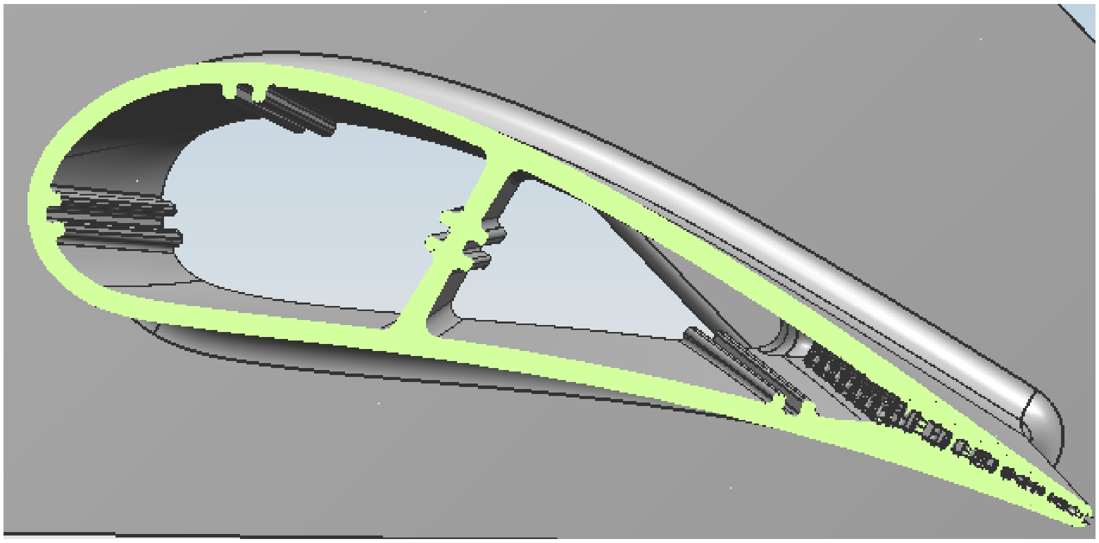


Figure 18: Spar-Shell Modification of Existing Hardware

This is the most prominent change required in the vane structure. The spar-shell team completed modal and lifing analyses that show this alteration will not have an adverse affect on the durability of the component.

- In order to create multiple impingement plenums between the spar and vane structures, sealing provisions were added to the casting core in order to create a suitable surfaces for the seal. The original design approach was to cast these features as solid ribs that would need a subsequent machining (EDM) operation in order to create a groove to create te sealing surfaces. After further discussion with the supplier, PCC – Deer Creek, regarding expected tolerances; it was suggested that the seal grooves be added to the core in order to eliminate a difficult EDM operation. Electro-Discharge-Machining (EDM) of 4 out 5 of the slots would have been fairly straight forward, but access was limited at the trailing edge seal location due to an Inner diameter platform rail. Although machining operation is possible, the team chose to eliminate the extra process and expense and to cast the seal pedestal with the grooves.
- The last change that was made to the airfoil casting core was to eliminate special features contained in the original casting that were used to enhance heat transfer, guide flow and provide stiffening of walls. These features were not required of the spar-shell design, so they were not carried over to the spar-shell design.
- In addition to the casting core modifications the only other change to the vane was the airfoil film cooling hole pattern. All other machining (both conventional and non-conventional) processes remained the same as the current hardware. However, as previously mentioned, the spar-shell vane requires significantly fewer film cooling holes relative to the existing design, so many film cooling holes were eliminated and placement of the remaining holes was designed to conform with the needs and objectives of the spar-shell design.

The film cooling system of the Spar-Shell was modified extensively from the baseline, bill-of-material, configuration. While the baseline design contains a copious number (>450) of film cooling holes, the Spar-Shell design optimizes the internal convection cooling, so the need for film cooling holes is greatly reduced. In fact, the number of film cooling holes defined for the Spar-Shell configuration was reduced to less than 300. The Spar-Shell film cooling arrangement is illustrated in Figure 19. With this design, the showerhead and forward pressure side film cooling holes have been totally eliminated.

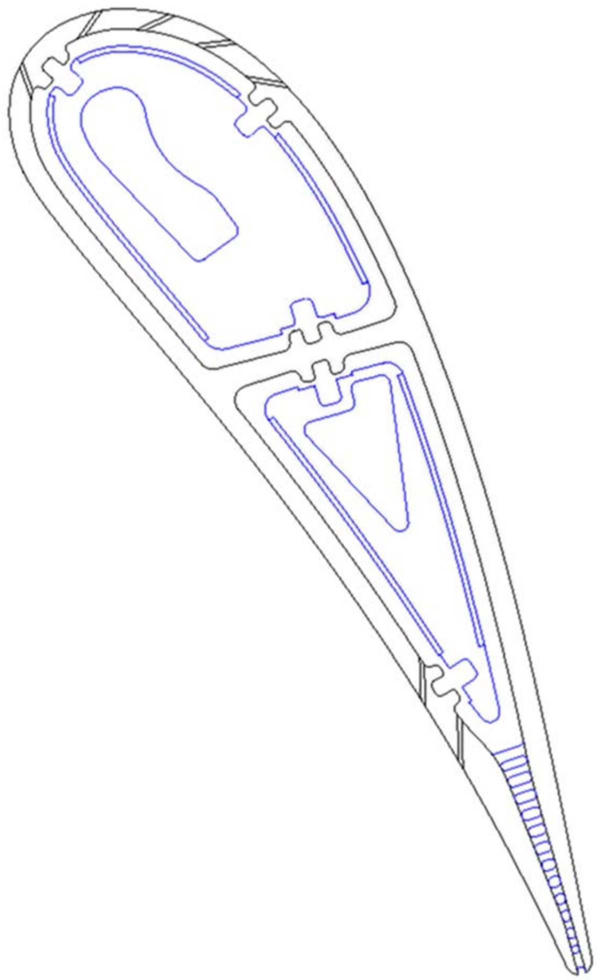


Figure 19: Spar-Shell Film Cooling Arrangement Reduces Number of Holes

5.2.5 Detailed Spar Design

The main function of the spar is to serve as coolant router inside of the vanes' internal cavity. Another critical function of the spar is that it serves to divide the internal vane cavity into separate impingement zones which define the sequential impingement cooling circuit. Due to the desire to have uniform impingement cooling on the internal vane wall, the spar structure is quite complex with multiple chord wise cooling layers stacked radially. The final spar design can be seen in Figure 20 below. The spar skeleton was cast and then separate impingement panels were welded to the exterior to complete the impingement scheme.

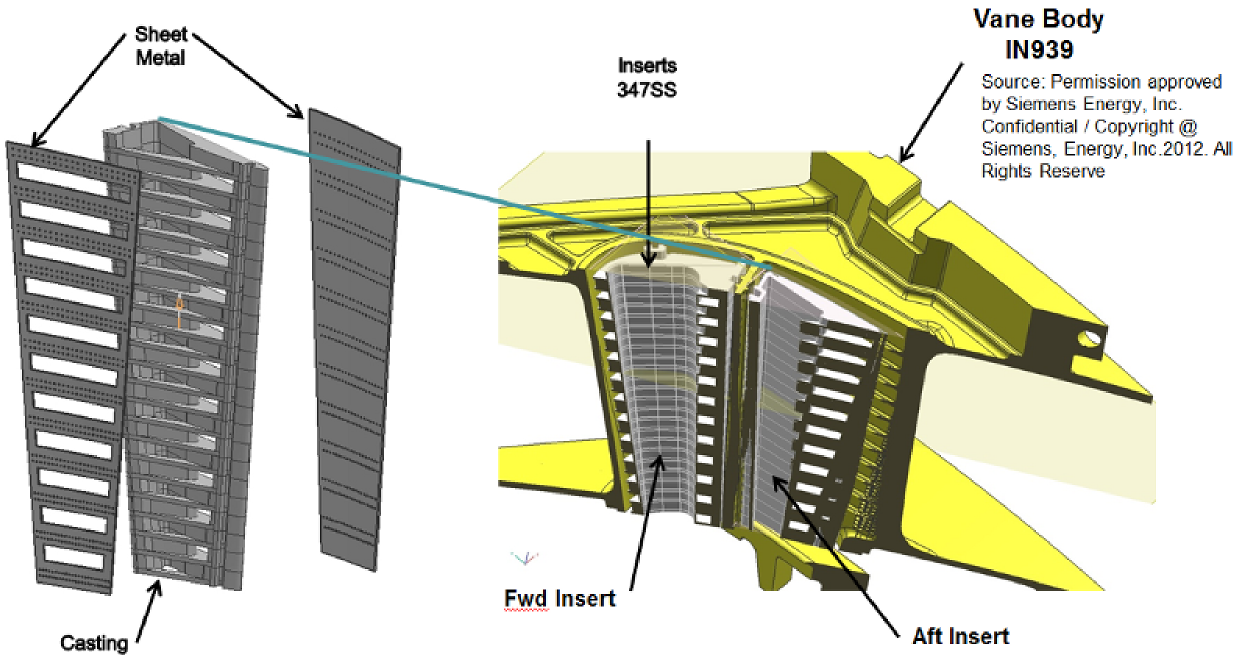


Figure 20: Spar - Exploded Cross-Section

The ideal spar-shell design would be to remove all internal rib structures and the aerodynamic shell would be supported using structural ties, hooks, or other supporting features connected to the spar. However, to reduce the risk and complexity associated with the primary objective of demonstrating the sequential impingement cooling system in this pre-commercial prototype demonstration, the team decided to retain one internal structural rib because the additional benefit to the cooling scheme did not justify the additional risk. This design approach eliminates the aerodynamic loads from being transferred through the spar to the end walls, which allows the spars to be made of 347 stainless steel instead of a more expensive, i.e.: IN625, alloy. Retaining the internal rib expanded the cooling scheme to include to two serpentine cooling circuits; one for the forward leading edge region and the other for the aft trailing edge region.

The most challenging aspect of the spar's design was to package all of the feed and return plenums within the spar's body, while still maintaining acceptable air flow losses. The cooling scheme has been designed so that flow metering locations (large pressure drops) are across the internal impingement and airfoils cooling holes. Thus, all of the return plenums should have relatively low airflow Mach number in order to minimize pressure losses.

The spar skeleton will be a cast component made of 347 stainless steel because of its strength at temperature and a reduced cost. The spar assembly also consists of multiple impingement plates which serve to form the metering orifices through which the cooling air is directed to impinge on the internal vane wall. The impingement gap between the vane wall and the spar structure has been designed to be 3mm for optimum heat transfer efficiency.

Castability of the internal spar was assessed using Procast software. This software is used to simulate the casting process including the effects of heat transfer, the solidification process from molten to solid metal and residual stresses that may be manifested in the part as a consequence of the way that it was solidified. These analyses precipitated changes to the design to improve its castability.

To facilitate the use of the rapid-prototyped spar casting approach, the number of layers in the radial dimension was limited to 24. With this number of layers, the radial spacing between layers was about 16mm, which is large for an impingement hole spacing. To reduce the radial spacing of impingement holes from one layer to another, two rows of impingement holes were designed into each layer as shown in Figure 21. With this definition, each layer has a radial height of 8mm. The radial spacing of impingement holes within a layer is 3mm and the minimum spacing of impingement holes between layers is 13mm. Axial spacings of impingement holes were set to deliver the rquired cooling flows and to control the impingement pressure ratios.

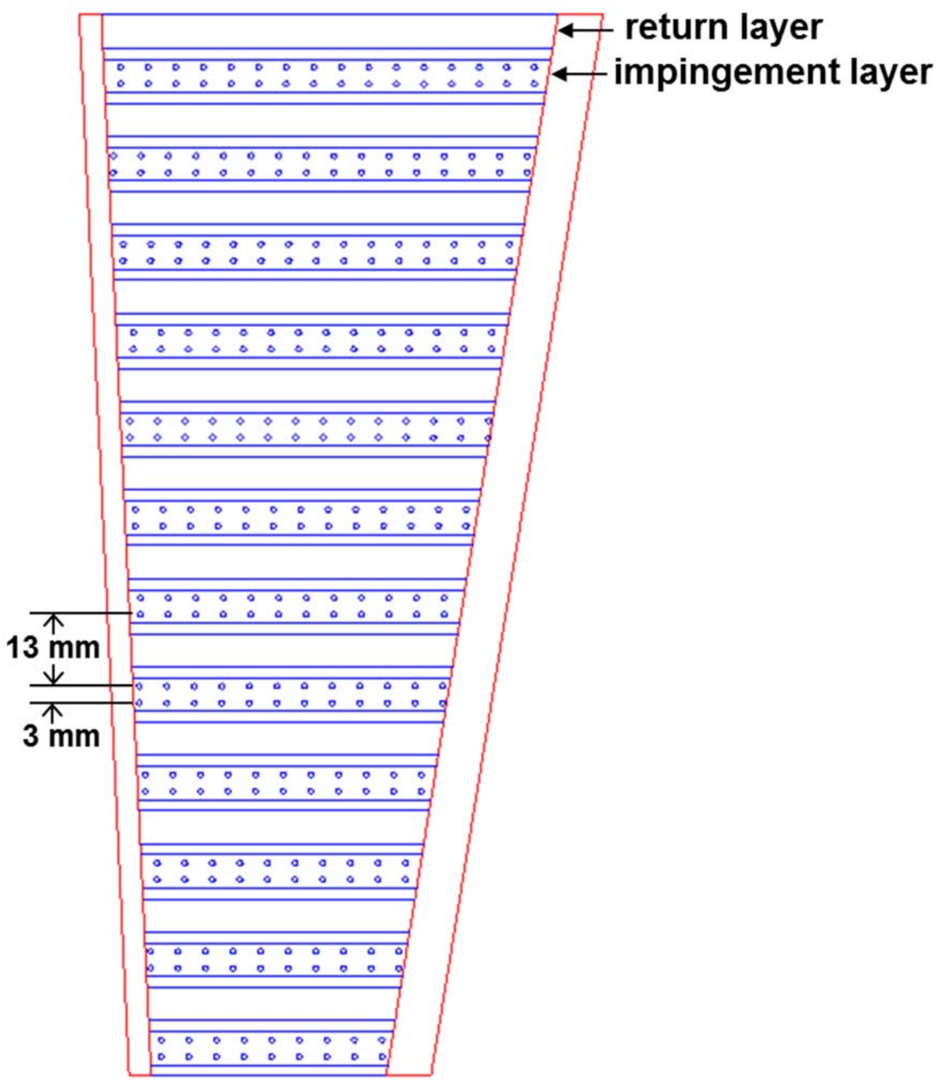


Figure 21: Spar Impingement and Coolant Flow Return Arrangement

Since this arrangement differs from the historical databases of experimental and computational research works available to predict heat transfer characterisics, additional work was required to determine the impingement heat transfer behavior with certainty. In one approach, experimental testing was performed to verify the heat transfer behavior produced by this configuration. A summary of this heat transfer testing is provided in section 5.3.1 of this report. In addition, analytical studies were performed to estimate the local heat transfer behavior. Specifically, a two-dimensional finite element analysis to determine potential radial TBC surface and structural material variations based on the expected variations of backside impingement heat transfer.

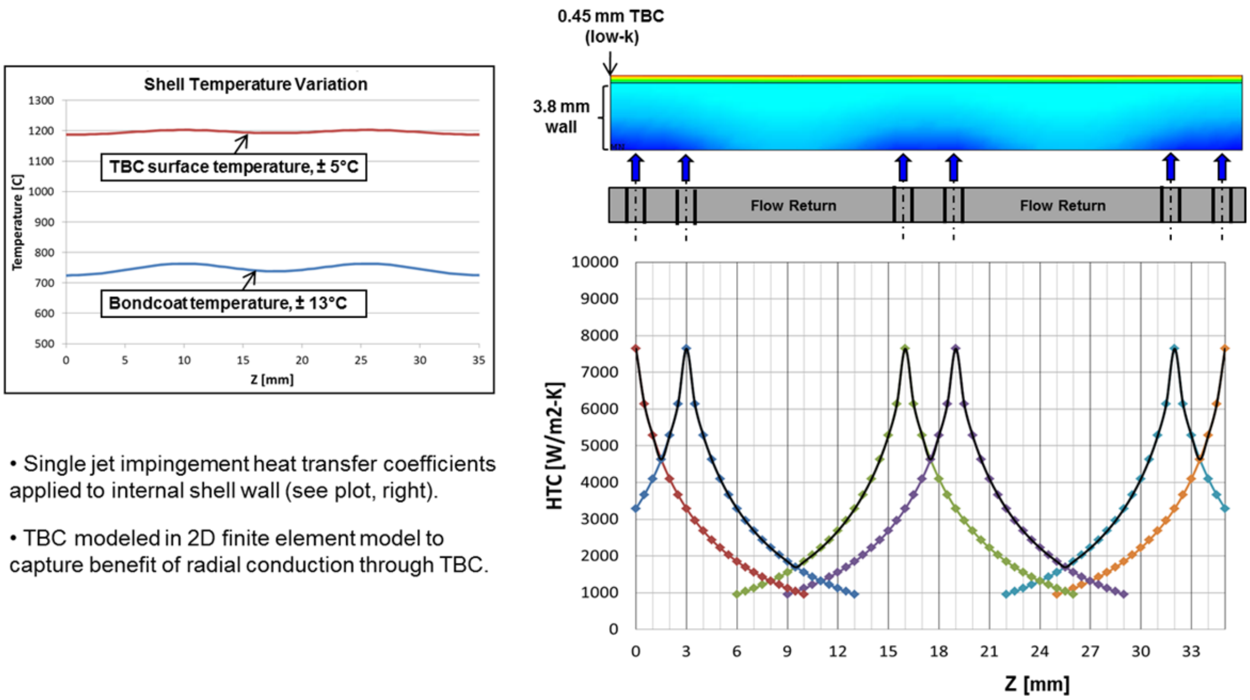


Figure 22: 2D Finite Element Study Shows Acceptable Variation of Metal Temperature Due to Radial Gaps of Impingement Holes

5.2.6 Seal Design Considerations

5.2.6.1 X–Seal: Detailed Design

The spar-shell cooling concept relies on radial seals to separate the different impingement zones. If the radial seals leak excessively, the cooling air will not be properly routed through the spar and the vane metal temperatures will increase. The optimum amount of leakage would be zero, but this is not physically possible. Realistically, an acceptable amount of leakage is less than a 0.127mm effective gap. This basically means that the amount of air that leaks by the seal must be less than the amount of air that will flow through an un-obstructed area of 24mm^2 or less.

This is usually not a difficult task, but the surface profile of the sealing surface will have an estimated tolerance of +/- 0.254mm. This loose tolerance is due to the fact that the seal groove on the vane wall will be "as cast" and will not be mirror-finished.

In addition to the surface profile's uncertainly, the seal must be compliant enough to be able to accommodate both normal and tangential movement of the sealing surfaces. Finite element analyses show excursions can be as large as 0.5mm in either direction. These excursions are due to the fact that the vane and the spar operate at different temperatures, and therefore thermally/structurally deform differently at the steady state operating point.

The final challenge is that the pressure differential across the seal is not large enough to ensure that the seal stays seated on the working surface. Therefore, the seal must be self-energizing in order to reach our leakage goals.

These requirements forced the team to design a new seal, as no current production seals would be acceptable. The FTT-patented X-seal, as seen in Figure 23 below, was envisioned to fulfill this need.

This seal is basically two leaf springs that have been welded or brazed back-to-back. This allows for a very flexible, high contact seal that will not leak excessively during the thermal excursions.

In order to prevent the leakage due to the profile tolerance of the as-cast seal groove on the vane, the seal is oversized and required to yield in order to fit conformally into the seal groove. This yielding will force the seal to conform to the undulating surface instead of sitting on the 3 highest points on the seal surface. The goal was to have the seal yield to approximately 20% during installation to ensure proper seating during install. Once the seal has been installed, it has been designed to stay in the elastic deformation region of the stress – strain curve during the thermal excursions.

The X seal was tested in a test rig and was found to have a leakage equivalent of a 0.076mm.

5.2.6.2 Wedge Seal: Detailed Design

An alternate version of this seal concept is to have the two leaf spring halves un-attached to each other, with a wedge installed in between them. This variant has the advantage that each seal half can be loosely fit into the seal groove and then wedge driven in between the two springs to set the pre-load. Another advantage of this concept is that if the width of the seal groove narrows near the middle and then widens near the end walls the driven end of the seal won't be over compressed during installation.

A seal test rig was procured to determine the effectiveness and practicality of each seal. Both seal concepts have pros and cons: The X-Seal is a stiffer more robust seal that has the ability to withstand large thermal excursions of the working faces. The wedge seal is not quite as compliant as the X seal, but shouldn't have any issues accommodating the expected thermal excursions. The wedge seal was designed to be back up in case the X-seal had installation issues.

X - Seal Design Parameters				
Material	Yield Strenth @ 25°C (Mpa)	Stress @ Install (Mpa)	% Yeild @ Install	Initial Deflection (mm)
X - 750	615	737	119.84	0.3

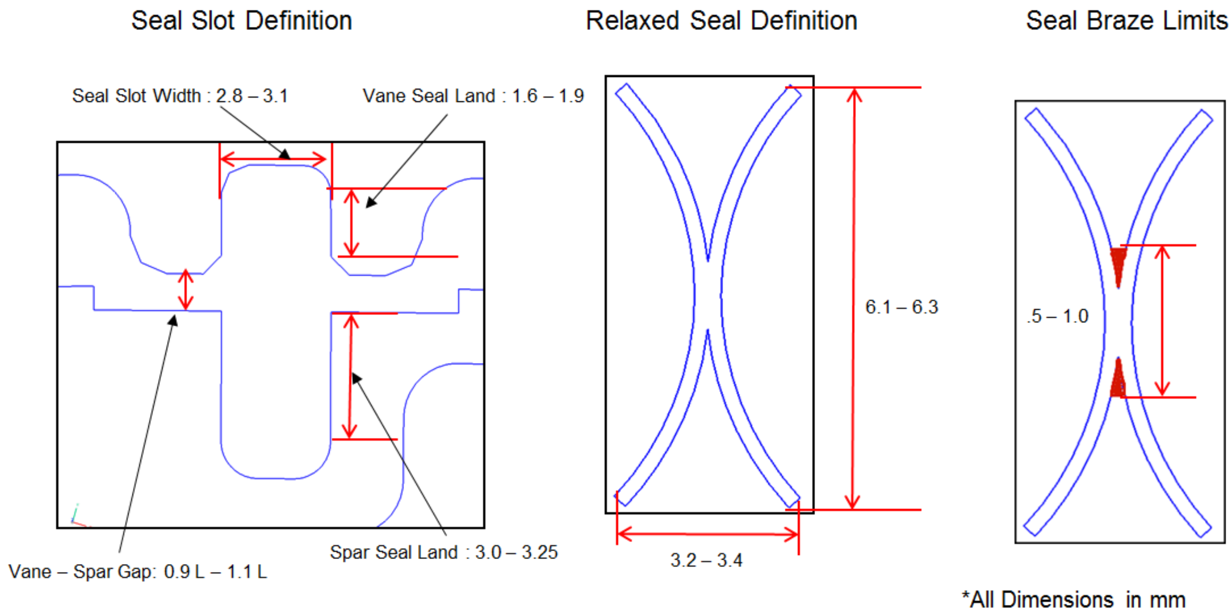


Figure 23: X-Seal Design Parameters

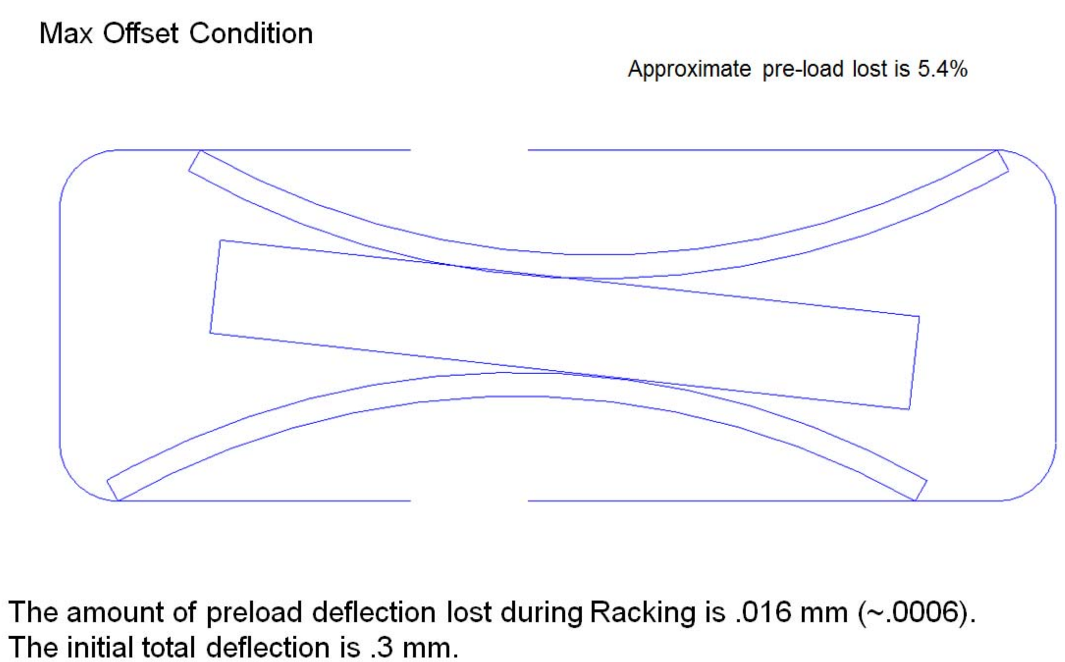


Figure 24: Wedge Seal - Max Offset Study

Sensitivity studies were performed to verify cooling flow performance under varying seal leakage conditions. The following describes the geometry, assumptions and results from this study for the forward, leading edge spar insert.

The geometry and flow modeling assumptions used in the analysis are shown in Figure 25. The geometrical boundary conditions include the number of impingement and film cooling holes, their controlling orifice, or diametrical sizes and assumed discharge coefficients for each orifice. The environmental conditions include the coolant supply pressure and temperature and the discharge pressures for each of the film cooling holes which discharge into the hot gas flowpath. Based on these parameters, coolant flows and internal pressures were determined using a one-dimensional flow network analysis.

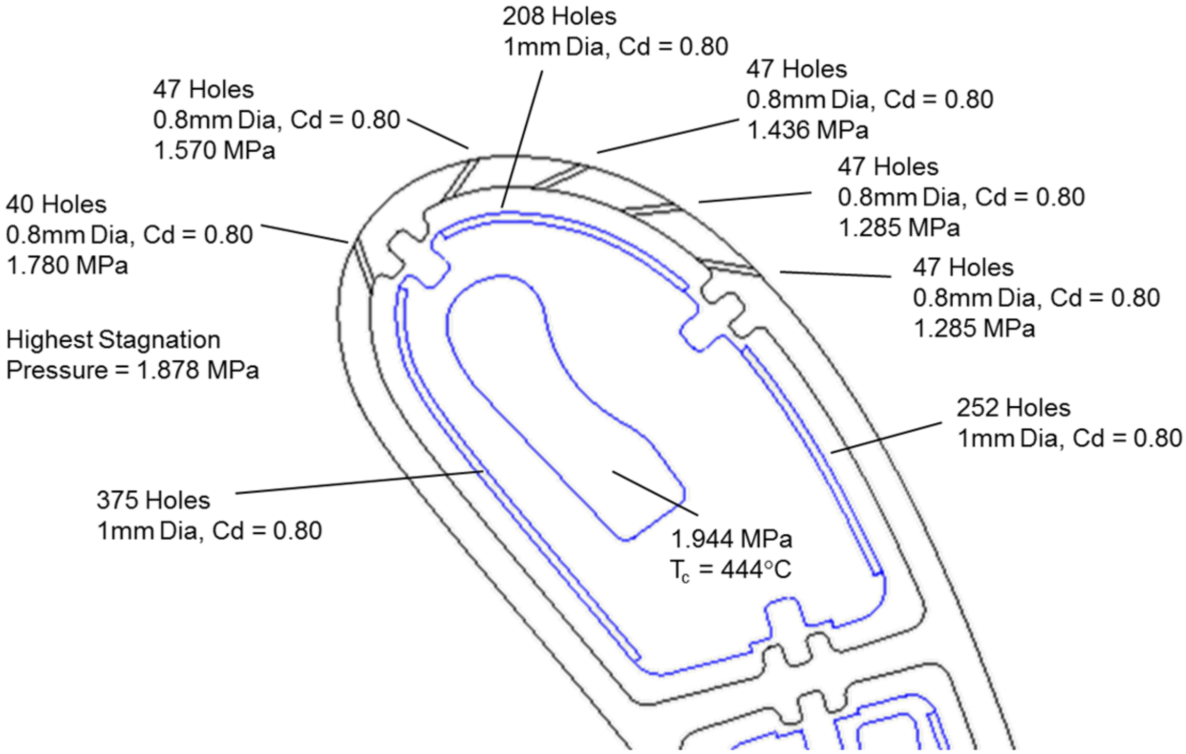


Figure 25: Flow Modeling and Boundary Conditions for Seal Leakage Sensitivity Study

To establish a baseline, the distribution of coolant flows and pressures within the flow network were computed assuming the seals perform perfectly, or do not leak at all. The results from this analysis are shown in Figure 26. These results indicate the minimum outflow margin, the pressure margin available to insure coolant will outflow in the event a crack or other opening is produced in the part, is 1.7%, which is healthy for a first stage turbine vane design. Meanwhile, the backflow margin, which is the pressure ratio across film cooling holes, is significantly higher than that experienced in typical modern first stage turbine vanes because this design does not include showerhead cooling holes which discharge coolant to the highest gaspath pressures on the airfoil. The geometry defined here were set to provide coolant flow and impingement pressure ratios consistent with Spar-Shell design goals, and the results of this analysis are consistent with those expectations.

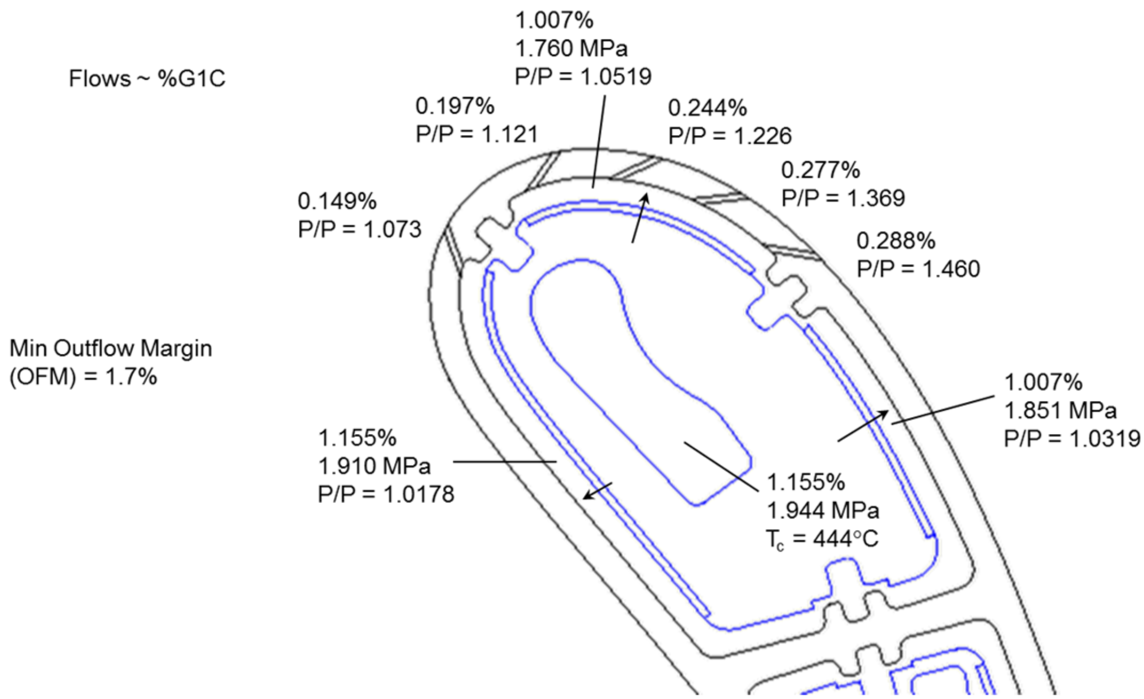


Figure 26: Base Seal Sensitivity Results - Perfect Sealing

A second analysis was performed with the assumption that the seals would leak with an assumed clearance gap of 0.05mm (0.002"), which is consistent with the expected effective gap. With this assumption, cooling flow will leak across the seals from the igh pressure impingement chambers to those that operate at lower pressures. Results from this analysis, shown in Figure 27, indicate total cooling flow increases by about 3.4%, which increases suction side film cooling flow and minimum backflow margin is reduced slightly, but is maintained at a healthy level of 1.58%. Meanwhile, reflecting on the robust nature of the design, impingement heat transfer behind the leading edge and forward pressure side actually increases as a result of the additional flow and increased first impingement pressure ratio.

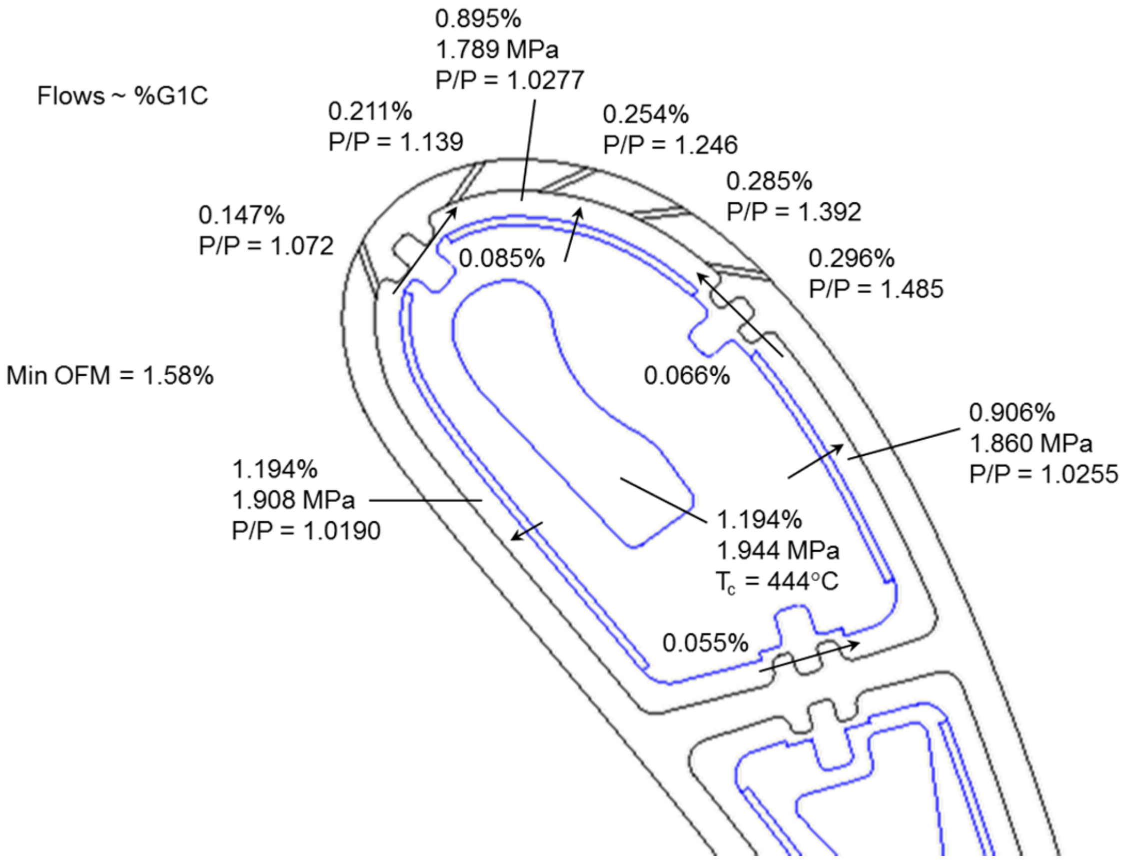


Figure 27: Results for Assumed 0.05mm (0.002") Effective Leakage Gaps

Finally, an analysis was performed with the assumption that the forward seal experiences a catastophic failure resulting in a very large 1mm (0.040") effective gap. This type of failure would permit a large amount of leakage flow from the first impingement to the third, or last impingement chamber. Results from this analysis, shown in Figure 28, indicate total cooling flow would increase by an additional 9.1% and a positive outflow margin of 1.2% is maintained.

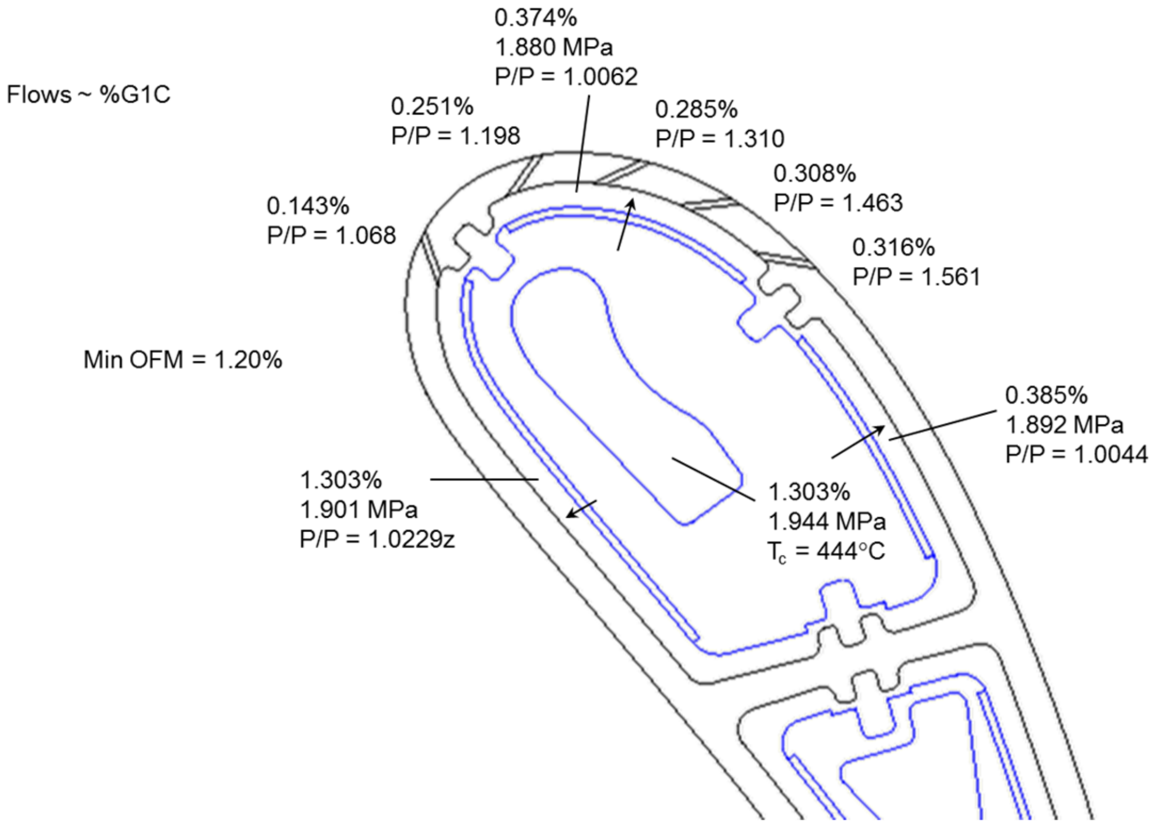


Figure 28: Predicted Cooling Flows and Pressures Assuming Failure of Forward Seal Resulting in 1mm (0.040") Effective Leakage Gap

5.2.7 Thermal and Structural Analysis Results

A full three-dimensional analytical model of the geometry was constructed in Ansys for the purpose of evaluating structural temperatures and stresses. Thermal and structural loads were applied to the applicable surfaces and temperatures and stresses were computed within Ansys. Contour plots of the temperatures and stresses are shown in Figure 29 and Figure 30, respectively. From a thermal standpoint, the average surface temperature of the stuctural material increased less than 10°C relative to current hardware while cooling flow was reduced 35%. From a structural viewpoint, predicted stresses and cyclic life was also consistent with values predicted for the baseline design.

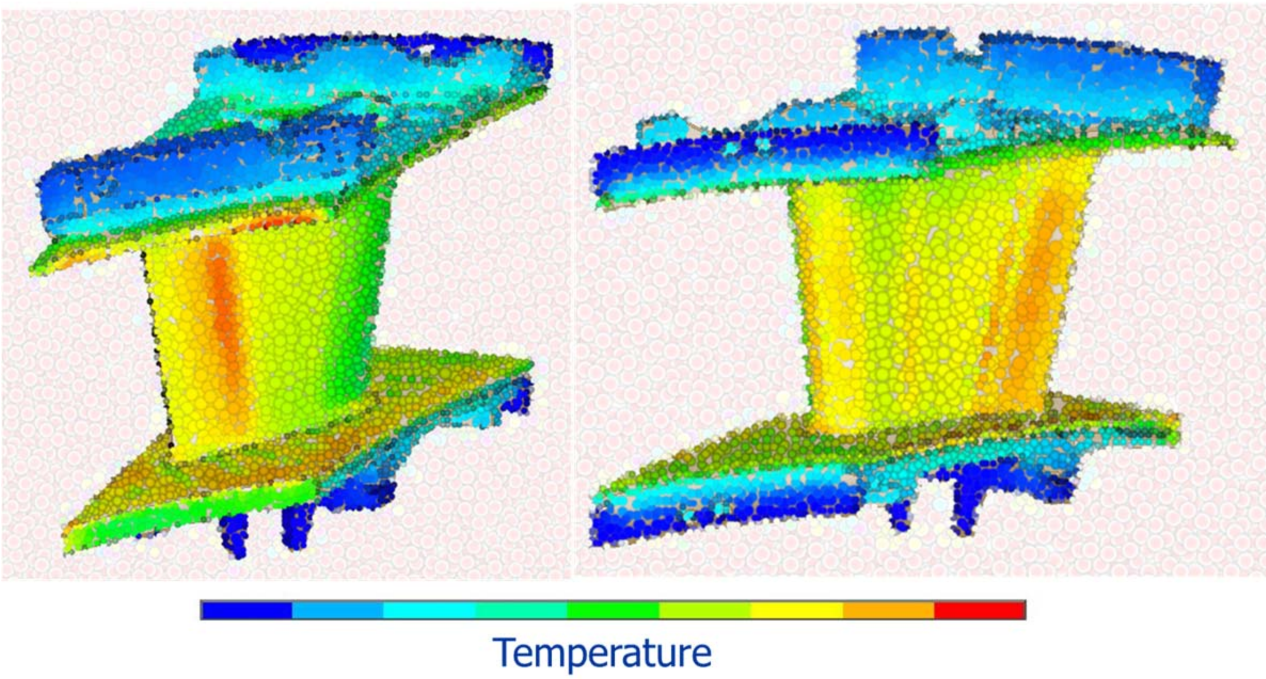


Figure 29: 3D Thermal Analysis Results

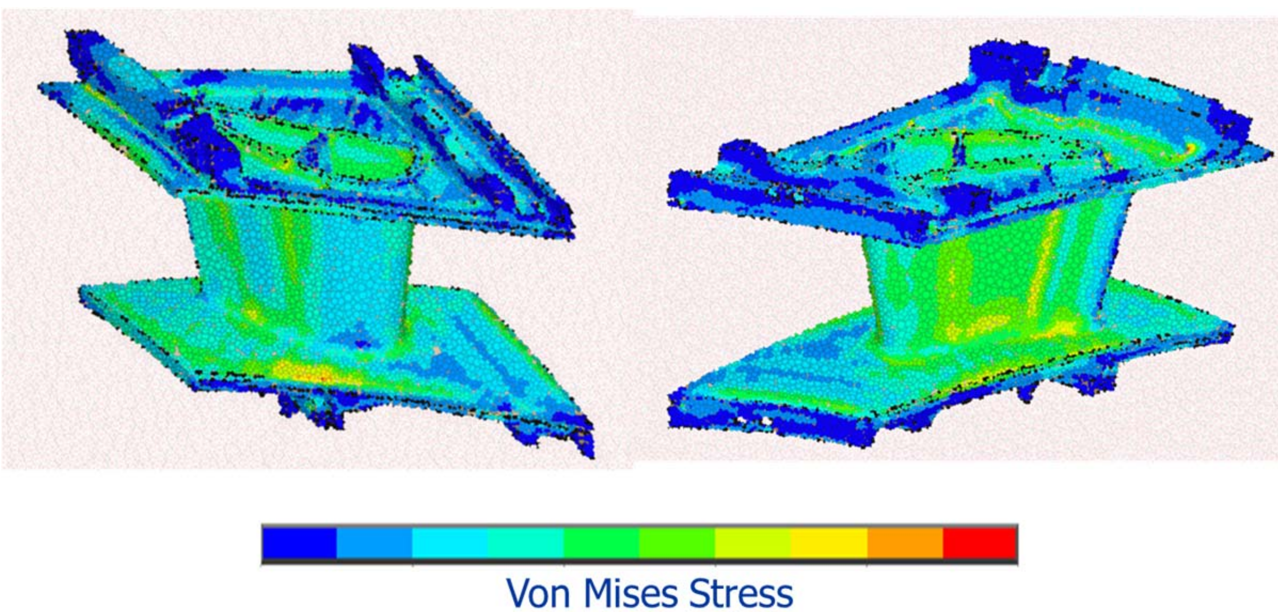


Figure 30: 3D Stress Analysis Results

5.3 Component Testing

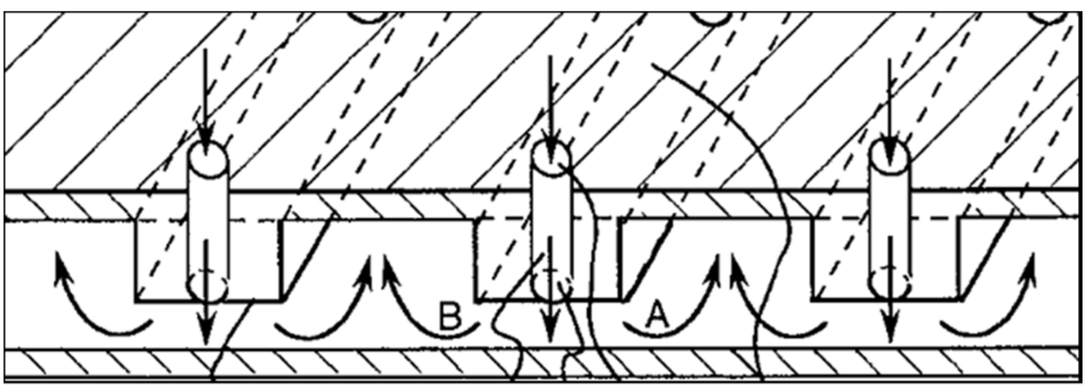
Component technologies and verification testing were important to the success of this program. To reduce the risks associated with testing in an actual IGT engine, several test campaigns were performed to verify expected performance and to improve our overall engineering understanding of the sequential impingement cooling system.

5.3.1 Bench-Scale Heat Transfer Testing

Accurate prediction of the structure temperatures is critical to the life of the part in the operating environment. The ability to predict temperatures accurately depends on whether a corresponding standard exists and how close the design is to the standard. Testing to validate and/or strengthen the coefficients used in the standards helps improve accuracy.

While impingement heat transfer performance has been studied for many years, the heat transfer performance of the specific impingement cooling system for the Spar-Shell vane was investigated during this task. This work was performed in conjunction with the University of Central Florida (UCF) and was carried out by UTSR Fellow, Roberto Claretti.

The downstream rows of large-scale jet impingement arrays suffer from heat transfer degradation resulting from the effects of cross-flows from the upstream rows. The purpose of this testing was to verify the expected heat transfer performance for the Spar-Shell cooling system which mitigates the effects of cross-flow degradation. Figure 31 Illustrates one example of prior art that aimed to increase the effective flow area of the cross-flow to



Bunker. US Patent No. 6,000,908

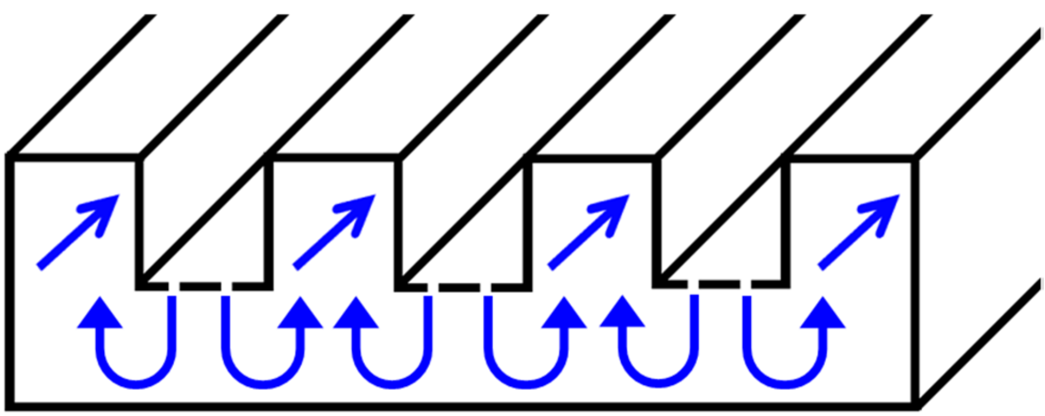


Figure 31: Prior Art - Mitigation of Heat Transfer Degradation by Increasing Cross-Flow Area

The test technique utilized at UCF employs a constant heat flux methodology and a measurement system that utilizes temperature sensitive paint. This is a proven experimental test technique that delivers accurate results. A photograph of the experimental test rig, illuminated by Light Emitting Diodes (LED's) is illustrated in Figure 32.

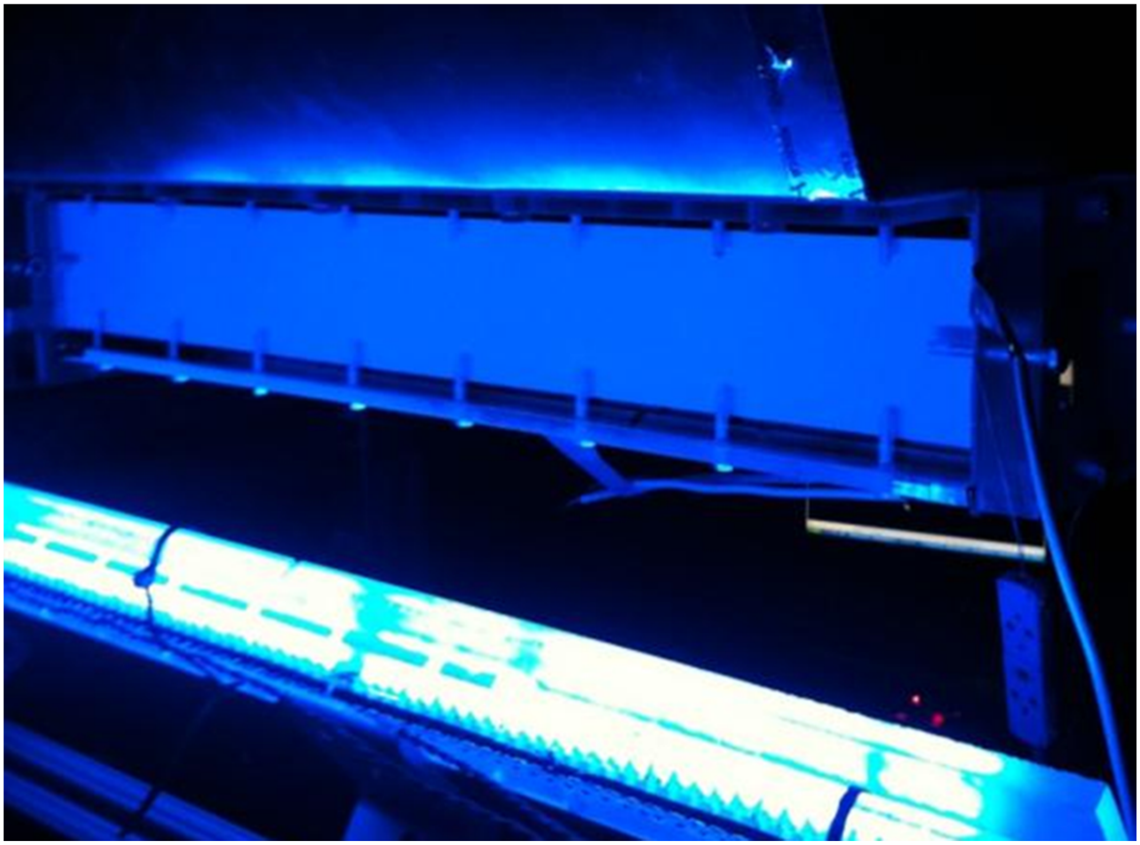


Figure 32: UCF Heat Transfer Test Rig

To insure the test method produced accurate results, a smooth channel validation test was performed to show the UCF test technique could repeat the results of prior works. The geometry was created by blocking the impingement holes of one of the test geometries from the impingement test arrangements. Also, the hydraulic diameter of the flow channel was decreased by attaching a spacer to the wall opposite the heaters. An entrance region having a length of 23 hydraulic diameters was attached to the inlet of the test section to provide a fully developed momentum flow boundary layer prior to the start of the thermal boundary layer. The channel had an aspect ratio of 21.67 and the heated section was 20 hydraulic diameters in length. Tests were performed for three Reynolds numbers; 23,000, 41,000 and 60,000.

Results from the smooth channel validation test are shown in Figure 33. These results have been normalized to the classical smooth-wall Dittus-Boelter correlation. The results indicate heat transfer augmentation occurs as a result of an entrance effect at the onset of the heated section, but the heat transfer decays within the expected length of about ten hydrauilc diameters to the fully-developed smooth tube value consistent with the Dittus-Boelter correlation. These results illustrate the ability of the test method to produs accurate resuls.

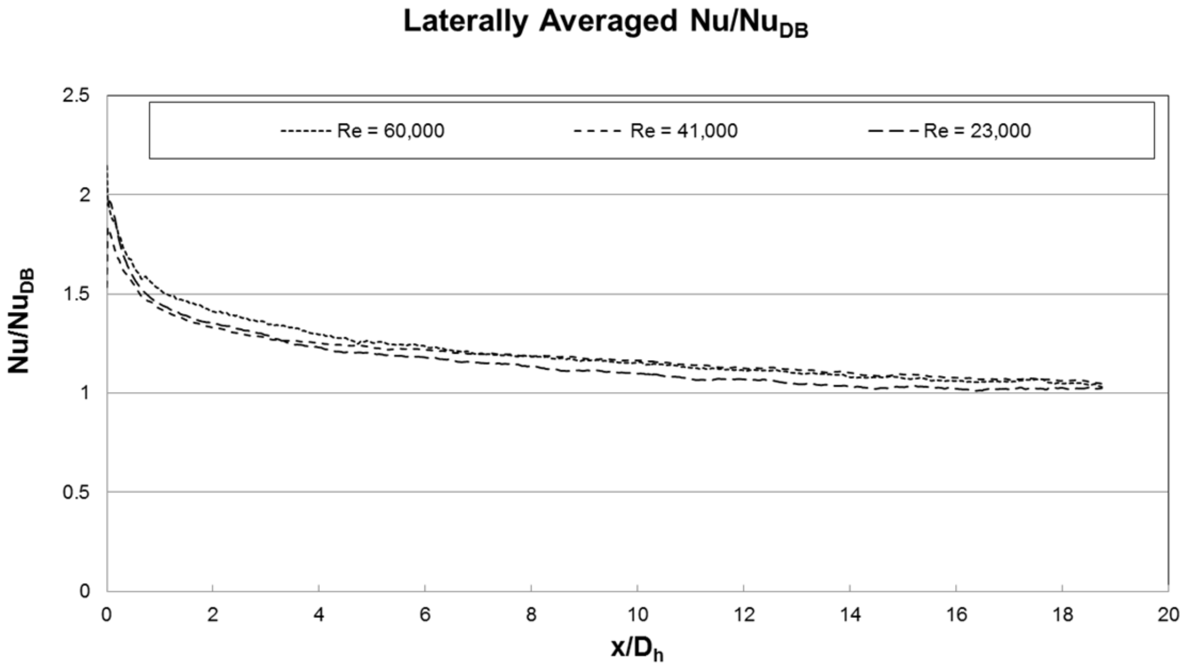
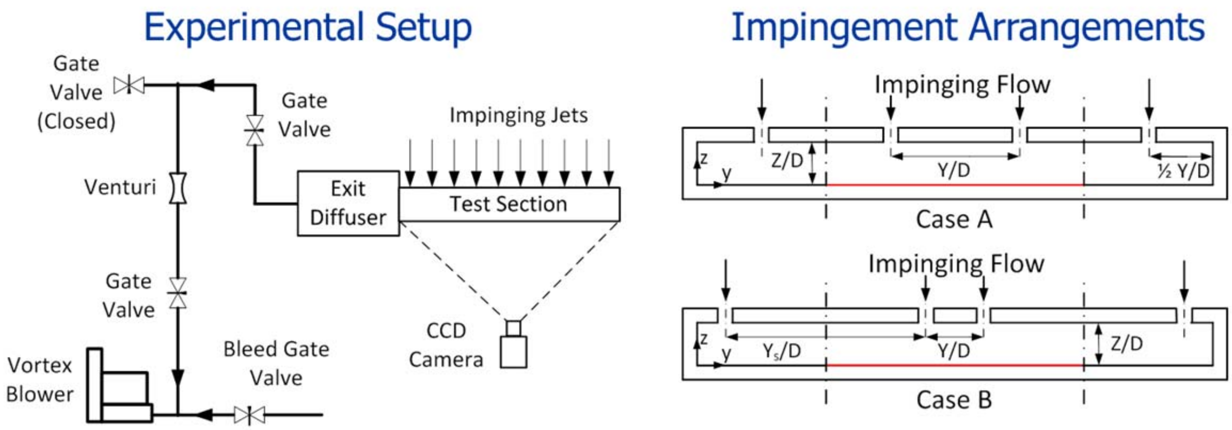


Figure 33: Smooth Channel Validation Test Results are as Expected

The experimental setup, impingement arrangements and test matrix are shown in Figure 34. Air enters the test apparatus from the atmosphere and is pulled through the model using suction from a vortex blower. The flow system contains a series of valves to condition and control the flow passing through the test apparatus. A venturi flow meter is used to measure the air flow rate. A CCD camera is used to record the images of the temperature sensitive paint during the experiment.

Two impingement arrangements were evaluated in this test. One arrangement, Case A, simulates the impingement geometry of prior research by Florshuetz, et. Al. A second arrangement, Case B, simulates the geometry of the Spar-Shell sequential impingement cooling system.



Test Matrix

Case	X/D	Y/D	Z/D	Y_s/D	$Re_{javg} \times 10^3$
A	3	8	3	-	10, 13, 16
B	3	3	3	13	

Figure 34: Experimental Setup, Impingement Arrangements and Test Matrix

Experimental results for test conducted with cross-flow are shown in Figure 35 for both Case A and Case B for Reynolds numbers of 10,000, 13,000 and 16,000. For Case A, which simulates uniform spacing of the holes in the radial direction, the highest heat transfer lies along the lines of impingement holes, and heat transfer is lower in between the rows. For Case B, heat transfer is highest within the zone of paired rows and diminishes outside of that region. However, the overall area-weighted heat transfer was comparable (within about 10%) for both configurations when compared at the same Reynolds numbers.

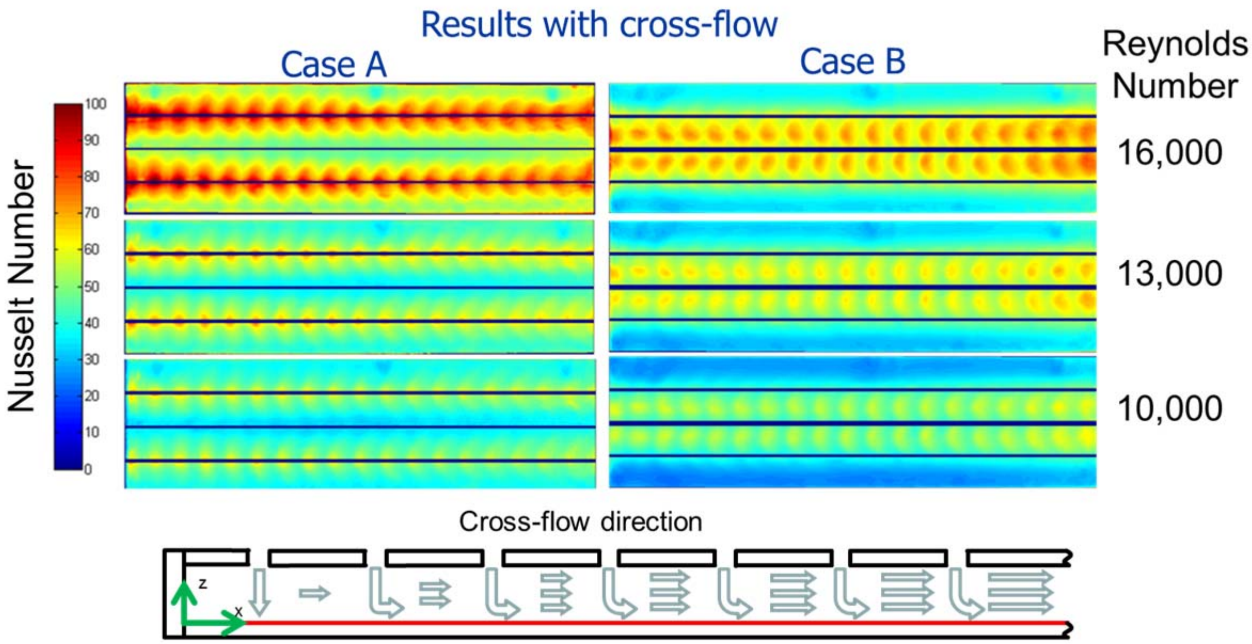


Figure 35: Test Results from Experiments with Cross-Flow

5.3.2 Seal Testing

Sequential impingement cooling is facilitated by successively impinging cooling flow from one impingement chamber to another. For the concept to work, the pressure within the impingement chambers must successively step down from the first impingement chamber to the next. Sealing is therefore required to segregate cooling flow from one impingement chamber to another and to prevent excessive leakage between impingement chambers. To address this risk item, a sealing rig was developed and fabricated under this program and various seal arrangements. Testing was used to evaluate competitive seal designs and to arrive at the best approach for this application.

A sealing rig was designed and built at FTT for the purpose of evaluating various sealing approaches. As shown in Figure 36, the seal rig consists of two blocks which contain grooves to simulate seal lands.

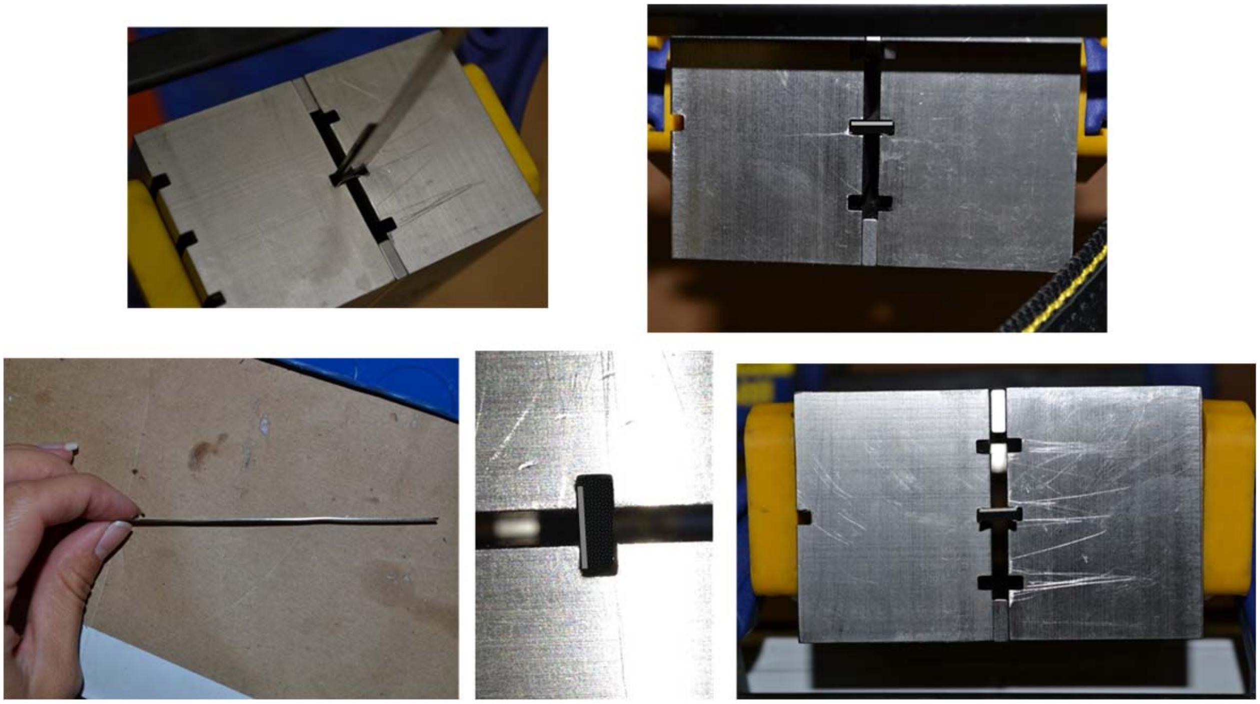


Figure 36: Seal Rig Constructed to Test Leakage

Most seals, and in particular, feather seals which are common in the industry, can be expected to function well under ideal conditions. However, mateface misalignment causes the leakage performance of most sealing systems to degrade precipitously. These offsets can be caused by many factors such as machining/fabrication tolerances, assembly deviations and thermal/structural deviations. Examples of such misalignments and seal land position non-conformances are shown in Figure 37. To insure the seals selected for the spar-shell vane perform well under all condtions, the seal rig was designed to permit the relative position of the blocks to be controlled using shims to simulate various offsets of seal lands from one part to another.

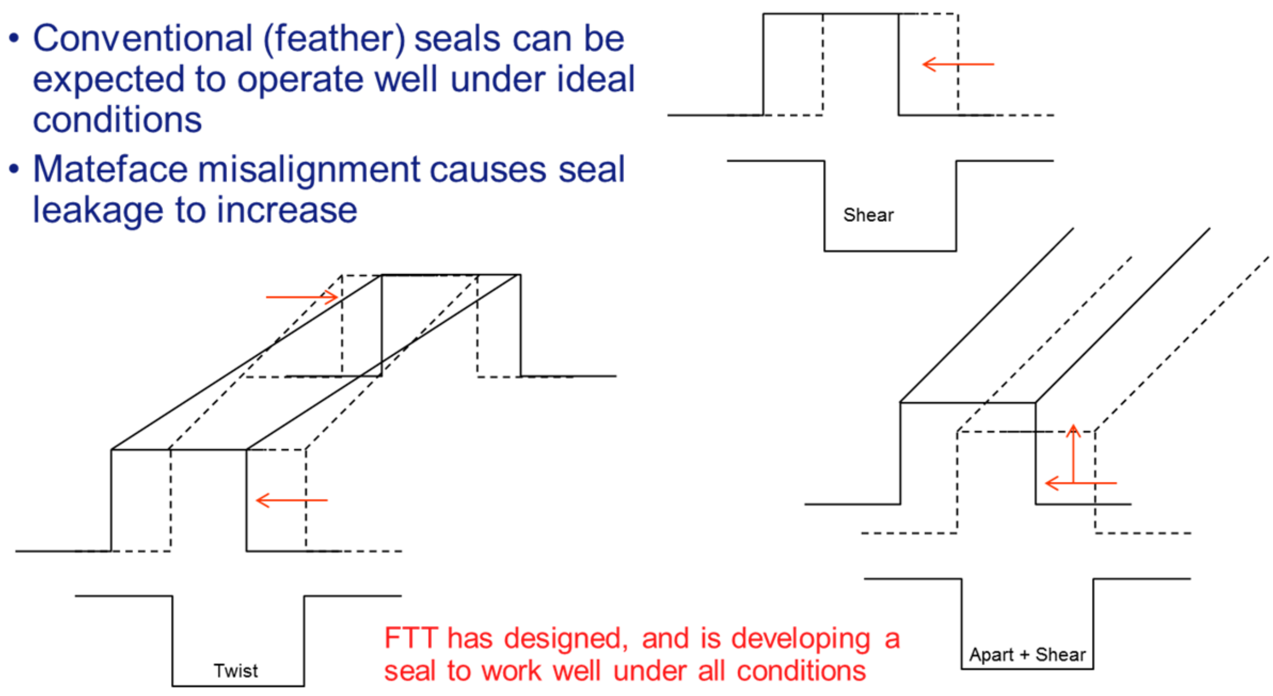
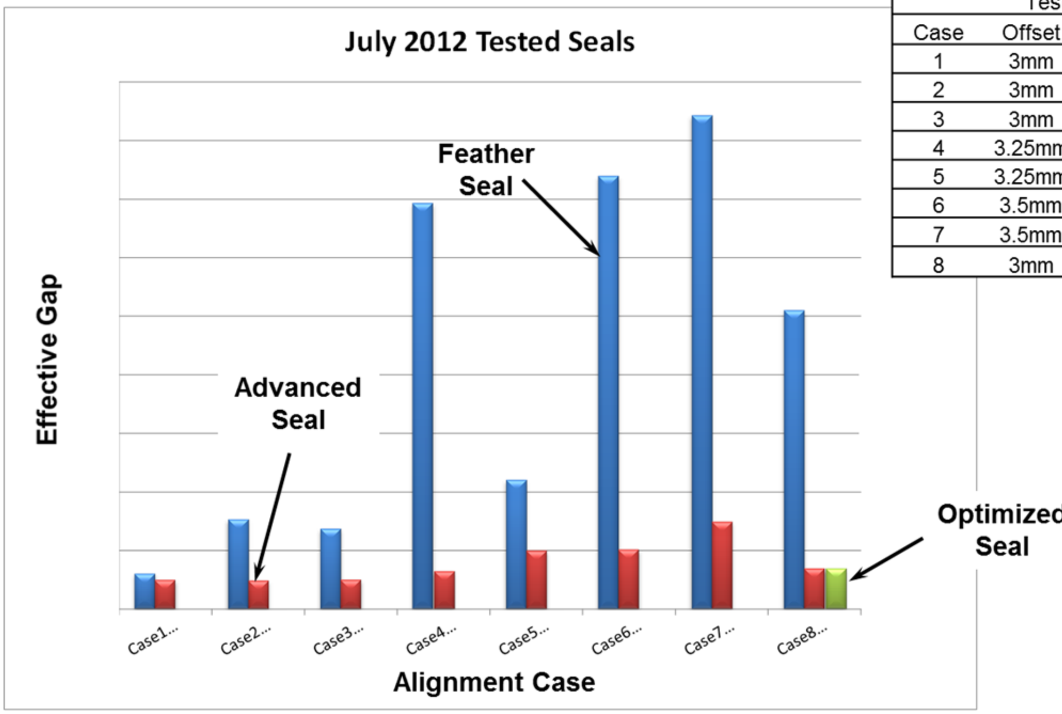


Figure 37: Examples of Seal Land Misalignments that can be Simulated in FTT's Seal Leakage Rig

Results from seal leakage test results performed in FTT's Testing Center are shown in Figure 38. These results show the effective gap measured for feather seals and FTT's advanced seal concept over a range of seal misalignment cases. A third seal geometry, noted as an Optimized Seal is an enhancement of the Advanced Seal configuration. The effective gap indicates the amount of relative leakage that passed through the seal, so smaller effective gap indicates better sealing performance. As shown, the conventional feather sealing technology works quite well under ideal and near-ideal circumstances. But, the performance degrades when specific seal land misalignments exist. Conversely, the FTT advanced seal performance is greatly improved when these seal misalignments exist.



Test Matrix			
Case	Offset	Shear	Bow
1	3mm	0mm	0mm
2	3mm	0.25mm	0mm
3	3mm	0.5mm	0mm
4	3.25mm	0.25mm	0mm
5	3.25mm	0.5mm	0mm
6	3.5mm	0.25mm	0mm
7	3.5mm	0.5mm	0mm
8	3mm	0mm	0.125mm

Figure 38: Seal Leakage Test Results

5.3.3 Fabrication Trials

The final design configuration of the Spar-Shell vane used existing, proven, manufacturing techniques, processes and procedures to the extent possible. However, while the construction of conventional first stage turbine vanes incorporates formed sheet metal impingement inserts, the Spar-Shell impingement inserts must also accommodate a unique coolant flow network system to insure the coolant in a sequential fashion to the first and then subsequent impingement chambers. The original concept to produce and fabricate such a flow network was to construct the spar insert as a stack of bonded layers, with each layer supporting a specific function of flow routing. To verify the manufacturing feasibility of such a stack of bonded layers, FTT performed a fabrication trial as shown in Figure 39.

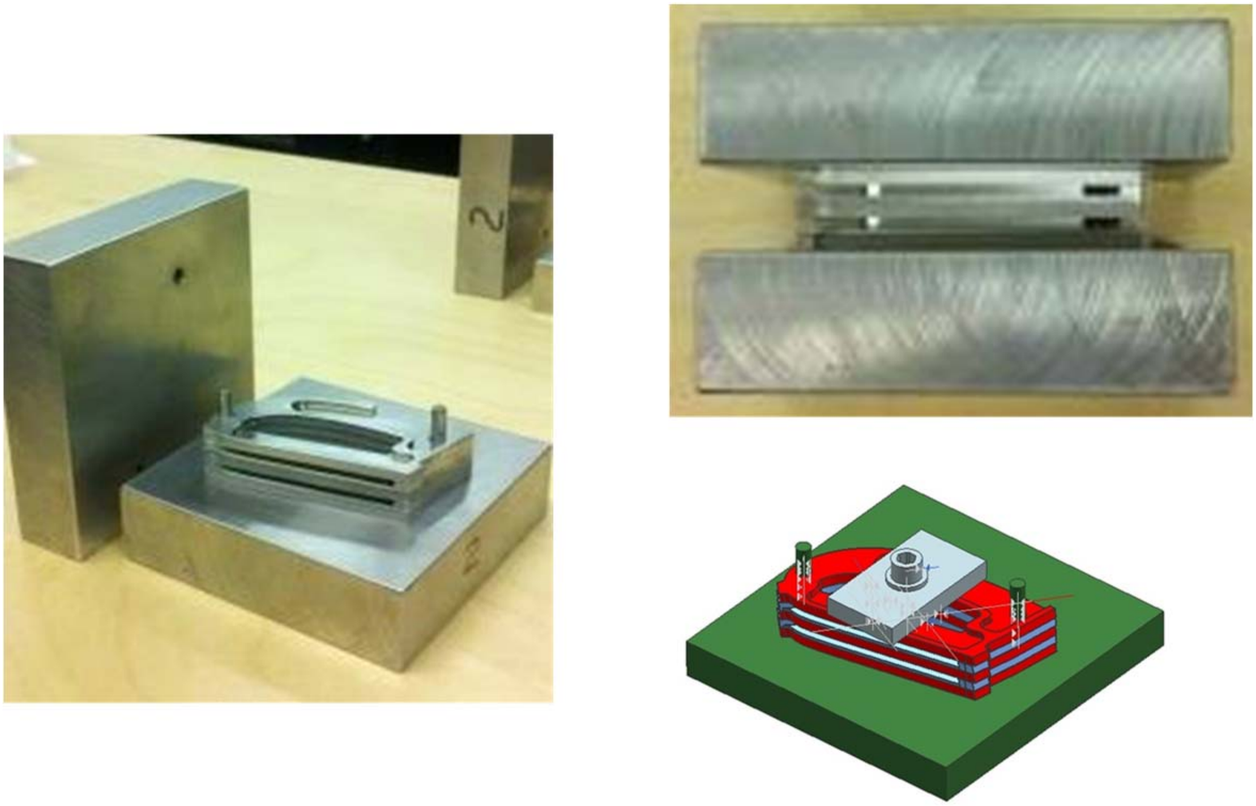


Figure 39: Spar Fabrication Feasibility Trial

5.3.4 Cold Flow Verification

Several current airfoil (shell) castings were obtained from Siemens and were cold air flowed to measure the flow capacity of the trailing edge cooling circuitry which the Spar-Shell^{TM} will utilize without change. Results from this testing showed the trailing edge flows were consistent (within a few percent from one casting to another), and the overall flow capacity was very near the expected value based on analytical modelling of the internal flow circuitry.

5.4 Manufacturing and Assembly Procedure

The proper spar-shell vane assembly procedure is as follows:

The airfoil was procured in the "as-cast" condition; the initial conventional and non-conventional machining was completed per the appropriate specifications. *Note the airfoil cooling hole quantity and location was altered from the the original non-conventional machining specification.*

5.4.1 Assembly Process

First, the spar is inserted into the inner vane cavity along with the radial seal slot using spar alignment tools. These tools, consising of guides having a rectangular cross section, serve to align the seal slots in the spar with respect to the seal slots cast into the airfoil's wall. These tools should remain installed until the vane is ready for the post–weld heat treat cycle.

After the tools have been installed, the spar's ID alignment cap is fitted over the bottom of the spar's alignment rail. After ensuring that the spar and the inner diameter cap are properly engaged; the cap is tack-welded to the inner diameter of the vane end wall.

The next step is to align the outer diameter spar cap with the standing rail on the top of the spar insert and tack weld it to the outer diameter vane end wall.

At this point the assembly can be fully welded sealing the insert inside of the vane.

Next, the seal alignment tools should be removed through the portals located in the outer diameter spar cap and the vane assembly should be properly heat treated before proceeding forward.

After the Post-Weld heat treatments are completed the Wedge X-Seal(s) should be installed through the portals located in the outer diameter cap. The two parabolic shaped pieces should be inserted in to the seal slot ensuring the sealing surfaces of the x-seal are properly oriented with sealing surfaces in each slot. After the two "leaf spring" components have been properly inserted; the seal wedge should be driven in between them causing a pre-load on the seal. All seal components are located by inner diameter cap, thus should be fully inserted in to the seal slot. Figure 40: Assembly Cross Section below illustrates a cross section of the assembly during installation.

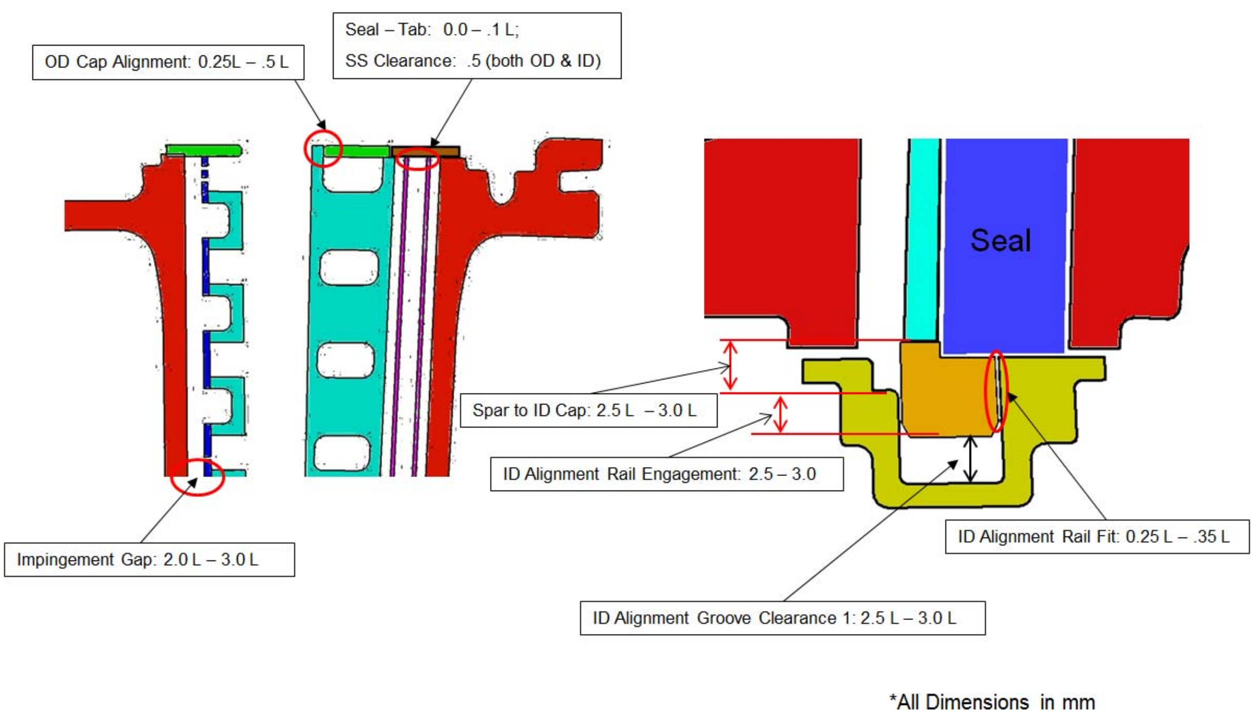


Figure 40: Assembly Cross Section

Finally, the seal plugs should be inserted and subsequently welded at each of seal locations.

5.4.2 Cooling Insert Fixity Scheme

The location of the spar in relation to the vane is important because the seals are not designed to locate the spar with-in the vane. Thus, the spar will need to be located by the outer and inner diameter end walls/platforms. This was accomplished by fixing (welding) the spar at the outer diameter of the vane and by aligning it to the inner diameter of the vane with a radial slip joint. This mechanism can be thought of as a guided cantilever. The main reason for this type of fixity is to allow the vane and the spar to grow independently of each other. Even though the thermal expansion of the 347 stainless steel is larger than In 939, the metal temperature of the vane is such that the vane will grow approximately 1mm more in the radial direction than the spar. The guided cantilever ensures that the spars supporting structures are not subject to large deflections/bending moments and subsequent cracking. A cross-section of the fixity scheme can be seen in Figure 41.

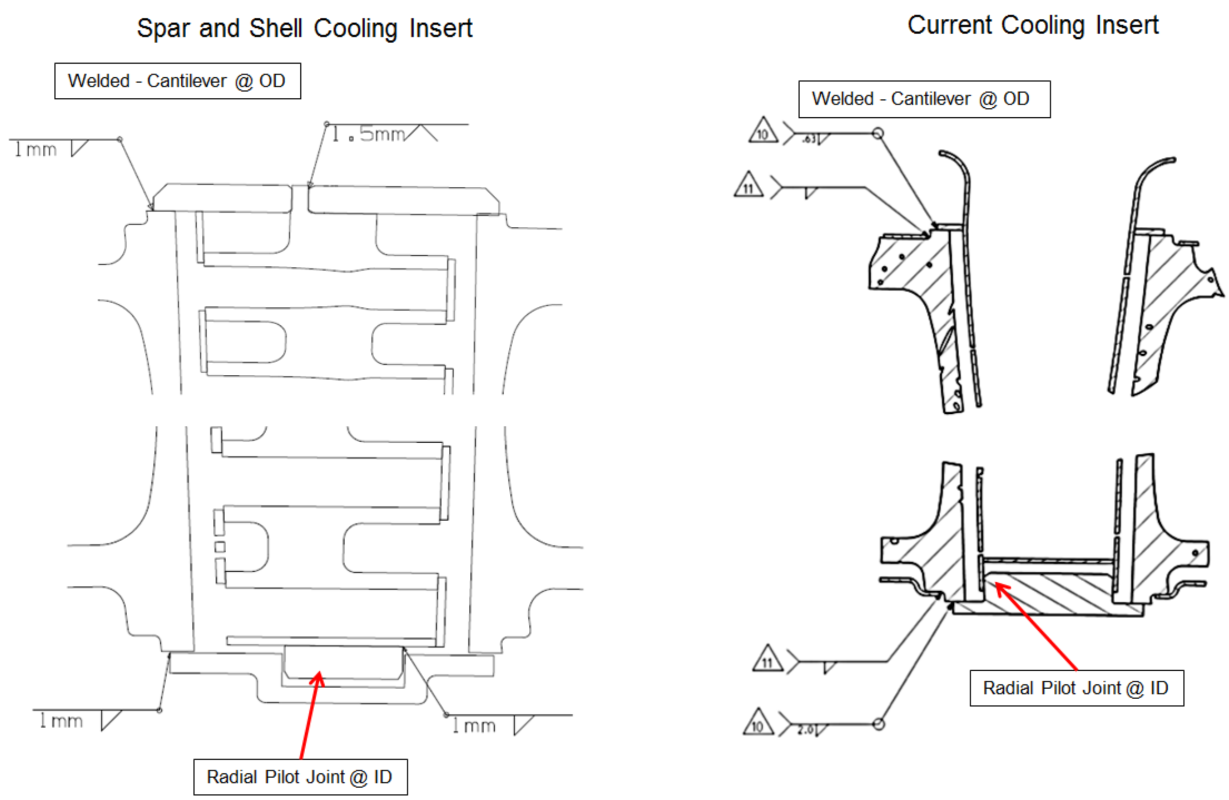


Figure 41: Spar Fixity Scheme

The greatest challenge in designing a mounting scheme for the spar was in developing an installation procedure that properly aligned the radial pilot with the spar. If this alignment feature isn't properly placed, the relative motion between the spar and the vane will be restricted. This could cause cracking of the supporting spar end caps and/or the alignment rails.

To mitigate such an event the following assembly procedure should be used: First, the inner diameter alignment rail should be welded to the inner diameter of the spar. Next, the spar's seal grooves should be machined to match the position of the as cast grooves on the vane. A datum transfer notch has been located at the rib seal groove to help position the spar's seal slots. Using this locating feature, the spar's seal grooves can be properly placed in relation to both the vane's as cast grooves and to each other. Ideally, each as cast groove would be located by its adjacent seal slot, but due to a limited number of datum surfaces.

5.4.3 Critical Fit / Clearances

Proper Fits and Clearances are possibly the most critical aspect to ensuring the design will assemble and function properly. The following clearances are critical to make sure that the spar cooling insert can be properly assembled in to the vane.

First, the spar must be able to fit within the internal vane; this clearance will set the cooling scheme's impingement distance. For this particular test, 3mm has been determined to be optimum distance for heat transfer efficiency.

The second most critical fit is the alignment and position of the seal slots on the vane and the spar. Since the serpentine cooling pattern relies on these seals to separate the different zones, the seal grooves must be closely aligned to minimize cooling air leakage. If the seal leakage is excessive, larger than .5 mm^2 effective gap, then the cooling air will short circuit the cooling scheme and heat transfer efficiency will drop.

Another critical fit/clearance is between the spar's inner diameter alignment rail and the inner diameter mounting cap. Figure 42 illustrates the tongue and groove mechanism serves to limit the amount of cooling air that can circumvent the cooling scheme by flowing underneath the spar instead of through it. The tolerances on the tongue and groove features have been designed to be tight enough (approximately a .5 mm - loose fit) to create a tortuous path, encouraging the air to flow through the spar.

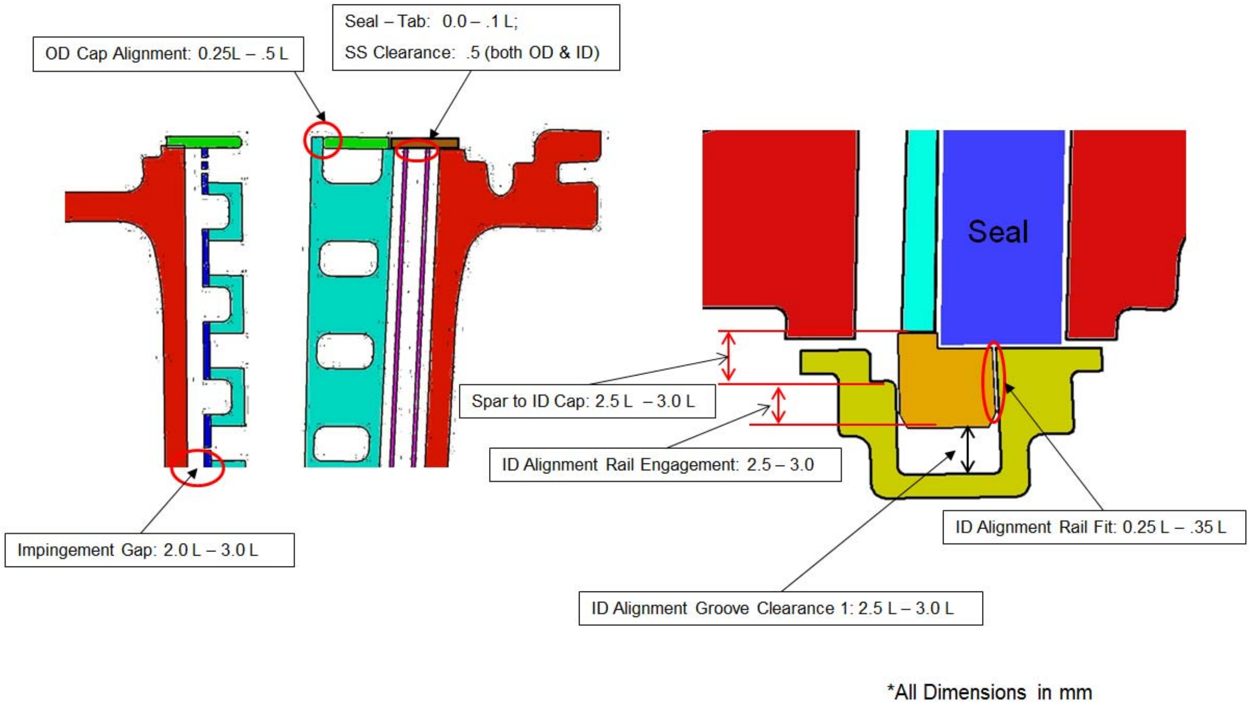


Figure 42: Spar Inner Diameter Alignment

Not only is it important to align and position the seal grooves properly, but it is also critical that the seal properly fit into the grooves. Due to the large amounts of thermal excursions experienced during operation, the seal must be flexible and compliant enough to endure this type of environment. The seal was designed to have an interference fit of .3 mm which should provide enough pre-load force to ensure the seal doesn't lift off the sealing face when pressurized. Since this interference causes the seal to yield during assembly, the additional leakage caused the profile tolerance of the as cast seal surface should be minimal.

The last and most critical fit is the seals within the slot provisions between the spar and the vane. The seal will serve to separate the internal vane structure in to multiple zones, thus defining the serpentine cooling circuit. Any leakage air around the seals will circumvent the impingement cooling circuit; reducing the effectiveness of the spar and shell cooling design. The target leakage number through the seal (not including seal end leakages) was equivalent to a .127mm effective gap along the length of the seal. Due to the relative movement of the sealing surfaces, it was difficult to design a seal that could meet the leakage requirement. The X or Wedge seal was designed to fulfill this purpose. Many factors were considered such as Vane – Seal slot surface finish & position tolerances as well as the relative movement of the sealing surfaces during transient and steady state excursions. The final seal parameters can be found in Figure 43.

X - Seal Design Parameters				
Material	Yield Strenth @ 25°C (Mpa)	Stress @ Install (Mpa)	% Yeild @ Install	Initial Deflection (mm)
X - 750	615	737	119.84	0.3

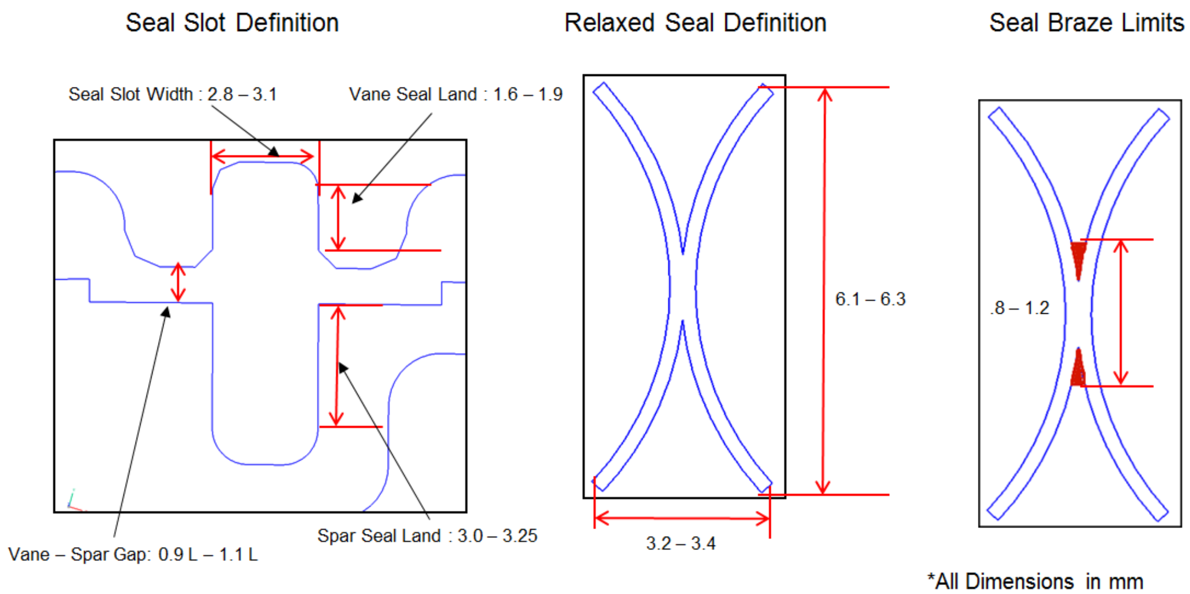


Figure 43: Seal Design Parameters

5.4.4 Final Manufacturing and Fabrication

Both the airfoil shell and spar inserts were manufactured using the investment casting process. In fact, the airfoil shell casting was based largely on the existing airfoil casting having integral endwalls and support features. Only minor modifications of the internal geometry were required to support the sequential impingement spar inserts which were also cast. Figure 44 shows these cast features with the spar castings inserted partially into the airfoil casting.

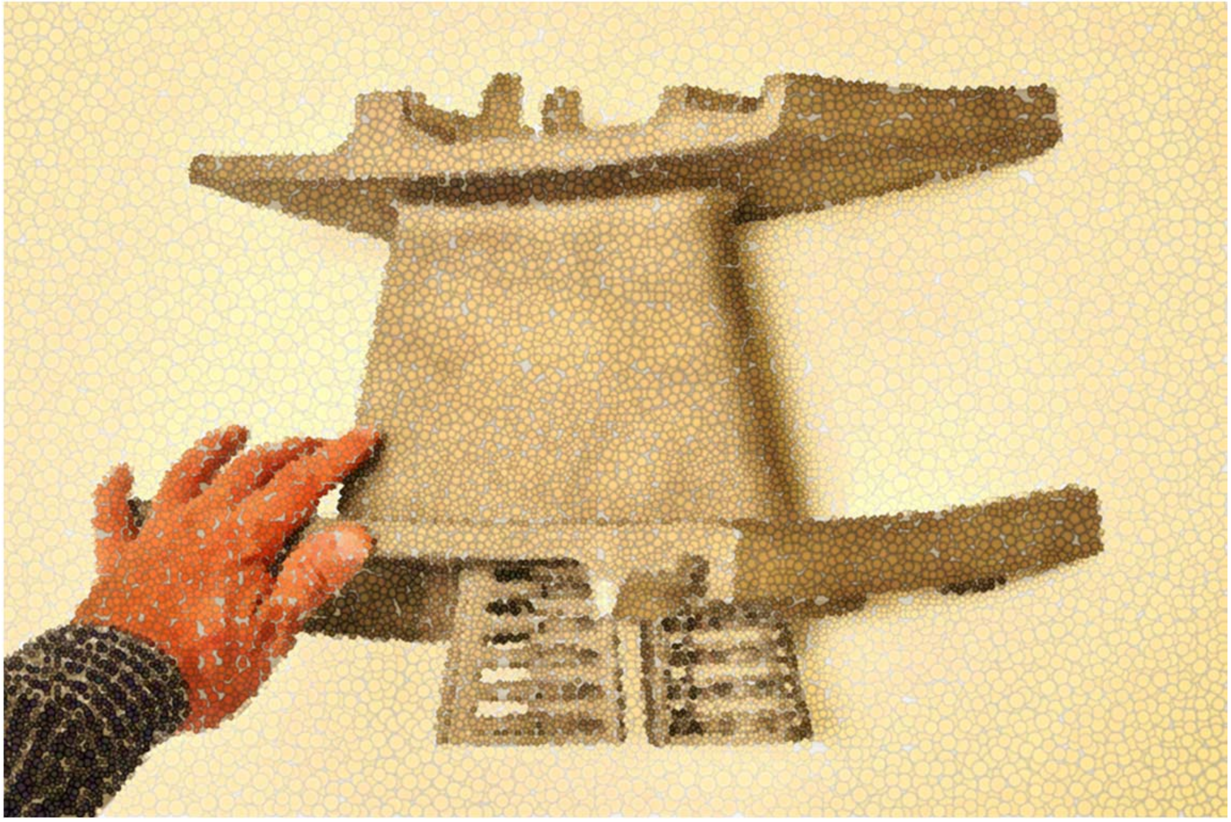


Figure 44: Demonstration Hardware Produced Using Rapid Prototyping Technologies

The spar-shell configuration was designed with a thermal barrier coating on the external surfaces of the airfoil to insulate the structural material from the hot gases that flow around it. However, the engine test schedule and hardware delivery constraints precluded application of such coating to this hardware. Consequently, additional thermal and structural analyses were performed to indicate the magnitude and impact of increased structural temperatures and stresses on the durability of the part and the safety of test in a short-duration full-engine test campaign. Results from these analyses showed the risk of operating these uncoated parts in a short-term test to be reasonable and both FTT and partner Siemens agreed the risk of minor distress, namely local cracking, that might be experienced to be manageable within the context of such a short-term test. Further, the uncoated condition actually gives more confidence in metal temperature measurements because it eliminates the uncertainties associated with TBC thickness and thermal conductivity, which are both variables that would be difficult to ascertain with certainty.

5.5 Engine Test

Four fully-instrumented parts were shipped to Germany for testing within Siemen's Berlin Test Bed. Three parts were actually installed in the engine, and one part was held in reserve, as a spare, and was held at FTT's office in Germany.

5.5.1 Instrumentation

Spar-Shell was highly instrumented with temperature and pressure sensors to permit the design concept to be validated. The lcations and types of instrumentation applied to each part is summarized in Figure 45. Within this plan, each part contains seven (7) thermocouples to measure metal temperatures near the external surface of the airfoils. This instrumentation was installed within grooves with the thermocople junction located near the external surface of the part. Wedge wire was used to hold the thermocouple wires in place and to reestablish smooth and conformal airfoil surfaces. Each part also contained seven (7) internal thermocouples positioned approximately opposite the external metal thermocouples to measure internal coolant temperatures throughoutthe part. Each vane contained five (5) internal static pressure taps to measure the pressure in each of the five impingement cavities. Finally, each vane contained sensors to measure the temperature and static pressure delivered to each vane. These sensors were located in the coolant delivery stream on the O.D. end of each vane.

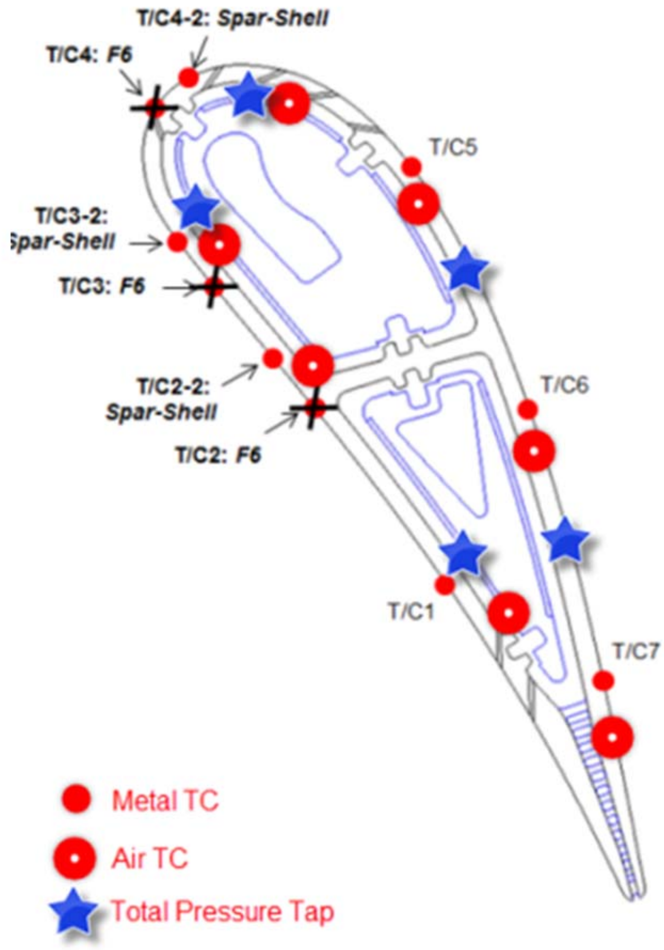


Figure 45: Extensive Instrumentation Installed on Test Articles

Health was monitored (data monitoring and visual borescope inspections) during engine test to assure the integrity of the hardware.

All of the sensors were installed in FTT's instrumentation lab, and representative examples of the sensor terminations are shown in Figure 46. In this figure, the thermocouples used to measure external surface metal temperatures are shown in the picture on the lower left, while the internal coolant temperature thermcouples and static pressure taps are shown in the picture on the upper right.

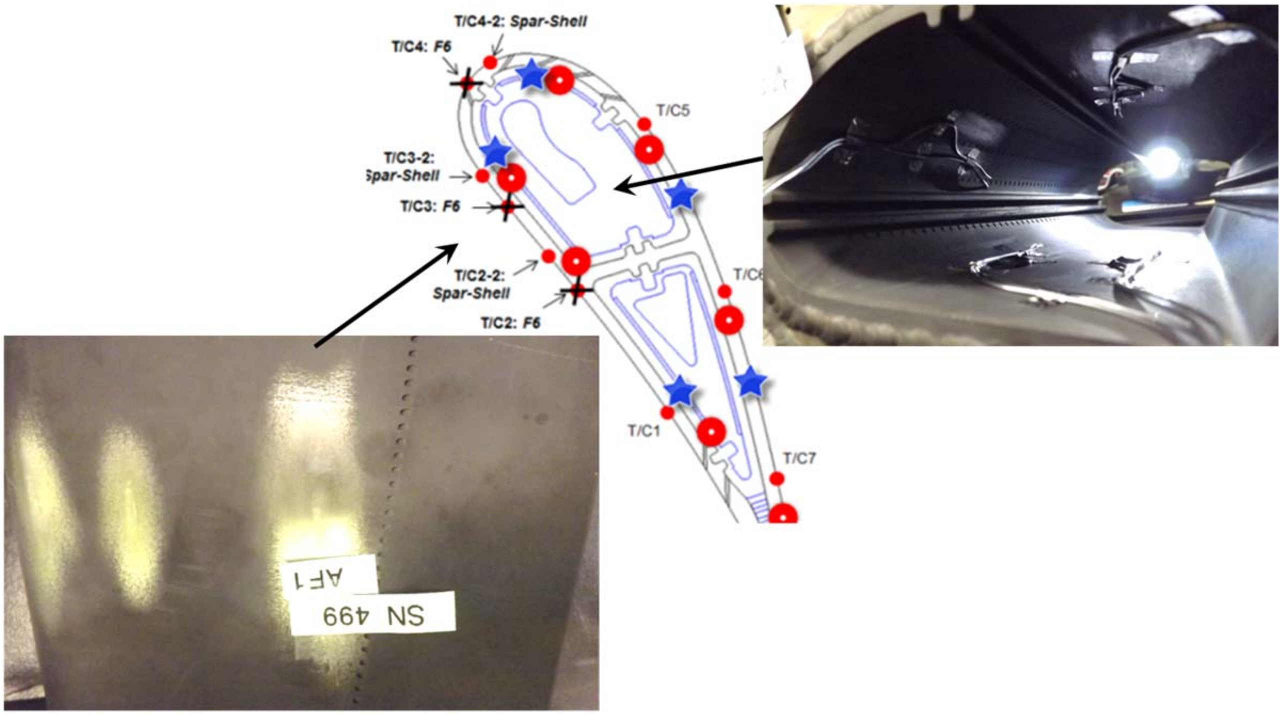


Figure 46: Representative Terminations of Internal and External Sensor Terminations

5.6 Post-Test Data Reduction & Hardware Evaluation

The ARTIC^{TM} concept incorporated in the Spar-Shell vane is meant to provide equvalent levels of part temperatures relative to Siemens’ most recently fielded first stage turbine vanes, but with reduced cooling flow. While the Spar-Shell was originally targeted to reduce cooling flow by 40% relative to the existing state-of-the-art at the time, recent advances of the cooling and coatings technologies of the production equipment limited the cooling flow reduction of the Spar-Shell hardware to about 17% relative to the most-recently fielded hardware. Further, a casting deviation in the trailing edge of the Spar-Shell hardware caused the trailing edges to overflow. To prevent a slip in the delivery schedule of the parts, the casting deviation was accepted for the limited number of Spar-Shell parts produced. Consequently, the Spar-Shell hardware ran in the engine with about 10% flow reduction relative to the other, most-recently fielded configuration, parts in the engine.

The ARTIC^{TM} concept relies on a thermal barrier coating (TBC) to reduce through-wall thermal gradients. Without extensive film cooling, through-wall gradients can be very high without TBC. The present experimental test of Spar-Shell was not meant to be a direct implementation (production release), but rather a concept demonstration and verification of the technology.

Three Spar-Shell vanes were installed in known hotter regions in a particular build (#3) of Siemens 2013/2014 test bed campaign, and testing was completed in the Spring of 2014. The vanes were installed in the top half of the engine as shown in Figure 47. The remainder ofte vanes in the ring consisted of Siemens bill-of-material production hardware. The Phase 3 test duration was 115 hours, of which 25 hours were hot (base load), and there were 65 attempted starts of which 38 were successful. These numbers are relatively typical for a short-duration experimental validation test campaign as was performed for this particular engine build.

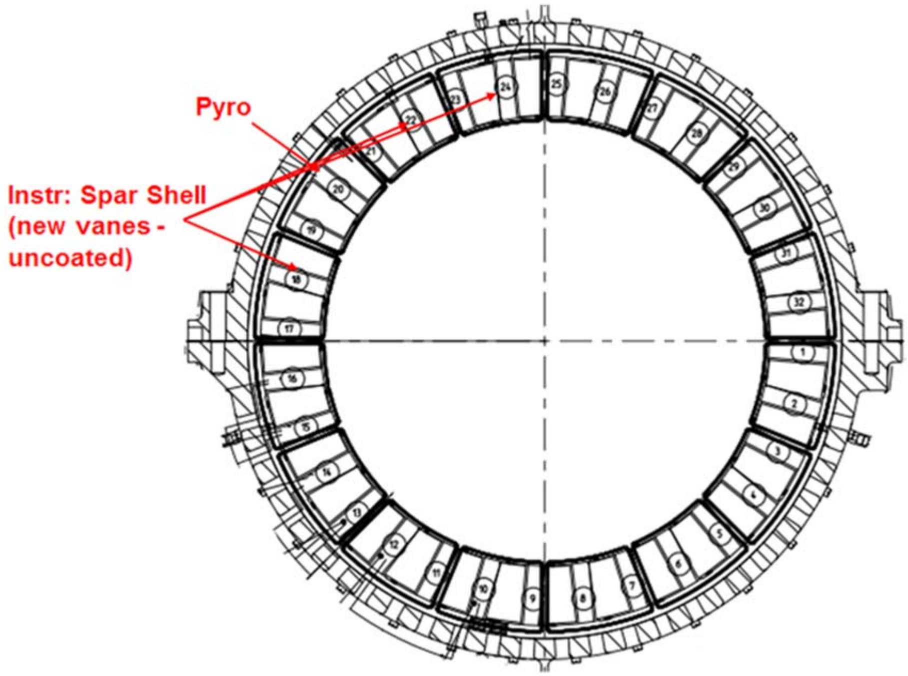


Figure 47: Location of Spar-Shell Vanes in Phase 3 Berlin Engine Test

The entire planned test campaign was completed successfully and the vanes were removed from the engine. At the comletion of the engine test, all of the Spar-Shell pressure and temperature sensors continued to be functional, which is an extraordinary retention rate of instrumentation in an actual engine test.

The typical hardware condition following test is shown in Figure 48 in an "unwrapped" view with the leading edge in the center, the pressure side on the left and the suction side on the right. Worthy of note in this figure is the fact that the leading edge, which contained no showerhead, appears to be in good condition following the test. This reflects a reversal of the trend to cool first stage leading edges by adding more and more cooling flow in showerheads, and it illustrates that a showerhead-less configuration is feasible given the appropriate backside cooling. All of the parts exhibited chordwise thermal stress indications on the pressure side. These cracks are coincident with the internal rib and were precipitated by a thermal fight between the hotter pressure side wall exposed to the hot gases flowing around the airfoil and the cooler internal rib. The thermal fight, and the precipitation of cracks, was exacerbated by the lack of thermal barrier coating on the airfoil. In addition, all of the parts exhibited an oxide scale on the exernal surfaces of the airfoil. These deposits locally flaked-off, or spalled from the pressure side of the airfoil. The increased roughness associated with these areas likely increased the heat load and measured surface temperatures in that region.

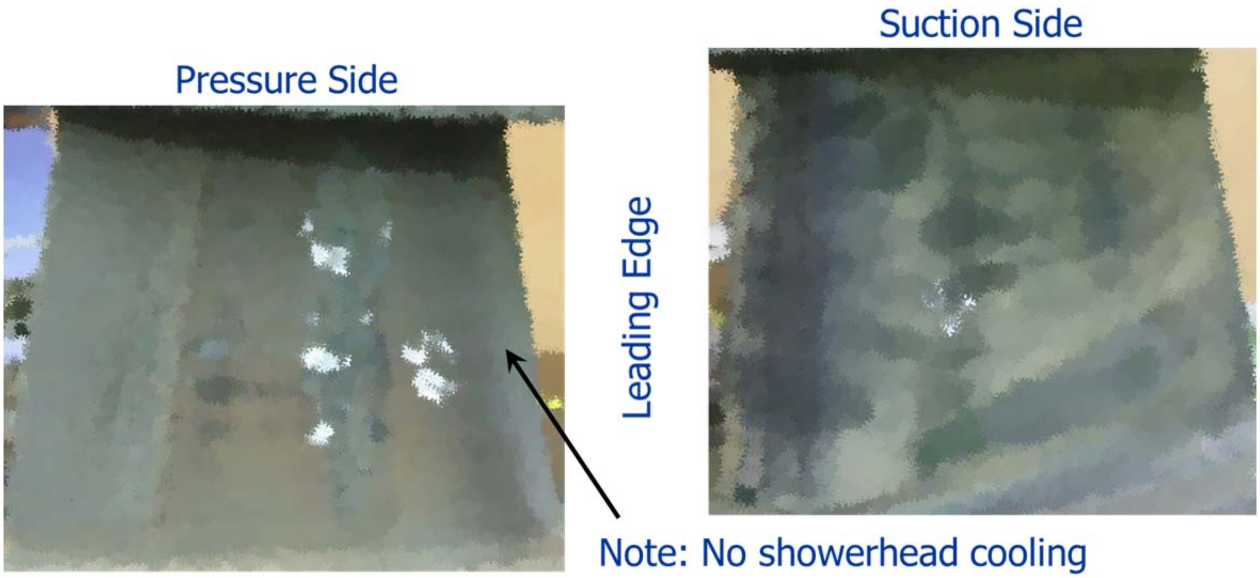


Figure 48: Typical Spar-Shell Hardware Condition Following Test

Measured metal temperatures were generally in good agreement with predictions. A comparison of themeasured temperatures –vs- predictions is shown in Figure 49. As shown, the leadingedge and suction side measured values are very close to the pre-test predictions, while the pressure sidetemperatures tended to operate somewhat warmer than predicted. The exact cause for this difference continues to be evaluated by engineering. As mentioned previously, increased roughness caused by spallation of the oxide scale is one possible contributor to the increased temperatures. Another possible candidate is a difference between the radiation characteristics of TBC and base material. Since these parts did not contain TBC, it is possible that heat loads may have been higher than predicted if the base material absorbs radiant energy better than the TBC. As mentioned previously, the instrumentation survivability was excellent with 100% of the sensors remaining functional at the conclusion of the test campaign.

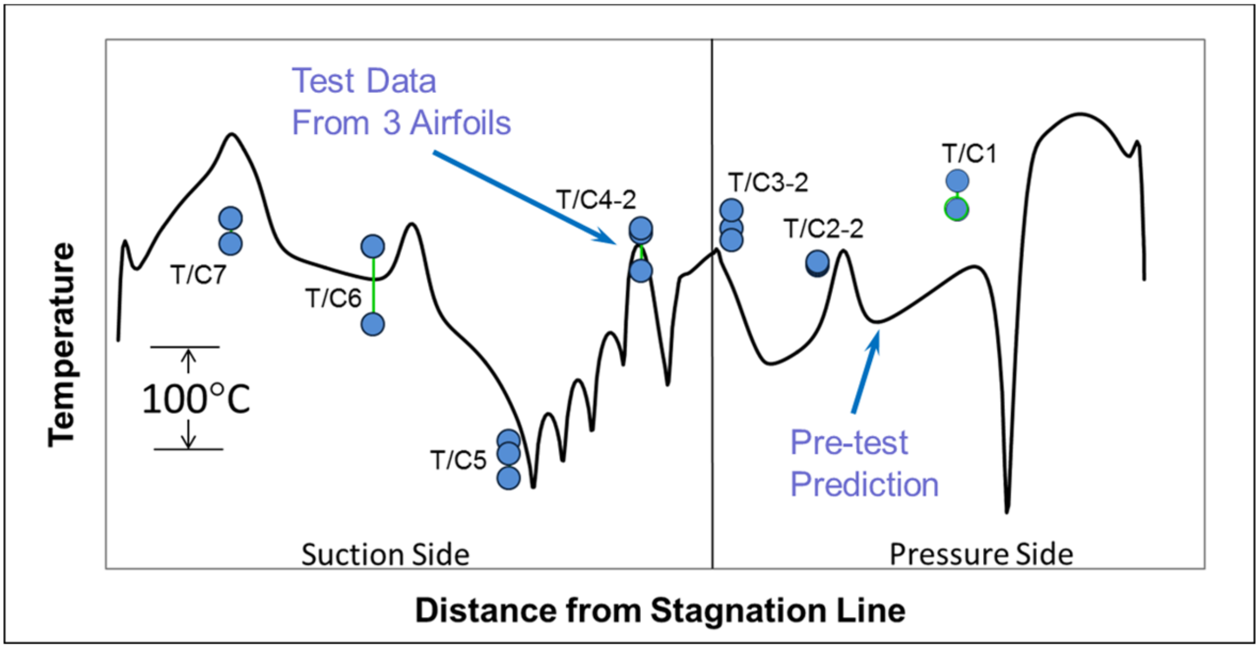


Figure 49: Measured Metal Temperatures in Good Agreement with Predictions

Based on these results, looking forward to productionizing thisconcept for commercial scale, the concept would be optimized by redistributing a small part of the flow from the suction side to the pressure side with no increase of total flow to reduce the pressure side temperatures.

Coolant flow reductions were confirmed by way of pre-test and post-test cold flow measurements. These results also indicated the seals worked well, providing good segregation of the impingement cavities, and the results also showed the seals continued to work well from the beginning to the end of te test.

6 Opportunities for Training and Professional Development

This project provided synergistic opportunities for high skill-level technical training in concert with FTT's ability and capacity for mentoring and training of young engineers. The training is provided by a large number of highly-skilled and experienced gas turbine engineers who have accumulated a wealth of knowledge and first-hand experience pertaining to all aspects of gas turbine design and engineering. This cadre of engineering professionals is uniquely capable of mentoring and training the host of recently-degree'd and new engineers who are accepted as employees into the company. To further enhance this process, FTT employs engineering interns on a regular basis to provide real life experience to future engineers while still in high school or college. FTT has also joined and participates in the Department of Energy – National Energy Technology Laboratories' (DOE-NETL) University Turbine Systems Research (UTSR) program. During the summer of 2011, FTT retained an engineering intern under the UTSR Industrial Fellowship program and now employs this individual full-time. In addition, FTT has since retained three more UTSR Fellows as summer interns and they were utilized to work on a variety of tasks that are of interest to the advancement of power production technologies. This approach has been very successful in building meaningful relationships with universities, screening of potential new-hire candidates and transitioning the first hand knowledge and expertise of experienced FTT engineers to those in academia or who are new to the company.

7 Dissemination of Results to Communities of Interest

An initial summary of work related to Spar-Shell^{TM} projects was presented at the UTSR workshop which was held at the Ohio State University October 25-27, 2011. During this workshop, Jim Downs presented: "Demonstration of Enabling Spar-Shell^{TM} Cooling Technology in Gas Turbines" during a parallel session on aero/heat transfer. During this workshop, Jim also presented a related topic: "Perspectives on R&D Needs for Gas Turbine Power Generation" as part of an Original Equipment Manufacturer (OEM) panel.

The Principal Investigator of this program, Jim Downs, presented a summary overview of the program and its accomplishments at the Department of Energy's (DOE) National Energy Technology Laboratories (NETL) University Turbine Systems Research (UTSR) workshop held on the campus of Purdue University in West Lafayette, Indiana, October 21-23, 2014.

8 New Inventions and Intellectual Property Produced During this Program

Many new inventions have been conceived during the course of this program. A comprehensive list of such patents is summarized in Table 1.

Table 1: New Inventions and IP Produced During this Program

	Title	Inventor	Date Reported	DOE"S" NO.
1	Air cooled turbine airfoil with impingement insert (F1213P)	Russell B. Jones, Judson Krueger	08/10/2012	S-131,114
2	Passively adjustable split air riding seal for gas turbines (F1167)	Robert Memmen, John Fedock, James P. Downs	08/10/2012	S-131,115
3	Radial seal (F1194)	John Fedock	08/10/2012	S-131,116
4	Seal ring test rig (F1196)	Michelle Valentino	08/10/2012	S-131,117
5	Sequential cooling insert for turbine stator vane (F1201P)	Russell B. Jones, Judson Krueger, William Plank	08/21/2012	S-131,118
6	Spring loaded compliant seal for high temperature use (F1167R – 8,556,578)	Robert Memmen, John Fedock, James	10/04/2012 05/07/2014	Same as 2 S-131-115

		P. Downs		
7	Industrial stator vane with sequential impingement cooling inserts (F1218R – 8,500,405)	Russell B. Jones, John Fedock, Gloria Goebel, Judson Krueger, Christopher Rawlings, Robert Memmen	10/04/2012 08/15/2013	S-131-490
8	Machined triple impingement spar (F1201R – 8,684,668)	Russell B. Jones, Judson Krueger, William Plank	12/12/2012 05/07/2014	Same as 5 S-131-118
9	Air cooled turbine airfoil with impingement insert (F1213R)	Russell B. Jones, Judson Krueger	05/23/2013	Same as 1 S-131,114
10	Industrial stator vane with sequential impingement cooling inserts (1218C)	Russell B. Jones, John Fedock, Gloria Goebel, Judson Krueger, Christopher Rawlings, Robert Memmen	08/15/2013	S-134,994
11	Impingement cooling insert for an air cooled turbine stator vane (1218C2)	John Fedock, Gloria Goebel, Judson Krueger, John Ryznic	05/07/2014	S-137,445
12	Sequential cooling insert for turbine stator vane (F1201D)	Russell B. Jones, Judson Krueger, William Plank	05/07/2014	S-137,444
13	Sequential cooling insert for turbine stator vane (F1201CIP)	Russell B. Jones	10/16/2014	
14	Air cooled turbine airfoil with sequential impingement cooling (F1136CIP)	William Plank, James P. Downs, John Fedock	10/16/2014	

9 Conclusions and Recommendations

This program represented a successful advanced technology development collaboration comprised of FTT, DOE NETL and Siemens. The program was executed on an accelerated schedule and successfully leapfrogged the technology from a successful Phase I Small Business Innovative Research (SBIR) program to a pre-production prototype demonstration program. Spar-Shell cooling technology based on sequential impingement was successfully demonstrated in a full-scale industrial gas turbine engine test. Potential commercialization of the technology is pending continued engineering evaluation of the technology and development of a suitable business relationship among the principals of the technology. Finally, a spin-off of the technology for potential use in an aircraft engine has been under development with funding provided by an Air Force Phase I SBIR program (FA8650-13-M-2413), and FTT has recently won and is now under contract to continue development in a Phase II SBIR program.

10 List of Figures

11 Nomenclature

ARTIC^{TM}	Advanced Recirulating Total Impingement Cooloing
DOE	Department of Energy
FTT	Florida Turbine Technologies, Inc.
IGT	Industrial Gas Turbine
NETL	National Energy Technology Laboratory
OEM	Original Equipment Manufacturer
SBIR	Small Business Innovative Research
TBC	Thermal Barrier Coating
UCF	University of Central Florida
UTSR	University Turbine Systems Research

12 Acknowledgements

FTT wishes to acknowledge the Department of Energy (DOE), National Energy Technology Laboratory (NETL), the various program managers and contract administrators for their support and guidance during the course of this program, and in particular, Mr. Rich Dennis, the Turbine Branch Manager. We also wish to acknowledge Siemens Energy for providing the experimental test vehicle to which this program so greaty depended on and for their role as a business and technical partner to assist in the development of Spar-Shell sequential impingement cooling technology.

13 References

1) RPPR-5, "Research Performance Progress Report", Agreement: DE-FE0006696, 31 October, 2012.
2) Project Management Plan, "Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbine", November 15, 2012.
3) ASME Paper GT2013-94469, "Heat Transfer Characteristics of Jet Array Impingement at Low Streamwise Spacing", Roberto Claretti, Jahed Hossain, S.B. Verma, J.S. Kapat, James P. Downs and Gloria E. Goebel, June 3-7, 2013