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GE Energy

High Efficiency Steam Turbines with Ultra Long Buckets

Final Report

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ABSTRACT

The "High Efficiency Steam Turbines with Ultra Long Buckets" program developed and analytically validated the conceptual designs for full-speed 54" steel-hybrid and 62" titanium-hybrid last stage buckets (LSBs). It identified, tested (both environmentally and operationally), and selected candidate lightweight filler materials suitable for steel and titanium LSBs, with extensibility to upstream bucket stages. To mitigate risk and accelerate the introduction of this technology, the project designed and built a full-scale demonstrator 33.5" steel-hybrid LSB, with an advanced 3-dimensional aerodynamic shape that may serve as the basis for the first introduction into service. The project included subscale testing of a stage of 33.5" buckets in the GE Energy Low Pressure Development Turbine (LPDT) facility. Preliminary investigation into high temperature materials was studied to broaden applicability of this technology. Finally, the program assessed the benefits of hybrid bucket technology including bucket/system dynamical tuning, damping and mid-span damping devices.

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Introduction

The goal of this program was to develop a revolutionary approach to last stage bucket (LSB) design, potentially resulting in dramatic improvements in low pressure (LP) turbine section efficiency by as much as 2% to 3%, and Rankine cycle efficiency improvements of up to 0.5%. The eventual introduction of full-speed ultra-long steam turbine bucket technology will set new industry standards in terms of bucket length, section efficiency, cost effectiveness, and turbine output. This program showed that ultra-long steam turbine buckets could be manufactured from hybrid materials comprised of conventional bucket materials (steel or titanium) and rugged lightweight filler materials. The GE Energy and GE Global Research teams used a risk-mitigated approach to develop, mature, and eventually introduce the technology. This was initially accomplished through subscale stage testing and will be eventually followed by the full-scale testing as a retrofit within an existing steam turbine.

Coal-fired steam turbines account for approximately 50% of the total power generating capacity in the United States. When steam turbines used in combined cycle applications are taken into account, steam turbines account for more than 60% of total US generating capacity. Therefore, significant improvement in Rankine cycle efficiency will dramatically reduce fuel costs and emissions and help provide low-cost, environmentally acceptable power generation, as the existing steam turbines are replaced or improved. One high-impact, cost-effective approach to improving Rankine cycle efficiency is technology advancement that maximizes low-pressure (LP) turbine efficiency, since the LP turbine section generates about 50% of the total power output of a large steam turbine in a central power plant.

LP turbine efficiency is a function of the aerodynamic design of the steampath and exhaust hood and can be characterized by total exhaust loss, which provides a measure of the energy remaining in the steam as it leaves the LP turbine section. Total exhaust loss is affected by aerodynamic design of the LSB, the exhaust annulus area, condenser backpressure, and overall mass flow. Longer LSBs directly support a larger annulus area. Increased annulus area also enables configuration changes from four-flow to two-flow machines, which are inherently more efficient by having less seal leakage. Bucket length is limited by the mechanical strength of the materials used to manufacture the bucket. As length increases, bucket weight increases, as well as stresses in the bucket and at the attachment point on the rotor due to centrifugal loading. Conventional materials constrain the bucket length to approximately 48 and 54 inches, respectively, in the 50 Hz market (40" and 45" in the 60 Hz market) – due to aeromechanical constraints buckets are designed at discrete lengths.

The use of hybrid bucket materials will enable the design of a new class of lightweight ultra-long buckets that have advanced aerodynamic profiles, which together, maximize LP turbine efficiency. This technology can be used in all steam turbine product applications – industrial, combined cycle, Integrated Gasification Combined Cycle (IGCC), sub critical, super critical, and ultra super critical applications. The development of lightweight ultra-long buckets will expand design space and revolutionize the ability to produce next generation turbine designs. The introduction of ultra-long buckets, incorporating advanced aerodynamic design technology in LP turbine sections, will improve section and cycle efficiency, thereby, minimizing emissions, and reducing life cycle operating costs.

This 24-month program was comprised of five strongly interrelated technical tasks.

Task 1.0 – 54" Steel-Hybrid Bucket Design: This task developed a conceptual design for an ultra-long 54" steel-hybrid configuration developed from concurrently active inputs from Task 3. This bucket demonstrated the ability to use conventional steel in last stage bucket applications to go beyond current steel bucket lengths. Included in the conceptual design were subtasks (1) Airfoil and Hybrid Definition and Optimization, (2) Steady State Stress and Life Estimation, and (3) Aeromechanics Analysis.

Task 2.0 – 62" Titanium-Hybrid Bucket Design: This task developed a conceptual design for an ultra-long 62" titanium-hybrid configuration. This bucket demonstrated the ability to use titanium in last stage bucket applications to go beyond current titanium bucket lengths. Included in the conceptual design were subtasks (1) Airfoil and Hybrid Definition and Optimization, (2) Steady State Stress and Life Estimation, and (3) Aeromechanics Analysis.

Task 3.0 – Hybrid Materials and Process Development: Initial steel-hybrid material system was specified resulting in a material with a high fatigue margin and a relatively low temperature capability (330°F). Testing of subscale buckets using this material system was completed in Task 5. A flexible composite caul sheet matching the expansion of the steel substrate was developed to result in a net finished edge and corrected for material shrinkage to maintain aerodynamic shape. The requirement for materials with a higher temperature capability (>600°F) was identified. This will expand the application space for off-design operation and upstream stages. Project scope was revised to assess feasibility of high temperature materials for this application. Two candidate polyimide composite materials were identified. Adhesion systems were developed to attain cohesive failure and 4 times improvement in single lapshear adhesion strength. Risks for the high temperature material were identified for residual strength after thermal aging and residual stress, and mitigation strategies were identified.

Task 4.0 – 33.5'' Steel-Hybrid Prototype Development: This task provided the "Early Technology Demonstration" of a steel-hybrid bucket design, including fabrication processes, using retrofit advanced aerodynamic design of an existing GE Energy 33.5 inch LSB. This technology can be used to incorporate advanced 3-dimensional aerodynamic profiles to airfoil geometry leading to significant component and system efficiency improvements. The main subtasks were (1) 3-demensional Aerodynamic Redesign for a 33.5" Airfoil, (2) Advanced Analytical Design Methodology Development, (3) Mechanical Design of 33.5" Steel-Hybrid Bucket, (4) Steady State Stress and Life Estimations, and (5) Aeromechanics Analysis.

Task 5.0 – Test Validation of Sub-Scale Steel-Hybrid Bucket: This task demonstrated the durability of the steel-hybrid LSB in an actual steam turbine environment. Testing was performed in a modern subscale low pressure turbine test facility and included the full effects of centrifugal loading; hot & wet steam conditions; various mass flow rates; and high and low backpressure conditions. The test program was designed to validate the material life while exposed to hot & wet steam conditions, as well as to measure the system's natural frequencies and mechanical damping. Subtasks included (1) Design and Fabrication of Subscale Steel-Hybrid 33.5" LSB's, (2) Subscale Testing of these buckets in the GE Energy LPDT facility and (3) Post-Test Data Reduction and Component Evaluation.

Executive Summary

During the period from 1 October 2003 to 30 September 2005, GE made significant progress in the development of full-speed ultra-long buckets for high efficiency steam turbines. Tools, design methodology, and hybrid material systems were developed. Operational testing of the endurance of the initial material systems was completed. Program results during this period were reviewed with DOE-NETL staff in Morgantown, WV on 20 October 2004 and 21 November 2005. The work completed under this program will be discussed in detail in this report. A high level summary of this work is provided in the following paragraphs.

Task 1.0 – 54" Steel-Hybrid Bucket Design: Using a scale-up of an existing GE Energy 45" titanium last stage bucket (LSB) design, a conceptual design for a 54" steel-hybrid LSB was developed. Tools developed in Task 4 were used to define rib and pocket topology resulting in a single outboard pocket design. Pocket tapers were optimized to maximize polymer adhesion. The overall weight savings was 7%. A UniGraphics model was developed and was used for finite element modeling to determine stresses and natural frequencies. Modeling analysis determined that the predicted stresses exceeded GE's design practice allowable stresses although natural frequencies were acceptable. A mechanical design study was conducted to understand the effect on stress through the modification of vane section stacking and hub section area. The modification of the hub section area helped lower the average section stress but it will compromise the efficiency of the blade. A new aerodynamic design will be required to make the 54" the longest steel hybrid blade possible.

Task 2.0 – 62" Titanium-Hybrid Bucket Design: The pocketing tool developed in Task 4 was first enhanced to allow for more flexibility in the definition of the geometry of the pocket. The tool was then used to complete the conceptual design of a 62" titanium bucket scaled-up and modified from an existing GE Energy 45" titanium LSB design. Initial mechanical design evaluations indicated that the predicted stresses did not meet design practice requirements. A one-dimensional analytical expression was then developed to estimate the ideal cross-sectional area distribution needed to meet the stress design requirements. This analytical expression was employed to appropriately scale the 62" aerodynamic design to develop a titanium-hybrid bucket with a single outboard pocket. The resulting design met design practice requirements for stress and natural frequencies. The scaling methodology developed can be applied to both the steel and titanium buckets. The overall weight savings was 7%.

Task 3.0 – Hybrid Materials and Process Development: Initial steel-hybrid material system was specified resulting in a material with a high fatigue margin and a relatively low temperature capability (330°F). Testing of subscale buckets using this material system was completed in Task 5. A flexible composite caul sheet matching the expansion of the steel substrate was developed to result in a net finished edge. Additionally, through the subscale test it was learned that a higher temperature epoxy primer should be used for the Steam Turbine application of the Hybrifil3 material. The requirement for materials with a higher temperature capability (>600°F) was identified. This will expand the application space for off-design operation and upstream stages. Two candidate materials were identified. Work scope was added to the program to permit evaluation of these materials as well as the development of adhesion systems.

Task 4.0 – 33.5'' Steel-Hybrid Prototype Development: Tools to optimize pocket design based upon stress limitations were developed using UniGraphics and ANSYS. These tools were used to design an advanced 3-dimensional aerodynamic design 33.5" steel-hybrid last stage bucket. This blade design consisted of single outboard pocket having a "wide chord" profile that had a larger tip section relative to the root section. This "wide chord" feature allowed for the reduction of bucket count by one-half, providing for a significant cost savings in terms of material and manufacturing. The predicted improvement in the group efficiency of the last three stages of the LP turbine is greater than 1%. This design can be applied to both "finger" or curved axial entry style dovetails and therefore can be applied to retrofit designs. To mitigate risk and to accelerate the introduction of this technology, a single 33.5" full-scale bucket based upon this advanced design was manufactured.

Task 5.0 – Test Validation of Sub-Scale Steel-Hybrid Bucket: A subscale validation test was completed in the GE Energy Low Pressure Development Turbine (LPDT). The buckets used in this test were based upon an existing GE Energy 33.5" LSB design. Steel-hybrid buckets were designed with two pockets resulting in a weight savings of 13.5%. The resulting design met design practice requirements for stress and natural frequencies. Eight buckets (4 steel-hybrid & 4 baseline) were instrumented with strain gages and thermocouples. A total of 106 endurance hours were completed, including a 105% overspeed run. Borescope inspections were conducted at 20 min, 10 hrs, 50 hr, and 100 hrs. During the first 50 hours of testing, there was no visible degradation of polymer material. During the last 32 hours of high temperature testing, one bucket experienced loss of the inboard hybrid pocket material. Records show that this was the first manufactured bucket. A root-cause-analysis (RCA) was conducted to understand the failure mechanism. Evaluation showed that an adhesive failure had occurred. It was determined that the primer used was not capable of the high temperature test points. There are other primers that are capable of the higher temperatures up to 330F. Throughout the test program, strain gages responded as predicted and showed that the steel-hybrid and baseline buckets had a similar dynamic response.

Results and Discussion

The results of the program are presented on a separate task basis in this report. Detailed task results are discussed for each active subtask, as appropriate, for activities during this program. An overview section has been included to clarify each task's (and subtask's) intentions, and to aid the understanding of the program.

<u>Task 1.0 – 54" Steel-Hybrid Bucket Design - Status / Discussion</u>

Overview: This task developed a conceptual design for an ultra-long 54" steel-hybrid configuration developed from concurrently active inputs from Task 3. This bucket demonstrated the ability to use conventional steel in last stage bucket applications to go beyond current steel bucket lengths. Included in the conceptual design were subtasks (1) Airfoil and Hybrid Definition and Optimization, (2) Steady State Stress and Life Estimation, and (3) Aeromechanics Analysis.

Aerodynamic design: The aerodynamic design is a scale of a 45" 60hz LSB. The same aerodynamic shape is currently used to design the bucket in titanium. The use of less expensive hybrid material steel/polymer will demonstrate the potential cost saving for equivalent stage efficiency. This bucket will be used on 50Hz units, the inner radius diameter is 66.67 inches, and the preliminary design uses 70 buckets in the stage (Figure 1).

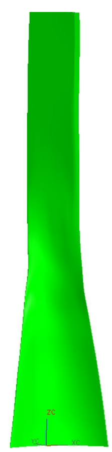

Figure 1 - 54" Steel-Hybrid: Aerodynamic Design

Structural design: The 54" aerodynamic design operates in the L-0 (last row) row of 50-hertz machines. The row, as analyzed, consists of (70) buckets with continuous ties in both the tip (snubber cover, Figure 2a) and the mid-span (winglet, Figure 2b). The design features to connect the buckets have been successfully implemented on the analytical design of the 33.5" advanced aerodynamic design bucket (Task 4 of this report). The dovetail was not modeled, as both vane stresses and natural frequencies are only secondarily affected by the dovetail design. It will need to be a curved axial entry dovetail; which is the current design of choice for the long buckets. Details of the design process flow and methodology are reported in Task 4 of this report.

(a) (b)

Figure 2 - 54" Steel-Hybrid: Design Features (a) Winglet; (b) Snubber Cover

FEA model details: Figure 3 shows details of the finite element (FE) model used to perform the analysis. The multiple interface/attachment regions of the bucket tip/snubber cover and mid-span winglet are featured. Snubber cover and winglet meshes do not change with the pocketing definition, allowing those components to be meshed just once at the start of the process.

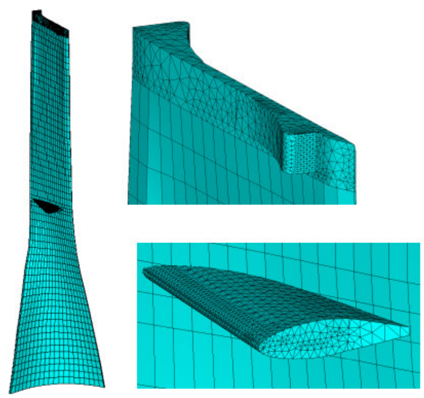

Figure 3 - 54" Steel-Hybrid: Detailed Mesh - Static & Cyclic Symmetry Analysis

As shown in Figure 4, the snubber cover connection is done at both leading and trailing edge of the bucket. The model is built in a way that connection is established and no contact elements are used. In essence, the cover is in contact and not free to move at zero RPM. In reality as the rotor speed gradually increases, the airfoils untwist under the centrifugal load and the snubber cover structure deforms. The contact between adjoining buckets starts to become established at about half speed. Given their complexity, it is not known exactly how strong the connections are in each joint before the rotor reaches full speed. In the approach used to model this design, as full speed is achieved, the snubber cover comes in contact with the adjoining buckets and thereby forms a 360^{o} continuous linkage ("continuously coupled").

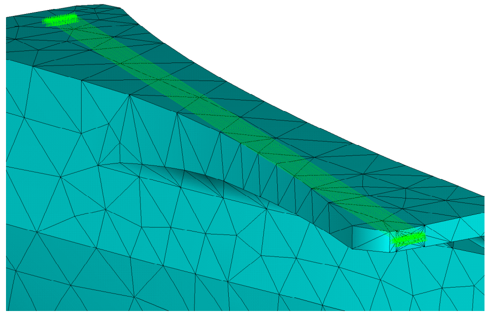

Figure 4 - 54” Steel-Hybrid: Snubber Cover Connection

Hot geometry and small deformation is used as it is consistent with the geometry of the bucket at speed and it simplifies the problem. Although deformations are computed, the mesh is not updated. The final hybrid bucket design is dependent on properly modeling the hot to cold geometry, along with contact at the contact interfaces. Current assumptions though are reasonable for preliminary design.

To model the bucketed disc at full speed, a small number of selected nodes were connected at both interfaces. For both the snubber cover and winglet, mid line contact is assumed with all degrees of freedom coupled (Figure 5). All degrees of freedom are fixed at the base of the bucket.

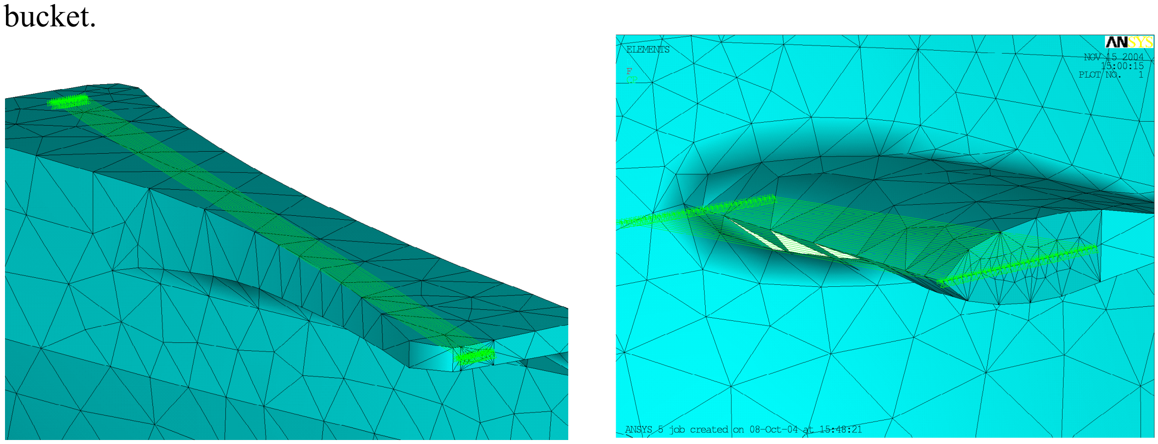

Figure 5 - 54” Steel-Hybrid: Detailed Boundary Conditions Snubber Cover, Winglet

The weight density applied to the bucket and disc was 0.283 lb/in^3 and the elastic modulus was assigned at 29 ksi. An angular velocity of 3000 RPM was defined to establish centrifugal forces at operating speed. The steady steam bending force was calculated based on original stage data and is negligible compared to centrifugal loads. Design limits for static and frequency analysis were specified by GE’s design practice.

Static analysis results: Average section stress limits were not achieved with a single outboard pocket. A second pocket in the inboard section of the bucket was not implemented because the average section stress with one pocket was already too high. The level of stresses is mainly due to bending stresses; which increase as the pocket depth increases. Two options to modify the airfoil geometry were studied. The first option was to stack the vane section area to provide a position aligned with the center of rotation and avoid large bending stresses in the outboard section. This solution did not significantly decrease the average section stress. The second solution was to increase the vane section area below the winglet and provide more stress support. This solution significantly reduced the average section stress. Unfortunately increasing the area hub vane section decreases the aerodynamic performance of the blade. A 50% area vane hub section was chosen as a compromise between average section stress and aerodynamic efficiency. Despite the improvement from the original aerodynamic design, the average section stress still remained below the GE's design practice limit. The results presented below are for the best possible outboard pocket design using an increased vane section area below the winglet.

An optimum weight reduction of 7% and a root average section stress reduction of 9.5% were achieved with the single outboard pocket. It is a considerable but insufficient reduction, as the average section stress for the solid bucket is above the limit.

The static analysis clearly shows that there are bending stresses in addition to the centrifugal stresses. As the pocket is deepened, the center of gravity is further displaced toward the suction surface, providing for increased bending stresses. The pocket is at the minimum wall condition from the top part of the pocket to 85% of the bucket length. From 85% of the bucket length to the end of the pocket (above the winglet) the back wall thickness increases (Figure 6). The pocket is deeper on the leading edge side of the bucket because of additional airfoil thickness as compared to the trailing edge.

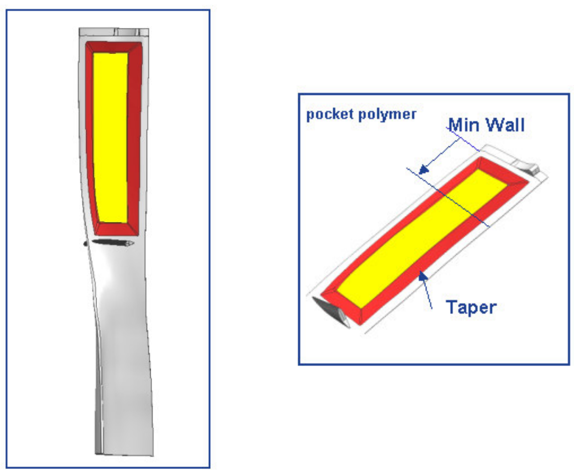

Figure 6 - 54" Steel-Hybrid: Optimum Pocket Design

It is important to note that the design process could not deepen the pocket at the trailing edge because of peak stress constraints.

A large elastic stress occurs in the vane toward the leading edge of the bucket. The high stresses at the cover are due to the assumed boundary conditions. High stresses in this region then are not real and not considered in the pocketing definition.

Where local stress exceeds the yield strength of the material, stress relaxation caused by plasticity in these sites would occur. The amount of relaxation is not factored into the results. However, the overall magnitude of equivalent stress suggests that they would likely be significant in terms of influencing the low cycle fatigue (LCF) life of the buckets. The potential rate of LCF damage produced by these stresses will be addressed later.

Natural frequency analysis at 3000 rpm: Based on the motion of the buckets about the circumference of the disk, the resulting vibration modes were categorized as families of tangential modes, axial modes, torsional modes and higher order modes. Because of the phase relationship between individual buckets, there are 36 nodal diameters (including nodal diameter 0) in each mode family for a stage with 70 buckets.

The natural frequencies were evaluated at 3000 RPM (50Hz). The optimum design wasn't achieved; therefore, those results are only qualitative.

As noted, all modes indicate a +10 hertz margin from the nearest forcing except Mode B, which has a 2.3% margin for the 5 nodal diameter mode, Mode C, which has a 5.8% margin for the 6 nodal diameter mode, Mode D, which has a 0.02% margin for the 8 nodal diameter mode and Mode F, which has a 4.2% margin for the 10 nodal diameter mode. A wheel box test is needed to validate the prediction for the higher modes at higher nodal diameters. This higher mode and higher nodal diameter are generally difficult to excite.

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Task 2.0 – 62" Titanium- Hybrid Bucket Design – Status / Discussion

Overview: This task developed a conceptual design for an ultra-long 62" titanium-hybrid configuration. This bucket demonstrated the ability to use titanium in last stage bucket applications to go beyond current titanium bucket lengths. Included in the conceptual design were subtasks (1) Airfoil and Hybrid Definition and Optimization, (2) Steady State Stress and Life Estimation, and (3) Aeromechanics Analysis.

Aerodynamic design: The aerodynamic design is a scale and modification of a 45" titanium 50 Hz LSB. The use of less expensive hybrid material (polymer) with the longest titanium blade in the industry will demonstrate the potential of hybrid technology by providing higher power output for the low pressure turbine. This bucket, as analyzed, is used on a 50Hz unit, the inner radius diameter is 40 inches, and uses 70 buckets in the stage (Figure 7).

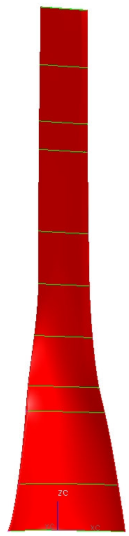

Figure 7 - 62" Ti-Hybrid: Vane Aerodynamic Definition

The scaling of a 45" titanium blade to 62" wasn't aerodynamically designed to obtain a hybrid bucket design with an average section stress below the allowable. In an attempt to obtain a feasible design, an analytical mathematical expression was developed to optimize the area distribution of blade vane section. The results obtained showed that an increase of the vane section area by 5% from the analytical solution below the winglet was sufficient to design a titanium 62" hybrid blade. One outboard pocket was designed using the tool developed in Task 4 with a 7% weight reduction.

Structural design: The 62" aerodynamic design operates in the L-0 (last row) row of 50-hertz machines. The row consists of (70) buckets with continuous ties in both the tip (snubber cover, Figure 8b) and the mid-span (winglet, Figure 8a). These design features to connect the buckets have been successfully implemented on the analytical design of the 33.5" advanced aerodynamic design bucket (Task 4 of this report). The dovetail was not modeled, as both vane stresses and natural frequencies are not affected by the dovetail design. It will need to be a curved axial entry dovetail; which is the current design of choice for the long buckets. Details of the design process flow and methodology are reported in Task 4 of this report.

Figure 8 - 62" Ti-Hybrid: Design Features (a) Winglet; (b) Snubber Cover

FEA model details: Figure 9 shows details of the finite element (FE) model used to perform the analysis. The multiple interface/attachment regions of the bucket tip/snubber cover and mid-span winglet are featured. Snubber cover and winglet meshes do not change with the pocketing definition, allowing those components to be meshed just once at the start of the process.

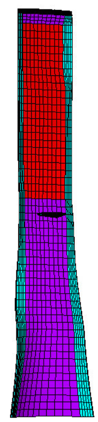

Figure 9 - 62" Ti-Hybrid: Detailed Mesh - Static & Cyclic Symmetry Analysis

As shown in Figure 10, the snubber cover connection is done at both leading and trailing edge of the bucket. The model is built in a way that connection is established and no contact elements are used. In essence, the cover is in contact and not free to move at zero RPM. In reality, as the rotor speed gradually increases, the airfoils untwist under the centrifugal load and the snubber cover structure deforms. The contact between adjoining buckets starts to become established at about half speed. Given their complexity, it is not known exactly how strong the connections are in each joint before the rotor reaches full speed. In the approach used to model this design, as full speed is achieved, the snubber cover comes in contact with the adjoining buckets and thereby forms a 360^{o} continuous linkage ("continuously coupled").

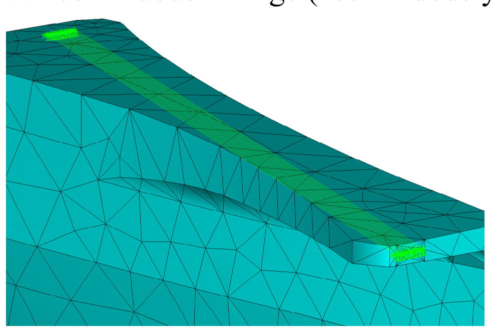

Figure 10 - 62" Ti-Hybrid: Snubber Cover Connection

Hot geometry and small deformation is used as it is consistent with the geometry of the bucket at speed and it simplifies the problem. Although deformations are computed, the mesh is not updated. The final hybrid bucket design is dependent on properly modeling the hot to cold geometry, along with contact at the contact interfaces. Current assumptions are reasonable for preliminary design.

To model the bucketed disc at full speed, a small number of selected nodes were connected at both interfaces. For both the snubber cover and winglet, mid line contact is assumed with all degrees of freedom coupled (Figure 11). All degrees of freedom are fixed at the base of the bucket.

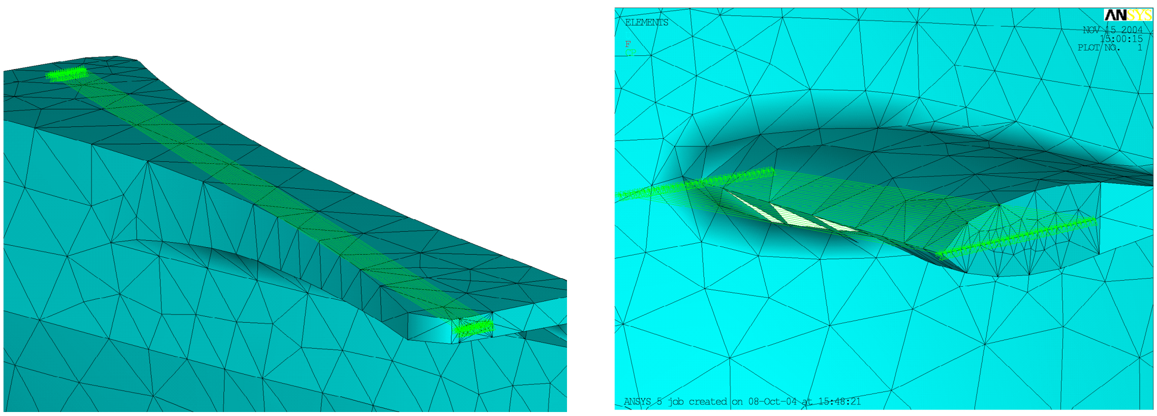

Figure 11 - 62" Ti-Hybrid: Detailed Boundary Conditions Snubber Cover, Winglet

The weight density applied to the bucket and disc was 0.283 lb/in^3 and the elastic modulus was assigned at 29 ksi. An angular velocity of 3000 RPM was defined to establish centrifugal forces at operating speed. The steady steam bending force was calculated based on original stage data and is negligible compared to centrifugal loads. Design limits for static and frequency analysis were specified by GE's design practice.

Static analysis results: Preliminary mechanical analysis indicated that the 62" did not meet design practice requirements for strength. A 1-D analytical expression was developed to estimate the ideal cross-sectional area distribution needed to meet the stress design limit requirements. This analytical expression was implemented in an Excel spreadsheet to estimate the scale factor needed as a function of radial location to meet the design practice. The scale factor necessary to meet design limits was applied to each cross-sectional profile of the solid blade below the mid-span winglet (Figure 12).

The pocketing tool was then used to optimize the design for a single out-board pocket. Scaling methodology developed can be applied to both the steel and titanium buckets. The optimized pocketed blade is shown in Figure 13. This task successfully demonstrated a 62" titanium-hybrid conceptual design. An optimum weight reduction of 7% was achieved. The resulting design met design practice requirements for stress.

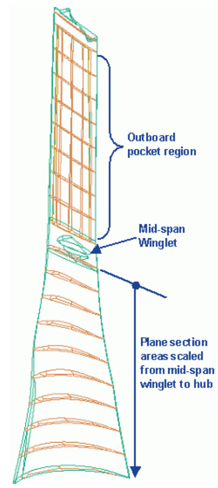

Figure 12 - 62" Ti-Hybrid: Area Scaling Below The Winglet

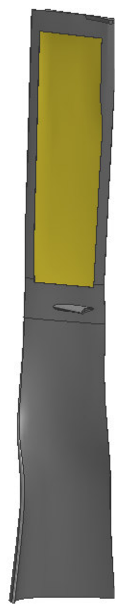

Figure 13 - 62" Ti Hybrid: Optimum Pocket Design

It is important to note that the design process could not deepen the pocket at the trailing edge because of peak stress constraints.

A high elastic stress occurs in the vane toward the leading edge of the bucket. The high stresses at the winglet are due to the assumed boundary conditions. High stresses in this region then are not real and not considered in the pocketing definition.

Where local stress exceeds the yield strength of the material, stress relaxation caused by plasticity in these sites would occur. The amount of relaxation is not factored into the results. However, the overall magnitude of equivalent stress suggests that they would likely be significant in terms of influencing the low cycle fatigue (LCF) life of the buckets. The potential rate of LCF damage produced by these stresses will be addressed later.

Natural frequency analysis at 3000 rpm: Based on the motion of the buckets about the circumference of the disk, the resulting vibration modes were categorized as families of tangential modes, axial modes, torsional modes and higher order modes. Because of the phase relationship between individual buckets, there are 36 nodal diameters (including nodal diameter 0) in each mode family for a stage with 70 buckets.

The natural frequencies were evaluated at 3000 RPM (50Hz). The optimum design wasn’t achieved therefore those results are only qualitative.

As noted, all modes indicate a +10 hertz margin from the nearest forcing except Mode A, which has a 9.2% margin for the 2 nodal diameter mode, Mode C, which has a 0.3% margin for the 5 nodal diameter mode, Mode E, which has a 1.6% margin for the 8 nodal diameter mode and Mode F, which has a 1.7% margin for the 9 nodal diameter mode. This higher mode and higher nodal diameter are generally difficult to excite. Use of composites or rib geometry can be used to alter the higher mode frequencies in the outer panel. Additionally, a wheel box test is needed to validate the frequency prediction. The wheel box test will validate not only the frequency but also the connection type at the cover and the winglet between adjacent blades.

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Task 3.0 – Hybrid Materials and Process Development - Status / Discussion

Overview: This task identifies rugged, lightweight (<2.0 g/cc) filler materials and corresponding processes and adhesion systems to meet the requirements for Steam Turbine's ultra-long bucket applications, for both steel and titanium construction. Materials testing will provide allowable stresses for design and analysis. The material and adhesion system will meet requirements for density, fatigue, erosion, temperature, interfacial stress, corrosion, deformation, and moisture. This project builds on GE's extensive experience related to the development of an aircraft engine titanium-hybrid fan bucket. The primary differences for steam turbine applications are the life expectancy (30 years vs. 20 years), adhesion to steel, moisture and erosion, and exposure to ammonia.

Materials and process development for bonding to titanium airfoils was matured under prior GE programs and is documented in US patents US6544002B1, US6454536B1, US6431850B1, US6290895B1, US6287080B1, and US6282786B1.

All tests to evaluate adhesive and material durability show significant margin. Hot/wet and exposure to ammonia show no degradation in lap shear strength. LCF tests at 4 times the anticipated stress ran out at greater than 100,000 cycles. Thermal aging tests indicate that the Hybrifil material should last 30 years at 150°F if the maximum temperature does not exceed 285°F. If the higher modulus Hybrifil 3 is used, the maximum service temperature capability can be increased up to 330°F. Low angle (20°) water erosion tests indicate ~2 times increase in erosion capability with the Hybrifil 3 over Hybrifil. This can be further improved if an epoxy/fiberglass composite layer is bonded onto the Hybrifil 3 surface. Hybrifil 3 showed improvement over Hybrifil in all areas.

Process optimization efforts to the baseline process developed in 2004 include the introduction of a glass fiber reinforced composite caul sheet and a masking material to reduce surface roughening in the areas outside of the pockets during the etching and surface preparation process. Surface preparation durability tests were also evaluated indicating that the part may be left in 100% RH for up to 2 weeks in a dust free environment after etching and/or priming without degrading adhesion. Further assessment on the robustness of the surface preparation procedures indicate that plating tape can be used to protect the non-bonded surface of the metal airfoil during the etching process without degrading adhesion and exposure of primed surfaces to air shipping prior to bonding does not degrade adhesion. To mitigate risk and to accelerate the introduction of this technology, a single 33.5" full-scale bucket with advanced aerodynamic geometry was fabricated using the new caul sheet. The resulting part showed smooth transition between the metal and Hybrifil at the pocket edges and no irregularity on the Hybrifil surface due to cure shrinkage.

600°F capable, low-density polyimide/glass composites were evaluated and adhesion systems were developed to increase adhesion by a factor of four and enable cohesive failure odes. Residual stresses were assessed using bi-material strips to determine that reduction in residual stress is possible by reducing glass fiber content in the composite. Aggressive thermal aging in air was performed to determine that there was minimal impact on tensile modulus, but that tensile strength was reduced by. Further funding will be required to understand the impact of thermal aging on the design and assess the material under more realistic environment (vacuum and thermal cycling).

Discussion: This task builds extensively on prior GE efforts on materials and process development for Hybrid fan bucket technology and prior internal efforts on hybrid LSBs for steam turbines. Based on these efforts a GE patented formulation (ref. Hybrifil Patent) for a toluene-diisocynate-ether urethane (Hybrifil) was selected as a starting point for low cost, robust manufacturing, as well as for adhesion and environmental resistance.

Materials tests were performed to address the key material requirements:

- Adhesion (~200 psi shear strength requirement identified through FEA analysis)
- Hot/wet environmental resistance at 100%RH and 125-150°F steady-state temperature
- Fatigue
- Ammonia in water spray to minimize steel corrosion
- Maximum temperature spikes during low flow windage
- Thermal aging (30 years)
- Water erosion

Materials and process development for bonding to titanium airfoils was matured under prior GE programs and is documented in US patents US6544002B1, US6454536B1, US6431850B1, US6290895B1, US6287080B1, and US6282786B1.

Prior GE efforts identified Chemlok 213 primer (from Lord Chemicals) and HF/nitric acid etch (described in the Experimental section Task 3) as a primer and surface preparation procedure for stainless steel that provided 150°F lap shear adhesion strength that is 10 times the shear stress requirement of 250 psi. Tests also indicate that Hybrifil is insensitive to environmental effects. A week immersion in 150°F water and 1-week immersion in 150°F water with 1-ppm ammonia did not degrade the lapshear strength.

Low cycle lapshear fatigue tests were run at 150°F for Hybrifil on stainless steel (GTD450) and on titanium (Ti-6Al-4V) at 0.5Hz and r-ratio of 0.05. Except for one specimen, all tests were run outs (>100,000 cycles) at greater than 4 times the anticipated running stress.

Thermal aging tests were performed with Hybrifil where the lapshear specimens were exposed to temperatures ranging from 180°-300°F for 1-12 week intervals. Hybrifil exhibits no degradation after 12-week exposure until the temperature exceeded 270°F. In fact, the strength shows an increase for 180°F exposure. This is a phenomenon we have noticed before. Hybrifil will continue to cure, and its strength will continue to increase up to a point before the strength starts to degrade. Note that the 270°F data after 2 weeks of exposure exhibits the highest strength. Owing to this non-equilibrium behavior (in these short term tests), the effects of short term aging and degradation cannot be de-convoluted. Data at higher temperatures (>270F) do show the expected strength vs. time behavior and are representative of the worst-case scenario in the scope of these tests. For these temperatures, the following procedure can be used to estimate the durability as a function of temperature.

The following procedure was used to estimate durability as a function of temperature:

1. Log fits were used to determine equations for lap shear strength (s) as a function of time (t in years) at 270°, 285°, and 300°F exposures.

2. The above equations were solved to determine time required to reach 250 and 1000 psi respectively at each temperature.

3. An Arrhenius expression can be used to fit the data points for 250 psi and 1000 psi to generate the following relationship to estimate life in years (t), as a function of temperature (T) in °R:

If we assume the turbine will see one hour of low speed windage every other day for 30 years at 250 psi, that would lead to an estimate of 285°F as an upper temperature limit.

There is currently no spec limit on the erosion (because the pocketed area is out of the area that typically sees erosion); so, this test was performed to determine if there are risk abatements that may be introduced in the event erosion is found to be a problem in the field.

Two potential methods that may be used to improve low angle erosion capability:

1. One approach is to use a higher modulus version of Hybrifil that we will call Hybrifil 3. This uses the same chemistry, toluene-diisocyanate-ether urethane, but starting with a lower molecular weight system to increase cross-linking and stiffness. The resulting modulus is 18 ksi compared to 12 ksi with Hybrifil. This increase in stiffness and hardness reduced the erosion.

2. Another approach that may be used is to bond a fiberglass composite to the top surface of the Hybrifil that resulted in further improvement in erosion resistance. However, this is a less desirable approach as it means another step in manufacturing.

Additional advantages of Hybrifil 3 are summarized in Table 1. It has lower density as well as higher modulus which results in lower Hybrifil to steel interfacial stresses caused by centripetal loads. Most important of all, lapshear adhesion strength is 75% higher than Hybrifil, and it has higher thermal stability. Aging Hybrifil 3 at 330°F still resulted in higher strengths than aging Hybrifil at 285°F. Based on these advantages, GE decided to focus on Hybrifil 3 as the primary filler for this program in 2004.

Table 1 - Hybrifil Comparison

Property	Hybrifil	Hybrifil 3
Density (g/cc)	1.2	1.15
Modulus (ksi)	12	18

Hybrid LSB Hybrifil Process – In production, the metallic portion of the Hybrid LSB will be forged and the pockets, such as the one shown in Figure 14, will be machined in during the final airfoil machining step.

Figure 14 - Machined Pocket: 33.5" Advanced Aerodynamic Design Hybrid LSB

Grit Blast:

1. Mask off areas adjacent to pockets for protection during grit blasting
2. Rinse with distilled water – use water break check to inspect for grit residue on bond surface.

Stainless Steel Etch:

1. Wipe buckets solvent or immerse in solvent in ultrasonic bath for 30 minutes
2. Mask surfaces outside of bond areas with plating tape
3. Immerse in Stainless Steel Etch solution for desired time at desired temperature
4. Immerse in hot distilled water for 1–2 minutes
5. Immerse in room temperature distilled water for 1 minute
6. Rinse with room temperature distilled water
7. Remove plating tape
8. Place in rack and dry in oven overnight
9. Wrap loosely and protect from dust if priming operation cannot be performed immediately. Priming operation should be completed shortly after etching.

Figure 15 - Surface of Primed Pocket (Prior to Hybrifil Filling)

Prime Pockets in Steel Hybrid LSB:

1. Primer: Apply primer with spray gun (see Figure 15). Figure 16 shows an overview of the casting and curing process.
2. Dry in oven
3. Wrap loosely and protect from dust if filling operation cannot be performed immediately. Filling operation should be completed shortly after priming.

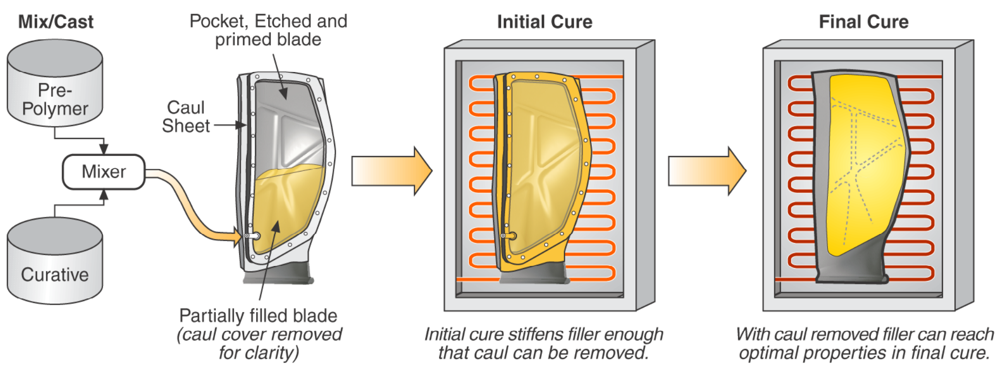

Figure 16 - Casting and Curing of Hybrid LSB

Fabrication:

1. Apply mold release to caul sheet and allow drying for one-hour minimum.
2. Clamp composite caul sheet to Hybrid LSB and preheat (see Figure 17)

Figure 17 - Caul Sheet Partially Clamped on the Bucket

3. Add pre-polymer into Part A tank and curative into Part B tank in heated mixer dispenser equipment (See Appendix II for example specification of acceptable mixing/dispensing equipment)
    a. Allow urethane and curative to preheat and degas in tanks.
4. Prepare urethane for casting
    a. Check for correct ratios from mixer dispenser
    b. Check for correct flow rate to ensure filling operation is completed in less than 2 minutes. If filling takes more than 2 minutes, Hybrifil 3 will start to gel inside pocket and block flow.
5. Check temperature on preheated LSB. Remove from oven and insulate LSB to minimize heat loss during filling operation. If temperature is outside of this range, there is potential for shrink back and cracking to occur.
6. Fill part from bottom of pocket to facilitate air removal through vent at top of caul sheet (see Figure 18).

Figure 18 - Bucket Standing Upward during the Hybrifil Filling Operation

7. Place LSB into oven to cure to green state
8. Remove caul sheet carefully and place LSB back in oven for post cure
9. After post cure remove LSB from oven (see Figure 19)
10. Gently trim excess if needed with hand held belt sander
11. Hybrid LSB may be assembled into a turbine at this time

Figure 19 - Pocket Filled with Hybrifil after Caul Sheet Removal

Surface Preparation Durability – The surface preparation procedure and durability was assessed using lapshear. The durability of the etch process was checked by waiting 1 week and 2 weeks respectively before priming. The samples were also placed in a container during this time to protect them from dust and particles. One set was also placed inside a closed container over water to represent 100%RH. The same procedure was also used to check for durability of the surface after priming. Results indicate that there are no detrimental effects over 2 weeks even with 100% humidity.

Another check on the surface preparation includes the effect of using plating masking tape adjacent to the bonding surface during etching operation. Allowing the use of plating masking tape minimizes surface roughening caused by the immersion etching process outside of the bond area. This eliminates the need to re-polish the steel surface to maximize aerodynamic efficiency of the bucket.

A third check on the surface preparation process involved the effect of air shipping the parts after priming. Airfreight could potentially have a more detrimental effect on the surface than ground shipping because of temperature changes during shipping and potential for moisture condensation. Lapshear specimens were etched and primed in Niskayuna, NY, placed inside a sealed bag, then air freighted to Cincinnati, OH. Parts were dried at 210°F for minimum one hour prior to bonding. There is no degradation in adhesion from air shipping.

High Temperature Material Feasibility Study

In view of the Hybrifil 3 material disbond during the final elevated temperature LPDT testing performed under Task 5 to assess high temperature risk, GE revised this task to include assessing feasibility and risks of using newly commercialized polyimide composites with glass transition temperatures greater than 600°F. Three specific criteria need to be satisfied for feasibility of using a polymeric material for windage conditions up to 600°F include:

1. Thermo-oxidative stability:
    a. The material should be able to withstand highest spike temperatures of 600°F. Assuming 1 hour of windage every week for 30 years, the total time spent at 600°F will be 1560 hrs.
    b. As the load (power output) of the turbine fluctuates, the stress on the blade and the temperature fluctuate too. Fatigue and thermal cycling need to be addressed.
    c. Testing to understand properties:
        i. Tensile testing
        ii. Fatigue tests
2. Adhesion to steel: The polymer needs to adhere well to the bucket metal (GTD450 grade steel). Lap shear testing allows the measurement of the adhesive shear strength. Apart from measuring lap shear strengths (on 1” X 1” coupons), it is important to understand the residual stresses induced in large panels due to the CTE mismatch between the polymer and the steel bucket. We have developed a model to understand the stresses induced due to CTE mismatch and curing of the polymer next to a steel plate.
3. Water erosion: Water droplets hit the face of the blade with high velocity and water erosion test allows the measurement of resistance to water erosion.

Tensile testing of the two selected materials show good stability at elevated temperatures. Lap shear measurements show that appropriate surface treatment can maximize the adhesive capability. Residual stress measurement was carried out on thin sandwich layers and verified using computer modeling. Initial fatigue testing in bending mode was carried out. Water erosion, complete effects of aging and thermal cycling will be conducted with future funding.

Materials selection:

Figure 20 shows the qualitative merits of various material classes considered for this application. Larger area indicates better material for this application. Metallic foams have the highest temperature capability. However, they rated very low in the rest of the attributes. Polyimides were the next in terms of temperature capability and had reasonable rating for the other properties.

However, polyimides are inherently brittle and reinforcement is used to impart strength. A prepreg (ready-to-mold material in sheet form which may be cloth, mat, or paper impregnated with resin and stored for use) with an 8 harness satin S2 glass weave was selected for optimum properties and ease of lay-up. Two resin systems: RP46 (developed by NASA) and AFRPE-4 (developed by the US Air Force) were selected. Both resins have been developed as replacements for the well-known, PMR15 class of materials. PMR15 monomer includes carcinogens and is banned from use in new applications in USA. RP46 and AFRPE-4 prepregs were obtained from YLA and Cytec Corp. respectively.

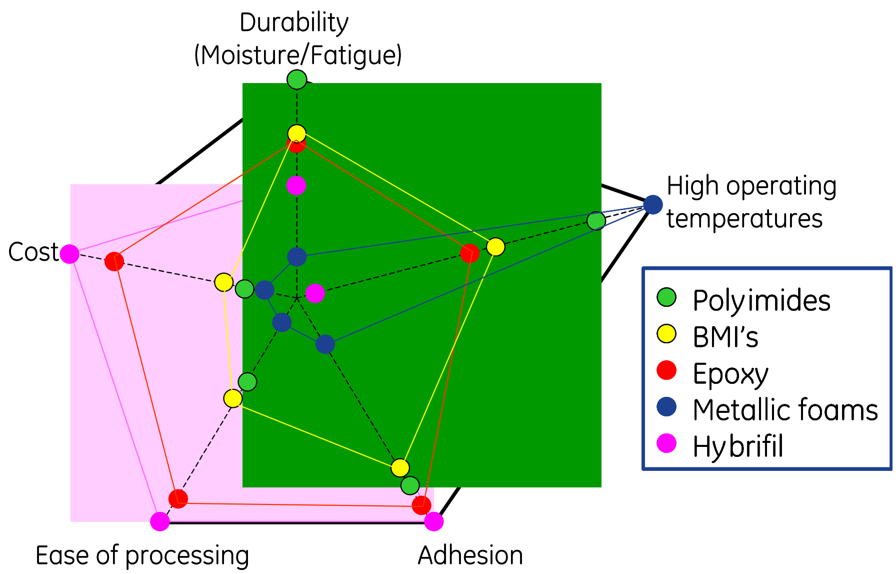

Figure 20 - Various Classes of Materials Qualitatively Classified

There are two basic steps in curing of polyimide resins – (1) imidization taking place between 350-410°F: during this step, the amine and the anhydride react to form an imide and this product is capped with the capping agent, and (2) crosslinking taking place between 570-610°F: this step involves the crosslinking of the imide oligomer at the end caps. Both these steps involve release of water and low alcohols as byproducts. The chemistry of RP46 resin is well known and published in open literature. Figure 21 is a schematic showing the reaction steps involved. The structure of AFRPE-4 has not been verified, Figure 22 lists the reactive monomers. To maximize the shelf life, both resins are stored at 0°F.

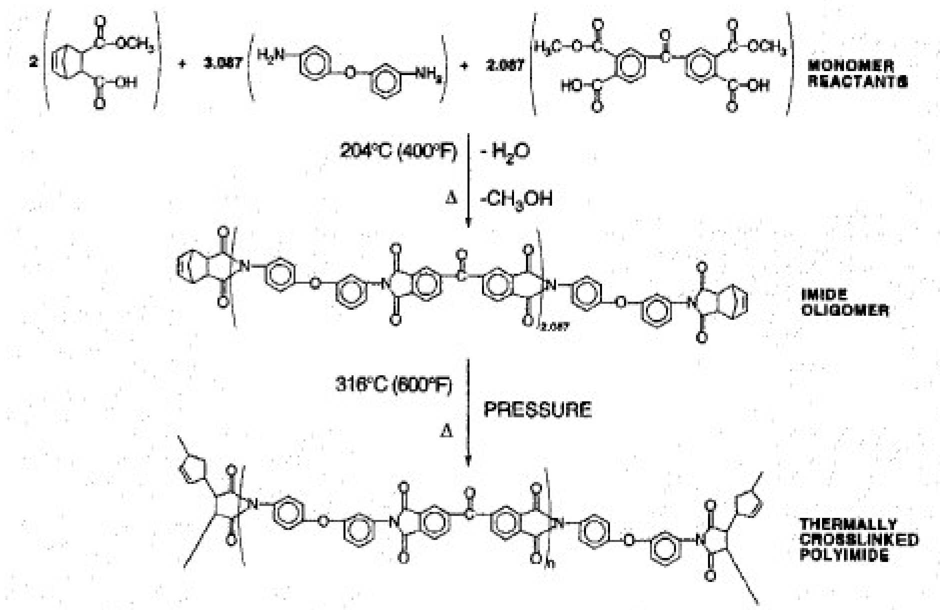

Figure 21 - Resin Monomers and Reaction Chemistry for RP46

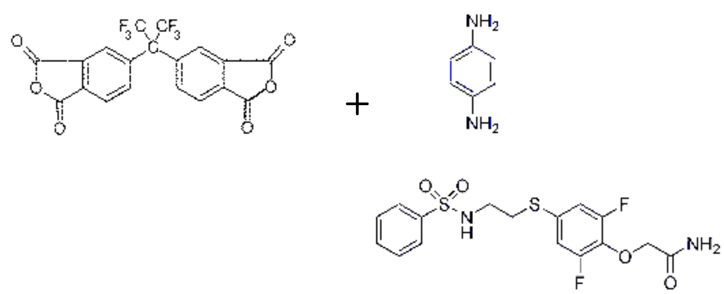

Figure 22 - Reactive Monomers in AFRPE4

Materials processing:

For optimum properties, the gaseous byproducts of polymerization need to be removed completely (to avoid porosity). Applying a high vacuum or high-pressure help release these products. The latter requires an autoclave and typical pressures of 200-250 psi. An autoclave necessary for achieving these pressures at high temperatures was not available for this project. It was decided to compression mold the prepregs with simultaneous application of high vacuum (using a Kapton vacuum bag). This process is shown schematically in Figure 23.

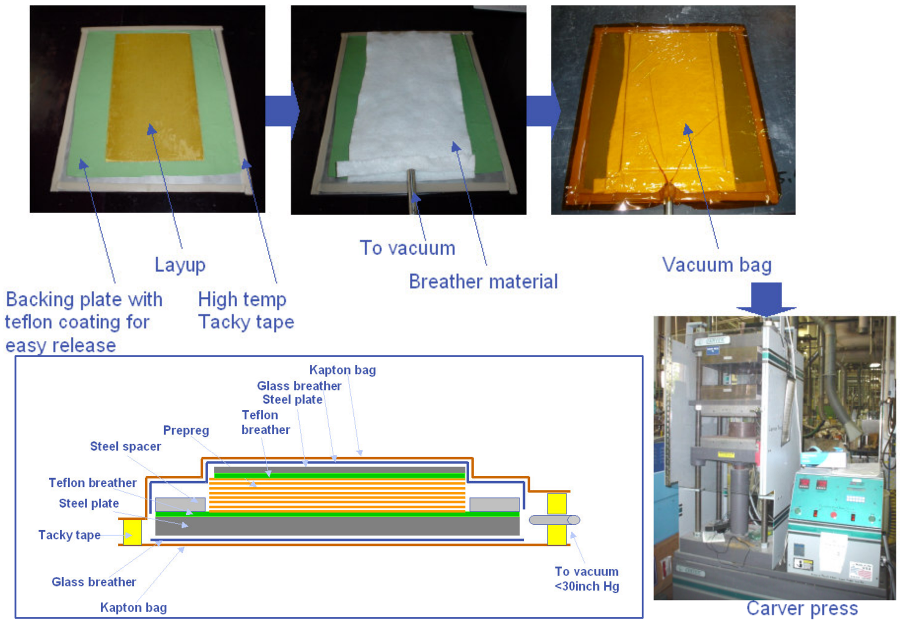

Figure 23 - Lay-up and Bagging Sequence for Compression Molding

A cure cycle suggested by the supplier was initially used (see Figure 24). However, high porosity was observed (see Figure 25). To reduce porosity and improve properties, dynamic mechanical rheology was used to determine the temperatures and times optimum for compaction. Slight modifications to the supplier suggested cure cycle greatly reduced the porosity (see Figure 26). Although some porosity can still be observed, this was the best achievable compaction and taken to be standard for all testing. Typical hand lay up consisted of 8 plies of the prepreg (8 inches × 8 inches), followed by vacuum bagging. Care was taken to ensure that the directionality of the woven fibers was maintained.

After increasing time for imidization, two other variables were used to optimize the processing of the prepregs into test samples: pressure and cooling rate. The optimal pressure and cooling rate was determined so that optimum properties in a reasonable time period.

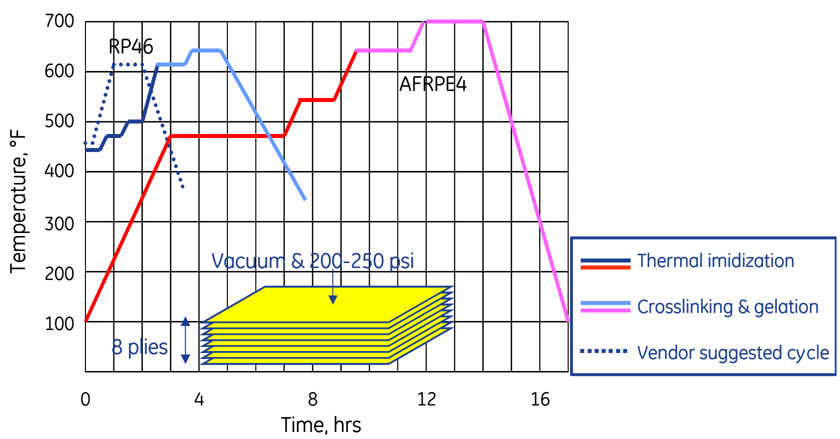

Figure 24 - Cure Cycles Suggested by Manufacturer for RP46 and AFRPE-4

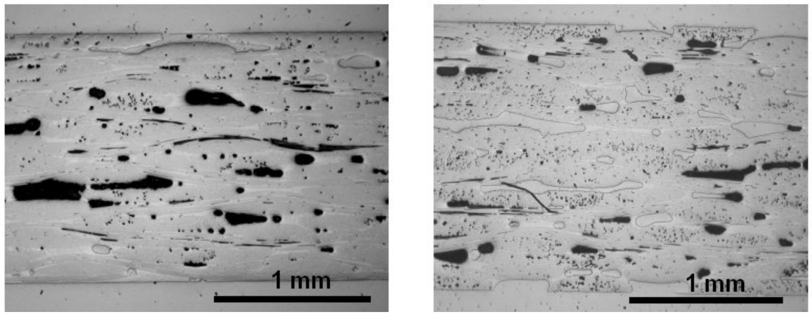

Figure 25 - Cross Sections of RP46 and AFRPE-4 using Supplier Suggested Cure Cycles

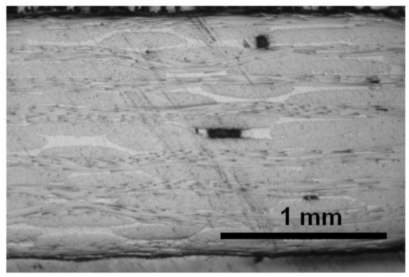

Figure 26 - Cross Section of RP46 Laminate Molded using Modified Cure Cycles

Material characterization

Materials characterization not only serves to test the material durability, but also feeds into the simulation and design of the bucket and the turbine. Table 2 summarizes the material testing results.

Table 2 - Mechanical Testing Results for RP46 and AFRPE4 Laminates

Property	Units	Orientation/condition	RP46 Avg	AFRPE4
Modulus	Msi	11	5.7	5.4
		12 Wet	5.7	4.6
		22	4.9	5.0
		23 Wet	5.1	4.6
Poisson's ratio		12	0.128	0.116
		12 Wet	0.114	0.069
		23	0.111	0.086
		23 wet	0.109	0.067
CTE	uin/inF	11	3.4	2.6
		22	4.0	3.3
		33	31.1	22.2
T_g (Dry)	F	DMA, tanδ	675	833
T_g (Wet)			615	725

Both materials performed well at all given temperatures up to 600°F (see Figure 27). Even the hot/wet samples exhibit high UTS and stiffness values (>50 ksi). AFRPE-4 performs better than RP46 at higher temperatures and under hot/wet conditions, which would be expected given the dry and hot/wet Tg of both materials was found to be higher than 600°F. This is favorable since many physical properties change abruptly at the Tg.

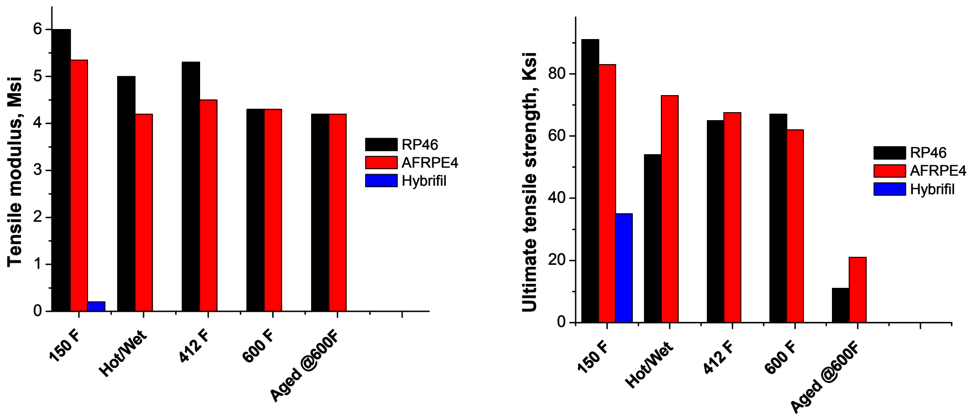

Figure 27 - Tensile Modulus and UTS

Aging for 1560 hrs at 600°F does not impact the stiffness as much as it affects the ultimate tensile strength (UTS). Degradation in the polymeric matrix and fiber/matrix interfacial adhesion however greatly impacts failure propagation and reduces the UTS greatly. See Figure 28 for failure surface of RP46 (aged and un-aged samples). Analysis of a bucket with this material is required to determine if 10 ksi tensile strength is adequate. Current designs using 18 ksi modulus filler material are not dependent on the filler material strength. However, we expect stress distributions to be different with a 5.5 msi modulus filler material.

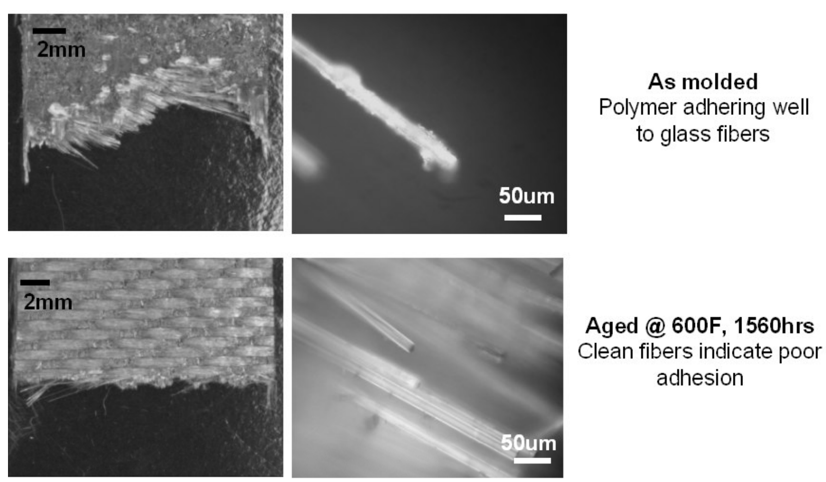

Figure 28 - Tensile Failure Surface of RP46 before and after Aging

Significant improvement to the adhesion of polyimide to steel was made through this program. All tests were done after thorough cleaning of the surface with ethanol. The adhesion of RP46 prepreg to the smooth steel surface was poor and adhesive failure mode was observed. It was interesting to note that once debonded, the composite would leave the glass weave pattern on the steel surface – indicating that there was significant amount of glass/steel interface instead of the preferred polymer/steel interface. To improve the adhesion, several surface treatments were identified.

1. **Grit blasting** was used to increase the surface roughness.
2. **Polymer layers as adhesion promoters**: To enhance the surface area between polymer and metal, a layer polymer solution was applied to the grit blasted. Subsequently, the prepreg was molded on top of this layer.
3. **Silane treatment of the surface**: Two silanes were chosen as adhesion promoters l. These were applied to cleaned surfaces from an alcohol solution.
4. **Acid etching of the steel surface**: An acid etch of the polished surfaces gave the best results for adhesion.

In summary, the adhesive strength was improved from an adhesive mode failure to cohesive mode failure. However, it was surprising to note that with all cohesive failures, the lap shear strength plateaus; whereas, the literature reported values of ILSS for RP46 laminates is of the order of 14 ksi. A possible reason for this inconsistency could be that single lap shear samples tested here "bow" during testing (as shown schematically in Figure 29). This induces a high peel stress at the bond edges. To obtain true adhesive shear strength values, we would need to run a thick adherent test (ASTM D5656) which is a difficult test to run and typically only used to generate shear stress design values for final material systems. The single lapshear test is however, a good test for comparing relative adhesion capability and failure modes.

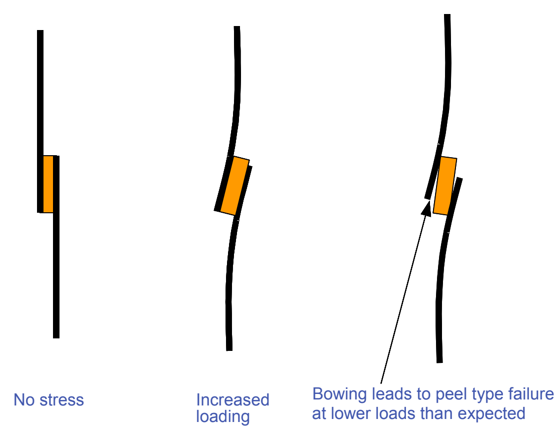

Figure 29 - Bowing of Lapshear Specimens during Testing and prior to Failure.

Because polyimides need to be processed at very high temperatures (>600°F), our prior experience indicates that residual stress will have a significant impact on the adhesion. It is widely believed that such stresses are minimized in lapshear samples because of their small sizes (typically 1" (W) X 1" (L) X 0.032" (T)) such that the measured lapshear adhesive strengths are not completely representative of the full size adhesion capability. The total material adhesion capability is the adhesive strength (using thick adherent test) minus the residual stress.

To understand residual stress behavior, 1” wide, 10 inch long and 40 mil thick layer of RP46 prepreg was molded onto a 15 mil thick steel plate. Upon removal from the vacuum bag, this strip bends – revealing qualitatively the residual stress at the interface (see Figure 30). We have modeled the behavior of a thin strip from curing at 620°F to cooling to room temperature and the bending behavior can be captured quantitatively with our model. Since bending (directly proportional to residual stress) is affected by the thermal expansion mismatch where the composite has a smaller expansion than the steel, a convenient way to retire this risk is to decrease fiber loading in the prepreg.

The coefficient of thermal expansion was found to be in the range of 3.4 – 4.0 μin/in-°F (in plane) and 31.1 μin/in-°F (out of plane) for RP46 laminates. This matches closely with calculated values (based on a simple parallel model for in plane and series model for out of plane) of 4.2 μin/in-°F (in plane) and 24.2 μin/in-°F (out of plane). Similar observations were made for AFRPE4.

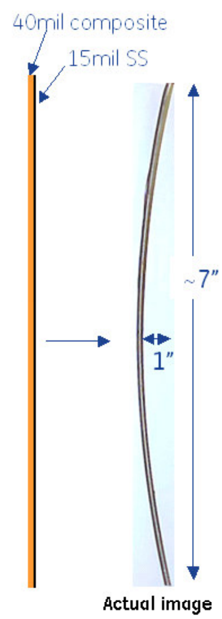

Figure 30 - Bi-material Strip Showing Bending after Molding

Tensile tests on samples aged for 1560 hours at 600°F were performed as a worst-case scenario for thermal aging. Significant reductions in tensile strength were noted. From cross sectional and fracture micrographs, it was clear that the aging process caused much of the surface polymer to erode – leaving behind exposed fibers (Figure 31). Both composites show extensive damage at the surface, where exposed fibers can be observed. In addition, the fibers seem darker than in the un-aged samples. Very little micro-cracking (if any) was observable. Further, the polymer/matrix adhesion seems also to have been affected. Physical inspection revealed powder like residue upon fracture of the specimens indicating poor material integrity. The actual in-service environment for the buckets is in a vacuum. The removal of oxygen may slow the thermal aging process. In addition, more realistic transient/cyclic thermal exposure may slow the aging process; although, this type of exposure could increase degradation through micro-cracking. As a result of this test, we would expect to investigate the thermal aging conditions more closely and perform analysis to assess the strength requirements if this program were to be continued. Other risk mitigation steps might be investigated such as thermal barrier coatings.

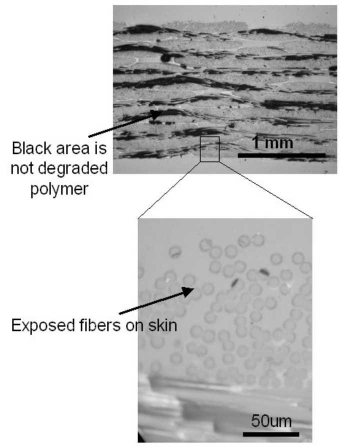

Figure 31 - Cross Sections of RP46 Laminates Subjected to 600°F for 1560 hrs in Air

In summary, two key risks and potential mitigation paths were identified:

1. Reduction in strength after thermal aging: Test the materials in environments closer to true environment and evaluate barrier coatings capable of withstanding temperature of 600°F.
2. Residual stress at the interface: Reducing the fiber volume fraction in the laminate can decrease residual stress. This will however need to be traded off with strength capability. More work in this area is thus warranted.

Task 4.0 – 33.5" Steel-Hybrid Prototype Development - Status / Discussion

Overview: This task provides the "Early Technology Demonstration" of a steel-hybrid bucket design, including fabrication processes, targeting an existing GE Energy LSB (33.5H) stage as a retrofit design allowing a pathway to incorporate advanced 3-dimensional aero-profile modifications to airfoil geometry, leading to significant component and system level efficiency increases. The key to this design is the advanced aerodynamic design for a retrofit application. Additionally, the major process and tools are developed under this task.

Discussion: A design process and tools were developed to accelerate the time to design the bucket with polymer pockets and improve the accuracy of the pocket geometry.

Design Process Flow: The design process flow to reduce the time to design and optimize a pocket definition for any bucket is defined by three steps. These three steps are:

1. Aerodynamic design development
2. Preliminary hybrid design with advanced analytical tool development
3. Frequency margin assessment

Step 1 - Aerodynamic design development: The goal of this step is to design a bucket with maximum stage efficiency. With the addition of pockets of light hybrid filler material, the radial mass distribution is no longer strictly a function of the cross sectional area. This allows larger tip sections relative to the root sections so a more aerodynamically optimum solidity distribution can be obtained.

Step 2 - Preliminary hybrid design with advanced analytical tool development: The goal of this step is to replace steel material by a lighter material and reduce the average section stress (P/A) below the design limit when the bucket is at full running speed. The pocket characterizes the volume of steel or titanium replaced by hybrifil material

The starting point of this step is an aerodynamic vane definition defined in Step 1. A mid-span connection and cover is added to the vane to establish the connection to the adjacent buckets. This is critical to establish representative boundary conditions and properly evaluate bucket stresses. The mid span connection is the design of choice for GE Energy LSBs to provide bucket-to-bucket connection. It also provides good damping during running speed. For this particular bucket, a new mid span connection concept currently used on aircraft engine buckets (winglet) was chosen. It provides a connection to adjacent buckets from half speed to full speed via a contact surface. As the bucket untwists due to centrifugal forces, the winglet surfaces come in contact with adjacent buckets. Compared to the conventional design, termed nub-sleeve, the frequency response is less sensitive to the applied boundary conditions.

A snubber cover design was chosen for this bucket to provide tip coupling. It is a simple one-piece construction positioned at the tip of the vane. Like the winglet, surface contact to the adjacent buckets is established during running speed as the bucket untwists.

The pocket is designed from the pressure face of the bucket. Outboard and inboard pocket terminology is used to denote pocket location. The outboard pocket is placed between the winglet and the cover while the inboard pocket is placed between the dovetail and the winglet. Geometric constraints are established in order to avoid leading and trailing edge erosion, as well as breaking through the back wall during machining (Figure 32).

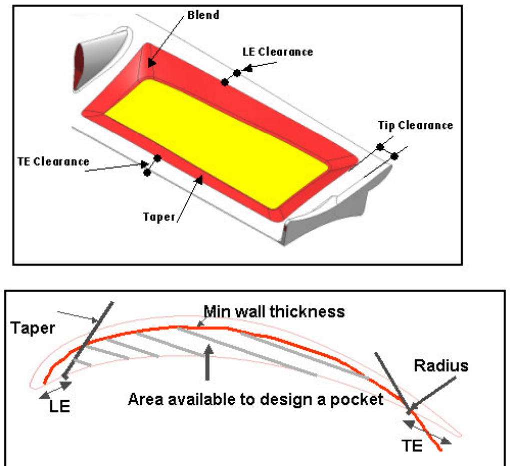

Figure 32 - 33.5" Advanced Aero Design: Pocket Detail Design

A minimum back wall thickness was used based on initial inputs from manufacturing. This is consistent with machining tolerance. It corresponds to the maximum possible depth of the pocket geometry.

A clearance of 1 inch was used between the edge of the pocket and the leading edge of the bucket to avoid erosion of the hybrifil material. The same clearance at the trailing edge side of the pocket was established to preserve the integrity of the trailing edge.

The weight of the bucket in the tip region has a lot of influence on average section stresses. Starting the pocket as close as possible to the cover of the bucket, then, gives the lightest and/or longest possible bucket. Unfortunately, the bucket region beneath the cover is highly stressed because of the contact to adjacent buckets. There is then some clearance needed to the cover to avoid putting the hybrifil in a highly stressed region. As a design rule then, a radial clearance from the pocket to the cover and from the pocket to the winglet was set at 1 inch. The final geometric consideration is the taper angle from the start of the pocket to full pocket depth. This is set to limit shear stresses in order to prevent adhesive failure.

Pocket corners have been blended to eliminate sharp corners and minimize the concentration of stresses.

The pocketing approach always starts with a single outboard pocket. If the average section stress limit cannot be reached in the inboard section either the aerodynamic design of the section is modified (area increase) or a second pocket is implemented in the inboard section.

Pocketing Tool: The pocketing tool is a closed loop optimization process where the points defining the hybrifil/back wall interface are positioned in order to meet both average and peak stress limits in each section.

Pocketing starts with an outboard pocket. If the average section stress limit cannot be reached in the inboard section either the aerodynamic design of the section is modified (area increase) or a deeper, longer outboard pocket is implemented. In order to minimize the time and effort needed to study various pocketing options, an automated pocketing tool was developed with the use of APDL (ANSYS Parametric Design Language) in ANSYS.

Pocketing Tool (PT) is a closed loop optimization process that optimizes the hybrifil/back wall interface while keeping the average and peak stresses below the set design limits. The process has three levels; first, pocket definition points at predefined radial locations are assigned as design variables. These design variables define the interface surface between hybrifil / backwall. As a second step, the vane is pocketed, meshed and analyzed. The third and final step is to post process the static analysis results to check section and peak stresses with respect to design limits. The process will stop when the objective functions are achieved.

The process starts with the UG definition of an arbitrary vane. Section curves are generated at predefined radial locations and the corresponding IGES model is imported into ANSYS. Solid geometry is created after the imported section curves are renumbered for easy manipulation. Minimum wall thickness, LE–TE clearances, beginning – ending pocket radial locations, as well as meshing parameters are defined as variables in an input macro. At each radial section, 5 key points – design variables for the optimization - are assigned to the pressure face. Placements of 1st and 5th points are defined by LE-TE clearances, and they stay on the pressure surface. 2^{nd}, 3^{rd} and the 4^{th} points can move along a perpendicular path towards the suction surface of the vane, hence defining the pocket contour.

Typical results are a setting of pocket depths to the minimum back wall thickness at the highest radial stations. It is important to note that the bucket weight can be further reduced with smaller back wall thickness, radial clearances to the cover and winglet, and chord-wise offsets to the leading and trailing edges.

Output from the optimization process is the point definition at each radial section of the hybrifil/back wall. The coordinate of each point is read into UG for surface definition and final model development of the bucket.

Additionally, composite material capability was coded into the pocketing tool. The orientation of the composite fibers can be added during preliminary analysis.

Step 3 - Frequency margin assessment: In this step the pocket design from step 2 is used to assess frequency margins at running speed. As the geometry is cyclic-symmetric, cyclic symmetry modal analysis is used to solve the eigenvalue problem in ANSYS.

Frequencies are assessed at each nodal diameter from zero to ten with respect to the multiple of running speed. With pre-established margins for each type of mode for each nodal diameter, a particular hybrid design can be fully assessed. If frequency margins are not met, iteration on the pocket definition is required. Options in this case include changing pocket depths or adding a rib inside the pocket. If either option is exercised, average and peak stresses must be re-evaluated per step 2.

Aerodynamic design: LSB aerodynamic design is often compromised due to mechanical constraints. The root sections require large cross sectional areas while the tip sections require small areas to obtain radial mass distributions that result in acceptable centrifugal stresses. This often results in solidities that are larger at the root and smaller at the tip than the aerodynamic optimum. With the addition of pockets of light hybrid filler material, the radial mass distribution is no longer strictly a function of the cross sectional area. This allows larger tip chord lengths relative to the root sections so a more aerodynamically optimum solidity distribution can be obtained. In the case of the 33.5 inch design, the bucket count was reduced to half of the original design to reduce root solidity while the tip chord was increased to increase tip solidity (Figure 33). In addition, bucket profiles were modified for improved aerodynamics. The nozzle was also redesigned, incorporating area changes and compound lean for higher stage root reaction. Although there may be an optimum bucket count for the given stage, this design had to be shifted to a half count design to maintain the ability to be a retrofit design. The half count is closer to optimum.

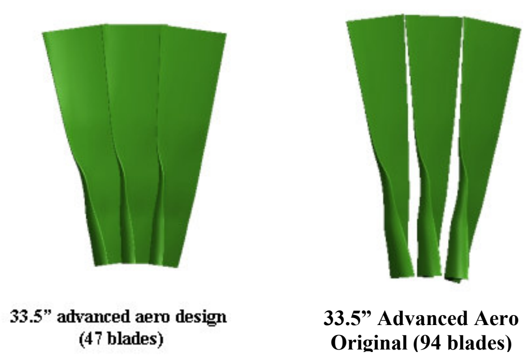

Figure 33 - 33.5” Advanced Aero Design: Bucket Count

Structural design: The 33.5” advanced aerodynamic design bucket can be used to retrofit existing single flow units. Bucket count is reduced by a factor of two with this new design, reducing the number of buckets from 94 to 47. The other detail that was addressed is attachment of the new bucket to the wheel. The current finger dovetail has 7 fingers and 6 pins per bucket. For the new design, the existing dovetail was doubled. Although the same number of fingers is used, the number of pins and their location were determined analytically. The number of pins for each bucket was changed to 9 pins, with their positions moved to balance centrifugal forces (Figure 34). The centrifugal force acting on each pin was shown to be equivalent to those of the 94-count dovetail design because of the weight reduction of the hybrid bucket. This new 33.5” advanced aerodynamic design can now be retrofit to existing units by simply re-drilling the rotor for proper pin location.

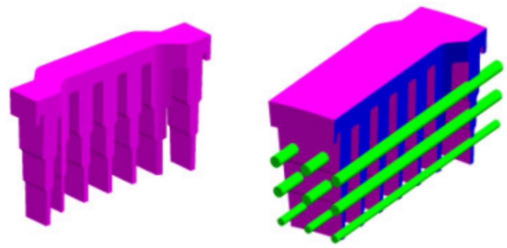

Figure 34 - 33.5" Advanced Aero Design: Dovetail Design to Retrofit Unit

FEA Model Details: The 33.5" advanced aerodynamic design operates in the L-0 row of 60-hertz machines. The row consists of (47) buckets with continuous ties in both the tip (snubber cover) and the mid-span (winglet). The dovetail was not modeled, as both vane stresses and natural frequencies are not affected by the dovetail design. Figure 35 shows details of the finite element model used to perform the analysis. The multiple interface/attachment regions of the bucket tip/snubber cover and mid-span winglet are featured. Snubber cover and winglet meshes do not change with the pocketing definition, allowing those components to be meshed just once at the start of the process.

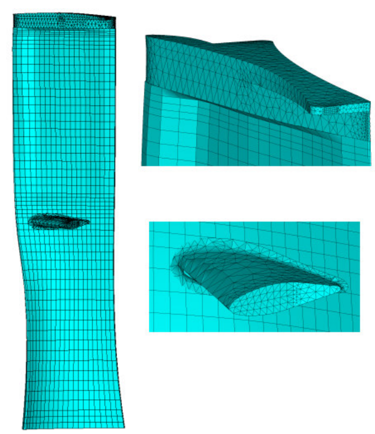

Figure 35 - 33.5" Advanced Aero Design: Detailed FEA Mesh

As shown in Figure 36, the snubber cover connection is done at both leading and trailing edge of the bucket. The model is built in a way that connection is established and no contact elements are used. In essence, the cover is in contact and not free to move at zero RPM. In reality, as the rotor speed gradually increases, the airfoils untwist under the centrifugal load and the snubber cover structure deforms. The contact between adjoining buckets starts to become established at about half speed. Given their complexity, it is not known exactly how strong the connections are in each joint before the rotor reaches full speed. In the approach used to model this design, as full speed is achieved, the snubber cover comes in contact with the adjoining buckets and thereby forms a 360^{o} continuous linkage. Hot geometry and small deformation is used as it is consistent with the geometry of the bucket at speed and it simplifies the problem. Although deformations are computed, the mesh is not updated. The final hybrid bucket design is dependent on properly modeling the hot to cold geometry, along with contact at the contact interfaces. Current assumptions are reasonable for preliminary design.

To model the bucketed disc at full speed, a small number of selected nodes were connected at both interfaces. For both the snubber cover and winglet, mid line contact is assumed with all degrees of freedom coupled (Figure 36). All degrees of freedom are fixed at the base of the bucket.

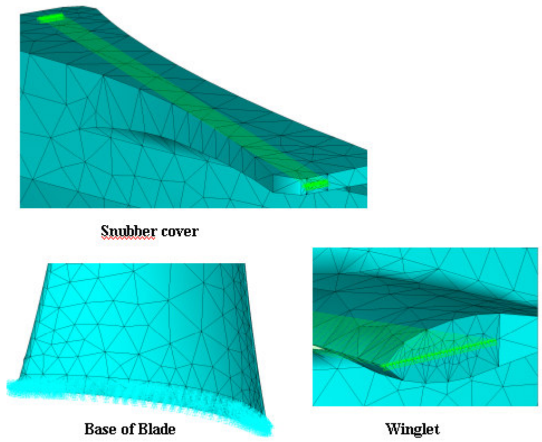

Figure 36 - 33.5" Advanced Aero Design: Detailed Boundary Conditions

- The weight density applied to the bucket and disc was 0.283 lb/in^3 and the elastic modulus was assigned at 29 ksi. An angular velocity of 3600 RPM was defined to establish centrifugal forces at operating speed. The steady steam bending force was calculated based on original stage data and is negligible compared to centrifugal loads. Design limit for static and frequency analysis was specified by GE's design practice.

Table 3 - Steel - Material properties

Young Modulus	2.90E+07
Poisson Coefficient	0.3
Density	0.000725

For the average stress limit, a stress value between the bucket gross yielding and the bucket ductile failure was used. The ultimate stress limit was defined as per GE's design practice for peak stress.

Table 4 - Polymer - Material properties

Young Modulus	18000 Psi
Poisson Coefficient	0.3
Density	0.000112

Static analysis results: Average section stress limits were achieved with a single outboard pocket. There is then no need to implement a second pocket in the inboard section.

A weight reduction of 12% and a root average section stress reduction of 26% are effected with the single outboard pocket. These are considerable reductions, as the average section stress for the solid bucket was about 43% above the limit.

The static analysis clearly shows that there are bending stresses in addition to the centrifugal stresses. As the pocket is deepened, the center of gravity is further displaced toward the suction surface, providing for increased bending stresses. The pocket is at the minimum wall condition from the top part of the pocket to 85% of the bucket length. From 85% of the bucket length to the end of the pocket (above the winglet) the back wall thickness increases. The pocket is deeper on the leading edge side of the bucket because of additional airfoil thickness as compared to the trailing edge (Figure 37). It is important to note that the design process couldn't deepen the pocket at the trailing edge because of peak stress constraints.

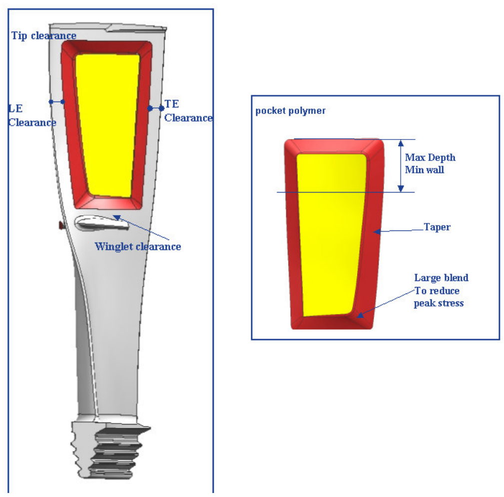

Figure 37 - 33.5" Advanced Aero Design: Optimum pocket design

A high elastic stress occurs in the vane at the upper right corner. The high stresses at the cover are due to the assumed boundary conditions. High stresses in this region then are not real and not considered in the pocketing definition.

Figure 38 - 33.5" Advanced Aero Design: Von Mises Stress - Optimum Pocket Design

Where local stress exceeds the yield strength of the material, stress relaxation caused by plasticity in these sites would occur. The amount of relaxation is not factored into the results. However, the overall magnitude of equivalent stress suggests that they would likely be significant in terms of influencing the LCF life of the buckets. The potential rate of LCF damage produced by these stresses will be addressed later.

The shear stress at the contact between hybrifil material and steel of 500 psi is below the design limit of 3900 psi.

Natural frequency analysis at 3600 rpm: Based on the motion of the buckets about the circumference of the disk, the resulting vibration modes were categorized as families of tangential modes, axial modes, torsional modes and higher order modes. Because of the phase relationship between individual buckets, there are 24 nodal diameters (including nodal diameter 0) in each mode family for a stage with 47 buckets. The mode shapes of the 3rd nodal diameter tangential mode, the 7th nodal diameter axial mode, and the 8th nodal diameter torsional mode revealed a motion in the tangential mode mainly flap-wise, and the motion in the axial mode mainly edge-wise. The torsional mode has a reflecting point near the mid-height of the bucket. The natural frequencies were evaluated at 3600 RPM (60Hz).

As noted, all modes indicate a +10 hertz margin from the nearest forcing except Mode A, which has a 9% margin for the 3 nodal diameter mode, Mode B, which has a 2.3% margin for the 7 nodal diameter mode and Mode C, which has a 0.8% margin for the 8 nodal diameter mode. The mode A for the 3 ND has a margin close enough to 10% and is not of concern. A wheel box test is needed to validate the prediction for the higher order modes at higher nodal diameters. This order higher mode and higher nodal diameter are generally difficult to excite.

Machining of the bucket and parts: A full-scale blade was machined from a block of steel. The finger dovetail has been replaced by a curve axial entry dovetail to introduce the latest technology and the design of choice for new units. A rib has been incorporated diagonally in the pocket with the top surface recessed by 0.03 inch from the pressure face of the vane. It provided an opportunity to gain some rib manufacturing experience (Figure 39).

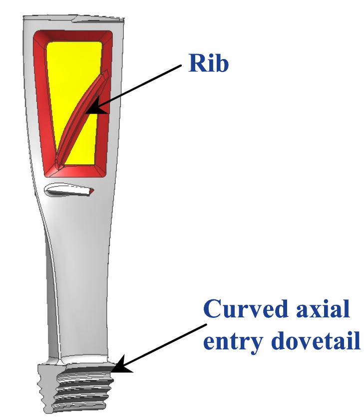

Figure 39 - 33.5" Advanced Aero Design: Full Blade Machining Detail

A caul sheet tool made of the same material as the bucket was machined. It has been used to make a glass composite caul sheet. The glass composite caul sheet is used as the mold for the casting. It provides a good match of thermal expansion with steel and good flexibility. A landing zone around the pocket perimeter is provided for the introduction of a gasket and the pressure face is lightly increased to provide for shrinkage of the hybrifil material during casting; about 1% of the total depth of the pocket (Figure 40 and Figure 41).

43).

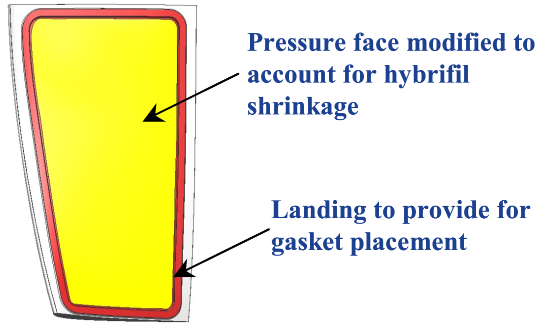

Figure 40 - 33.5" Advanced Aero Design: Caul Sheet Machining

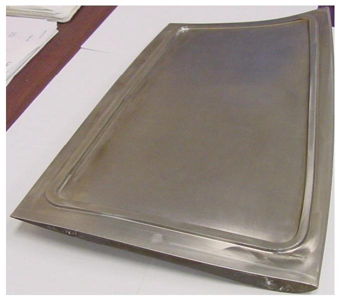

Figure 41 - 33.5" Advanced Aero Design: Caul sheet tool

An FEA analysis of the caul sheet was performed to size the thickness of the glass composite material and provide the clamping location for adequate sealing. The results show that a 2mm glass composite outside of the clamping zone and 3mm glass composite on the clamping zone provided enough ratio compliance/stiffness which is important to preserve the aerodynamic shape and proper sealing. Figure 42 shows the caul sheet clamped on the airfoil. A contact zone between the caul sheet and the airfoil was provided between the edge of the pocket and the edge of the gasket all around the perimeter. This contact zone provided a tight seal and an excellent transition between the hybrifil and the airfoil along the edge of the pocket.

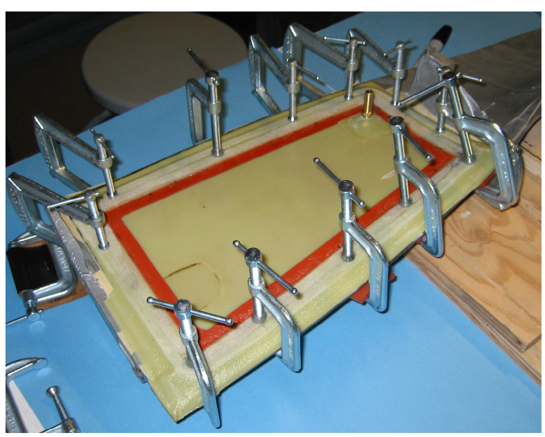

Figure 42 - 33.5" Advanced Aero Design: Caul Sheet Clamped on the Airfoil

The pocket was prepared as recommended in Task 3.0. The polymer injection lasted less than a minute. The full scale blade was done at the end of the curing cycle provided in task 3.0 (Figure 43).

Figure 43 - 33.5” Advanced Aero Design: One Outboard Pocket with One Rib

Task 5.0 – Hybrid 33.5" Subscale Design and Test –Status / Discussion

Overview: This task demonstrates the durability of the steel-hybrid LSB in an actual steam turbine environment. Testing will be performed in a modern subscale low pressure turbine test facility and included the full effects of centrifugal loading; hot/wet steam conditions; various mass flow rates; and high and low backpressure conditions. The test program was designed to validate the material life while exposed to hot-wet steam conditions, as well as to measure the system's natural frequencies and mechanical damping. A 33.5"H hybrid subscale bucket was designed following the design practice. Output of this task is a concept design using computer analysis and one demonstrator bucket for process development.

Structural design: The 33.5"H solid bucket has been used to develop an hybrid subscale bucket. The scale of 0.421 has been used to fit the bucket on the last row of the Low Pressure Development Turbine. The task consisted of modifying the original bucket by introducing two pockets while keeping the structural integrity. At this stage of the program, the design tools currently used were not developed yet. An iterative approach was used to design the pockets. This task provided the learning experience to promote the methodology and the current design tools.

33.5"H solid bucket design description: The 33.5"H bucket operates in the L-0 row of 60-hertz machines. The row consists of (94) buckets with continuous ties in both the tip (the side entry covers) and the mid-span (the nub-sleeve). The dovetail of each bucket has seven fingers attached to the disc rim by means of three dovetail pins. The multiple interface/attachment regions of the bucket tip/cover tenons, the mid-span nub, and the dovetail are featured.

As shown in Figure 44, the admission side tenons are both peened to the leading edge of the bucket tip. For a properly peened tenon, it is assumed that the 0.10" end section of the tenon head is fully expanded such that a rigid connection with the bucket tip platform is made. On the exit side, the tenon is flared, but remains loose between the cover and the tip platform at zero rpm. In essence, at zero rpm the piece is loose or free to move. As the rotor speed gradually increases, the airfoils untwist under the centrifugal load and the cover-tenon structure deforms. The contact between the exit side tenons with the tenon holes starts to become established. Given their complexity, it is not known exactly how strong the connections are in each joint before the rotor reaches full speed. In the approach used to model this design, as full speed is achieved the exit side tenons come in contact with the adjoining buckets and thereby form a 360^{o} continuous linkage (Figure 44). As for the mid span connections, the sleeve joints are loose and behave like a hinge.

A set of boundary conditions at the tenon cover connection and the sleeve joints have been established by GE Energy Steam Turbine and will be used to analyze the hybrid bucket (Figure 44).

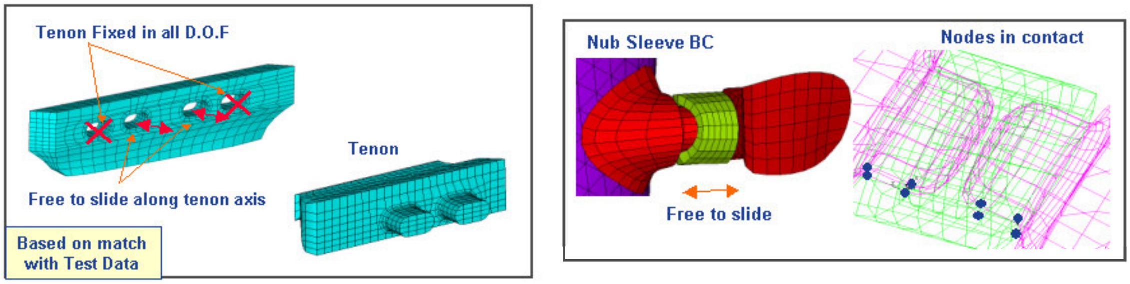

Figure 44 - 33.5H Hybrid: (a) Tenon (b) Sleeve Joints Boundary Conditions

The scale factor provided some geometrical challenges because the bucket gets much thinner. The clearance limit of 0.5 inch was used between the leading edge, trailing edge and the edges of the pocket. A clearance limit of 1 inch was used between the cover, nub sleeve and the top and bottom edges of the pocket. A minimum wall clearance of 0.03 inch was used. Two pockets were implemented in the bucket; one pocket in the outboard section and one in the inboard section (Figure 45).

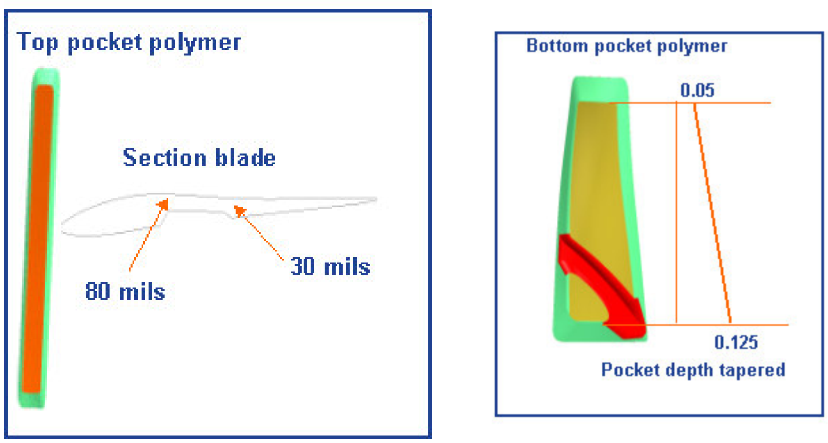

Figure 45 - 33.5H Hybrid: Pocket design

The outboard pocket is a narrow pocket and has been designed to respect clearance limits and to reduce the average section stress. The width of the bucket was limited to 1 inch to reduce the bending stress. For this reason, the outboard pocket has been positioned toward the leading edge where the bucket is thicker. The depth of the pocket is constant and at minimum wall. There is a 0.5 inches clearance from the leading edge to the closest edge of the pocket and 1 inch clearance from the trailing edge to the closest edge of the pocket.

The inboard pocket is much larger and uses the clearance limit; which provides a large area. The depth of the bucket is tapered from the top (below the nub sleeve) to the bottom of the bucket (hub section). A clearance of 0.5 inches was used between the edges of the bucket to the edges of the pocket. A clearance of 1 inch was used between the pocket edges and the mid span connection and the dovetail.

A rib at the bottom of the inboard pocket was added. The top surface of the rib was recessed by 0.03 inches from the pressure face of the bucket (Figure 46). The rib doesn't add structural value but was implemented to gain some manufacturing experience. A weight reduction of 13.5% was achieved.

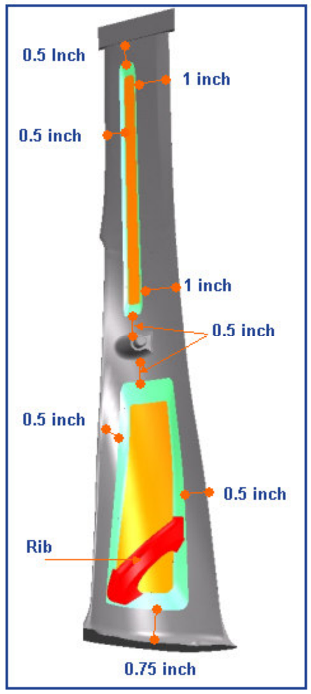

Figure 46 - 33.5H Hybrid: Pocketed Blade Design

FEA model: The 33.5" hybrid bucket operates in the L-0 row of the LPDT at 8551 RPM. The row consists of (94) buckets with continuous ties in both the tip (snubber cover) and the mid-span (winglet). It is important to note that only 4 hybrid buckets will be placed in the last row of a total of 94 buckets (90 solid bucket + 4 hybrid bucket) for the test. The analysis will consider the entire row (94 buckets) as being made of hybrid bucket. It will simplify the problem and will be accurate enough considering the geometry of the pockets (small pockets).

The dovetail was not modeled, as both vane stresses and natural frequencies are not significantly affected by the dovetail design (although the wheel is run for final frequencies). Figure 47 shows details of the finite element model used to perform the analysis. The multiple interface/attachment regions of the bucket tip/tenon and mid-span connection (nub sleeve) are featured.

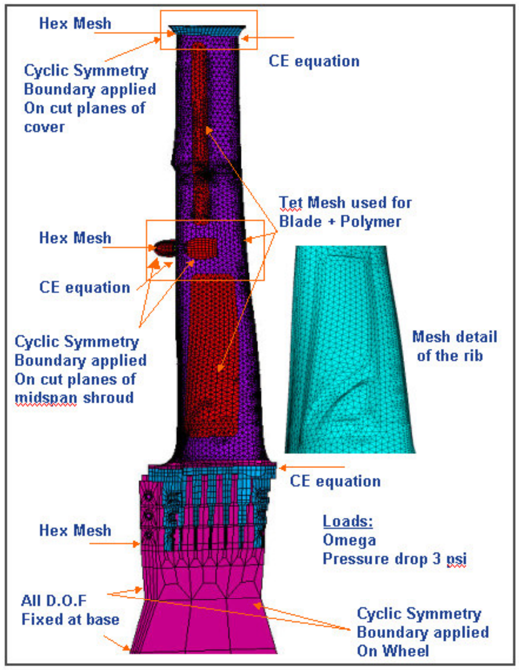

Figure 47 - 33.5H Hybrid: Finite Element Model

Ultimately, to model the bucketed disc at full speed, a small number of selected nodes in each tenon were connected at the interface. The nodes on the outer holes were fully fixed and the nodes of the inner holes were free to slide in the axial direction of the holes. As for the mid span connections, the sleeve joints are loose and behave like a hinge. Therefore only a small area (4 nodes) in the sleeve at the 6 o'clock position is connected to the nub on the bucket.

The model is built in a way that connection is established and no contact elements are used. In essence, the cover is in contact and not free to move at zero RPM. In reality, as the rotor speed gradually increases, the airfoils untwist under the centrifugal load and the tenon cover structure deforms. The contact between adjoining buckets starts to become established at about half speed. Given their complexity, it is not known exactly how strong the connections are in each joint before the rotor reaches full speed. In the approach used to model this design, as full speed is achieved, the tenon cover comes in contact with the adjoining buckets and thereby forms a 360^o continuous linkage. Hot geometry and small deformation is used as it is consistent with the geometry of the bucket at speed and it simplifies the problem. Although deformations are computed, the mesh is not updated. Current assumptions are reasonable for preliminary design. All degrees of freedom are fixed at the base of the bucket.

The weight density applied to the bucket and disc was 0.283 lb/in^3 and the elastic modulus was assigned at 29 ksi. An angular velocity of 8551 RPM was defined to establish centrifugal forces at operating speed. The steady steam bending force was calculated based on original stage data and a 3 psi pressure drop was applied on the pressure face. Design limits for static and frequency analysis were specified by GE's design practice.

Static analysis results: A high elastic stress occurs in the vane toward the trailing edge. Compared to the solid bucket, the stresses increased due to bending stress. The high stresses at the cover are due to the assumed boundary conditions. High stresses in this region then are not real and not considered in the pocketing definition.

Where local stress exceeds the yield strength of the material, stress relaxation caused by plasticity in these sites would occur. The amount of relaxation is not factored into the results. However, the overall magnitude of equivalent stress suggests that they would likely be significant in terms of influencing the LCF life of the buckets. The potential rate of LCF damage produced by these stresses will be addressed later.

The shear stress at the contact between hybrifil material and steel is 150 psi. There is also a concentration of stresses at the bottom of the inboard pocket. The value is close to the design limit, but the temperature at this region will be small and not in a critical region therefore the value is acceptable.

The maximum stress in the dovetail is lower for the hybrid bucket than for the solid bucket (92% of baseline stress level). This result is due to the weight reduction therefore the dovetail current design is considered safe (Figure 48).

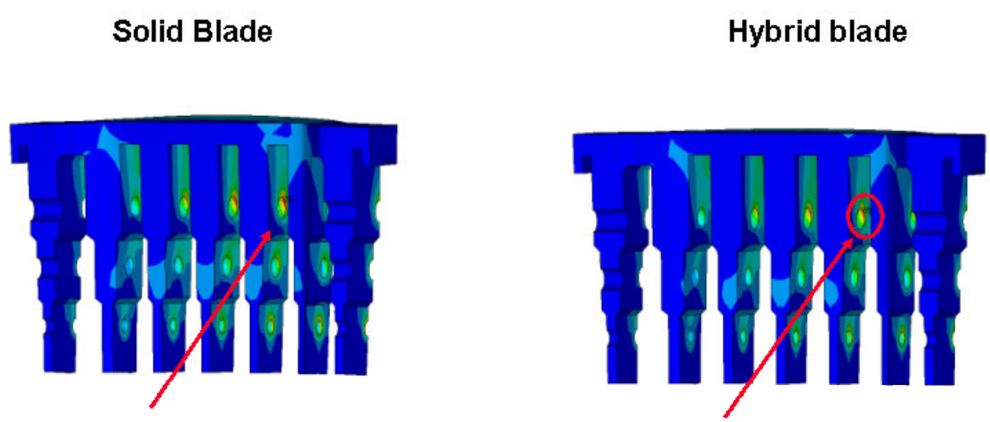

Figure 48 - 33.5H Hybrid: Von Mises Contour in Dovetail for Solid and Hybrid Blade

A comparison of P/A versus the design practice limit was made between the solid bucket and the hybrid bucket. The bucket gross yielding and the bucket ductile failure material characteristics were used at 400F and 125F for the average and 3 sigma standard deviation stresses.

The over-speed limit results show no significant difference between the solid and the hybrid bucket. Some of the limits are slightly below the design requirement for the average stress limit at 125F while differences are significant for 3 sigma standard deviation limit at 400F. Some prior CFD works showed a temperature gradient increasing from hub to tip. Only the tip region of the bucket can be exposed at 400F temperature for a short period of time. The stress level at the tip is smaller than the rest of the bucket therefore using 400F over speed limit for the entire bucket seems to be very conservative. The solid bucket has been running successfully on unit without any failure; therefore, we consider the stress level in the hybrid bucket being identical to the solid bucket to be safe.

Natural frequency analysis at 8551 rpm: Based on the motion of the buckets about the circumference of the disk, the resulting vibration modes were categorized as families of tangential modes, axial modes, torsional modes and higher order modes. Because of the phase relationship between individual buckets, there are 47 nodal diameters (including nodal diameter 0) in each mode family for a stage with 94 buckets. The mode shapes of the 2^{nd} nodal diameter tangential mode, the 6^{th} nodal diameter axial mode, and the 9^{th} nodal diameter torsional mode revealed a motion in tangential mode mainly flap-wise, and the motion in axial mode mainly edge-wise. The torsional mode has a reflecting point near the mid-height of the bucket. The natural frequencies were evaluated at 8551 RPM.

As noted, all lower modes indicate a 10% margin and higher mode indicate a 5% margin from the nearest forcing except Mode A, as a 8.8% margin for the 3 nodal diameter mode, Mode C, as a 3.4% margin for the 6 nodal diameter mode, Mode D, as a 3.4% margin for the 8 nodal diameter mode, Mode E, as a 1.7% margin for the 9 nodal diameter mode.

A comparison of the frequency between the solid bucket and the hybrid bucket showed minor differences. The frequency margins for the solid bucket or the hybrid bucket are slightly below the design requirement for some of the modes. The frequency margin difference being so minor between the solid bucket and the hybrid bucket and the fact that the solid bucket has been successfully running for many years, the hybrid bucket has been considered a safe design and passed the design review.

Conclusions

Task 1.0 – 54" Steel-Hybrid Bucket Design

The aerodynamic design used for this task was a scale of 45" 60Hz to 54" 50Hz last stage blade (LSB). This blade is currently under development using Titanium material. Titanium is more expensive than steel by a factor of 2-3 therefore the use of steel/hybrifil material enables a significant cost reduction by using a less expensive material. Because the aerodynamic definition is scaled from an existing design the task did not address a stage efficiency gain but rather a reducton in cost.

The row consist of 70 buckets with continuous tie in both the tip and mid-span. The pocket was designed using the tool developed in Task 4 with the objective to reduce the average section stress and Von Mises stresses below the limits required by design practice.

One major solution to reduce the average section stress could be to redefine a new aerodynamic shape. Instead of scaling the 45" LSB design, a completely new aerodynamic design could be developed to take into account the hybrifil implementation. The new aerodynamic design should provide more area in the outboard to reduce the bending effect as the pocket gets deeper.

Two other solutions were investigated using the existing aerodynamic design. One of the solutions was to use a different stacking of the vane section. The technique was used with a combination of an optimized pocket design. Unfortunately, the result showed a small improvement on the average section stress. The best possible hybrid design didn't show a sufficient improvement of the average section stress. The other solution is to linearly increase the blade section area from mid span to hub. A feasible pocket design was achieved with an average section stress below the limit, but the blade efficiency degraded too much. None of the potential solutions provided a feasible design.

With respect to the objective, the optimum pocket design could not reduce the average section stress below the limit. An optimum weight reduction of 7% and a root average section stress reduction of 9.5% were achieved with the single outboard pocket. It is a considerable but not a sufficient reduction as the average section stress for the solid bucket was about 33% above the limit.

The high level of stresses is mainly due to bending of the outboard blade. Under the centrifugal load, as the pocket gets deeper the outboard blade exhibits a large bending behavior resulting in higher stresses. Those results limited the shape and the depth of the pocket; therefore, the average section stress limit could not be reached. The frequency was analyzed using the optimum pocket design. Although the result is irrelevant because the average section stress is above the limit, the frequencies didn't show any significant issues. This is especially true for the low mode and nodal diameter.

Task 2.0 – 62" Titanium-Hybrid Bucket Design

The aerodynamic design used for this task was a scale of 45" 50Hz titanium last stage blade (LSB). Titanium is a lighter material than steel therefore the use of titanium/hybrifil material enables the design of the longest blade possible using GE Steam turbine material limits. Because the aerodynamic definition is scaled from an existing design the task did not address an aerodynamic stage efficiency gain but rather a gain in power extraction from the low pressure turbine due to the increased annulus area.

The row consist of 70 buckets with continuous tie in both the tip and mid-span. The pocketing tool developed in Task 4 was first enhanced to allow for more flexibility in the definition of the geometry of the pocket. The tool was then used to complete the conceptual design of the 62" titanium bucket. The objective was to reduce the average section stress and Von Mises stresses below the limit required by GE's design practice.

In its original configuration, the 62" Titanium hybrid blade was designed with the best pocket possible but failed to satisfy the average section stress. Consequently, a one-dimensional analytical expression was derived to scale the section area of the blade below the mid span connection (winglet). The analytical solution allowed an estimate of the ideal cross-sectional area distribution needed to meet the stress design requirements.

In order to provide for extra margin between the design limits and the actual P/A distribution, an alternative design with additional 5% area scaling was implemented. The new aerodynamic vane was used with the pocketing tool to design an optimum pocket. A successful design was achieved with one outboard pocket.

The frequencies were evaluated. Some of the mode at certain nodal diameter did not show enough margin and a more rigorous design work and testing will be required to finalize the design.

Overall the optimum design was achieved with one outboard pocket and a 4 lbs weight savings, which corresponds to 7% weight reduction.

Task 3.0 – Hybrid Materials and Process Development

All material tests indicate that the polymer material and adhesion has sufficient capability to meet durability requirements for 30 years provided the temperature is kept below 285°F for Hybrifil and 300°F for Hybrifil 3. Hybrifil 3 shows improvement in all properties (adhesion, fatigue, and erosion) over Hybrifil and is the material of choice for the Hybrid bucket program provided temperatures can be kept below 300°F.

Process optimization efforts in 2005 focused on development of a caul sheet and assessment of the robustness of surface preparation procedures. Two significant changes were made to the process with the introduction of a glass fiber reinforced composite caul sheet and a masking material to reduce surface roughening in the areas outside of the pockets during the etching and surface prep process. Evaluation of surface preparation durability tests indicate that the part may be left in 100% RH for up to 2 weeks in a dust free environment after etching and/or priming without degrading adhesion. Further assessment on the robustness of the surface preparation procedures indicate that plating tape can be used to protect the non-bonded surface of the metal airfoil during the etching process without degrading adhesion and exposure of primed surfaces to air shipping prior to bonding does not degrade adhesion.

Briefly process steps for fabricating a Hybrid LSB involves:

1. Forge a near net shape bucket
2. Form pockets for low density filler during final machining
3. Grit blast pocket surface
4. Mask and etch pocket surface
5. Prime
6. Attach caul sheet over pocket
7. Preheat LSB with pocket
8. Mix and cast Hybrifil into pocket
9. Cure to green state
10. Remove caul sheet and post cure

The process is relatively simple with low investment cost for reducing weight in a metal airfoil.

To mitigate risk and to accelerate the introduction of this technology, a single 33.5" full-scale bucket with advanced aerodynamic geometry was fabricated using the new caul sheet. The resulting product showed smooth transitions between the metal and Hybrifil at the pocket edges and no irregularity on the Hybrifil airfoil surface due to cure shrinkage. This task successfully provided definition of the material and process procedures needed to fabricate Hybrid stainless steel LSB.

For peak temperatures exceeding 300°F, higher temperature materials were identified with capabilities up to 600°F under hot/wet conditions. Continuous glass fiber/polyimide composites (RP46 and AFRPE-4) were selected for this study based on literature search and close thermal expansion match to steel. Adhesion development efforts under this task successfully enhanced the adhesion 4X to single lapshear values of 3.2 ksi and cohesive failure mode. This task also identified risks based on significant reduction in strength after 1560 hours at 600°F and residual stress due to low thermal expansion in the composite. Mitigation steps were identified to reduce the fiber volume fraction in the composite to better match the steel expansion and assess thermal aging effects in a vacuum environment under thermal cycling to better simulate the turbine environment.

Task 4.0 – 33.5" Steel-Hybrid Prototype Development

A significant portion of the tool development and methodology work was done under this task. The result provided an improvement on how to design the pocketed blade and ultimately on the design itself.

A design process and tools were developed to accelerate the time to design the bucket with polymer pockets and improve the accuracy of the pocket geometry. Three steps defined the design process flow. These three steps are:

1. Aerodynamic design development
2. Preliminary hybrid design with advanced analytical tool development
3. Frequency margin assessment

The aerodynamic design of the blade was new and used the addition of pockets of light hybrid filler material. This allows the radial mass distribution to be no longer strictly a function of the cross sectional area. This allows larger tip chord lengths relative to the root sections so a more aerodynamically optimum solidity distribution was obtained. The bucket count was reduced to half of the original design to reduce root solidity while the tip chord was increased to increase tip solidity. In addition, bucket profiles were modified for improved aerodynamics. The nozzle was also redesigned, incorporating area changes and compound lean for higher stage root reaction. Although there may be an optimum bucket count for the given stage, this design had to be shifted to a half count design to maintain the ability to be a retrofit design. The half count is closer to optimum.

The 33.5" advanced aerodynamic design bucket can be used to retrofit existing single flow units. Bucket count is reduced by a factor of two with this new design, reducing the number of buckets from 94 to 47. The other detail that was addressed is attachment of the new bucket to the wheel. For the new design, the existing finger dovetail was doubled with an appropriate location and number of pins. This new 33.5" advanced aerodynamic design can now be retrofit to existing units with by simply re-drilling the rotor for proper pin location.

To optimize the design of the pocket, an automation tool was developed using ANSYS. The pocketing tool is a closed loop optimization process where the points defining the hybrifil/back wall interface are positioned in order to meet both average and peak stress limits in each section.

Average section stress limits were achieved with a single outboard pocket. Currently there seems to be no need to implement a second pocket in the inboard section. A weight reduction of 12% and a root average section stress reduction of 26% are effected with the single outboard pocket. These are considerable reductions, as the average section stress for the solid bucket is about 43% above the limit. It is worth noting that this blade could not be designed without the use of hybrifil material. All of the stresses are below the limit established by GE's design practice.

The frequencies were estimated and a sufficient margin was established for the lower mode and lower nodal diameter. A wheel box test will be required to assess the frequency and validate the boundary conditions used during this study.

The machining of the hybrid bucket was completed. The finger dovetail was replaced by a curve axial entry dovetail to introduce the latest technology and the design of choice for new units. A rib was incorporated diagonally in the bottom of the pocket with the top surface recessed by approximately 0.25 inch from the pressure face of the vane. Implementing the rib provided an opportunity to gain some rib manufacturing experience. A caul sheet tool made of the same material as the bucket was also machined. It was used to make a glass composite caul sheet used as mold for the casting. A landing zone around the pocket perimeter is provided for the introduction of a gasket and the pressure face is lightly increased to provide for shrinkage of the hybrifil material during casting.

This task successfully provided the “Early Technology Demonstration” of a steel-hybrid bucket design, including fabrication processes, targeting an existing GE Energy LSB (33.5H) stage as a retrofit design allowing a pathway to incorporate advanced 3-dimensional aero-profile modifications to airfoil geometry, leading to significant component and system level efficiency increases.

Task 5.0 – Test Validation of Sub-Scale Steel-Hybrid Bucket

Design: The mechanical design meets the current GE design practice criteria (based on a relative analysis between the baseline and hybrid bucket analysis) with the pocketed hybrid bucket.

The test was run in accordance to the stated test conditions as proposed in the contract. The results were very positive for the majority of factors of interest. An RCA was completed on the hybrid bucket with the material adhesion failure at the high temperature conditions. Below is a summary of test results. Major post test observations are summarized in Table 5.

- Strain gage response as predicted
- Dynamic response of Hybrid and solid buckets are similar
- No abnormal response during various backpressure and flow conditions, including the high backpressure testing conditions.
- During the high temperature testing one bucket had material adhesion failure of about 0.75 inches near the outer pocket “nub sleeve” area (this happened during the additional 40.5 hours of testing).
- No visible degradation of outer pocket hybrid material on 3 hybrid buckets (see Figure 49 and Figure 50).
- During high temperature testing, one bucket had inner pocket material loss
    - One bucket with inner pocket with material loss
    - Inner root area could have seen >250F (no gages)
    - Dis-bonded bucket was first bucket processed
        - Identified issues with maintaining temperature during casting
        - Cold substrate causes local shrinking away from surface
    - Adhesive failure mode observed on steel substrate a less robust process (confirmed on liberated material)
    - Talc (contaminate) was found in the adhesive layer during analysis
    - High temperature (>330F) conditions may have been a significant factor due to primer temperature capability.

Table 5 - Post Test Bucket Observations

	Hybrid Outboard	Hybrid Inboard	SS Strain Gages
H1 (sn: 88AND) filler sanded smooth	-Loss of 1" of polymer near nub sleeve	-No degradation	-Loss of gages (epoxy) up to 35% span
H2 (sn: 45AACD)	-No degradation	-Complete loss of inboard polymer	-Loss of gages up to 50% span
H3 (sn: 92ACD)	-No degradation	-No degradation	-No degradation
H4 (sn: 81AAMD)	-No degradation	-No degradation	-No degradation

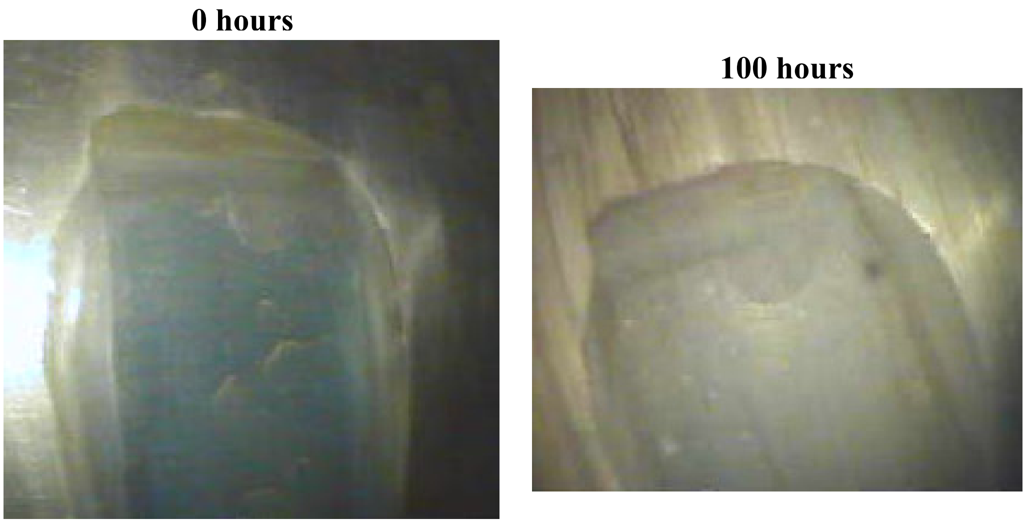

Figure 49 - Representative Photographs of Bucket Tip

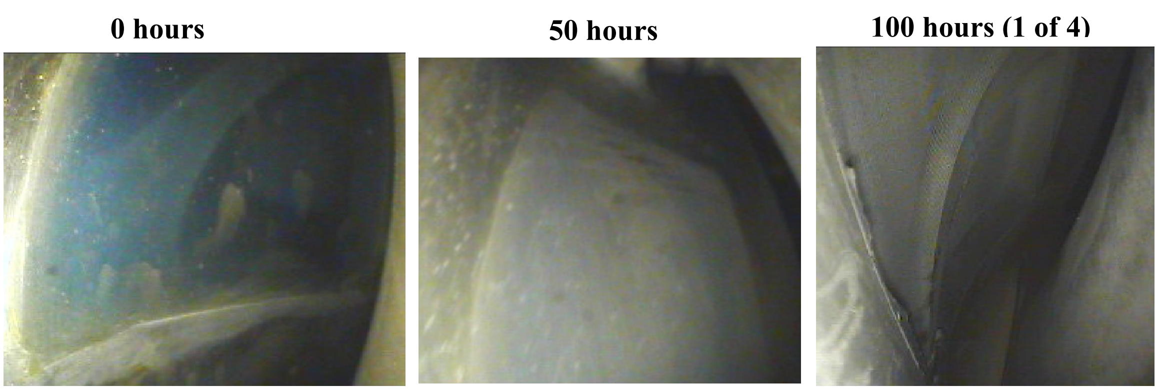

Figure 50 - Representative Photographs of Bucket Root

Appendix I – Experimental Processes & Procedures

This section presents a descriptive summary of the experimental methods in use for the conduct of this project. Described below are the experimental methods being used for the research efforts by Task, and where appropriate Subtask, during this reporting period. Not all tasks/subtasks have yet been initiated during this quarter of the program.

Task 3.0 – Hybrid Materials and Process Development:

Lapshear tests were used as the primary assessment for adhesion and environmental durability since the adhesion interface is loaded primarily in shear. Lapshear specimens were fabricated by bonding 1"x 4" strips of metal with a 0.5"x 1" overlap bond area using the following procedure:

Grit Blast:

- Grit blast a 1"x 1" area of bond surface using alumina (Al_2O_3)
- Rinse with distilled water – check for grit residue on bond surface.

Stainless Steel Etch:

- Wipe samples with solvent or immerse in solvent within Ultrasonic bath
- Immerse in Etch solution for desired time at desired temperature
- Immerse in hot distilled water
- Immerse in room temperature distilled water
- Rinse with room temperature distilled water
- Place in rack and dry in oven overnight

Prime Steel

- Primer: Apply primer with spray gun target
- Dry in oven

Single Lapshear (SLS) Fabrication:

- Pre-heat curative and urethane
- Prepare mold:
    a. Spray mold and top of shim with mold release
    b. Preheat mold
- Prepare single lapshear pieces
    a. Place the lapshear substrates into oven with molds and let pre-heat
- Prepare urethane for casting. Degas these in a heated vacuum oven prior to any mixing
    a. Heat vacuum oven
    b. Degas until bubbling ceases,
- Casting/Molding
    a. Remove Mold and SLS pieces and place near Speedmixer DAC 400 (Figure 51) used to mix urethane and curative.

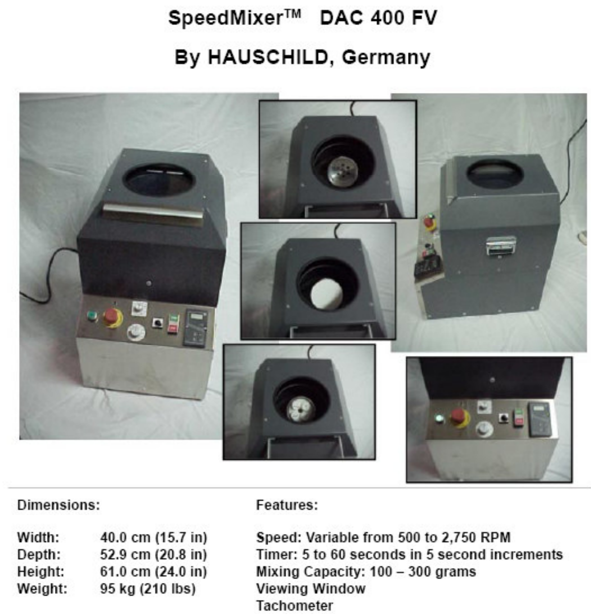

Figure 51 - Centrifuge mixer used for mixing small batch samples

b. Place disposable Speedmixer container on balance and tare. Pour in preweighed curative and urethane.
c. Place top on container and place in mixer.
d. Mix for 10 seconds at 2800 rpm.
e. Remove container and then remove top.
f. Quickly pour polyurethane contents across the surfaces of the single lapshear pieces within 1 minute.
   i. Place top single lapshear pieces. Make sure they are aligned and lightly press down on them to ensure good contact
g. Place mold with SLS pieces into oven
h. After 30 minutes remove SLS pieces from mold and place pieces in oven at 130°C for post cure

- After post cure remove SLS pieces from oven and let stand at room temperature
- SLS preparation
  c. Clean up SLS pieces by removing polyurethane from sides, top and bottom
     i. Razor buckets, *Exacto* knife and brass wheel are very helpful
  d. Measure the width, thickness, and length of the bondline
     i. Calculate bond line area
     ii. Calculate bond line thickness
- Test at 0.2”/min. Shear stresses are reported two ways: as simple P/A and with a peaking factor estimated through analysis using the following equation:

$$f = 7.415t^2 - 0.4681t + 1.4416$$

$$\sigma = f\frac{P}{A}$$

where f = peaking factor to account for stress concentration at edge of lapshear with 12 ksi modulus material

t = bondline thickness (in)
σ = peak stress (psi)
P = maximum load at failure (lb)
A = bond area (in^2)

DynaFlow, Inc. (Jessup, MD) performed the low angle (20°) water erosion tests using the setup shown in Figure 52. Interrupted water jet (Servojet) was run at 750 ft/sec and weight loss measurements over time were used to measure relative erosion resistance. Sample size was 2"diameter x 0.125" thick.

Figure 52 - Erosion Test Set-up.

Task 5.0 – Test Validation of 33.5" Subscale Steel-Hybrid Bucket:

Design Objective: Design a hybrid bucket out of an existing 33.5H" LSB that meets all of the GE Design Practice requirements for use in the LPDT facility.

Test Objective: Validate the material life while exposed to hot/wet steam conditions. This is fundamentally to validate durability endurance of the material and adhesion to the bucket.

- Material Endurance
- Proof of concept
- Frequency Validation
- High Temperature endurance (with existing material Hybrifil3)

Test Plan:

- Monitor and evaluate the bucket vibration characteristics.
- Dynamic strain gages to be used to ensure adequate frequency margins and low dynamic stresses are maintained during the testing
- 100 hours testing
- 8 Total buckets to get instrumented (4 Hybrid / 4 Baseline) spaced 90 degrees apart
- Various flow rates & Backpressure
- Prior to assembly: Single bucket Ping test after pocket machining and after filling is complete.
- Goal is to spend time at lower temperatures (200F-285F) and spend significant time near the end of test as hot as possible (300-350F) near bucket tip (windage heating). This is beyond the predicted usable range for the material under these loading conditions.

Required Test Hardware:

Hybrid Long Buckets (L-0)

- Buckets are a subscale of the 33.5H bucket
- Buckets to be tested were originally manufactured to GEdrawings. These had additional "pocket" machining done on the pressure side by Manufacturing Tech.). Test buckets were then willed with a polymer material.
- Baseline buckets used in this test are the standard LPDT subscale 33.5H buckets.
- Buckets & Side entry covers to have final "cut clearance" done after assembly
- Spare pins need to be procured as needed for bucket replacement
- Spare nub sleeves and reamers should be on hand in case of damage or loss during assembly.
- Hybrifil was bonded on to the buckets by Parkway Products (Cincinnati, OH):
    - Grit blasting, etching, and priming were performed as described in Task 3.
    - Aluminum caul sheet with the machined airfoil shape was mounted over the top of the pocket on the hybrid buckets prior to casting on Hybrifil (Figure 53).

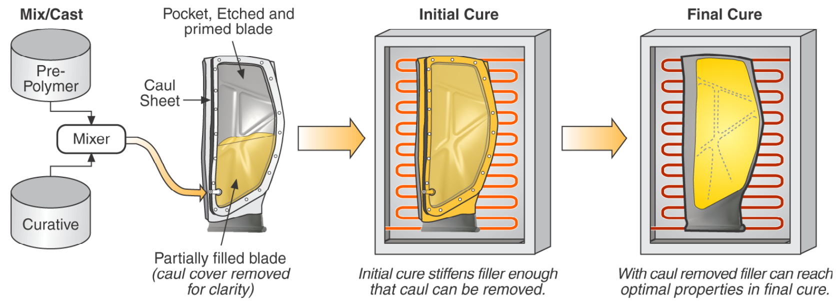

Figure 53 - Hybrid Bucket Casting

- Caul sheet and buckets were preheated to 230°F prior to casting.
- Casting was performed by pumping the pre-polymer and curative into a dynamic mixer and fed directly through the caul sheet into the pocketed areas.
- Buckets were placed into the oven at 230°F for 30 minutes to attain green strength.
- Caul sheet was removed and buckets were placed into an oven at 266°F for 48 hours to achieve full strength.

Test Hardware, Set Up & Instrumentation:

- 8 Total buckets to get instrumented - 4 Hybrid / 4 Baseline (see Figure 55)
- Diagram for gage locations (see Figure 54 and Figure 58)
- Double redundancy for all strain gage locations is planned (24 gages total for Hybrid and 24 for the Baseline buckets)
- All gages are to be placed on the suction side (convex) of all buckets
- Two strain gages at all locations (48 stain gages total)
- 2 Strain ranges to be used for the strain gages. The lower range (approx. 20u peak) in positions “SGB”, the higher range (approx. 60u peak) to be in position “SGA”.
- 2 Thermocouples near the tip on Suction Side of all Baseline and Hybrid buckets
- Instrumented Hybrid buckets to be spaced 90deg apart (set of 4 instrumented Baseline buckets to be 45deg to these and 90deg to each other)
- Gages will be connected via. DDAS through rotor bore
- Bucket not to be taken above 265 (deg F) during application of any gages. Temperature charting needs to be done on buckets (oven) during the curing cycle.
- Hybrid Bucket Serial numbers 45AACD, 81AAMD, 92ACD and 88AND (vinyl mask use during etch).
- The diaphragms used can be either the standard diaphragms for the 33.5” scale or the Aero. Engineering test diaphragm for the 42” L-0.

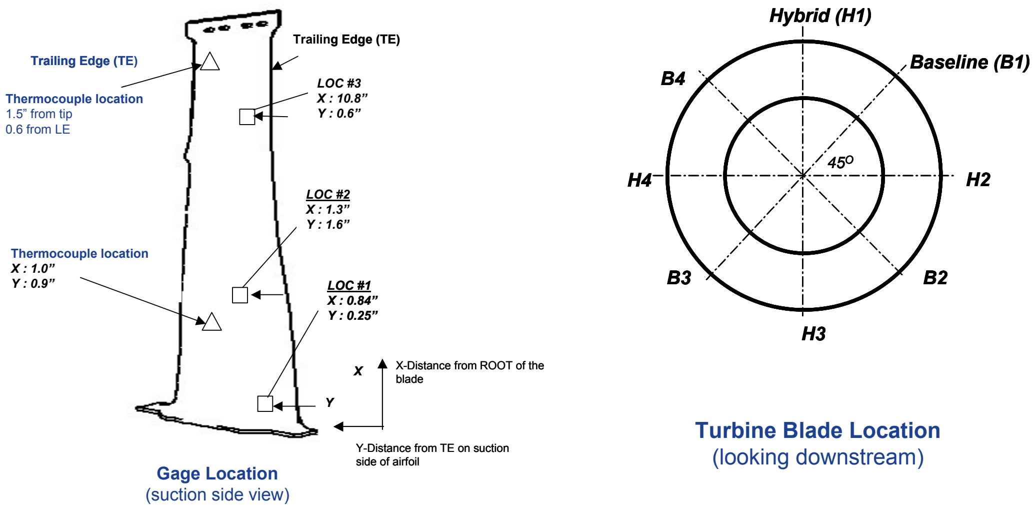

Figure 54 - Bucket Instrumentation Locations

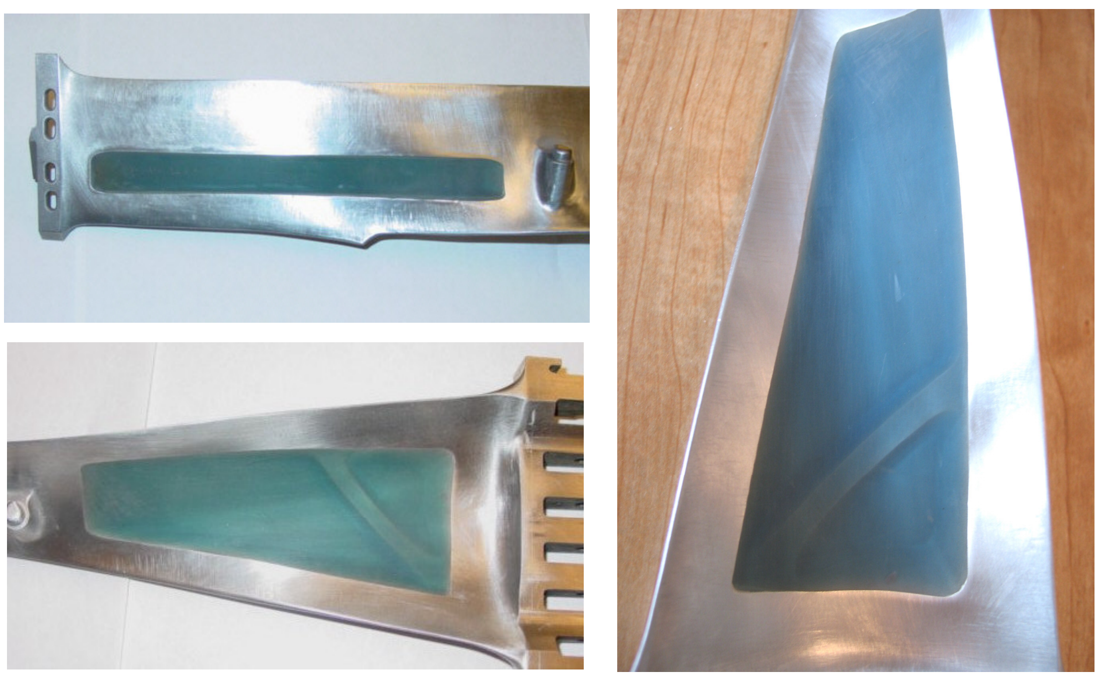

Figure 55 - Pre-test Bucket Pictures

Data Collection and Additional Test Stipulations Instructions:

- Record all transient strain gage data during the run to full-speed full-load and during all shutdowns
- Transient run – all transient data recorded on magnetic tape as a minimum
- SS point once turbine has stabilized (Test Plan)
- Turbine to be run at normal (scaled) speed of 8551 RPM
- Real time display
  - Strain gage data on oscilloscope, LMS system or via DDAS system
  - Strain gage data at all times even during testing when not recorded directly to tape

    - Thermocouple values
- Data reduction format
    - Order plots for all instrumented buckets (1 - 14/rev), Campbell diagrams, waterfall plots, & peak hold vs. frequency & peak hold vs. order.
- Yellow alarm to be set for the Bucket tip thermocouples at 300F for entire test until the last test run.
- Maximum Alarm limit to be set at 105% and trip limit to be set at 110%
- Initial Borescope (videotape) after assembly and prior to testing with steam.
- Borescope and videotape per Test Plan
- Borescope as required by test team decision (event related)
- After an unscheduled event no testing is to commence until the root cause is determined for the event
- High Backpressure Test: The goal of this test is to get to high backpressure conditions (ramp up) to determine if the buckets show any instability.

Post Test
- Non-destructive evaluation of filler material & adhesive system
- Comparison of strain gage response between baseline and hybrid buckets
- Results to be tabulated & conclusions drawn

Test Details
- 106 total endurance hours at below 220F degrees bucket temperature
- One 105% over speed run
- Borescope inspection completed at 20min, 10 hour, 50 hour and 100 hours
- Various flow and backpressure conditions with no degradation of polymer during first 50 hrs of testing
- Last 32 hours the turbine was run to high temperature tip windage (~330F) condition
- Additional 40.5 hours of GE Energy testing done after Hybrid test was completed

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Appendix II – LPDT Facility Technical Description

Low Pressure Development Turbine (LPDT) Facility

The LPDT is located in Schenectady, NY and is the world's most advanced Low Pressure Development Turbine. During the past four years, GE Energy has made an investment of over $40M in this facility. Figure 56 shows an overhead photograph of the facility. The capabilities of this facility include:

- LPDT~1/3 scale
- Capable of testing scaled LSBs up to ~63"
- Inlet temperature range: 180ºF – 700ºF
- Inlet pressure range: 6 psia – 80 psia
- Steam flow rate: 20,000 – 295,000 lbm/hr
- Nominal rotor speeds of 8000 – 12,000 RPM
- Minimum exhaust pressure: 0.6 inHg
- Maximum power output: 17 MW (~23,000hp)
- Load absorption: 2 water brakes (14 MW & 3 MW)
- 2 inline torque meters
- Steam flow measured via ASME PTC 6 flow nozzle
- All condensate flows measured via Coriolis Flow Meters

Figure 56 - GE Energy LPDT Facility

LPDT Data Acquisition System (DAS)

The LPDT facility has a world-class data acquisition that has extensive capability to characterize and validate the aerodynamic and aeromechanic design of low pressure turbine steampaths. Figure 57 shows a photograph of the control room for the LPDT facility.

- Real time data collection capability
- Software interface: TestView based on National Instrument's LabView
- All parameters associated with determining turbine performance including:
- 600 pressures & 400 temperatures
- 8 condensate mass flow rates
- Speed
- Multiple torque measurements
- Interstage flow path mapping
- Automatic bad sensor disabling
- Interfaced with DCS (Distributed Control System)

Figure 57 - GE Energy LPDT Facility - Digital Data Acquisition System

Appendix III – Detailed bucket instrumentation map

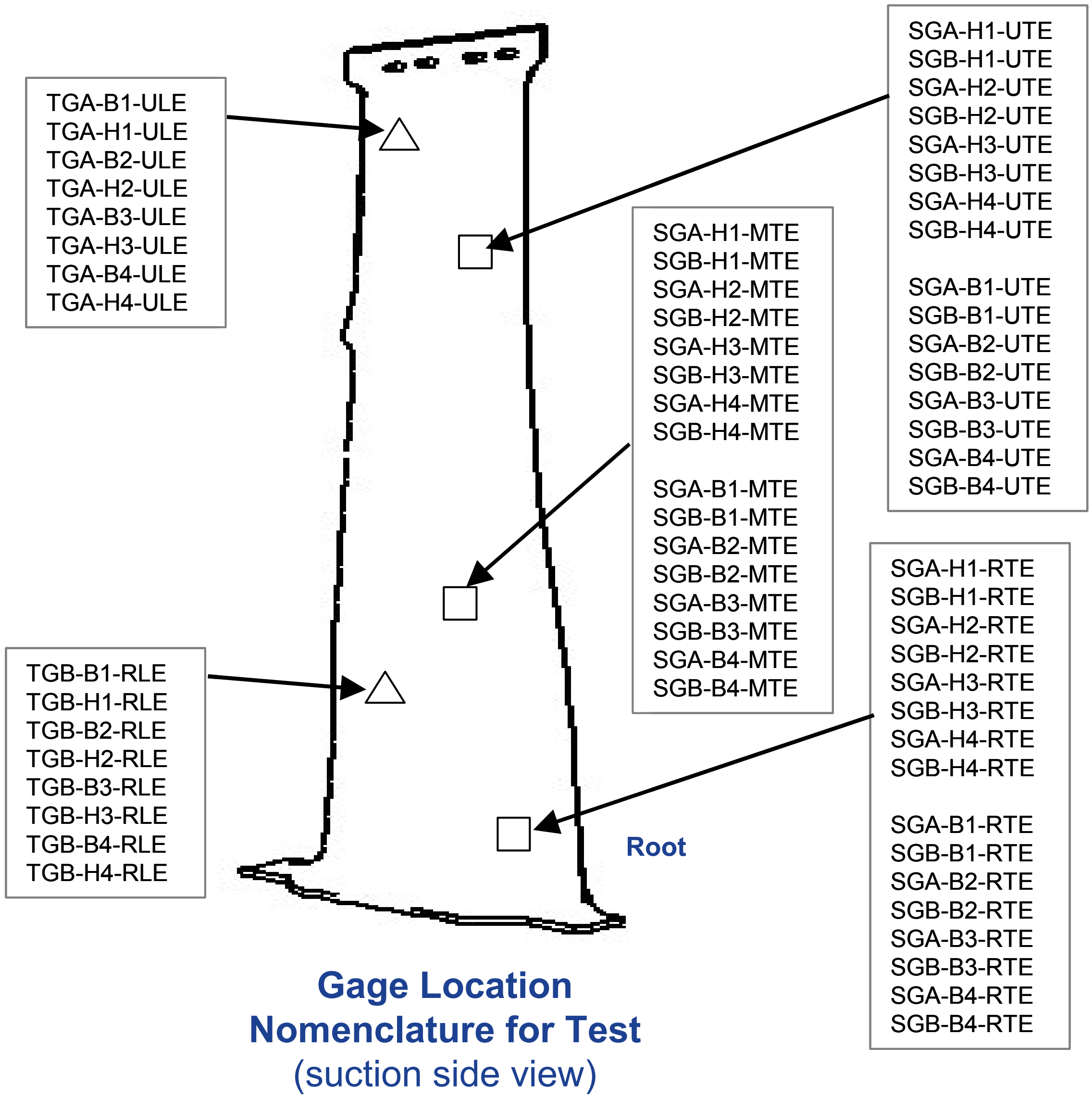

Figure 58 - LPDT Bucket Gage Locations

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Appendix IV – References

1. Evans, C.R., Ward, D.D., Lin, W.W., Chao, H.S. and Begovich, J.T., "Elastomeric Formulation Used in the Construction of a Lightweight Aircraft Engine Fan Bucket", US Patent US6287080, Sept. 11, 2001.

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Appendix V – List of Acronyms and Abbreviations

APDL	ANSYS Parametric Design Language
DAS	Data Acquisition System
GE	General Electric Company
Hybrifil	Toluene-diisocynate-ether urethane
Hz	Hertz
IGES	Initial Graphics Exchange Specification
L-0	Last stage bucket row
LCF	Low cycle fatigue
LE	Leading edge (bucket)
LP	Low Pressure
LPDT	Low Pressure Development Turbine
LSB	Last Stage Bucket
ND	Nodal diameter
ppm	Part per million
RCA	Root Cause Analysis
RPM	Revolutions per minute
TE	Trailing edge (bucket)
Ti	Titanium material
UG	UniGraphics modeling tool

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