Final Technical Report

SLH Timing Belt Powertrain
Award # DE-EE0005412

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Contents

1 Executive Summary

The main goal of this proposal was to develop and test a novel powertrain solution for the SLH hydroEngine™, a low-cost, efficient low-head hydropower technology.

Nearly two-thirds of U.S. renewable electricity is produced by hydropower (EIA 2010). According to the U.S. Department of Energy; this amount could be increased by 50% with small hydropower plants, often using already-existing dams (Hall 2004; [2]). There are more than 80,000 existing dams, and of these, less than 4% generate power (Blankinship 2009; [1]). In addition, there are over 800 irrigation districts in the U.S., many with multiple, non-power, low-head drops. These existing, non-power dams and irrigation drops could be retrofitted to produce distributed, baseload, renewable energy with appropriate technology. The problem is that most existing dams are low-head, or less than 30 feet in height (Ragon 2009; [3]). Only about 2% of the available low-head hydropower resource in the U.S. has been developed, leaving more than 70 GW of annual mean potential low-head capacity untapped (Hall 2004; [2]). Natel Energy, Inc. is developing a low-head hydropower turbine that operates efficiently at heads less than 6 meters and is cost-effective for deployment across multiple low-head structures.

Because of the unique racetrack-like path taken by the prime-movers in the SLH, a flexible powertrain is required. Historically, the only viable technological solution was roller chain. Despite the having the ability to easily attach blades, roller chain is characterized by significant drawbacks, including high cost, wear, and vibration from chordal action.

Advanced carbon-fiber-reinforced timing belts have been recently developed which, coupled with a novel belt attachment system developed by Natel Energy, result in a large reduction in moving parts, reduced mass and cost, and elimination of chordal action for increased fatigue life. The work done in this project affirmatively addressed each of the following 3 major uncertainties concerning a timing-belt based hydroEngine™powertrain:

1. Can a belt handle the high torques and power loads demanded by the SLH? (**Yes.**)
2. Can the SLH blades be mounted to belt with a connection that can withstand the loads encountered in operation? (**Yes.**)
3. Can the belt, with blade attachments, live through the required cyclic loading? (**Yes.**)

The research adds to the general understanding of sustainable small hydropower systems by using innovative system testing to develop and demonstrate performance of a novel powertrain solution, enabling a new type of hydroelectric turbine to be commercially developed.

The technical effectiveness of the methods investigated has been shown to be positive through an extensive design and testing process accommodating many constraints and goals, with a major emphasis on high cycle fatigue life. Economic feasibility of the innovations has been demonstrated through many iterations of design for manufacturability and cost reduction.

The project is of benefit to the public because it has helped to develop a solution to a major problem – despite the large available potential for new low-head hydropower, high capital costs and high levelized cost of electricity (LCOE) continue to be major barriers to project development. The hydroEngine™represents a significant innovation, leveraging novel fluid mechanics and mechanical configuration to allow lower-cost turbine manufacture and development of low head hydropower resources.

2 Project goals and objectives: actual vs proposed

The main goal of this proposal was to develop and test a novel powertrain solution for the SLH hydroEngine™, a low-cost, efficient low-head hydropower technology.

The project proposal outlined 5 objectives.

Objective 1 Complete design and testing of belt-type SLH powertrain components at 50 kW- and 500 kW-scales.

Actual: Load specifications were generated for 50 kW- and 500 kW-scale belts. A scale-model hydraulic test facility was designed, built, and commissioned to provide experimental verification of analytical (CFD) loads. Finite element analysis was performed on attachment system parts. Tests were conducted on coupons of a variety of candidate attachment designs using an Instron universal testing machine. "v1" and "v2" belt attachment design recommendations were generated for deployment in endurance tests.

A third-generation attachment, incorporating lessons learned from the small scale endurance tests, was designed and prototyped at the 500 kW scale. Multiple fatigue test rigs were designed, built, and operated for tens of millions of cycles, forming the basis for a final recommended blade/belt articulation and attachment design.

Objective 2 Phase I, System Endurance Testing: Integrate v1 belt/blade attachment design into small-scale (50 kW) SLH model and conduct long-duration laboratory testing, across a full range of potential operating scenarios.

Actual: The v1 belt/blade attachment design was integrated into a full belt powertrain for the SLH10 (50 kW) prototype. The machine was commissioned and tested at Alden Research Laboratory across a range of operating scenarios. Several iterations on this powertrain design were created based upon observations of performance leading to design improvements and recommendations for a "v2" belt attachment.

Objective 3 Phase II, System Endurance Testing: Integrate v2 belt/blade attachment design into a 50 kW SLH model, and conduct long-duration laboratory testing.

Actual: An SLH10 unit was assembled with a "v2" belt attachment design. This unit was installed and commissioned in a field setting for long-duration testing. Periodic observation and inspection of the unit resulted in further improvements to the belt attachment design.

Objective 4 Design-For-Manufacture, both 50 kW and 500 kW scale

Actual: Attention was focused on the 500 kW scale powertrain, due to better market potential. Design-for-manufacture exercises were conducted, optimizing attachment system components both for medium and high volume production scenarios.

Objective 5 Calculate LCOE of SLH, as a consequence of new belt powertrain.

Actual: Powertrain costs have been identified, including upfront capital cost and levelized replacement cost. Supply curves (cost vs volume curves) were obtained through a multi-source bid process.

3 Summary of project activities

Because of the unique racetrack-like path taken by the prime-movers in the SLH, a flexible powertrain is required. Historically, the only viable technological solution was roller chain. Despite the having the ability to easily attach blades, roller chain is characterized by significant drawbacks, including high cost, wear, and vibration from chordal action.

As an alternative to roller chain, timing belts offer a large reduction in moving parts, reduced mass and cost, and elimination of chordal action for increased fatigue life. However, a timing belt based hydroEngine™powertrain has the following major uncertainties:

1. Can a belt handle the high torques and power loads demanded by the SLH?
2. Can the SLH blades be mounted to belt with a connection that can withstand the loads encountered in operation?
3. Can the belt, with blade attachments, live through the required cyclic loading?

Until recently, no timing belt could pass the first question – timing belts simply could not transmit the high level of torque required by the SLH. However, advances in materials, design, and belt manufacturing have resolved the main historical limitations to the use of timing belt in many high torque applications. One American manufacturer in particular has been on the leading edge of belt innovation – The Gates Corporation. In the mid-2000s, Gates released the first-ever carbon-fiber reinforced timing belt, fundamentally improving the power and torque capability of timing belt. Their product, "Poly Chain Carbon GT", is now often considered a direct width-for-width replacement for steel roller chain in industrial power transmission applications.

* The Gates Corporation is in the process of developing large-pitch, ultra-high power timing belts that expand its product range beyond the standard 8 mm and 14 mm pitch belts, to 19 mm and 32 mm pitch belts. (Pitch is the distance between successive teeth on a timing belt.) Together with the 14 mm pitch line, these large-pitch belts promise to offer power capability and physical size capable of handling most of the range of operation of the SLH10, SLH50, and SLH100 machines. Neither of the larger-pitch timing belts are commercially available yet to the general public. Discussions with Gates sales engineers resulted in specification of widths of the large pitch belts, which would be able to withstand the loads of the SLH50 and SLH100 size machines, thus answering - on paper - the first major uncertainty.

The remaining two technical uncertainties formed the basis for the project workplan. It is critical for the success of the timing belt as an option for the SLH powertrain, that a successful design be created for the blade-to-belt attachment interface, and that this interface be capable of surviving all stresses likely to be encountered in operation, during the life of the project.

3.1 Objective 1: Component design and testing at 50 kW and 500 kW-scales.

Summary Natel Energy designed, built, and tested multiple generations of belt attachment and blade/belt articulation concepts, including 3 full-system endurance test machines at the SLH10 scale. Lessons learned from these systems informed the design of a new solution which promises to overcome each of the previous systems' drawbacks. Design loads for this system were verified through the operation of a scale model hydraulic test facility. The final solution has demonstrated the ability to withstand tens of millions of alternating load fatigue cycles with negligible wear.

3.1.1 Development of specifications

Fatigue life A target life of 15,000 hours between belt replacements has been established. This is based in part on a comparable design life for other belt and chain based industrial equipment.

The components in the powertrain will be subject to alternating loads. Each time a blade makes a full circuit, it will experience at least 2 fluctuations in load, from some low magnitude in the sprocket region, to a high magnitude in the linear portion, and back again.

In order to survive 15,000 hours of accumulated operation, the blades and associated belt attachment components in the hydroEngine™will need to survive on the order of 100 million fatigue cycles. (The number is actually somewhat less – about 77 million cycles for the SLH100 and 88 million cycles for the SLH10. The number of cycles increases for smaller machines due to the increased rate of rotation.)

Mechanical requirements Blade loads and moments in the the 500 kW SLH100 were calculated to vary as shown in Table 1.

Table 1: 500 kW SLH100 blade loads (at 6 meters net head, 47° GV angle)

	max (+)	max (-)	unit
lift	11.6	-4.9	kN
drag	5.2	-7	kN
moment	355	-325	N-m

The belt-to-blade articulation shall have the degrees of freedom shown in Table 2.

The belt-to-blade articulation shall have a lifetime of $\geq 5,000$ hours before replacement.

Additionally, the belt-to-blade articulation should have the following characteristics:

1. Life: $\geq 15,000$ hours.
2. No sliding surfaces (to minimize maintenance and wear).
3. Each blade should be able to disassemble from the belt individually.
4. The blade-to-belt attachment should be positioned coincident with the limit of belt reinforcing cords farthest from the belt teeth, centered on the belt width.

Table 2: Blade-to-belt articulation DOFs

DOF		value	reason
DOF1	trans x	0.5 mm	load-induced deformations[1]
DOF2	trans y	fix	
DOF3	trans z	fix; < 0.5 mm	slight compliance allowed
DOF4	rot x	$0.6°$	shaft windup; no larger rotation allowed[2]
DOF5	rot y	$+1°/-0.35°$	blade end slope (lift)[3]
DOF6	rot z	$\pm 0.5°$	blade end slope (drag)[3]

[1] Manufacturing tolerances will be much larger, but should be removed during assembly.
[2] This implies the maximum deviation in slope allowed, by the blade assembly, w.r.t. the x-axis.
[3] Blade-to-belt attachment should behave like a pinned joint for this DOF.

The blade lift and drag loads of the SLH10 were calculated to have a maximum value of 600 N and 125 N respectively, when the guidevanes are wide open. Since each blade is attached at two ends, the load can be considered to be split in half, or a maximum of about 300N (31 kgf, 67 lbf) at each blade/belt attachment location.

CFD Natel Energy has developed a number of advanced computational tools to assist in the design of its hydroEngine™products, including computational fluid dynamics (CFD) programs capable of simulating on a time-accurate (explicit) basis the motion of the entire cross-section of the machine. These CFD simulations allow the output of mechanical loads useful for powertrain design – in particular, since the simulations are time-accurate and not time-averaged, the loads have the potential to be used to inform fatigue calculations. In order to verify these loads, Nate Energy has invested in the ability to perform scale-model hydraulic testing in-house.

Scale model hydraulic test facility Referencing the International Electrotechnical Commission standard IEC 60193 "Hydraulic turbines, storage pumps and pump-turbines – Model acceptance tests" (Second edition 1999-11), and with advice from Alden Research Laboratory, Natel Energy designed and constructed a closed-loop hydraulic test facility capable of up to 0.3 m^3/s at low heads (0.3 m - 3 m normally). The facility was sized to allow testing of models in the range of 1:6 scale of the 500 kW SLH00 product. Figure 1 presents a schematic of the test facility.

A Sulzer ABS J 604 ND submersible pump mounted in a sump tank, controlled by a variable frequency drive (VFD), forces water through 13.6 meters of 0.25 m diameter pipe (53 pipe diameters) before entering a Model 2300 insert-type venturi manufactured by Westfall Manufacturing. Differential pressure across the Venturi is measured by an Omega PX419-015DWUI differential pressure sensor, with a combined accuracy of 0.08%. This venturi meter with its differential pressure sensor was calibrated by Utah Water Research Laboratory (UWRL) using a 12 point process over the range of 350 GPM to 4,500 GPM.

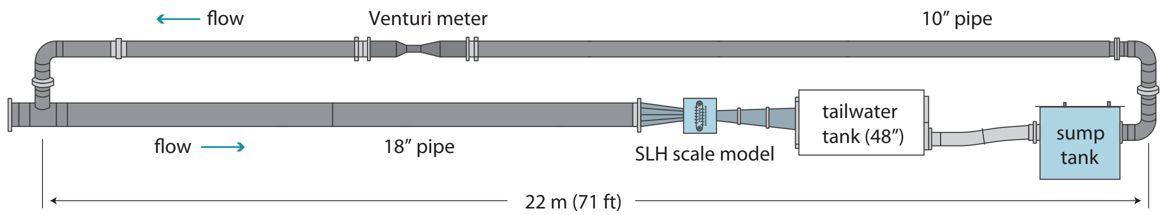

Figure 1: Scale model hydraulic test facility.

After leaving the Venturi flow meter, water flows through 6.2 meters of the same 0.25 m diameter pipe, to a pair of 90-degree bends. A flow straightener consisting of several guidevanes aids in improving flow through the last bend, as it transitions to a 0.46 meter diameter penstock. Water flows through 11.8 meters of penstock (25.8 pipe diameters) prior to entering a round-to-rectangular transition, leading into the scale model hydroEngine™. The facility is engineered to allow for a variety of different hydroEngine™configurations to be tested, including versions with various lengths or slopes of draft tube. A large diameter (1.2 m) tank simulates the sudden expansion flow will experience as it leaves the outlet of the draft tube.

The pressure drop across the SLH is measured using an Omega PX419-005DWUI differential pressure sensor. The sensor has a range of 0-5 psi, with an accuracy of 0.08%. Torque and speed of scale model hydroEngine™are measured with a Futek FSH02058 torque sensor. The unit has a 0-100 N-m range and 0.5% accuracy.

Torque on the test unit is provided by an induction motor coupled to the hydroEngine™and controlled with a regenerative VFD. The motor and VFD are sized to permit operation across a wide range of conditions including "no-speed" and "no-load" conditions.

Water temperature is measured with an Omega PR-21D-3-100-A-1/4-0600-M12-1 Pt100 Class-A RTD, with an Omega TX94A-1-SS-M12M-1RTD transducer.

Scale model hydraulic testing A 1:6.4 scale model of the 500 kW SLH100 unit was designed, built, and tested (Figure 2).

Results from the scale model tests show good agreement with CFD predictions, not only at the best efficiency point, but also at the low-flow and high-flow extremes. Figure 3) shows that the efficiency predicted by CFD simulations falls within the uncertainty limits of the scale model test facility from flows as low as 35%, and up to 115%, of peak-efficiency flow rate.

From the standpoint of hydroEngine™powertrain engineering, these results lend important confidence that the time-accurate loads from Natel Energy's CFD simulations can be utilized for design of parts capable of withstanding the high-cycle fatigue demands placed upon them.

3.1.2 50 kW scale

Natel conducted a number of preliminary analyses and bench-level prototyping activities to assess the feasibility of an attachment interface at the 50 kW scale. Gates PolyChain Carbon

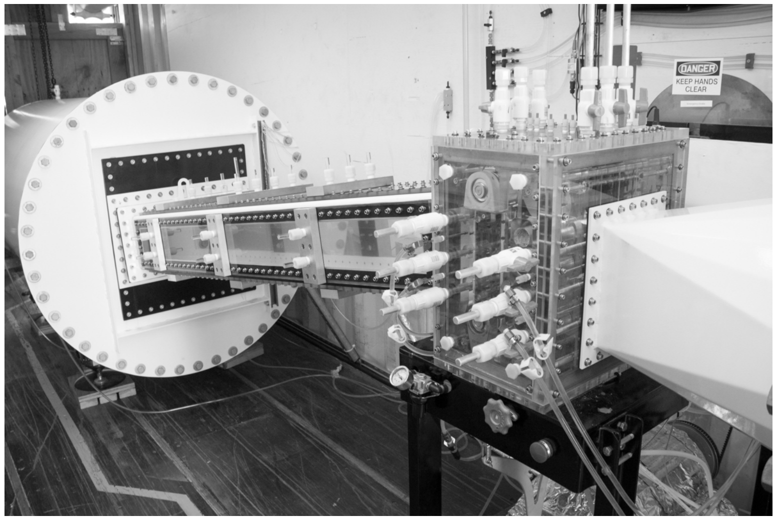

Figure 2: 1:6.4 scale model hydroEngine™installed in the test facility.

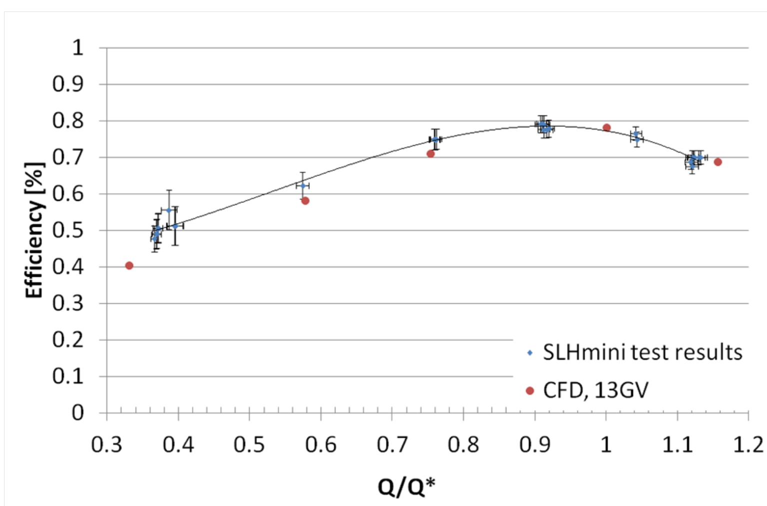

Figure 3: Experimental data vs CFD predictions, for a scale model hydroEngine™.

GT 14 mm pitch belt (the largest carbon reinforced belt pitch available over-the-counter) was selected as the basis of the powertrain.

*A series of potential belt attachment designs were brainstormed, physically prototyped, and tested with an Instron universal testing machine. The design options could be separated into two primary architectures:

1. Piercing through the tooth (ie: drilling holes along the axis of the tooth).
2. Piercing the belt perpendicular to the flat back.

*Both architectures held promise, although the first option is made more difficult as the width of the belt increases relative to the tooth size. Particularly, at small belt pitches (ie: 14mm) this approach was cumbersome to implement due to the difficulty of drilling a small, straight hole for a long distance.

*The second architecture – piercing the belt perpendicular to its flat back – is relatively easy to implement on a belt of any size. It can be further sub-segmented into two approaches for augmentation (increasing of strength and stiffness of the attachment):

1. Backside augmentation: with adhesives, mechanical cleats or grooves, etc
2. Tooth-side augmentation: via conformal tooth caps, compression "bridges", washers, etc.

A final recommendation for the "v1" attachment was created, and this design was subjected to fatigue loading using an Instron testing machine.

3.1.3 500 kW scale

Natel Energy worked with the Gates Corporation to obtain access to large pitch carbon-reinforced timing belt. Both 19 mm and 32 mm pitch options were evaluated as candidates for the SLH100 powertrain. The larger 32 mm pitch option was selected due to its ability to accomodate a greater range of attachment options within its larger teeth cross section.

Building on the coupon tests done at the 50 kW scale on 14 mm pitch belt, a series of attachments were designed and static Instron coupon tests conducted using the 32 mm pitch belt.

Fatigue testing: shear Based on the initial success of these tests, a pair of cyclic shear stress fatigue test rigs were designed and constructed. These test rigs isolated the attachment load to consist only of shear, and were intended to test the difference between alternate designs. Each test rig utilized a pneumatic cylinder to push and pull on a belt crossbar. The belt was clamped in the test rig and out-of-plane motions were restricted by a linear bearing (Figure 4).

Two alternate crossbar configurations were evaluated on the shear fatigue test rigs, which were identical except for one difference: one used a high performance epoxy adhesive to augment the connection between the crossbar and the belt. Both configurations used through bolts to hold the crossbar, which was equipped with crampon-like teeth, onto the belt. The coupon with adhesive augmentation has not failed after 66 million cycles and testing is ongoing. The coupon without adhesive augmentation experienced two failures of the attachment bolts, one after only 2.5 million cycles, and another after 48 million cycles. In both instances, the failures were caused by cracks initiated at stress concentrations located in areas having high bending moments in addition to shear stress. After redesign to move these features away from areas of high combined stresses, a third revision of this crossbar design is currently still running with no failures after 51 million cycles (Figure 5).

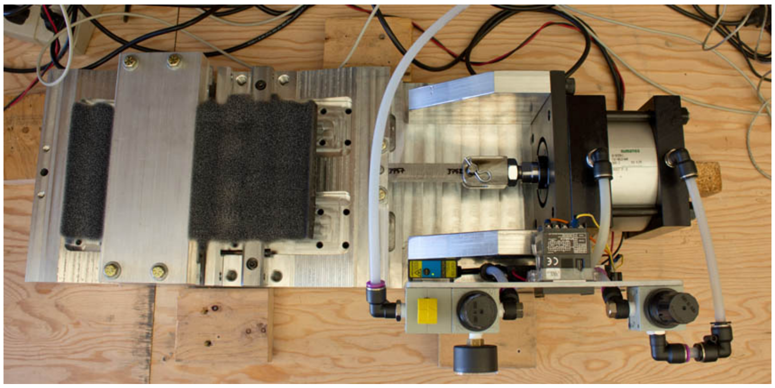

Figure 4: Shear fatigue test rig for 500 kW-scale belt attachment system.

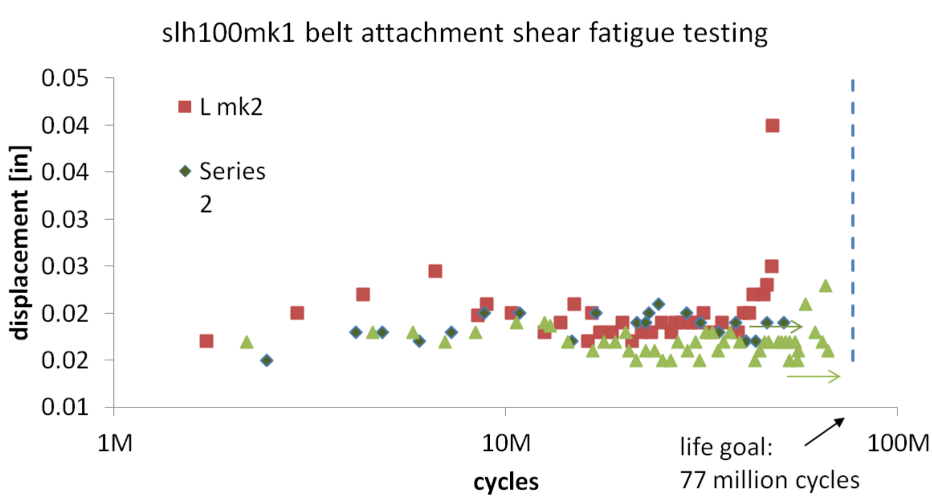

Figure 5: Shear fatigue testing of 500 kW-scale "v3" belt attachment system.

Fatigue testing: "v3" articulation concept After establishing the initial reliability of the crossbar concept on the shear fatigue test rigs, Natel Energy began working on a new belt-to-blade articulation design, incorporating lesons learned from the "v1", "v2a", and "v2b" concepts tested on the 14 mm pitch SLH10 belts.

A key design goal was the elimination of un-protectable sliding metal-to-metal interfaces, observed to result in rapid wear in the "v2" concepts. However, a design had to be created which could sufficiently restrain the blade against pitching moments, in contrast to the weak pivot of the "v1" design.

A solution was found in the idea of using multiple crossbar attachments, per blade pitch, to provide a sufficiently large moment arm that could restrain the blade against pitching moments. More specifically, each blade endplate attaches to the belt by mounting to a platform spanning a pair of crossbars. The platform is supported by special bearings embedded within each crossbar.

The entire system was designed to accomodate the fatigue life and loads of Table 1 and the degrees of freedom listed in Table 2.

A new fatigue tester was designed and built (Figure 6), capable of simulating the loads, moments, and most of the degrees of freedom that the actual belt/blade articulation system would experience in real life. Additionally this tester replicates the bending stress experienced by the belt as it flexes around the sprocket. Note that Natel chose to utilize this ability of the test rig to test belt bending stresses rather than building a full dynamometer as proposed, since it represented a better use of resources at this stage in the project.

Figure 6: Articulation fatigue test rig for 500 kW-scale "v3" belt attachment system.

Several iterations of design/build/test were completed, and after some preliminary failures and redesigns, a design emerged which demonstrated operation with negligible wear. To test the effect of operation with compromised and no lubrication, this coupon was disassembled, and reassembled, several times. The first time, disassembly and inspection after 5.5 million cycles of operation with "proper" lubrication showed minimal wear. The components were wiped clean, splashed with water, and reassembled. After another 8.5 million cycles (total of 14 million cycles), the test article was disassembled and inspection again showed minimal wear. Then, the parts were ultrasonically cleaned to remove all traces of lubrication. After re-assembled, the "dry" version failed within 1 million cycles. These tests showed both (a) the potential of the new articulation system to withstand very large loads under very large numbers of cycles, and (b) the importance of maintaining at least some lubrication within the bearings.

Additional iterations on this articulation concept have refined the system components further, particularly with respect to improved robustness and manufacturability. The outcome of design for manufacture work is summarized in Section 3.3.

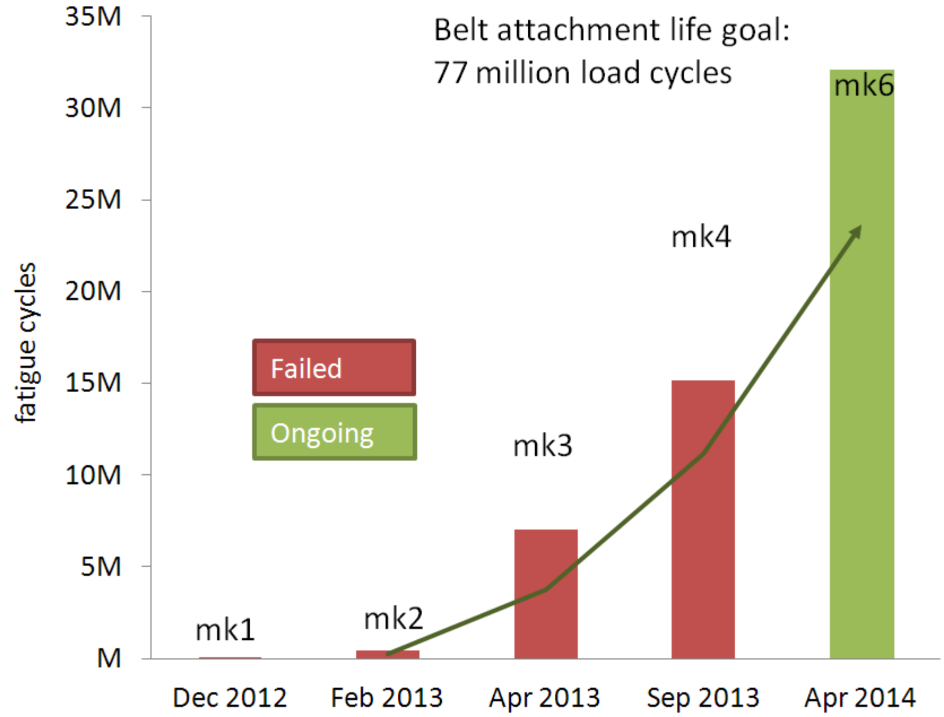

Figure 7: Progressive improvement of 500 kW-scale "v3" belt attachment system.

As of the date of this report, the final "v3" blade/belt articulation design has undergone over 32 million fatigue cycles with no failure and no sign of wear from its date of commissioning. (Figure 7).

3.2 Objectives 2-3: Phase I & II, System Endurance Testing

Summary The motivation of these objectives was to ensure that the powertrain solution meets performance specifications and performs as designed before full-scale commercial development. In the process of execution of the workplan, "v1" and "v2" articulation designs were created and tested at the SLH10 scale. Observations of these solutions showed the need for further improvement, which led to the work on the "v3" articulation designs described in Section 3.1.3.

3.2.1 50 kW "v1"

Out of a field of candidate designs, a version using a backside crossbar with backside augmentation in the form of a mechanical cleat ("crampons") plus a high-performance, water-resistant, flexible but strong epoxy was chosen as the "v1" attachment recommendation. The attachment to the blade was provided via a circular boss and cam-loc type fastener, which allowed the blade to behave in a simply supported fashion (Figure 8a).

An SLH10 hydroEngine™was subsequently constructed and installed at the Hooper Low Reynolds Number Facility at Alden Research Laboratory. Upon startup, undesirable mechanical noises were observed, and the unit was stopped. Closer inspection revealed the cause of the noise to be insufficient restraint of the blades in the "pitching" direction – the blades were allowed to pivot somewhat freely about the long axis of the blade during operation.

3.2.2 50 kW "v2a"

A new blade articulation system featuring very stiff pitching motion restraint was produced and swapped into the SLH10 test unit at Alden Research Laboratory. In this design, each blade was connected to its neighboring blades via pins and slots (Figure 8b). The interaction between the pins and slots allowed for smooth motion around the sprocket while almost completely locking out pitching motion.

As expected, this attachment system eliminated the excessive pitching motions of the "v1" design and allowed for a series of tests to be conducted. This configuration was operated across a wide range of flow rates and power levels, producing up to 30 kW. However, on closer inspection this architecture was revealed to posess a number of undesirable attributes, including the following:

- Blade forces are transferred to the edge of the belt, not its center. As a consequence, the load distribution at the belt attachment is non-uniform and will result in either reduced life, or require overdesign to compensate.
- Pitching moments are transferred to the belt, potentially unnecessarily increasing loads on the belt.
- Blade-to-blade pin/slot connection results in mechanical wear.

3.2.3 50 kW "v2b"

A third belt attachment system was designed and created to address the issues identified in the "v2a" design. This new design retained the interlocking endplate concept to control

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(a)

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(b)

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(c)

Figure 8: *Confidential: SLH10-scale belt attachment systems (a) "v1": ends pinned to crossbar, non interlocking blade endplates; (b) "v2a": interlocking blade endplates, monolithic pin along belt crossbar; (c) "v2b": interlocking blade endplates, segmented pin along belt crossbar.

pitching motions, but had a re-designed interface to transfer blade loads into the middle of the belt width, and allowed for the blades' pitching moments to be reacted directly at the endplate rather than through the belt (Figure 8c).

An SLH10 unit incorporating the "v2b" design was built and installed at Natel Energy's pilot test site at an irrigation drop in Buckeye, AZ. This setting allowed the belt attachment system to be tested in real-world conditions, including suspended sediment and a corrosive environment. Over the course of many months of testing, this attachment system proved its capability to operate, but also showed some key areas for improvement.

In particular, the pin-slot connection between overlapping blades mandated a metal-on-metal sliding interaction, creating a wear interface. This interface was open and unsealed, so the parts' rate of wear was accelerated by three-body abrasion from particles suspended in the water (Figure9). In order to achieve the desired minimum of 15,000 hours operation between belt replacements, intermediate replacement of the wearing parts would be required.

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Figure 9: *Confidential:"v2b" belt attachment system showing wear of pin/slot interface after endurance testing.

The experience gained in testing each of the three 50 kW-scale belt attachment solutions informed a new design effort to eliminate their primary limitation: wear. Details on the development and testing of this new solution are documented in Section 3.1.3.

3.3 Objective 4. Design-For-Manufacture

The motivation of this objective was to ensure manufacturability of the powertrain solution – minimizing cost while maintaining performance, and preparing the powertrain for commercial production.

After demonstrating the potential of the "v3" belt/blade articulation system to meet the performance specifications, Natel Energy worked to optimize the parts for manufacture. This involved a series of activities including:

- Symmetry: Every part in the system was evaluated for opportunities to reduce part count by re-using components in symmetric locations.
- Off-the-shelf parts: Each component was evaluated for the possibility of utilizing off-the-shelf (OTS) parts rather than custom manufactured items.
- Multifunctional parts: Opportunities were found to combine the functions of multiple components, allowing smaller number of components (with fewer and less expensive features) yet achieving the same function.
- Multi-use design: The articulation assembly was designed to allow for general use. As long as the attached accessory provides loads and deflections within the capability of the attachment system, the same powertrain components can be utilized for many possible applications, including hydroEngines of different sizes or form factors, as well as broader industrial applications.
- Modular design: The articulation assembly was architected to allow for construction in a modular fashion, adding versatility to the production process and mitigating against the impact of potential redesign as the product matures.
- Reduction of processing steps: High strength stainless steel was required for certain components. These parts would normally require heat treat, followed by a pickling process to remove tint/scale, and finally a passivation step to maximize corrosion resistance. It was found that the pickling process could be eliminated by performing final machining passes after the heat treatment step, prior to passivation.
- Near net shape: The most expensive custom CNC-machined-from-billet parts in the assembly were evaluated for opportunities to reduce costs through near net shape manufacturing. Investment casting was found to be a promising option for several of these components, with the potential to reduce per-part price by 50-75%. Tooling and production quotes were obtained and a development plan was created to evaluate this option for production.
- Tolerance optimization: Tolerance stackups were performed, within the attachment system as well as within the relevant portions of the blade assembly, to ensure adequate yet not overly-restrictive allocation of manufacturing tolerances.
- Development of assembly aids: A series of standard assembly processes and tooling/jigs/fixtures were developed to ensure repeatable quality.

3.4 Objective 5. Determine LCOE effects of new powertrain solution.

The motivation for this objective is to document the impact of the proposed timing belt powertrain solution on the levelized cost of energy (LCOE) of the hydroEngine™product, including effects on both the capital cost as well as the operation and maintenance profile.

Quotes in a range of quantities were obtained from multiple American vendors for each component in the new powertrain system, allowing Natel to create supply curves with statistical certainty. At a production volume of 100 SLH units per year, the 500 kW belt and sprocket levelized replacement cost contribution to LCOE is estimated to be about $6.50/MWh. Further design-for-manufacture and supply chain optimization can reduce this cost by approximately 40%, to about $4/MWh.

4 Products developed

Work products developed under the award include:

4.1 Publications

A summary of the work performed under this grant was presented at the 2014 DOE EERE Water Power Peer Review conference in Washington, DC.

4.2 Websites

www.natelenergy.com is the website for Natel Energy, Inc. The 'Technology' and 'Products' sections of the website refer to the hydroEngine™but do not disclose any aspects of the powertrain developed under this project.

4.3 Collaborations

Through the work effort in this grant, the project team have fostered several key relationships with important American suppliers, particularly of carbon-fiber reinforced components, such as Gates Corporation in Elizabethtown, KY (www.gates.com), and manufacturers of investment castings.

4.4 Technologies/Techniques

A novel attachment system has been developed to allow coupling of accessories such as blades to power transmission belting. The attachment system has been demonstrated to be capable of withstanding very high loads, under very high fatigue cycle counts, without failure.

Additionally, extensive fatigue testing and the fixtures and techniques required to operate these tests for extremely high cycle counts (approaching 100 million cycles), have been developed.

4.5 Inventions/Patent Applications

The following DOE "S" Number S-135,519 has been generated for inventions developed under this grant. A provisional application for patent, application number 61977207, was filed with the USPTO on April 9, 2014 referencing this S-Number and acknowledging the support of this grant.

References

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