PRESSURE ACTIVATED LEAF SEAL ASSESSMENT FOR SUPERCRITICAL CARBON DIOXIDE TURBOMACHINERY

ABSTRACT

Pressure Actuated Leaf Seals (PALS) technology readiness for shaft and shroud sealing in power generation and aerospace applications is reported in ASME paper GT2014-27046 presented at the June 2014 Turbo Expo in Dusseldorf, Germany. Test results reported there are relevant for assessment of PALS use in supercritical carbon dioxide turbomachinery and the paper will also be presented in this symposium. Seal designs tested were prototypical and constructed using processes appropriate for volume production. Results include both static and dynamic seal leakage measurements running against a 5.1in (129.54mm) diameter smooth surface test rotor and another that simulates sealing against turbine blade shrouds. The dynamic simulated shroud test includes steps, duplicating small discontinuities of adjacent shroud sealing surfaces and slots to inject air radially under the seal leaves as may occur between shrouds on blades with a high degree of reaction. Consistent seal performance over 15 hours confirms suitability for turbine blade tip applications. Controlled deflection of PALS leaves with operating differential pressure is effective for startup rub avoidance in service as well as conformal wear-in sizing of leaf tips with the rotor. Tested leaf tip wear-in of approximately 0.010in (0.25mm) against rotor discs without hard-face coating, shows potential to eliminate seal misalignment and run-out contributions to operating seal clearance. PALS design features prevent further rubbing contact with the operating rotor after initial wear-in sizing thereby sustaining a small effective seal clearance of less than 0.004in (0.1mm) and prospects for long seal life. Measurements of rotor surface wear tracks from the wear-in process and endurance runs are included as well as rotor and leaf tip photos. Test results support the technology readiness of the PALS concept as a viable, robust, low leakage dynamic seal for select commercial power generation and aerospace application. Assessment of PALS use in supercritical carbon dioxide turbomachinery will include discussion of their suitability for use at high pressure fluid sealing and speed as well as consideration of seal space requirements to integrate them in small scale equipment and manufacture cost. Other development issues that need to be addressed for PALS viability in supercritical carbon dioxide service will also be discussed. These include density differences relative to testing to date, power loss, the wear characteristics of leaf materials in the S-CO2 environment, and test facilities to adequately address these development issues.

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INTRODUCTION:
Shaft sealing is critical to turbomachinery performance and significant development effort has been undertaken to control clearances with advanced seal designs as summarized by Chupp, R.E., Hendricks, R.C., Lattine, S.B., Steinetz, B.M, “Sealing in Turbomachinery,” NASA/TM – 2006-214341, 2006. The PALS advanced dynamic seal concept, was introduced in AIAA-2005-3985 and initial test results presented in AIAA-2009-5167. The PALS design, illustrated in Figure 1, utilizes thin seal leaves that are elastically deflected in an axial direction by system differential pressure to close with the shaft, preferably above critical speeds, and minimum operating pressure. Once actuated the support member restricts further seal closure to maintain a small, non-contacting, clearance throughout the equipment operating pressure range. This sealing concept provides the designer with means to avoid rubs by providing sufficient seal clearance during startup and shutdown to avoid rotor dynamic transients but preserve low seal leakage at operating conditions. Seal function is independent of both direction of rotation and rotor speed.

![Figure 1: Pressure Activated Leaf Assembly](Image)

BACKGROUND:
Labyrinth seals are the most widely used shaft packing in turbomachinery because of relatively low cost and their high speed, high pressure and high temperature capability. However, labyrinth seal leakage control is limited by shaft clearance needed to avoid rubs that often occur in service and degrade unit operating performance.

Contributing to labyrinth seal design clearance is the manufacturing tolerance of seal components and their mounting surfaces within a turbine, i.e. the run-out of each seal interface as well as alignment of the seal ID with respect to the rotor seal surface. All of these eccentricities and thermal growth of both rotating and stationary parts must be addressed to avoid fixed tooth seal rubs. This is a daunting task and additional margin is also necessary to accommodate indeterminate part distortion and relative motion between shaft and stator such as occur traversing critical speeds that amplifies shaft displacement. These issues are illustrated in Figure 2 where axial view B shows asymmetric clearance contributors in contrast to the typical view A suggesting static seal clearance.
Figure 2. Turbine Seal Operating Clearance Considerations.

PALS CONCEPT OBJECTIVES:
A significant objective of the PALS development is rub avoidance. Figure 3 illustrates how the PALS functions to avoid start-up and shutdown rubs. In the ‘cold unit’ panel, frusto-conical leaves of the seal assembly have a large clearance. The ‘operating unit’ view shows differential seal pressure acting on seal leaves to elastically deflect them into contact with the support member’s front face arc, reducing leaf seal clearance for optimal performance. In the ‘unit shutdown’ panel, seal leaves are shown elastically disengaging from the support member arc surface as pressure diminishes during shut down, thereby providing a means of avoiding seal rubs while shutting down. The
differential pressure to bring seal leaves into contact with the support member is designed to meet specific application objectives such as leaf clearance and pressure to avoid a hot restart rub or to warm-up at low pressure to avoid rubs while traversing critical speeds going to operating speed before applying full operating pressure. Seal leaf deflection in response to pressure is a function of leaf thickness and length, support member forward face arc radius and the number of seal leaf layers. A design spread sheet facilitates the selection of parameters.

Avoiding damaging startup and shut down rubs is necessary to preserve seal integrity but minimum operating seal clearance is required to achieve performance gains. To that end, PALS can eliminate both run-out and mis-alignment of stator parts mounting shaft seals, that are significant contributors to seal clearance and leakage as noted in Figure 2. When PALS seal leaves are made to intentionally engage the rotor seal surface to the extent of cumulative run-out and mis-alignment of seal mounting components the leaf tips may be worn into close conformity with the rotor during initial application of operating pressure. This wear-in is similar to the use of abradable materials with labyrinth seals to mitigate non-uniform seal clearance issues in those applications. After the initial wear-in, PALS is a non-contacting seal at normal operating conditions. Seal leakage is reduced to that determined by rotor run-out and interleaf leakage. Wear-in of PALS leaf tips has been demonstrated in prototype testing as well as clearance change with pressure to provide a means of rub avoidance. In that testing rubs of up to 0.010inches had no deleterious effect on the uncoated rotor as reported in GT2014-27046.

**PROTOTYPE TESTING:**

This test seal shown in Figure 4 is prototypical in cross section, functional characteristics and assembly to demonstrate PALS technology readiness for commercial power generation or aerospace applications. A seal design envelope of 0.55in (14mm) radial height and 0.8in (20mm) axial length was specified to have application potential. The test seal illustration includes possible assembly in an application stator.

An installed leaf tip clearance of 0.045in (1.14mm) was chosen to illustrate PALS large cold clearance assembly to avoid seal rubs during startup and subsequent closure with the rotor as pressure across the seal increases to 80psid (550kPa), the test seal design pressure. Seal leaves are designed for desired deflection by selection of their length, thickness, number of leaf layers, support member radius, angle with respect to rotor axis and fence height along with mechanical properties of the seal leaf material. Haynes 25 material in the annealed condition was chosen for the seal leaves of this design because of its wear qualities, suitability for use in other high temperature seals and availability in 0.010in (0.025mm) thickness. There are 2 layers of sealing leaves and a shorter, damping leaf, beneath them that is in register with bottom seal leaf as shown in Figure 5. Space between adjacent bottom seal leaf tips assures that seal pressure drop occurs across top seal leaves. As leaves are pressure loaded they elastically deflect into compliance with the support member contour. Bending stress is held well below material yield stress for long cyclic life without high cycle fatigue. Leaf deflection and stress are typically analyzed using beams in bending elastic analysis. FEA was also performed for this
design. The difference in natural frequency of the shorter damper leaves mitigates leaf oscillation. Fence height is 0.06in (1.5mm) in this design.

There are 120 seal leaves in each leaf layer that are cut by wire EDM from sheet. Each leaf layer strip is then bent to the design leaf angle plus some interference of upper leaf tips with lower leaf layers to assure intimate leaf contact as strips are laid up about the cylindrical portion of the support member. When assembled with the backing ring, parts are joined by welding as shown in Figure 4. The final fabrication step is a wire EDM trim of the seal leaves while mechanically constrained in the fully deflected position. This provides a precision seal ID for desired clearance or ‘wear-in’ with respect to the rotor. The finished test seal is shown in Figure 6. Prominent in the picture is the shroud portion of the backing ring that protects seal leaves from handling damage.

The seal test facility and operation is discussed in GT2014-27046 as well as an investigation of noise emanating from the test seal at low differential pressure.

**Smooth rotor testing:** Seal tests were conducted against smooth test rotors made of a Ni-Cr-Mo alloy. Various diameter rotors were employed to characterize PALS clearance with pressure in static tests and in dynamic testing, to evaluate intentional rub tests to confirm PALS benign leaf tip ‘wear-in’ potential. A full 360 degree ‘wear-in’ test was conducted with a nominal leaf tip ‘wear-in’ of ~0.009 inches (0.35mm) simulated seal mis-alignment and run-out. At a rotor speed of 15,500RPM, a seal pressure of 30psid (207kPa) was supplied across the seal to displace the leaves toward the rotor. Borescope observation of the resulting ‘wear-in’ rub was a momentary flash of heat and light and then the leaf tip remaining in very close running with the rotor. Pressure was raised by steps to 80 psid (552kPa). As pressure was increased there was an occasional flicker of light at the leaf tip – rotor interface that is attributed to burning of loose leaf tip burrs evident in Figure 7. The rotor wear track was visible but not of any significant depth. No-further leaf tip wear occurred in repeat cycling to test pressure confirming non-contacting seal operation after the initial leaf tip ‘burn-in’. The repeatability of PALS closure with pressure was stable with no evidence of hysteresis.

PALS transition from large startup clearance to small effective clearance leakage at design point was demonstrated as shown in Figure 8 of effective seal clearance vs. pressure. The effective clearance at maximum test pressure of 120 psi was 0.004 inches. Tests were conducted to determine what portion of that leakage was from interleaf leakage. A base line with seal leaves exposed normally was conducted and in a second test, plastic tape covered the up-stream face of leaves to prevent passage of air between them. The difference in measured effective clearance is attributed of inter-leaf leakage. The effective
clearance of interleaf leakage was approximately 0.0025in (0.064mm). The rest of minimum measured effective seal clearance of 0.004in (0.1mm) is attributed to leakage at the seal backing ring and other test rig leaks, run-out of the rotor seal surface and instrument error.

**Simulated shrouded turbine blade testing:** Seal tests were also conducted against a simulated shrouded turbine blade. Details of the test installation and rotor are discussed in GT2014-27046. The test rotor was 5.12in (130.0mm) in diameter rotor with 12 equal spaced step and slot combinations around the circumference as illustrated in Figure 9.

The radial height of each step was 0.003in (0.076mm) with slots allowing for radial air to be injected under the seal leaves at a higher pressure than that at the front of the leaves. These rotor features simulates the discontinuity of sealing surfaces between shrouded steam turbine blades. The rotor was again uncoated Aubert & Duval 819B.

A 15 hour steady state dynamic test was conducted with a seal pressure of 55psi (379kPa), rotor pressure of 65psi (448kPa) and venting to atmosphere in both instances. The rotor speed was held at 20,000rpm, equating to a slot frequency of 4000Hz. The seal had a cold clearance of 0.018in (0.5mm) and an initial deflected leaf to rotor interference of 0.003in (0.076mm). Some changes in effective area occurred in initial stages of test before stabilizing between 0.0035 (0.089mm) and 0.004in (0.102mm) for the remaining 11 hours. Post test inspection of leaf tips showed small burr formation on both top and bottom seal leaves similar to that seen in Figure 7 with the smooth rotor. A rotor wear track was visible as seen in the smooth rotor test. Wear track depth of 0.0001in (0.0025mm) was measured after 1 hour of running and after the full 15 hour test was 0.0003in (0.0076mm). This dynamic testing confirmed the suitability of PALS for use on shrouded turbine blade tip applications. Even with a rotor pressure 10psi (69kPa) higher than the seal pressure and radial steps of 0.003in (0.076mm) all passing the seal at 4000Hz the seal maintained a consistent performance for 15 hours of running.

**PALS ASSESSMENT FOR sCO2 TURBOMACHINERY:**

Consideration of PALS seal technology for application in sCO2 turbomachinery is based on the following observations:

- sCO2 turbomachinery is smaller in size than current power generation equipment. Secondary flow leakage control is therefore more challenging and available seal space restricted.
- sCO2 turbomachinery operating speed is typically much higher than conventional power generation equipment limiting seal selection to some extent.
- sCO2 turbomachinery operating pressure is necessarily high to sustain supercritical fluid conditions and some high differential pressure dynamic seals appear necessary.
- sCO2 turbomachinery rotor stability can be affected by fluid phase change, i.e. ‘flashing’ within seals.
- Power loss from windage in sCO2 turbomachinery and shaft seals is a concern.
- Manufacturing cost to provide close running seal clearances may be substantial.

The power density of small size sCO2 turbomachinery is attractive for its use in waste heat power generation but sealing becomes more challenging because minimum seal clearance is physically limiting. Secondary flow control within sCO2 turbomachinery is therefore more important to performance than in larger equipment and will require
particular attention to optimal seal selection in its design. An effective seal clearance of 0.004 inches was demonstrated in PALS prototype testing. It is thought to be a viable candidate for both internal shaft sealing and shrouded turbine blade seal locations. The prototype seal clearance is expected to be achieved in PALS designed for a wide range of operating pressure as shown in Figures 10 and 11. Note that the unloaded clearance, i.e. with no applied pressure, and the pressure at which minimum clearance is reached are set in the PALS design process to meet specific application requirements. An effective seal clearance of less than 0.004 inches is possible in the future as PALS manufacture processes mature and interleaf leakage is reduced.

The envelope available for sealing in small sCO2 turbomachinery is anticipated to be limited. The prototype seal was made with leaves cut from strip stock and wrapped on a cylindrical surface. Section dimensions of it shown in Figure 4 are more suited for locations having axial seal space available but restricted height requirements. When axial seal length needs to be shorter and more radial height is accessible, a PALS designed with leaves fabricated from sheet stock can be used as shown in Figures 12 and 13. The seal diameter of the PALS shown in Figure 13 is 5.1 inches. Its OD is ~7.2 inches and axial length 0.5 inches. Seals of this configuration have been designed for 80 psid with an axial length less than 0.5 inches and radial height of approximately 0.6 inches.
PALS attributes compared to other seals: Aspects of candidate shaft seals are evaluated qualitatively in Figure 14 and the following discussion. In the chart a strength or weaknesses inherent to the design or operating experience for each seal type are indicated by an up arrow for positive design features and operating experience and a down arrow for negative design feature or unfavorable experience.

**Startup rub vulnerability:**
- Labyrinth seals ↓ - are often damaged by unplanned rubs compromising their effectiveness.
- Abradable seals ↑ - accommodate startup rubs.
- Brush seals ↑ - bristles accommodate startup clearance changes by their deflection.
- PALS ↑ - incorporates design features to avoid start-up and shutdown rubs.

**Operating rub tolerance:**
- Labyrinth seals ↓ - teeth are permanently deformed when rubbed.
- Abradable seals ↑ - seal tooth damage can be tolerated but with possible performance loss.
- Brush seals ↑ - bristles are designed to resiliently deflect on rubbing contact with acceptable wear.
- PALS ↑ - seal elements can resiliently deflect, with wear dependent on materials, pressure and speed.

**‘Wear-in’ seal compliance:**
- Labyrinth seals ↓ - seal teeth are damaged if rubbed.
- Abradable seals ↓ - abradable ‘wear-in’ is tolerated but without seal clearance compliance.
- Brush seals ↑ - bristles can resiliently deflect into compliance with the rotor.
- PALS ↑ - seal leaf tips worn into compliance with the rotor effectively eliminates run-out and misalignment of seal mounting components.

Figure 14. Pressure Actuated Leaf Seal Benefit Comparison.
### Low seal leakage:
- **Labyrinth seals**: ↓ - large seal clearance needed to avoid rubs, contributes to large seal leakage.
- **Abradable seals**: ↑ - effective seal clearance is reduced where there is adequate axial rotor movement between startup wear tracks and operating seal tooth path.
- **Brush seals**: ↑ - seal leakage ~10 - 20% of a 4 tooth labyrinth seal is often achieved.
- **PALS**: ↑ - non-contacting, shingled leaf seal members achieve small effective operating clearance.

### Long seal life:
- **Labyrinth seals**: ↑ - typically have long life when operated without rubs.
- **Abradable seals**: ↑ - have long seal life.
- **Brush seals**: ↓ - brush seal development has reduced bristle contact wear and expected life has improved to 8+ years.
- **PALS**: ↑ - initial ‘wear-in’ of leaf tips provides for non-contacting under normal operating conditions; and resilient leaf deflection contribute to long life expectancy.

### High seal differential pressure capability:
- **Labyrinth seals**: ↑ - can operate dependably at high differential pressure.
- **Abradable seals**: ↑ - can operate dependably at high differential pressure.
- **Brush seals**: ↓ - single stage designs to 400 psi differential pressure go beyond past limitations.
- **PALS**: ↑ - design at high differential seal pressure is feasible with multiple seal leaf layers.

### Reverse rotation capability:
- **Labyrinth seals**: ↑ - are non-contacting seals and capable of reverse rotation without damage.
- **Abradable seals**: ↑ - are non-contacting seals and capable of reverse rotation without damage.
- **Brush seals**: ↓ - though safely done under certain conditions, brush seals are at risk of damage with reverse rotation due to bristles contacting the rotor.
- **PALS**: ↑ - are non-contacting seals and capable of reverse rotation without damage.

### Axial seal length:
- **Labyrinth seals**: ↓ - are inherently long because sealing is derived from small pressure drops across a succession of seal teeth. Seal-packing length can adversely affect bearing span.
- **Abradable seals**: ↓ - length is similar to other labyrinth seals
- **Brush seals**: ↑ - seal with minimal axial length with a single pack of radial bristles.
- **PALS**: ↑ - require less axial length than power generation labyrinths but more than brush seals.

### Rotor dynamic issues:
- **Labyrinth seals**: ↓ - circumferential flow within seal cavities can incite rotor instabilities.
- **Abradable seals**: ↓ - similar rotor instability is possible.
- **Brush seals**: ↑ - have a stabilizing effect on rotor dynamics though an improperly designed brush seal can induce thermal distortion of a rotor while starting up by extended friction heating.
- **PALS**: ↑ - a single plane of seal leaves do not induce rotor instability and friction heat input on startup is minimized by accelerated wear-in of thin leaf tips.

### Cost to manufacture:
- **Labyrinth seals**: ↑ - are typically not expensive to manufacture.
- **Abradable seals**: ↑ - features such as honeycomb rub strips and coated teeth add cost.
- **Brush seals**: ↓ - use of a large quantity of small diameter bristles that must be oriented, closely packed and secured contribute to high manufacturing cost.
- **PALS**: ↑ - leaves fabricated from sheet metal and the assembly of a small number of parts is expected to be cost effective in PALS production.
**Conclusion:** The favorable evaluation of important seal attributes illustrate benefits of Pressure Actuated Leaf Seals features relative to both labyrinth and brush seals. Their consideration for application in sCO2 turbomachinery development is recommended.

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<tr>
<th>Feature</th>
<th>Benefit</th>
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<tr>
<td>Initial conformal ‘wear-in’</td>
<td>Mitigates seal runout and mis-alignment.</td>
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<tr>
<td>Large startup &amp; shut down clearance</td>
<td>Rub avoidance.</td>
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<tr>
<td>Minimum operating clearance</td>
<td>Performance gain.</td>
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<tr>
<td>Non-contacting operation</td>
<td>Long seal life.</td>
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