PRESSURE ACTUATED SHAFT SEAL DEVELOPMENT FOR sCO2 APPLICATION

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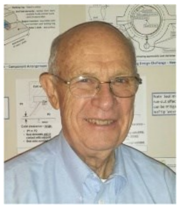
Clay Grondahl

Clay is president of CMG Tech, an LLC focused on advanced seal technology development and its application. At GE Power Systems he provided engineering and project management for modification and performance improvement of operating GE gas turbines with installation of new and advanced technology components including seals. His GE career included hot gas path component design and advanced technology projects at the GE Corporate Research and Development Center. His career started in the US Navy where he served on nuclear submarines making Polaris patrols and qualifying as Chief Engineer for the onboard nuclear steam plant.


Rich Armstrong

Rich is an experienced power machinery business leader having worked at GE for 17 years as well as for a Defense Company for 12 years focused on Naval Ship propulsion systems. At GE he worked in the Power/Energy and Oil and Gas groups spending much of his career focused on the commercialization of new products. In the Defense sector Rich lead a business unit advancing the state of the art in power and propulsion. For the past 3 years Rich has been supporting CMG Tech focused on bring the Pressure activated leaf seal to market. Rich holds a Masters in Mechanical Engineering and started his professional career as a Naval Nuclear Test Engineer.

ABSTRACT

Interstage shaft leakage in sCO2 turbomachinery is challenged by high differential pressure, high speed and relatively small shaft diameters where secondary seal leakage flow of conventional seals can adversely impact performance. Pressure Actuated Leaf Seals (PALS) technology is a promising candidate to meet those challenges. PALS technology readiness testing for shaft and shroud sealing in power generation and aerospace applications was conducted at Cross Manufacturing Company and is reported in ASME paper GT2014-27046. Contributing to their potential for sCO2 application is PALS design capability for high differential pressures, high shaft speeds and favorable rotor dynamics owing to their short axial length without cross-coupled stiffness hazard of labyrinth seals. This poster and discussion is about the design and static evaluation of PALS supplied to Sandia National Labs as part of their advanced seal commercialization efforts. Pressure Actuated Leaf Seals (PALS) is one of the technologies identified by the lab with significant application potential. Prior to dynamic testing, a static test of each seal configuration was conducted at CMG Tech using high pressure water to confirm seal closure and assess inter-leaf seal leakage. Both objectives were successfully demonstrated and provide a confident starting point for dynamic testing at the Sandia sCO2 test facility. PALS design features and static seal test results are presented. This information is abridged from ASME paper GT2023-102258 presented at the 2023 ASME Turbo Expo in Boston, Ma.

INTRODUCTION

Shaft sealing is critical to essentially all turbomachinery performance – steam turbines, gas turbines, compressors, pumps and turbo-expanders. sCO2 turbomachinery is further challenged by high differential pressure and high speed. To facilitate the commercialization of sCO2 power conversion cycles to be used on advanced nuclear reactors Sandia Brayton Energy Laboratory has developed a facility (Figure 1) for testing and developing the next generation of sCO2 seals. The test loop was specifically designed for testing dry gas seals at pressures and temperatures above the state-of-the-art, i.e. It can deliver sCO2 at 4000psi (275bar) and 1300°F (700°C) to the seal test cavity, for leakage flow rates in the range of 1 g/s to 30 g/s. Given the investment and system capabilities, the seal test rig was enhanced to facilitate development of other seal types which are also critical to the commercialization of sCO2 power conversion systems. The pressure-actuated leaf seal (PALS), is a novel seal already finding application within power conversion systems, that the Lab identified as the most promising candidate from several alternatives. The main advantages of this seal are as follows:

1. It has large clearances before actuation, avoiding damage during low-speed shaft excursions;
2. It does not induce the cross-coupling as with labyrinth seals;
3. It requires only a short axial length, a feature that helps design shorter more stable rotors.

Figure 1: sCO2 SEAL TEST FACILITY

Only minor changes were necessary to utilize the seal test rig for PALS testing: exchange the dry gas seals for PALS and replace the seal runner with a spacer, as depicted in Figure 2, which shows a simple cylindrical spacer instead of the seal runner. To actuate the PALS, larger diameter feed holes were added to accommodate flow capacity required to actuate the PALS on simulated startup. The Pressure Actuated Leaf Seal (PALS) design functionality is accomplished by elastic deflection of thin, shingle layered, seal leaves shown in Figure 3 that are oriented in an axial direction and flex over a support member shaped for the intended rate of closure with pressure. PALS sealing is independent of direction of rotation and rotor speed. Development and technology readiness testing, discussed in ASME paper GT2014-27046, has demonstrated PALS leakage comparable to state-of-the-art brush seals with effective clearance of 0.004in (0.1mm) at pressure drops of up to 120psi (8.3bar) and surface speeds to 300ft/sec (91m/s). PALS can, however, be designed for significantly higher differential pressure anticipated in advanced sCO2 applications by selection of seal leaf thickness, length and support geometry. To demonstrate that capability PALS test articles were designed for 3,000psid (207bar) differential pressure and fabricated to fit in the dry gas seal space of the Sandia Brayton Energy Laboratory sCO2 test rig with a 2.3inch (58.4mm) diameter rotor to be run at up to 40,000 RPM shaft speed. PALS leaf and support member geometry can be manufactured in different configurations to accommodate available seal space requirements of different applications. Two PALS configuration designs were fabricated with similar clearance closure with pressure and statically tested in a high-pressure water test rig. Only the 'Conical' seal leaf PALS configuration is discussed here for brevity. The 'Strip' style PALS configuration produced for Sandia dynamic testing is discussed in ASME paper GT2023-102258.

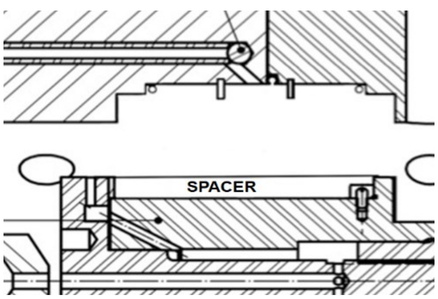

Figure 2: SPACER FOR PALS TESTING

PALS DESIGN

The PALS design, illustrated in Figure 3, 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 below 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

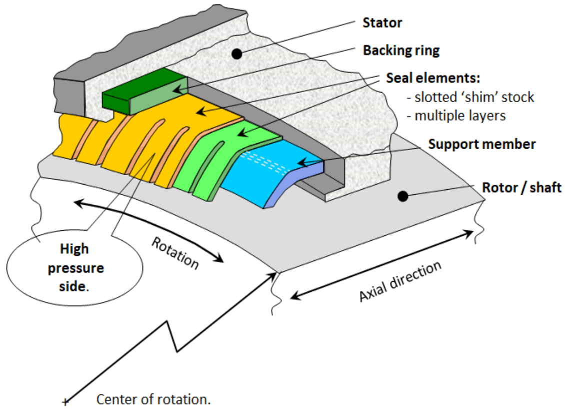

FIGURE 3: PRESSURE ACTUATED LEAF SEAL ILLUSTRATED

operating conditions. Seal function is independent of both direction of rotation and rotor speed. Fence height, the nominal clearance between rotor and the support member ID, is larger than any conceivable rotor excursion. For this design it was set at 0.015in (0.38mm). Leaf material is half-hard 301 stainless steel. Structural components of the seal are made of 300 series stainless steel. PALS for turbine application follow the same design principles, only employ higher temperature alloys.

A seal clearance change of about 0.010in (0.25mm) with pressure was set to demonstrate PALS closure capability. No startup critical speed shaft displacements were specified and nominal closure pressure was set for 500 psid (34bar). The seal closure plot shown in Figure 4 was calculated with selected bottom and top leaf thicknesses, leaf length, angle and up-stream surface geometry of the support member using leaf material mechanical properties.

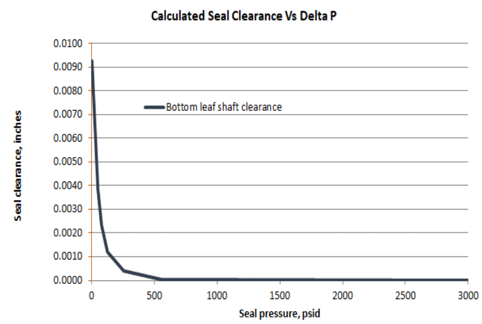

FIGURE 4: SEAL CLEARANCE WITH PRESSURE

PALS CONFIGURATIONS

Space allocated to shaft sealing in turbomachinery is an important design consideration that often drives both equipment performance and cost. Shorter bearing spans raise rotor dynamic critical speeds, reduce shaft excursions that hazard seals on startup and also reduce unit cost. Short axial length is therefore a significant benefit of PALS use in new turbomachinery. This is made possible by its single pressure barrier with low seal leakage at small shaft running clearance. Several approaches to fabricating PALS design elements have been developed. The 'Strip' style PALS configuration, discussed in ASME paper GT2023-102258, uses layers of slotted seal strips bent and wrapped on cylindrical surface. Its application is for situations where radial height is restricted. A shorter axial length PALS assembly in Figure 5 is fabricated from sheet stock with leaves bent out of plane from an outer band of material clamped between support member and backing ring. This 'sheet stock' PALS is used where radial seal space height is not restricted and can also be used in an axial stack of components with multiple interstage PALS.

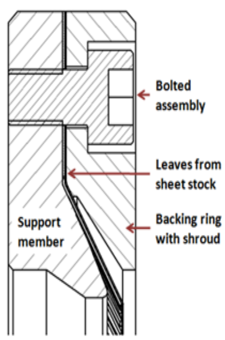

FIGURE 5: SEAL LEAVES FROM SHEET STOCK

'Conical' seal leaves, another PALS configuration, is formed without the axially clamped outer band of radial material shown in Figure 5. 'Conical' top and bottom seal leaf blanks are shown in Figure 6. They are designed to form a cone at the off-axis leaf angle of the support ring when the respective leaf layer ends are brought together. The angled seal leaf portion of Figure 5 is preserved but accomplished without a bending fabrication step. This configuration is also made from sheet stock. Axial clamping of 'conical' leaves occurs on the outer conical portion of the support ring face. Leaf layers are

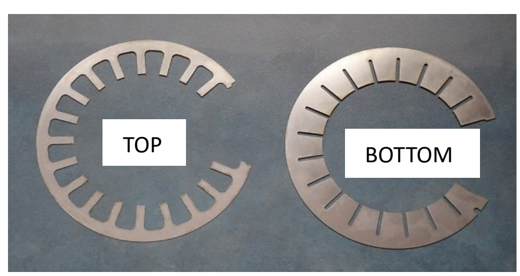

FIGURE 6: 'CONICAL' TOP AND BOTTOM SEAL LEAVES

aligned in registry for top leaf tabs to cover bottom leaf gaps. The 20degree conical arc segment tabs contribute to slightly higher actuation pressure than strip style leaves that are essentially flat beams in bending. Interleaf leakage, i.e., seal leakage through seal leaf layer gaps vs seal leakage under leaf tips with the shaft, is expected to be less with fewer conical leaf tabs.

PALS DESIGN FOR INTEGRATION IN SANDIA TEST FACILITY

External features of the PALS seal support ring and surrounding clamp ring were designed for assembly in the Sandia test facility without modification to sCO2 dry gas seal test pocket.

PALS ARRANGEMENT with 'CONICAL' SEAL LEAVES

This PALS configuration utilizes 'conical' top and bottom seal leaves previously described. The flat seal leaf blank is flexibly inserted into the clamp ring to form adjacent cones shown in cross section in Figure 7. Seal components are bolted together with cap screws. Electron beam welding is an alternate method of consolidating conical seal components as illustrated in Figure 7. EB welding is anticipated for commercial PALS assembly to provide both a robust assembly and accommodate smaller seal cross sections for tight seal spaces. The assembled seal ID was machined by wire EDM to provide a nominal interference of 0.002in (0.05mm) of leaf tips with the 'rotor' when the PALS is fully closed. Figure 8 is a picture of a 'conical' PALS with the inset view showing top seal leaves bridging the gap between bottom leaves.

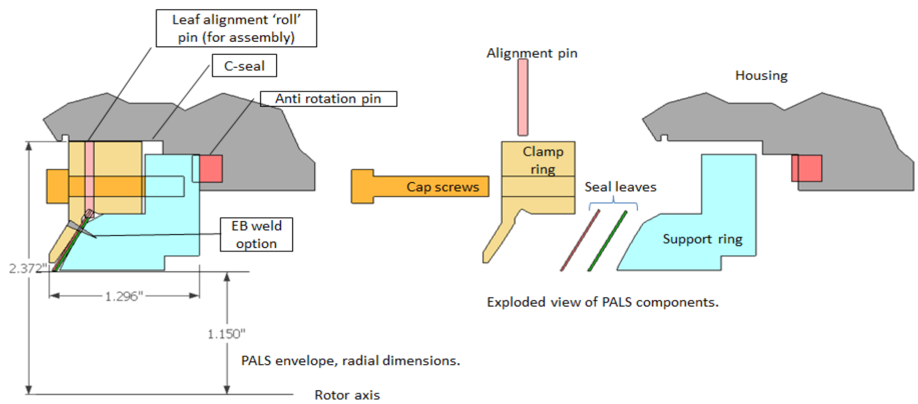

FIGURE 7: PALS COMPONENT ARRANGEMENT WITH 'CONICAL' SEAL

FIGURE 8: 'CONICAL' LEAF PALS ASSEMBLY

VERIFICATION TESTING

Each PALS provided for Sandia test was statically tested to confirm seal closure with pressure and measure inter-leaf seal leakage. This testing was conducted in a high-pressure water test rig designed for 3,000 psid (207bar) pressure. Seal leakage data was collected from the minimum sustainable pressure at intervals up to a test pressure of 1800psi (124bar) and briefly at higher pressure with an alternate pump. It was measured by weight of water collected per unit of time and taken at increments of pressure. While PALS leakage flow is low above actuation pressure, substantial flow is required at low pressure to close the PALS leaves with the shaft. This high rate of water flow is supplied from a pre-charged accumulator through a 1/2inch valve that is quickly opened. When PALS leaf tips are closured a residential high-pressure water pump sustained the smaller leakage flow rates. The verification test rig casing was designed to assemble 2 PALS in a 'back-

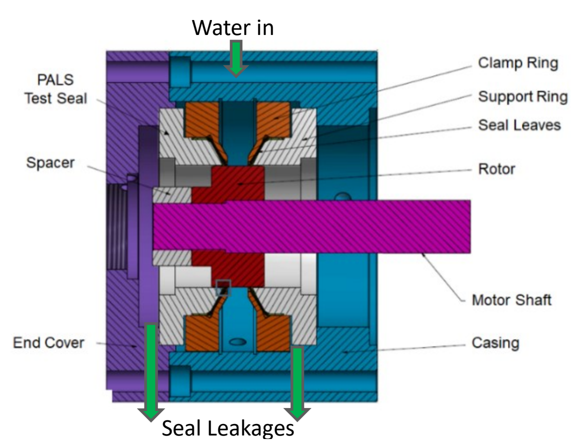

FIGURE 9: CASING AND TEST SEAL ASSEMBLY

to-back' configuration with high pressure water suppled between them duplicating essential features of the Sandia dynamic test rig seal installation and pressure loading. Concentric assembly of the casing and seals with the test 'rotor' was provided by mounting the casing on a close tolerance C-face electric pump motor with the test 'rotor' mounted on the pump shaft. The seal adjacent to the motor end of the housing was a modified PALS with a PTFE ring on top of a conical metal seal ring for essentially zero static seal leakage. The PALS test article was mounted in the housing away from the pump motor end. Arrangement of test rig casing, PALS, and rotor is illustrated in Figure 9.

VERIFICATION TEST RESULTS

'Conical' leaf PALS seal leakage is plotted versus pressure in Figure 10. The same seal leakage data is converted to effective seal clearance In Figure 11. That calculation is based on incompressible flow through an orifice. Decreasing leakage with increasing pressure below 500psid (33bar) in Figure 10 is evidence of leaves continuing to close with pressure over that pressure range. Above 500psid (35bar) seal leaves are fully closed and leakage area, plotted in Figure 11, is essentially constant and small, less than 0.0001in (0.0025mm) from 300psid (20 bar) to over 2000psid (140 bar). In Figure 10, seal leakage flow increases with pressure as expected through a constant area nozzle, but remains less than 0.5gpm (1.9lpm). Verification testing also demonstrated PALS seal leaf deflection to close seal clearance with pressure from a large, no flow clearance, to a tight clearance at pressure, i.e., PALS 'actuation'. Large seal leakage flow rates occur as PALS clearance is in transition. For test purposes it is supplied by discharging the accumulator to affect the closure but without flow rate measurement. A calculated leakage flow of 3.2gpm (12.1lpm) at 125 psid (8.5bar) and 0.001in (0. 025mm) clearance is plotted in Figure 10 as an indication of transition seal leakage flowrate. PALS closure was demonstrated in that stable leakage flow is established and measured above actuation pressure. Pressure actuation of both 'Strip' style PALS and 'Conical' leaf PALS 'actuated', very close to calculated design clearance shown in Figure 4 that is also plotted in Figure 10. Figure 10 also includes measured undeflected leaf tip clearance at 0 psid for reference. Since the assembled PALS ID was machined with a 0.002in (0.05mm) interference of leaf tips with the 'rotor' when fully closed, measured seal leakage is attributed to inter-leaf leakage and any O-ring leakage past the seal. In dynamic operation, the 0.002in interference is provided for leaf-tip 'wear-in' with the rotor for compliant close running seal clearance.

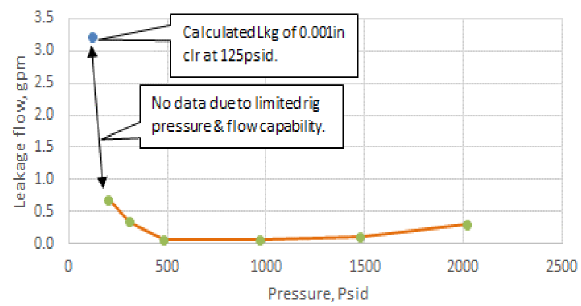

FIGURE 10: PALS 'CONICAL' LEAF SEAL LEAKAGE

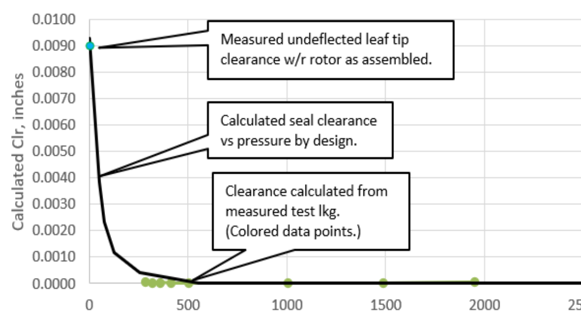

FIGURE 11: PALS CONICAL LEAF SEAL CLEARANCE

CONCLUSIONS

Pressure Actuated Leaf Seals have been manufactured and supplied to Sandia Brayton Energy Laboratory for dynamic testing in their sCO2 test rig. Static testing has demonstrated PALS design function to passively close seal clearance with pressure and that interleaf seal leakage is very low in tests to 2000psid (140bar). Results verify that PALS seals are a viable technology for sCO2 conversion cycles. If used at the concept stage of rotor design, they have the potential to significantly improve rotor dynamics and reduce secondary flow leakage.