# Final Design Review

Improved Combustor Liner Seal

Final Design Review Report

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# Abstract

The project's objective was to develop a mechanical seal to seal the gap between the combustion liner and the stage one nozzle of a Solar Turbines turbine. A metal axial E-seal was selected as the sealing mechanism. Hand calculations and finite element analysis were conducted to confirm the designs compatibility with existing turbine components and the operational environment. A small-scale test rig was built to confirm the remaining design specifications. Results from this test rig indicated the design met all specifications except leak rate. Causes for this low performance were identified as manufacturing issues and some were addressed, resulting in increased performance. Others outside the scope of this project were noted and discussed.

# Contents

# 1 Introduction

The objective of this design project is to redesign the sealing mechanism between the combustor liner and stage 1 nozzle in Solar Turbines' T250 SoLoNOx engine. The current fishmouth seal used in the engine is seen in Figure 1.1. This solution has been known to leak compressor exhaust air, also known as PCD air, into the combustor liner, reducing the efficiency of the engine and increasing emissions.

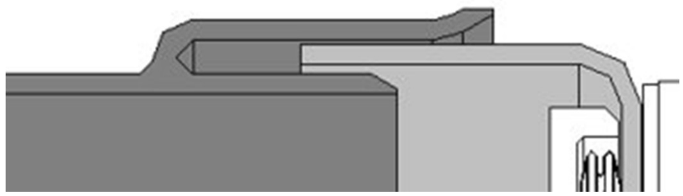
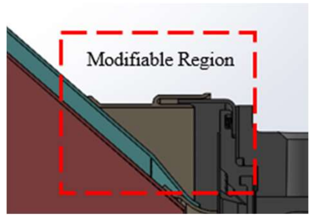


Figure 1.1. Fishmouth seal on Solar Turbines' T250 combustion liner to stage 1 nozzle [1].

A portion of this leakage occurs during the engine's startup when the fishmouth's sealing surfaces are not initially in contact with one another. The fishmouth seal operates by utilizing dissimilar metals with different coefficients of thermal expansion that allows the inner seal to expand into the outer lip of the mouth as the engine reaches its operation temperature. This means that they do not have an interference fit until steady-state operation at full or partial load, allowing leakage early in operation. The other issue that Solar Turbines determined might contribute to leakage is runout on the sealing surfaces, leading to uneven interference and gaps remaining at full load. An uneven pattern of contact wear in used fishmouth seals shows that there are sections of the seal that do not make contact even at full operating temperatures.

To solve this issue, Solar Turbines has tasked a team of Cal Poly Mechanical Engineering Students to develop a new seal to reduce or even prevent leakage into the combustor liner. This team is composed of Max Case, Mason Jones, Jacob Matties, and Christopher Ng, fourth-year Mechanical Engineering Students at California Polytechnic State University.

An initial scope of work written by the team has limited the team's focus to a concept sealing mechanism to be applied to the T250 SoLoNOx turbine as seen in Figure 1.2. Even more specifically, this report will only focus on the outer fishmouth seal area, but all findings and design concepts can be similarly applied to the inner fishmouth seal area on account of the very similar geometry. Prior to this report, Preliminary Design Review and Critical Design Review reports were produced, detailing choices and justification for the design. The Critical Design Review validates some parts of the design through mathematical analysis, and this report summarizes the verification done by testing a scaled-down prototype, also detailed in the Critical Design Review.




[Partially Redacted]
Figure 1.2. Fishmouth seal area to be modified [1].

This report will document the manufacturing, testing, and evaluation of the prototype. It will include recommendations for future design and testing by Solar Turbines based on the results of this testing and evaluation, as well as previously completed analysis of a full-scale model.

# 2 Design Overview

Two products were developed for this project, a full-scale CAD generated model of the E-seal design, shown in Figure 2.1 that would be implemented in the actual turbine, and a scaled-down prototype test rig, shown in Figure 2.2 that was used to determine critical features and potential issues in implementing the full-scale design. While this report will focus on the test rig and the manufacturing and testing of it, changes with the full-scale design will also be noted here.

## 2.1 Design Description

The design that was developed to replace the current fishmouth seal in the T250 turbine is the E-seal assembly as seen in Figure 2.1. This design implements a custom Inconel 718 E-seal with a high number of convolutions between two Inconel 718 mounts that are attached in-place of the current fishmouth mounts. These mounts would use the same fixturing methods that the current fishmouth mounts apply to connect to the combustion liner and turbine nozzle. To help facilitate alignment during assembly when the nozzle end is dropped into the combustion liner end, two extended lips are included below the E-seal. The grooves in these mounts are designed to and must follow the E-seal manufacturer's specifications including surface finish and tolerances.

The E-seal itself is a custom axial seal that Solar Turbines will need to work with an E-seal vendor to design. As found in the Critical Design Review, the seal from this selection must be specified to produce a maximum load of 33.7 lbf per inch circumference, be able to decompress 0.030" from the no-load deflection, and be rated for at least 1200 degrees F in an oxidizing environment.

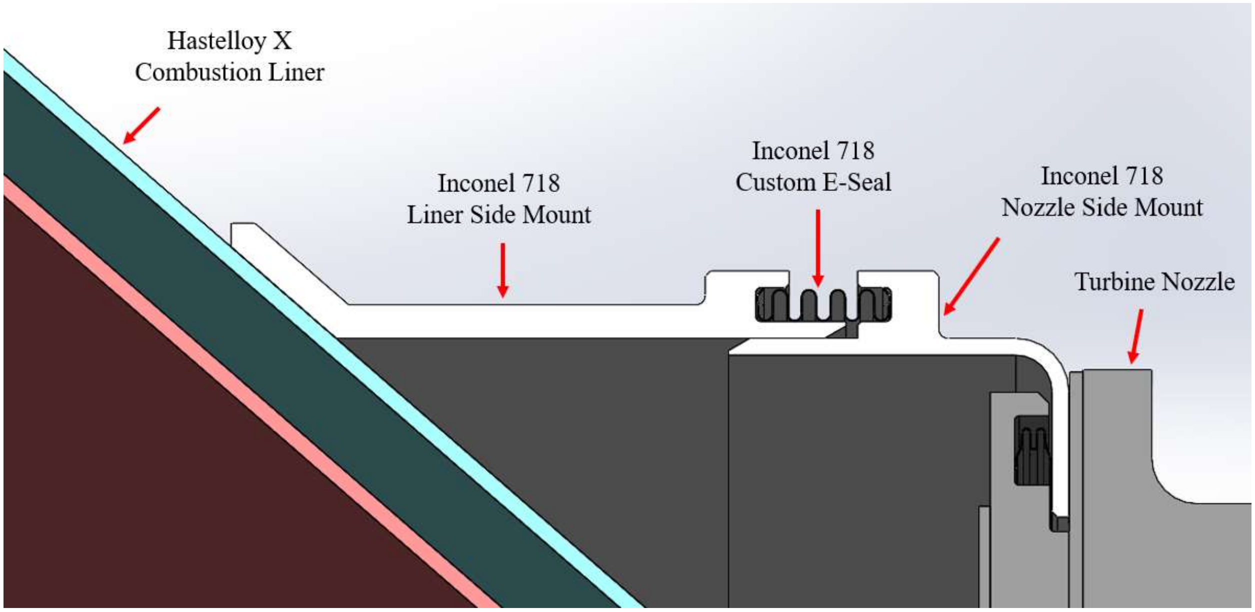



Figure 22.11. Section view of the E-seal assembly in-place of the current fishmouth.

The design that was manufactured and tested as a functional prototype for this design, and is the focus of this report, is the prototype test rig as seen in Figure 2.2. This design uses an around 7.8" diameter Inconel 718 E-seal that was donated by JETSEAL to simulate various environments that the full-scale design would experience. Features such as a pressure gauge, fill-valve, and additional load frame fixtures are included to facilitate leak and deflection testing. A cross-section of this design is seen in Figure 2.3 and shows the pressurized cavity and E-seal grooves that were CNC machined.

Figure 2.2. Functional prototype test rig.

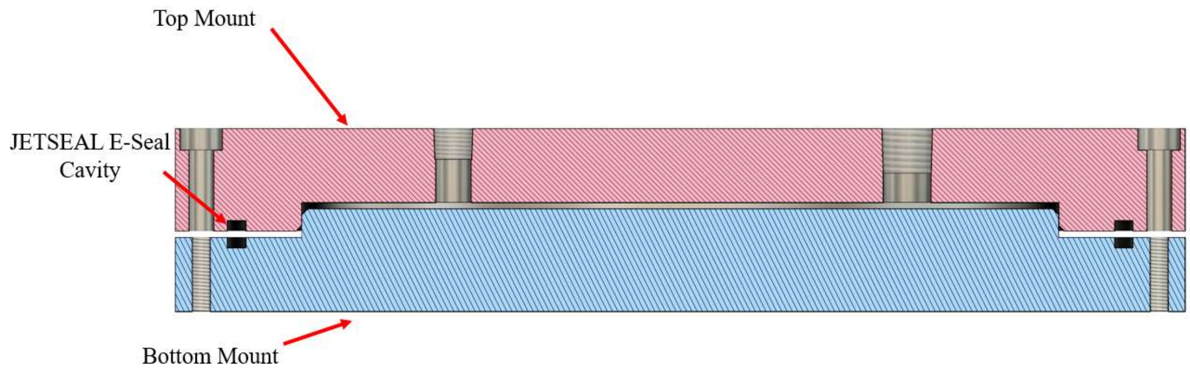



Figure 2.3. Section view of the functional prototype test rig.

## 2.2 Design Changes Since CDR

From the CDR presentation, a few features in the design were updated for the final full-scale design. These were mostly small updates in geometries including making the liner side mount thinner to reduce material costs and stress from the thermal transient period. This did not come with any additional analysis since, as noted in the CDR, the largest stresses that were in danger of not meeting yield requirements were located at the combustion liner and not at the mounts.

In addition to the final full-scale design, a few minor design changes were made to the final test rig design from the design shown in the CDR presentation. These changes do not affect the design's functionality and were made purely for manufacturing and testing. The first change is the addition of 4 tapped holes in a 3.5-inch by 3.5-inch square on the external face of each side of the mounts. These tapped holes are used to attach a fixture plate to clamp down on during CNC machining. The same holes can then be used to attach a welded fixture, creating a place for the load frame to hold the assembly during deflection testing.

# 3 Implementation

The team designed, manufactured, and tested a small prototype test rig. Components necessary for the test rig and the subsequent testing were procured through various manufacturers or vendors or machined from raw material using the Cal Poly Machine Shops. Manufacturing took place in the Cal Poly Machine Shops.

## 3.1 Procurement

The procurement of all materials and tools necessary for manufacturing and testing was done through Cal Poly, Solar Turbines, and JETSEAL. Equipment and components obtained through Cal Poly were ordered from Amazon, McMaster-Carr, MSC, and Harbor Freight. These included a digital pressure gauge, air fill valve, bolts, varying-sized shims, tapping fluid, a sheet of butyl rubber, and a torque wrench. Raw materials and tooling were obtained primarily through Solar Turbines or sourced through the on-campus Mustang '60 Machine Shop. Through Solar Turbines, the team acquired two 1-inch thick by 9-inch diameter 17-4 stainless steel rounds from Best Stainless and Alloys in Houston, Texas. Solar Turbines also ordered two end mills, three drill bits, and two taps from MSC. They purchased Mitee Bite Versa Grips and soft jaws from Monster Jaws to hold stock during machining. And as stated in previous reports, JETSEAL provided the team with an E-seal. Details of all purchased parts and their cost can be found in Appendix C.

## 3.2 Manufacturing

To test the overall functionality of the Axial E-Seal design, two main systems were designed for manufacturing – the prototype test rig and the baseline test rig as seen in Figures 3.1 and 3.2. These designs included the various external components listed in the procurement section including load frame fixtures, NPT fittings that required threading, and CNC fixtures.


Figure 3.1. Prototype test rig completed assembly.

Figure 3.2. The baseline test rig assembled and pressurized.

Manufacturing of the prototype test rig for the Axial E-Seal design was primarily done using a HAAS VF-4 CNC mill. CNC milling was chosen for the two stainless steel 1-inch thick by 9-inch diameter plates containing the seal groove to ensure that the strict tolerances and surface finish specified by the seal manufacturer were met. Unfortunately, the mill surface finish does not meet the circular lay requirement of the seal manufacturer, but due to the limits of the Cal Poly CNC lathes, a mill was used regardless. During CNC milling, several operations were performed on each side of each plate. As seen in Figure 3.3, the features for the design required facing the plates, drilling and tapping the bolt holes on the perimeter of both plates, creating the seal groove in both plates, and drilling holes for fittings on the top plate. The NPT holes were tapped later using a Bridgeport manual mill and a hand tap as shown in Figure 3.4.

Figure 3.3. Post CNC milled test rig plates.

Figure 3.4. Tapping the top plate on the Bridgeport mill.

After the CNC milling operations, an inspection was made for the E-seal groove to ensure a surface roughness of under 32 microinches. The as-machined surface finish can be seen in Figure 3.5. Unfortunately, the surface profilometer available to the team did not have a head that could fit into the bottom of the groove, so the surface roughness was only able to be visually determined as better or worse than the surface finish on the other flat surfaces.

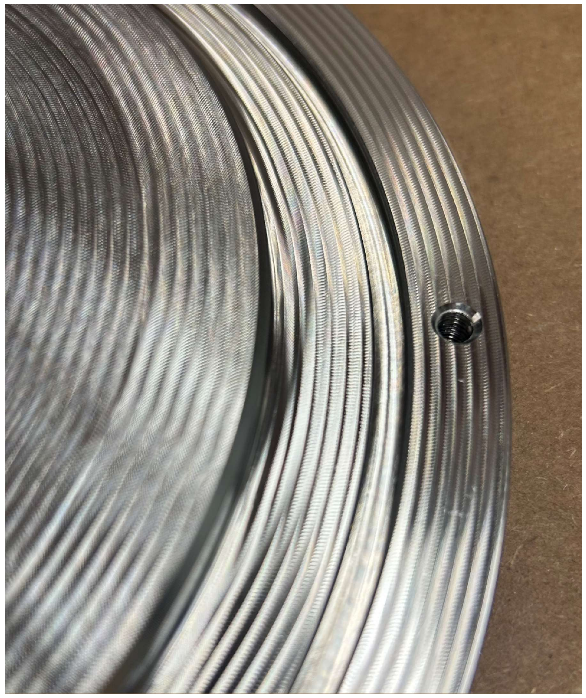


Figure 3.5. CNC milled E-seal groove surface finish.

Several smaller components were manufactured before and during the use of the CNC mill either for testing or assisting in the assembly or manufacturing iof the prototype test rig. The first component manufactured was a small pressure chamber intended to test the leak rate of the air-fill valve and the pressure gauge NPT fittings. Using a manual lathe in Mustang ‘60, a small section of 4-inch long by 1.5-inch diameter round steel stock was hollowed out to create a thick-walled tube with one entrance of the tube was widened to accommodate the larger thread diameter of the pressure gauge. Each end of the tube was tapped using an NPT tap, the smaller side using a 1/8th-inch and the larger side using a 1/4th-inch NPT tap. The full assembly can be seen in Figure 3.1.

The second component manufactured was a disposable rectangular plate, seen in Figure 3.6, used to provide a safe clamping area for the vice during CNC machining of the actual rig components. This component was not used in the actual test rig and was only used to assist in the manufacturing of other test rig components. The part was manufactured out of a 4x4-inch by ¾ inch-thick piece of aluminum on the Bridgeport manual mill in Mustang ‘60. An endmill was used to face and square all six sides of the block. After using an edge finder to accurately find the center of the block, 4 loose fit holes for size 10 bolts were drilled in a square pattern 3.5-inches from one another using a center drill and drill bit.

Figure 3.6. The fixture plate used to hold stock during CNC machining.

The next manufactured components, shown in Figure 3.7, were two identical fixture pieces to hold the seal test rig in the load frame machine. They were initially cut by the water jet out of a steel plate. The water jet cuts also included rectangular slots in two of the plates and teeth to fit into the slots on the side of the other two plates. The plate with the slots also included four holes, drilled in a square pattern 3.5-inches from one another, to attach to the test rig. These holes were pierced on the waterjet and widened out to size with a hand drill. The toothed piece was fitted into the slotted piece and MIG welded together as shown in Figure 3.8.

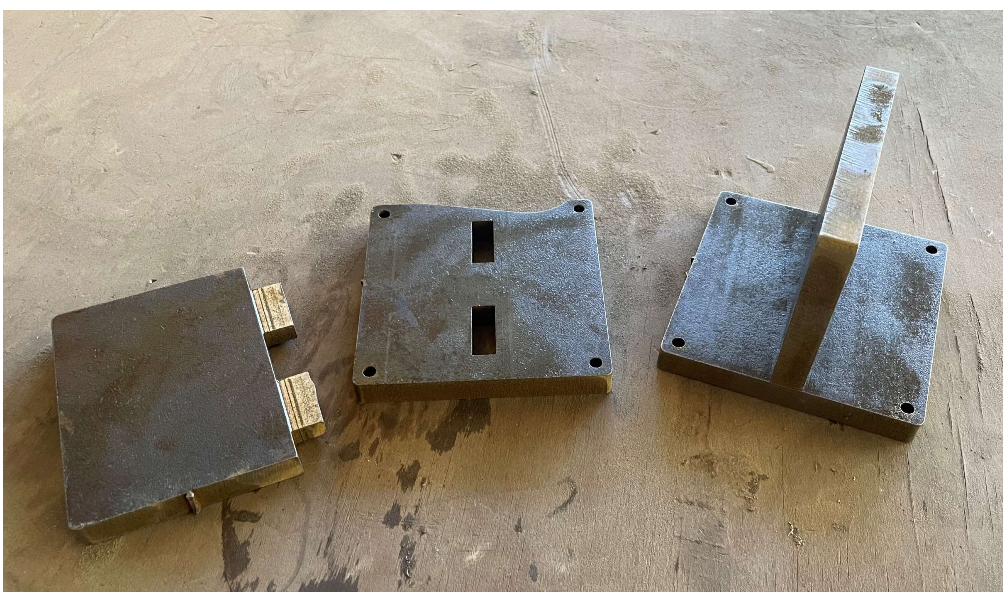


Figure 3.7. Post machining pre-welding of load frame attachment points.

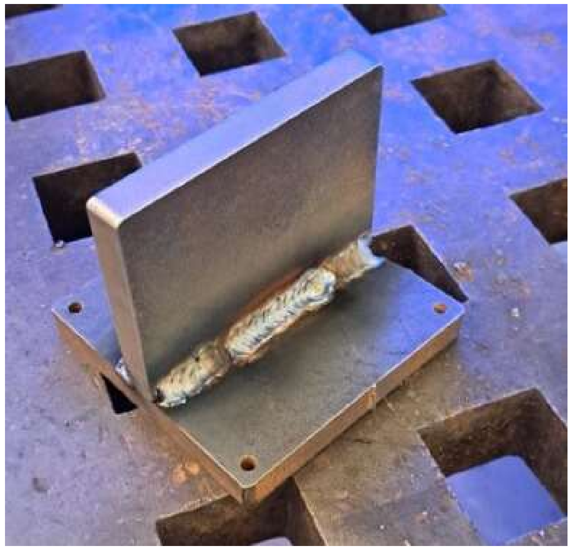


Figure 3.8. Welded fixture for load frame machine.

To facilitate an additional baseline test, a rubber gasket, shown in Figure 3.9, was made to test the baseline leak rate from both the air fill valve and pressure gauge fittings. The gasket was used in the prototype test rig between the two test rig plates instead of the E-seal. The gasket was cut from a butyl rubber sheet using the laser cutter in Mustang ‘60. An X-acto knife was used to cut holes in the gasket for the screws to pass through.


Figure 3.9. Additional baseline rubber gasket.

The final manufactured component was a custom crowfoot, shown in Figure 3.10, to be used to tighten the pressure gauge to the prototype test rig to the manufacturer specified torque. This crowfoot was required due to a low clearance between the head of the gauge and the top of the test rig. The crowfoot was initially cut from a 3/4-inch piece of aluminum using a waterjet. The team then used a Bridgeport manual mill to correct some dimensions of the crowfoot and to face off a significant amount of the material allowing the crowfoot to fit under the pressure gauge.

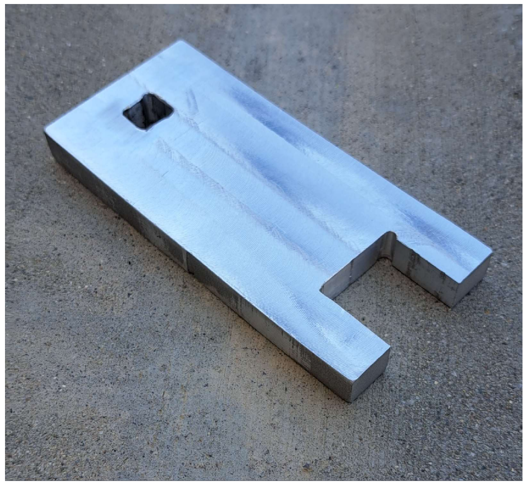


Figure 3.10. Custom crowfoot attachment.

## 3.3 Assembly

Assembly of the manufactured components was completed in Mustang ‘60. The two CNC machined plates were cleaned using 99% IPA, and the E-seal was placed in the groove between the parts. Shims were inserted between the plates outside of the sealing groove and using an incremental star pattern, the bolts were all tightened to 30 in-lbf. This compressed the seal to the desired height, as seen in Figure 3.11.

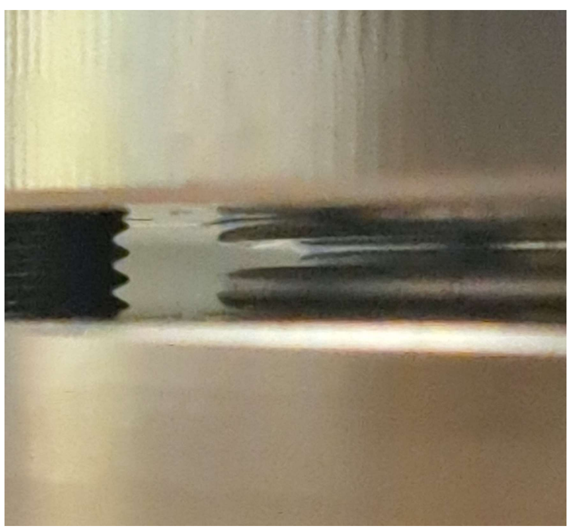


Figure 3.11. Compressed seal between the two plates.

The pressure fill valve and pressure gage were then attached to the top plate using thread tape and a torque wrench to ensure no leaks occurred through the fittings. The custom crowfoot was used to attach the pressure gauge while a standard attachment for the torque wrench was used for the air fill valve.

# 4 Design Verification

The design decisions made by the team were verified through various tests determined by the team from the specifications given by Solar Turbines. The specifications the team followed can be found below in Table 1. The testing performed and testing results can be found below in sections 4.2 and 4.3, respectively.

## 4.1 Specifications

A list of the engineering specifications for the project can be seen in Table 1. These specifications on what demonstrates a successful design have been compiled based on input from the sponsor, research on designs, and the end user and represent the criteria and constraints on which design decisions were based. Analysis provided in the previous reports have demonstrated sufficient evidence to show that the chosen design meets these specifications where applicable without testing. From the described testing in this report, further results are provided for specifications where analytical or computational analysis could not be used.

Table 1. Engineering specification table.

| Spec. No. | Description | Requirement/Target | Tolerance | Risk* | Compliance** |
|---|---|---|---|---|---|
| 1 | Size | Nominal 37-inch seal diameter | ±5” | H | I |
| 2 | Lifespan | 30,000 hours of continuous operation (60,000 ideal) | Min | H | A |
| 3 | Cycles | 5000 thermal cycles | Min | H | A, T |
| 4 | Material Temperature Rating | 1200°F | Min | M | S, I |
| 5 | Sealing | No leakage | Max | M | T |
| 6 | Serviceable | Accessible through standard practice in the field | Min | H | I, S |
| 7 | Assembly | Capable of attaching to turbine in standard assembly process. Nozzle support is aligned during assembly. | Min | H | S, I, T |
| 8 | Part Count | 2-part count seal system | Min | L | I |
| 9 | Safety Factor | 0.85 $S_y$ of any material | Max | H | A |
| 10 | Axial Thermal Expansion | 0.034 inches | Min | H | A |
| 11 | Radial Thermal Expansion | 0 inches relative to E-seal end of combustor liner and nozzle supports [2] | +0.010” | M | A |

* Risk of meeting specification: (H) High, (M) Medium, (L) Low
**Compliance Methods: A (Analysis), (I) Inspection, (S) Similar to Existing, (T) Test

Specifically, Specifications 3, 5, and 7 required testing to confirm that requirements were met. The two tests for leak rate testing and load frame deflection cycling as described in Appendix E were used to test the specifications for cycles, sealing, and assembly. Additional information for these testing plans can be found in the DVPR found in Appendix D.

## 4.2 Testing

While already partially confirmed by similarity to existing solutions and inspection, Specification 7, for assembly, also benefitted from some testing to confirm that the seal could be assembled per standard Solar Turbines procedure. This test was simple, consisting of the team assembling the prototype. With a similar orientation and geometry to the specified full-size design in previous reports, this test confirming the ability to assemble the parts in series per Solar Turbines procedure implies success of the seal's assembly strategy.

To verify specification 5, for sealing, leak rate tests were performed to determine the rate at which internally compressed air will leak out of the test rig for the full and no-load compressions using the 0.050" and 0.025" shims, respectively. This was determined by measuring the pressure of the compressed air over time which, knowing the test rig's internal volume, can be used to calculate the leak rate. The resulting values, evaluated at around 13.8 psig, were compared to 0.01 sccs, a value previously calculated using JETSEAL's expected leak rate converted for air [2]. This calculation can be found in the CDR report. Since this is a very idealized number and the team did not manufacture the seal to a high enough tolerance to match the manufacturer specifications, these values are more-so used to create a baseline to compare to. Full details of each leak test can be found in Appendix E.

To determine how much of the measured leak rates could be attributed to the seal as opposed to the two NPT fittings in the test rig, a baseline test was performed to measure the leak rate from the fittings alone. Initially, the baseline test rig shown in Figure 3.2 was used for this, where the two ends of the rod were made for the two NPT fittings. This, however, produced problems with at small chamber volume heating up as the air compressed, warping the pressure to include temperature and pressure effects. Instead, to better match the geometry and environment of the real leak rate test, the butyl rubber gasket shown in Figure 3.9 was used in place of the E-seal to provide what was assumed to be a "perfect" seal in the prototype test rig. This gasket was firmly compressed, and an identical leak test was performed as with the E-seal. Because of the large thermal mass, the temperature effects were negligible, calculated to decay over only a few seconds. More details of this test can be found in Appendix E.

Overall, four pairs of tests, with full and no-load tests comprising each pair, were conducted for leak rates during various scenarios. Two pairs prior to the test rig undergoing cyclic loading and two after. The first pair evaluated the leak rates of an unsanded groove surface finish and was used to evaluate the effects of an out-of-specification surface finish. The next pair evaluated the leak rates of the groove after sanding to compare the first set to. This test acted to simulate the leak rate that the seal would have at the beginning of its life in the turbine. An image of this test can be seen in Figure 4.1.

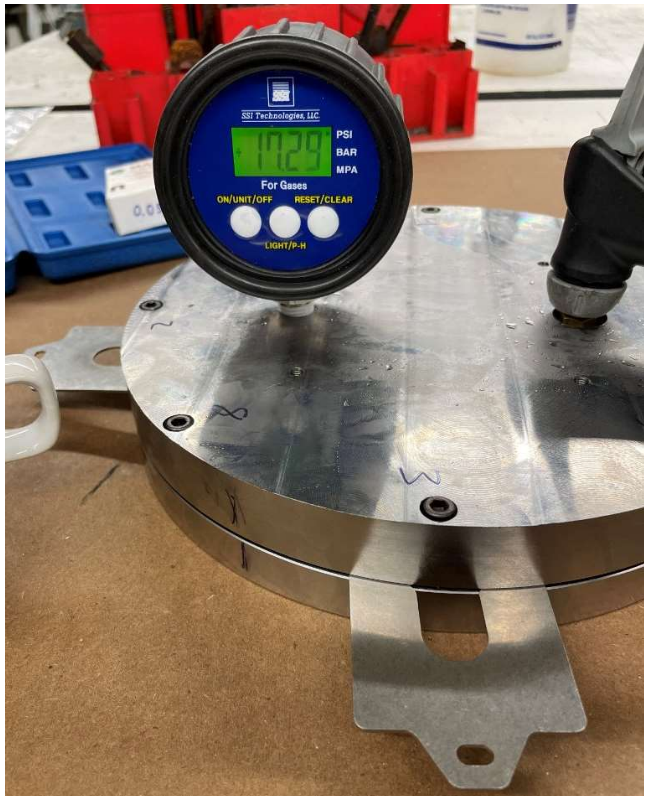



Figure 4.1. Leak testing setup. The bike pump pressurizes, and the digital gauge reads cavity pressure.

The load frame deflection cycling test served the purpose of determining if the seal will fail due to thermal cycling and allowing later leak testing for a simulated end-of-life seal, verifying Specifications 3 and 5 for cycling and sealing, respectively. Testing was done on a load frame material tester, shown in Figure 4.2, that compressed the seal in the test rig by 0.030 (no-load to full-load) for 5000 cycles. The force required to achieve this deflection was measured for each cycle to characterize seal characteristics over time. Full details of this cyclic loading test can be found in Appendix E.

After completion of cycling testing, further leak tests were performed to determine the impact of cycling on the test rig's sealing ability. First, the test rig was removed from the load frame without any disassembly. This was to ensure that the seal's position remained constant relative to any surface imperfections created by cycling. The team, however, had to rotate one half around 5 degrees to get the bolt holes to line up. Once leak tests were completed, the test rig was disassembled and inspected for damage caused by cycling. After inspection, another set of leak tests were performed to determine the impact of changing the seal's position.

Figure 4.2. Load frame test setup.

## 4.3 Results

Specification 7, for assembly, was confirmed with the testing described above. The test rig, which has an identical assembly procedure as the full size design specified in previous reports, was able to be assembled without problem. Putting together the liner side support, then seal, then nozzle side support in order vertically worked, and was able to be fastened together with only 1 side of access afterward. This validates Specification 7.

In order to verify Specification 5, for sealing, pressure decay tests were performed at full and no load conditions before and after the test rig was cycled. Since the tests were performed only being pressurized at the beginning of the test, it was expected that the pressure would then decay exponentially as a function of time as similar to one seen in Equation 1, where the gauge pressure, $P(t)$, can be represented as an exponential decay from an initial gauge pressure, $P_0$, with an exponential constant dependent on vessel and seal properties, $C$. This decay can be seen in Figure 4.3 with raw data provided in Appendix F.

Eq 1. $P(t) = P_0 e^{-Ct}$

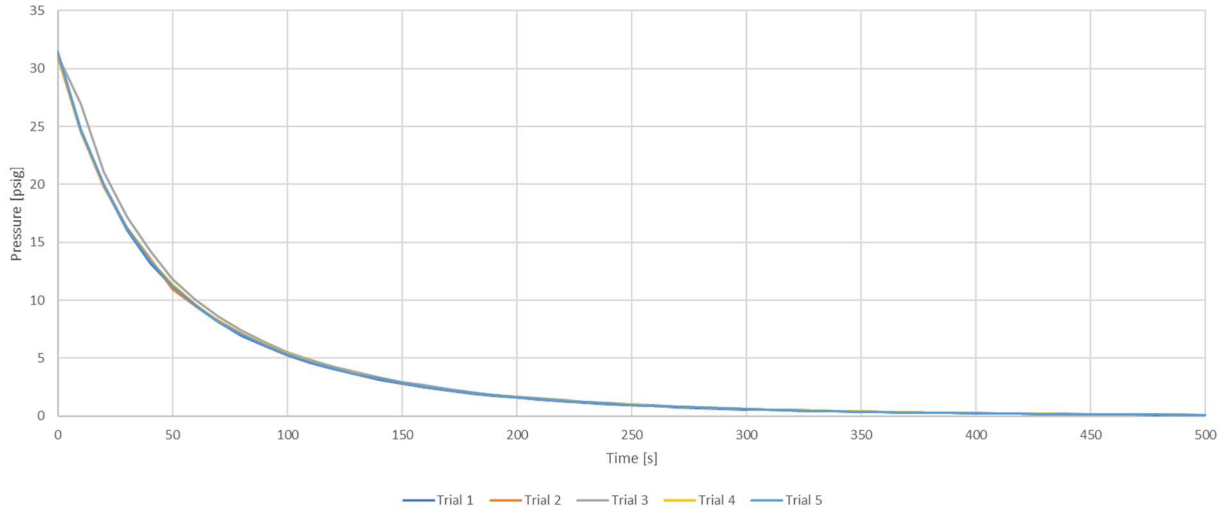



Figure 4.3. Characteristic pressure decay test results.

Leak rate results produced by these tests are shown in Figure 4.4 and Table 2. Figure 4.4 shows the leak rate across the seal at over varying pressure differences across the seal, at different conditions. The curves are second order polynomial fits of leak rate data points calculated from the pressure decay testing. The raw data can be found in Appendix F.

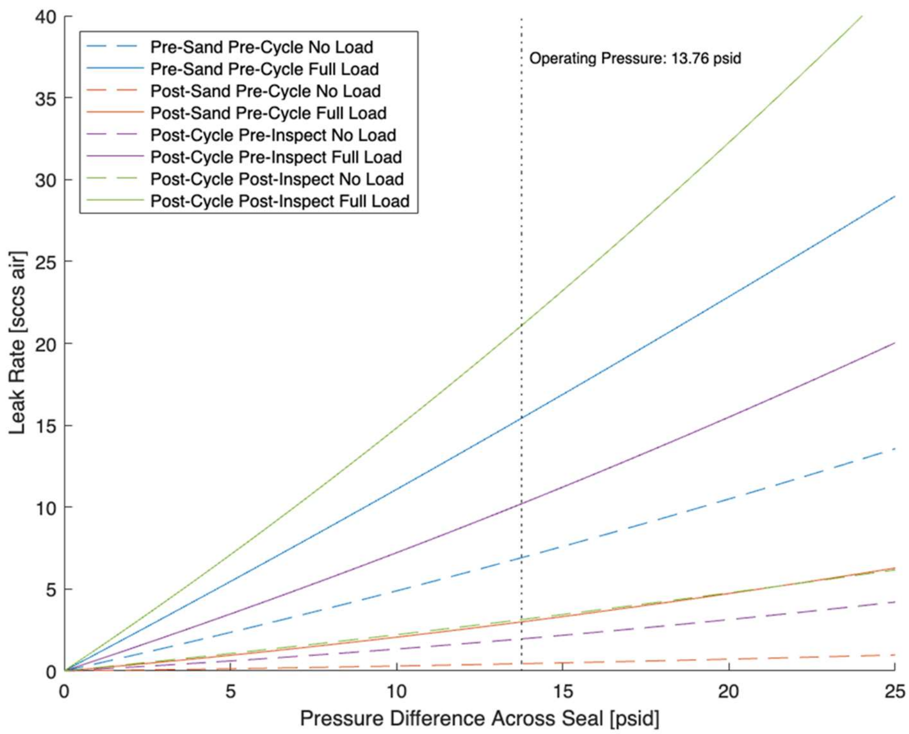



Figure 4.4. Curve fit leak rate results.

Table 2. Results from all leak rate tests at 13.8 psi gauge pressure.

| Test Scenario | Leak Rate at 13.8 psig [sccs] |
|---|---|
| JETSEAL Catalog Value | 0.01 |
| Before Sanding No Load (0.025” shim) | 6.91 |
| Before Sanding Full Load (0.050” shim) | 15.43 |
| After Sanding No Load (0.025” shim) | 0.44 |
| After Sanding Full Load (0.050” shim) | 2.99 |
| After Cycling No Load (0.025” shim) | 1.96 |
| After Cycling Full Load (0.050” shim) | 10.21 |
| After Inspection No Load (0.025” shim) | 3.13 |
| After Inspection Full Load (0.050” shim) | 21.09 |

As seen in Table 2, leak rates were significantly higher than the specified rate provided by JETSEAL. The best result, the no load test after sanding, was 44 times higher than the specified rate. At worst, after cyclic loading and inspection, the full load test grew to over 2000 times the specified rate. After cycling, leak rates for both full and no load increased by 340% or more from before cycling.

Figure 4.5 shows the peak values recorded by the load frame while compressing and uncompressing the seal during the cycle test. Overall, the net change in force required to compress the seal trended upward through the test.

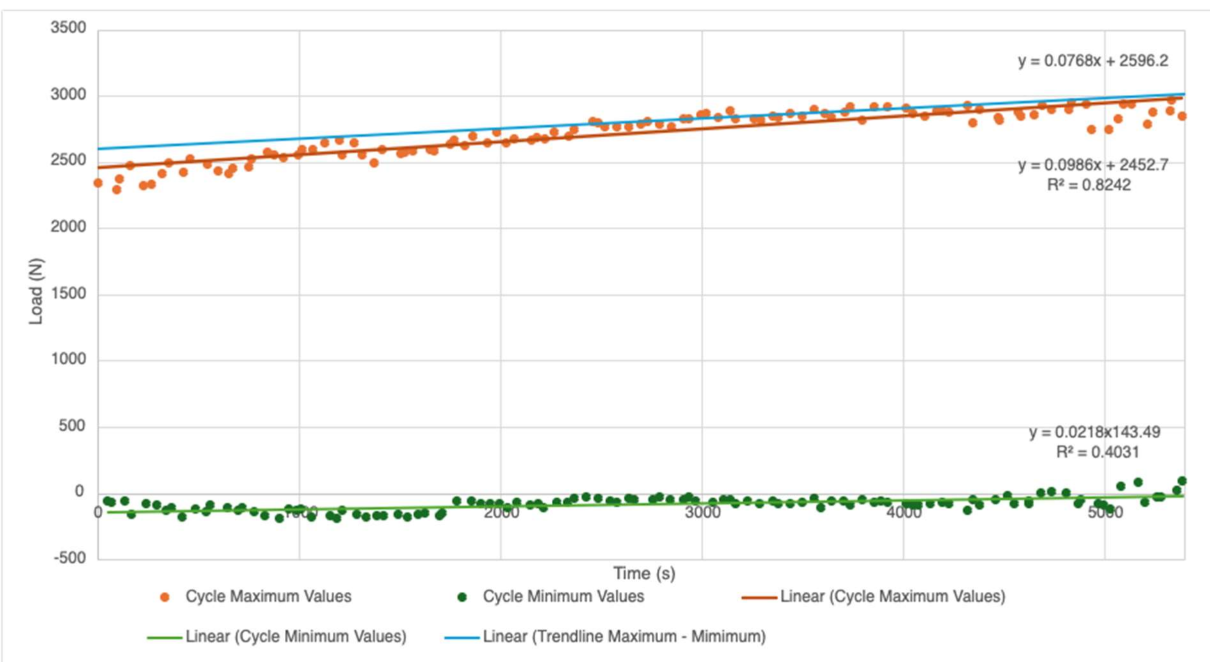



Figure 4.5. Force in Newtons required to deflect the seal by 0.030 inches. Peak compression and tension values shown.

The uncertainty of leak rate for the 0.050" shim, post sanding, pre-cycled testing can be seen in Table 3 and Appendix F. This propagated uncertainty includes the measurement resolution error, calibration error, and statistical error produced during measurements of the leak time, pressure, and cavity volume. These produced around 10% uncertainty in the final result with the effect of time measurement uncertainty being the largest contributor.

Table 3. Uncertainty analysis results.

| | Measured Value | Propagated Error | Percent Error |
|---|---|---|---|
| Leak Rate [atm-ft^3/min] | 6.34E-3 | 5.54E-4 | 8.73 |

# 5 Discussion, Limitations, & Recommendations

While progressing through this project, the team has gained several insights into the design and the process of creating and implementing it. These insights have come from analysis of the full-scale design as well as manufacturing and testing the scaled-down test rig. A description of these insights and the team's recommendations to the sponsor are discussed below.

## 5.1 Discussion

From all the testing and results above, a few major findings were realized as the team progressed. They follow, in chronological order of the team's progress:

From the initial leak testing results, before sanding and before cycling, the leak rates were very high. The pressure test rig completely depressurized from 30 psi in around 20 seconds or less. From a simple visual test with soapy water, it was determined that the seal was leaking all the way around its circumference, although especially so from the weld seam of the seal. Per discussion with the seal manufacturer, it was determined that the seal's weld was not the cause of fault as it was leaking from more area than just the weld seam. Given this information, the team decided that the high leak rate was either due to the roughness of the sealing surface, or the fact that at the time the sealing groove was a little narrow and the seal was difficult to remove after testing. First addressing the narrow seal groove, the team hypothesized that the seal was contacting the walls and getting stuck before it even contacted the intended sealing surface. To solve this, the test rig was post machined to widen the sealing groove slightly until the seal fit freely without touching the sealing surface at all. The results of a quick leak test following this yielded no difference in results, so the data wasn't recorded, and the cause of the leaky seal was likely the surface finish of the sealing faces.

To confirm that the sealing surface roughness and lay was causing the rapid leak rate, the team attempted to improve the surface finish and provide a circular lay by consistently sanding the sealing face. A 3D printed block was made to match the groove geometry, and successively finer sandpaper was glued to its face to make consistent sweeps around the groove. This was continued up to around 1200 grit sandpaper. Leak testing after this yielded much better leak rates. This implied the importance of the sealing surface finish in the final product and is reflected in the team's recommendations. The numerical improvement can be seen in Table 2. Sanding the seal groove lowered leak rates by 80% or more for both full and no-load conditions. Overall, leak rates were still not up to the standards that the seal manufacturer specified. While this does not meet Specification 5, for sealing, the team believes that modifications to the rig outside the scope of this project could produce a leak rate that meets the specified rate.

With the cycle testing also came more findings for the team. The testing itself went fairly smoothly, with only a few things to note. As the number of cycles increased, the test rig started emitting a squeaking noise with each cycle. More notably though, the data from the load frame shown in Figure 4.5 showed an increase in force required to compress the seal as it cycled more. Both the peak maximum and minimum values shifted up over time, implying that the entire test rig could have been shifting, but taking the difference between the maximum and minimum resulting in a still-increasing net value. This corresponds to an increasing spring rate, which seems counterintuitive to the team. Two hypotheses are proposed to explain this increase in load through the life of the seal. One is that the seal was being work hardened as more cycles were applied. This would imply the seal underwent slight plastic deformation in each cycle and work hardened. Without the seal or surrounding components failing, this is not necessarily a bad thing, as it increases sealing force minimally. The other explanation is that the two halves of the test rig themselves were rubbing against each other and wearing, increasing the load that was needed each cycle. This is confirmed by easily seen marks on the post-cycled test rig halves and markedly rougher surfaces than before. Figure 5.1 shows some of these surface imperfections. Unfortunately, with the data the team was capable of recording, the distinction between these two contributors could not be determined.

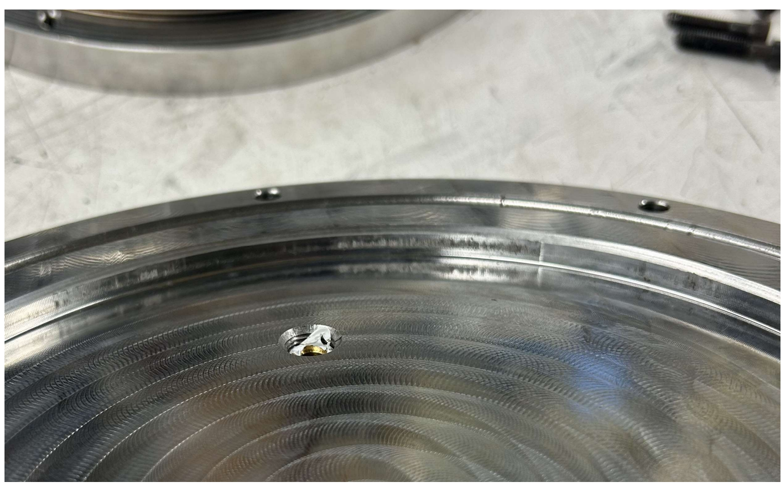


Figure 5.1. Wear on the inside of the test rig top plate where it contacted the bottom plate during cyclic loading.

After cycling the seal, the leak rate significantly increased, as shown in the results section above. Two leak test pairs were performed after cycling, one with the test rig kept as close to the cycled orientation as possible, and another after disassembling and reassembling the parts. Unfortunately, due to how the assembly was set up on the load frame, the two halves needed to be rotated around 5 degrees to line up and be bolted together for leak testing. After leak testing and then a full disassembly/assembly procedure, the leak rate increased even more. From inspection of the post-cycled seal and test rig halves, the seal itself seemed to be in perfect condition, but the sealing surfaces of the test rig had notable pitting/scoring where the seal was contacting it, seen in Figure 5.2. This was expected, using a softer 17-4 stainless sealing surfaces with a harder Inconel 718 seal, making an around 20 HRC difference. The team's proposed explanation for the increased leak rate is the formation of these surface imperfections and motion of the seal to no longer align the features that created these imperfections with the imperfections themselves. These small imperfections are likely the cause of increased leak rate.

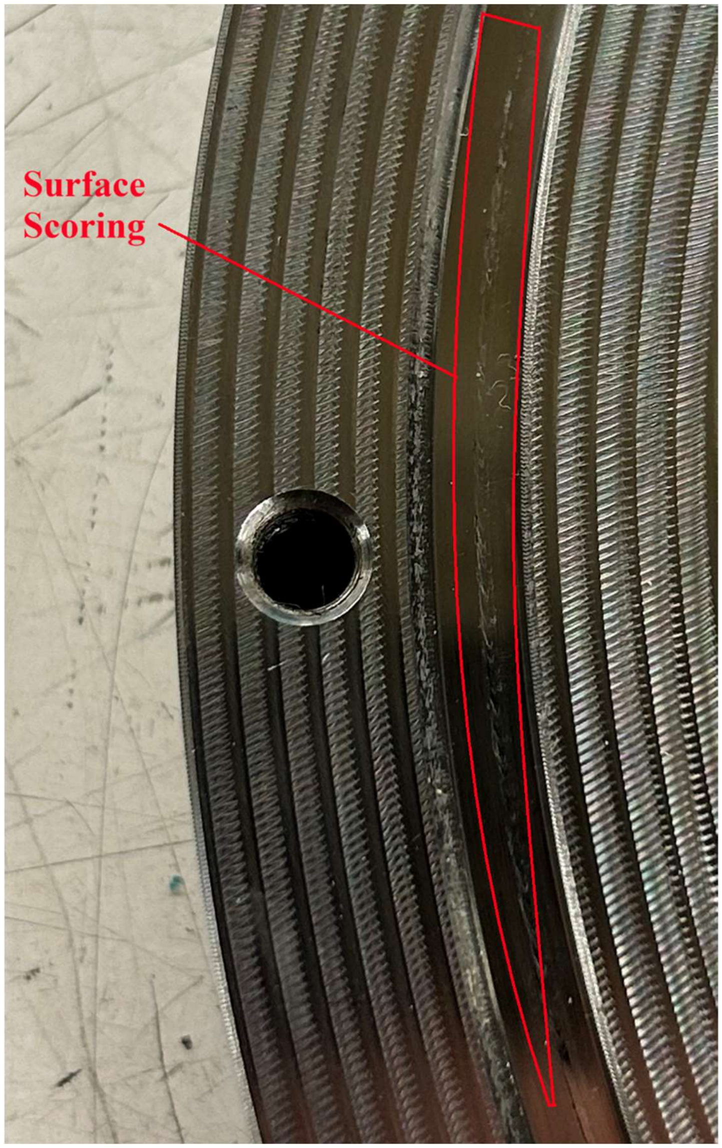



Figure 5.2. Wear on the sealing surface of the plate after cyclic load testing.

It is speculated that, in the full-size design with Inconel 718 sealing faces, this wear produced on the sealing surfaces would not be an issue. By matching hardnesses between seal and sealing surface, less wear would be created that decreases sealing at the end of the par s life. This would also imply the seal would be less affected by disassembly and reassembly. It is still worth being aware of though, as if moving the seal reduces sealing capability, it might be wise to replace the seal or refinish the sealing surfaces every time that part of the turbine is disassembled.

## 5.2 Limitations of the Scaled-Down Test Rig

Apart from the notes discussed in testing, it is also important to recognize the limitations of the scaled-down test rig in comparison to the to-scale design and environment. These include differences in seal applications, materials, and environment. The seal applied in this design was an internal E-seal, meaning that in comparison to the to-scale design, the pressure was internal and not external. Assuming the applications of both are very similar, this is not a major concern as if the E-seal surroundings are designed to specification, it would work the same. The geometry of the test rig E-seal groove was also modified for simplicity of CNC manufacturing. While this likely was not a concern in testing, designing closer to existing seal grooves as seen in the full-scale design will likely be beneficial. The environment was also significantly different, with the major differences being operating temperature and vibrations. The high temperatures change the properties of the materials, and while this was evaluated through analysis to be okay, the E-seal itself must be specified to operate and deform at this temperature.

The test rig was designed and developed with these limitations in mind, so these results could be much improved for a full-scale accurate model through further testing.

## 5.3 Recommendations and Next Steps

If the E-Seal Assembly were to be continued by Solar Turbines or pursued by another senior project team, the team has numerous recommendations for these future adaptations. The team believes these recommendations will yield a better seal and more accurate test results.

To create a better seal the team recommends changing the manufacturing process to create a smoother sealing surface on the plates, with an emphasis on a circular lay following tangent to the groove. As stated in section 3.2, the sealing surface was manufactured using a CNC mill and then sanded. Creating the sealing surface with a lathe or grinding or lapping the surface after manufacturing will create a smoother surface which the team believes will seal much better. More accurate tests can be performed if the E-seal seals better. With the current leak rate, tests were less accurate because the test rig depressurized so quickly. Any next steps taken on this design should focus on finding a more accurate way to manufacture the test setup as close to how Solar Turbines would manufacture a full-size design per manufacturer recommendation. In the case that this is not possible, testing should try to at least be conducted under constant pressure difference.

It is important to use material of similar hardness to the E-seal. In this test, the material used for the sealing plates was 17-4 Stainless Steel while the E-seal was Inconel 718. These materials are similarly hard but not as close as they should be. In a future test, the material used as the sealing surface should be the same hardness or if possible, the same material, as the E-seal. By matching the hardness of the E-seal and the sealing surface the tests done should show reduced wear from cycling and less leakage because of that. Small rings of Inconel 718 could be manufactured and adhered into a larger test setup made of an easier to work with material. This would give the correct sealing surface hardness without making the entire setup needlessly hard to manufacture.

The team also recommends testing the E-seal at full size with an accurate number of convolutions. A different diameter of the E-seal will alter the leak rate, and the increase or decrease in convolutions will be important for deflection and loading, giving more accurate results. These results will be comparable to the actual operation of the T250 Engine. Sourcing, manufacturing, and testing may be difficult for a seal of such size but is valuable to testing the actual function of the E-seal.

Another change the team suggests is using a coated seal. If the E-seal were to be applied to the T250 Engine, the E-seal used should be coated. As discussed in the Critical Design Review, there are a variety of common E-seal coatings that help with different properties. One benefit of including a coating on the E-seal allows for more surface imperfections of the sealing surface, resulting in a better seal. Using a coated E-seal in future tests should yield better sealing results. It should still be noted that the coating must be appropriate for the testing environment with concerns with temperature, oxidization, and other fluid and surface properties.

# 6 Conclusion

Through use of an E-seal, the proposed design met most of the required design specifications. Specifications regarding lifetime, assembly, safety, temperature, and thermal expansion were all satisfied through analysis or testing and although do need to be designed around, should not be a concern. While sealing performance was not ideal, several factors that may have contributed to low performance were identified and addressed for future design. By addressing some of these factors, sealing performance was improved significantly and was assumed, if extrapolated, would continue to improve with further adaptations.

# 7 References

[1] Solar Turbines, private communication, Oct. 5, 2023.
[2] JETSEAL, private communication, 2024.

# 8 Appendices

## Appendix A – User Manual

# Improved Combustor Liner

**Lessons Learned and Next Steps**

Written by Team F63: Improved Combustor Liner Seal
Max Case, Mason Jones, Jacob Matties, Chris Ng


## Introduction

To evaluate the functionality of the E-seal sealing mechanism that would be implemented in the Solar Turbines T250 SoLoNOx engine, a scaled-down test rig was designed, manufactured, and tested for leak rates and cycling endurance. As seen in Figure 1, the prototype test rig was manufactured to be sealed using the specifications for the E-seal donated by JETSEAL.

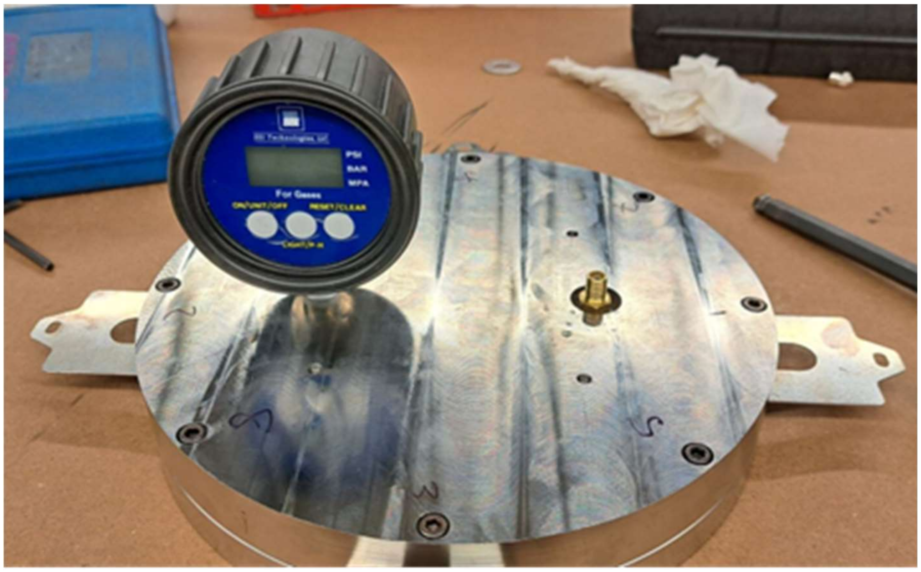



Figure 1. Scaled-Down Assembled Prototype Test Rig

Using this test rig, a leak rate test was conducted to determine how much internal fluid escapes through the E-seal, and a cyclic loading test was done to determine if the E-seal used in the uncommon application would continue operation after 5000 thermal cycles. The leak rate test consisted of observing pressure decay, where the test rig was pressurized to around a gauge pressure of double the operating internal pressure of the T250 engine and then allowed to leak. The cyclic loading test utilized a load frame machine to observe load variations and simulate the thermal cycling for a full life, where the E-seal underwent 5000 cycles of a deflection of 0.030" from the anticipated "full-load" to "no-load" of the prototype. The leak rate test was conducted for both 0.025" compression and 0.050" compression before and after the cyclic loading test.

Through the manufacturing, testing, and redesigning of this prototype, many discoveries and potential features to-be-changed in the future were found. These included the impact of the E-seal groove's surface finish on leak rates, the impact of testing environments, the impact of geometry on leak rate data resolution, and the impact of E-seal geometry. Acknowledging that this project's test rig and overall design will be reworked by Solar Turbines if they move forward with the design, this document aims to identify significant details that Solar Turbines should be aware of for their own future testing and adaptations.

## Lesson 1: Surface Finish is the Most Critical Feature for Sealing

One of the largest issues found during the manufacturing of the E-Seal test prototype was a low-quality surface finish of the sealing surface. The team chose to use a HAAS V4 CNC mill to machine all critical features of the prototype. This machine produced an acceptable surface finish per comparison with a surface measured with a profilometer, and the flatness of the sealing surface was within 0.0005" as measured in Figure 2. But while the finish meets the standards set by the E-seal manufacturer, JETSEAL, it did not have an appropriate circular lay pattern as shown in Figure 3a. After initial testing and consultation with the seal manufacturer, it was determined that the circular lay pattern is a critical aspect of creating a sealing surface between the groove and the E-seal. After carefully applying sandpaper to remove the CNC milled surface finish and creating a circular lay following the groove, testing showed significant improvements in ability to seal. The team believes manufacturing the groove with a lathe or grinding the sealing surface may further improve the seal, and if possible, a more accurate way to test the surface finish may be necessary.

Figure 2. E-Seal Groove Flatness Inspection

a) Pre-Sanding Groove Surface Finish b) Post Sanding Groove Surface Finish
Figure 3. E-Seal Groove Surface Finish a) Before Sanding and b) After Sanding

## Lesson 2: Pressure Tests Can Be Done at a Higher Pressure

The team decided to mirror pressures observed during the turbine's operation as closely as possible in their testing. To do this, the test prototype was pressurized to about 28psig – double the actual operating pressure – to see the full range of pressures. The team also only purchased a pressure gauge that could read up to 30psig. A better course of action to find the leak rate would be to pressurize the test prototype to a much higher pressure with a gauge accurate to a higher pressure. This option would yield a more accurate leak rate from testing. In the case of Solar Turbines' testing, a different route to determine leak rate is suggested. A more intensive test setup that ensures a constant pressure both inside and outside of the sealing surface and capability to evaluate leaks would allow for more consistent data around the actual operating points. Testing equipment is commercially available that will measure a leak rate for a setup while keeping its pressure differential constant.

Figure 4: The Pressure Gauge Overloaded at about 30psi While Testing.

## Lesson 3: A Larger Internal Volume Is Helpful

The team's prototype had a small internal volume to pressurize. A larger volume would lengthen the test time to depressurize and increase the resolution of the calculated leak rates. Additionally, a longer test time with slower pressure decay will provide more accurate data points on the leak rate of the seal. A small internal volume also made the pressure highly dependent on the surrounding metal's temperature, which would make testing a seal that doesn't leak very fast relatively hard without a temperature-controlled environment. Solar Turbines is able to operate at the actual environment, however, it should be noted that leak tests alone may be heavily dependent on temperature.

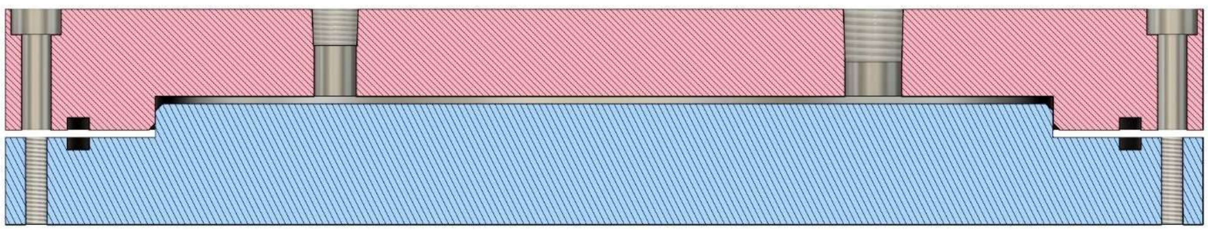


Figure 5. A Section View of the Test Prototype Showcasing the Small Internal Volume (Gray Area Between Plates) to Pressurize for Testing

## Lesson 4: Confirm the Accuracy of The Seal

The team was donated a seal by JETSEAL. They measured the seal using calipers to find the exact radius, height, and thickness. Some of the initial problems found in testing could have come from the fact that the seal was not perfectly symmetric. The seal appeared to be somewhat conical in shape. This is shown better in the image below where one side's diameter appears to be smaller than the other. This failure to measure the seal properly resulted in problems during assembly because only the smaller side fit into the groove of the test prototype properly.

Figure 6. The Seal Held Flat on a Surface Plate Next to a One-Two-Three Block Showcasing the Seal’s Asymmetry.

## Lesson 5: Use Similarly Hard Metals

This was something the team did well but not perfectly. It was suggested by JETSEAL to use the same material as the seal to create the sealing surface. The seal was made from Inconel 718 with a Rockwell hardness around 50 HRC. The team used 17-4 stainless steel as the metal to create the sealing surface with the Inconel 718 seal. The 17-4 stainless steel the team used had a hardness of around 38 HRC. This difference in hardness became apparent after testing cyclic compression on the load frame. After testing and disassembling the test prototype, there was noticeable scoring on the sealing surface of the 17-4 stainless steel. This scoring seemed to alter the leak rate of the test prototype. In a future test, using similarly hard materials for the seal and the surface is necessary to ensure the seal can last after thermal cycle

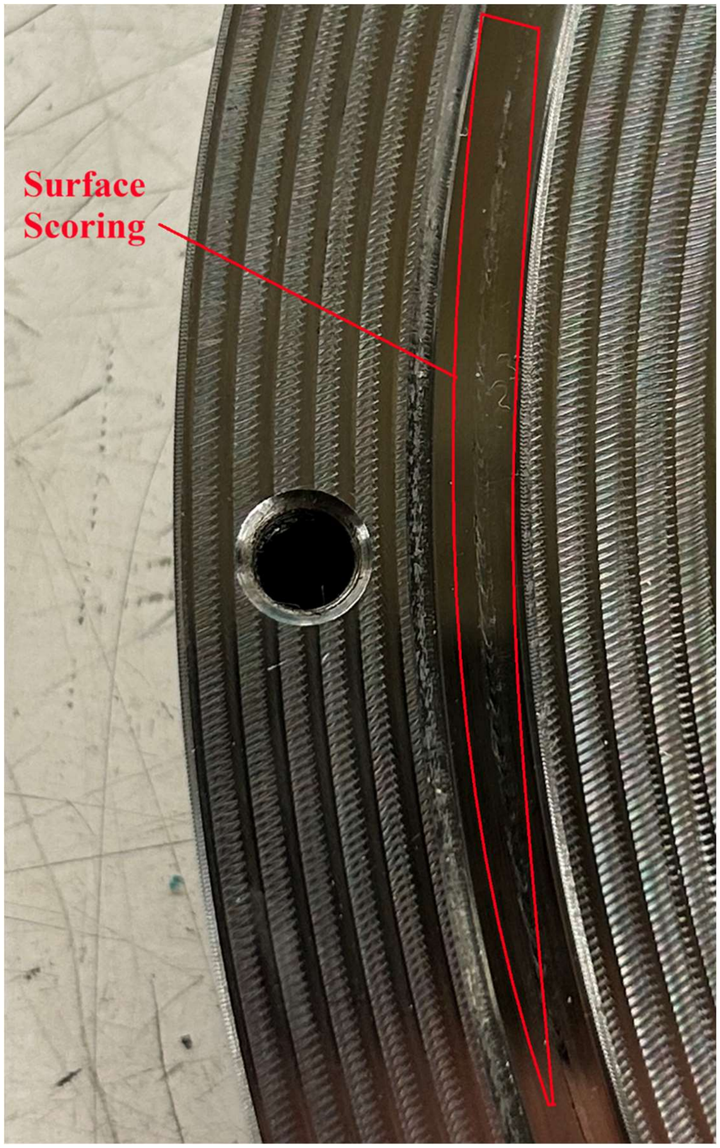


Figure 7: Surface Scoring on the Sealing Surface of the 17-4 Stainless Steel Plate

**Next Steps:**

This section will provide an outline of the suggested next steps for a team to pick up this project where it was left off.

The most informative path for Solar Turbines would likely be creating a relationship with a manufacturer of E-seals. There were several limitations to the test rig that was created for this project. Foremost of these was the team's inability to determine if the donated seal was correctly manufactured or scraped due to an unknown defect. According to our contact at JETSEAL, the donated seal came from a "samples box" and therefore there was no way to determine its origins. Because the seal had no identifiers, the critical dimensions for the sealing groove were extrapolated from publicly available data that JETSEAL publishes for their range of standard non-customized seals. This fact, combined with possible manufacturing defects, could have resulted in a lower performance than would be expected from a properly designed seal and groove. The best way to remedy this situation would be to purchase a seal from a manufacturer. Our contact made it clear that if a seal was purchased from his company, the company's engineers would assist in the process of designing the sealing interface. This would ensure that dimensions are accurate and that a high-quality seal was used.

One other limitation was the lack of a lathe that could hold a workpiece as large as the test rigs plates. During testing it was determined that a circular lay surface finish was critical to sealing ability. The surface finish left by the mill was determined to the best of our ability to meet the general surface finish requirements set by the manufacturer. Despite this the lay left by the mill prevented the seal from working as well as expected. When it was removed with sandpaper the seal performed significantly better. If this project is continued it is highly recommended that a lathe be used to create the sealing groove.

A continuation of this project should also prioritize using a material for the seal supports that has a similar hardness to that of the seal itself. After testing with the load frame, the test rig's sealing ability worsened significantly. Inspection of the test rig showed signs of wear or galling on the sealing surfaces. Since surface finish requirements are very strict in this area, it is likely that these imperfections led to this lower performance. According to our contact at JETSEAL, by using a material with a similar hardness, this issue might be avoided or at least minimized. A material harder than the seal should not be used as this damage might then occur on the seal.

A full-scale seal would likely provide the most beneficial data for use in a turbine. Differences in seal stiffness from convolutions and diameter and increased surface area might change sealing capability of the E-seal. This will again require conversation with the E-seal manufacturer to make a design that meets the required specifications of the turbine operation.

Sourcing a seal with an external coating is also recommended. Many manufacturers offer coatings to improve sealing performance. Specifically, a coating that would improve the seals ability to survive in a high temperature, oxidizing environment would be beneficial to seal used in a turbine rather than a testing environment.

# Appendix B – Risk Assessment

Seal Prototype 3/1/2024

**designsafe Report**

| | | | |
|---|---|---|---|
| Application: | Seal Prototype | Analyst Name(s): | Max C |
| Description: | | Company: | |
| Product Identifier: | | Facility Location: | |
| Assessment Type: | Detailed | | |
| Limits: | | | |
| Sources: | | | |
| Risk Scoring System: | ANSI B11.0 Two Factor | | |

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

| Item Id | User / Task | Hazard / Failure Mode | Initial Assessment Severity Probability | Risk Level | Risk Reduction Methods /Control System | Final Assessment Severity Probability | Risk Level | Status / Responsible /Comments /Reference |
|---|---|---|---|---|---|---|---|---|
| 1-1-1 | Testing operator normal operation | mechanical : cutting / severing Sharp Edges | Minor Unlikely | Negligible | Chamfer sharp edges, separate hazard / people in time or space /Not Applicable | Minor | | In-process Manufacturing personnel /To be completed in Manufacturing |
| 1-1-2 | Testing operator normal operation | noise / vibration : fatigue / material strength Material failure while fatigue testing or due to fatigue testing | Moderate Unlikely | Low | Wear protective equipment and follow best practices for equipment use /Not Applicable | Moderate | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 1-1-3 | Testing operator normal operation | fluid / pressure : high pressure Pressure vessel failure at 2 ATM | Serious Remote | Low | Wear protective equipment and follow best practices for equipment use, safety glasses, footwear, special clothing /Not Applicable | Serious | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 1-1-4 | Testing operator normal operation | fluid / pressure : fluid leakage / ejection High leak rate in concentrated area | Serious Unlikely | Medium | Wear protective equipment and follow best practices for equipment use, safety glasses, footwear, special clothing /Not Applicable | Serious | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 1-2-1 | Testing operator load / unload materials | mechanical : cutting / severing Sharp edges | Minor Unlikely | Negligible | Chamfer sharp edges, separate hazard / people in time or space /Not Applicable | Minor | | In-process Manufacturing personnel /To be completed in Manufacturing |

Page 1 Privileged and Confidential Information

| Item Id | User / Task | Hazard / Failure Mode | Initial Assessment Severity Probability | Risk Level | Risk Reduction Methods /Control System | Final Assessment Severity Probability | Risk Level | Status / Responsible /Comments /Reference |
|---|---|---|---|---|---|---|---|---|
| 1-2-2 | Testing operator load / unload materials | mechanical : pinch point Pinching when tightening fasteners | Moderate Unlikely | Low | Verbal confirmation that operators are clear of pinch point before tightening, standard procedures /Not Applicable | Moderate | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 2-1-1 | Testing passer by / non-user work next to / near machinery | slips / trips / falls : trip Tripping due to distractions or tripping hazards in work area | Serious Unlikely | Medium | Inspect work area for tripping hazards, warn passer by's of testing activity /Not Applicable | Serious | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 2-1-2 | Testing passer by / non-user work next to / near machinery | fluid / pressure : high pressure Pressure vessel failure at 2 ATM | Serious Remote | Low | Wear protective equipment and follow best practices for equipment use, safety glasses, footwear, special clothing /Not Applicable | Serious | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 2-1-3 | Testing passer by / non-user work next to / near machinery | fluid / pressure : fluid leakage / ejection High leak rate in concentrated area | Serious Unlikely | Medium | Wear protective equipment and follow best practices for equipment use, safety glasses, footwear, special clothing /Not Applicable | Serious | | On-going [Daily] Testing personnel /Follow shop safety procedures |
| 3-1-1 | Assembly Technician Common Tasks | mechanical : crushing Crane or lift failure | Catastrophic Unlikely | Medium | adjustable enclosures / barriers, safety mats / contact strip, safety glasses, head protection, footwear /Not Applicable | Catastrophic | | On-going [Daily] Maintenance department, Crane operators /Follow Solar Turbines standard safety practices |
| 3-1-2 | Assembly Technician Common Tasks | mechanical : cutting / severing Sharp edges | Minor Unlikely | Negligible | Chamfer sharp edges /Not Applicable | Minor | | On-going [Daily] Manufacturing personnel /Follow Solar Turbines standard safety practices |

Page 2 Privileged and Confidential Information

| Item Id | User / Task | Hazard / Failure Mode | Initial Assessment Severity Probability | Risk Level | Risk Reduction Methods /Control System | Final Assessment Severity Probability | Risk Level | Status / Responsible /Comments /Reference |
|---|---|---|---|---|---|---|---|---|
| 3-1-3 | Assembly Technician Common Tasks | mechanical : pinch point Appendages trapped or caught in part when assembly is brought together | Serious Unlikely | Medium | adjustable enclosures / barriers, delayed start, safety mats / contact strip, E-stop control, special procedures, safety glasses, head protection, footwear /Not Applicable | Serious | | On-going [Daily] Crane operators, assembly personnel /Follow Solar Turbines standard safety practices |

# Appendix C – Final Project Budget

| Team Expense from Cal Poly ME Budget | | | | | | | | | | | Remaining Funds |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | Vendor | Vendor PN | Our PN | Item Cost | Quantity | Ship/Tax | Total Cost | Date | Description | Location | $1,000.00 |
| Travel | NA | NA | NA | NA | NA | NA | $247.75 | 11/9/2023 | Trip to San Diego - touring Solar Turbines facility. | NA | $752.25 |
| Part | McMaster | 8063K33 | 2104 | $3.39 | 1 | $24.85 | $28.24 | 3/15/2024 | Test rig air fill valve. | 51 | $724.01 |
| Part | McMaster | 2798K211 | 2105 | $103.71 | 1 | | $103.71 | 3/15/2024 | Test rig pressure gauge. 0-30 psi | 51 | $620.30 |
| Part | McMaster | 91251A349 | 2106 | $17.91 | 1 | | $17.91 | 3/15/2024 | Test rig fasteners. 1 pack of 50. 10-32 x 1.25 | 51 | $602.39 |
| Part | McMaster | 94420A137 | 2108 | $4.06 | 4 | | $16.24 | 3/15/2024 | Test rig shims, no load (0.020"). Qty. 4 | 51 | $586.15 |
| Part | McMaster | 94420A152 | 2109 | $5.11 | 4 | | $20.44 | 3/15/2024 | Test rig shims, full load (0.050"). Qty. 4 | 51 | $565.71 |
| Part | McMaster | 94420A145 | 2110 | $4.74 | 4 | | $18.96 | 3/15/2024 | Test rig shims, no load (0.025"). Qty. 4 | 51 | $546.75 |
| Part | McMaster | 92620A417 | 2202 | $24.00 | 1 | | $24.00 | 3/15/2024 | Instron Fixture Bolts. 1 pack of 25 | 51 | $522.75 |
| Tool | Amazon | NA | NA | $37.24 | 1 | $5.00 | $42.24 | 3/15/2024 | Stainless tapping fluid. https://www.amazon.com/Cas | 51 | $480.51 |
| Tool | MSC | 1190297 | NA | $16.67 | 1 | $10.59 | $27.26 | 4/16/2024 | 29/64 cobalt drill bit | 51 | $453.25 |
| Tool | Home Depot | 1008719519 | NA | $18.98 | 1 | $1.38 | $20.36 | 4/16/2024 | Wireless thermometer | shipping | $432.89 |
| Tool | McMaster | 8609K1 | NA | $16.06 | 1 | $10.77 | $26.83 | 4/23/2024 | Rubber Gasket | TBD | $406.06 |
| Tool | Harbor Freight | 63881 | NA | $18.99 | 1 | $1.90 | $20.89 | 4/30/2024 | 20-200 in-lb Torque Wrench | TBD | $385.17 |
| | | | | | | | | | | Total Remaining Funds: | $385.17 |

| Solar Turbines Expense | | | | | | | | | | | Total Spent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | Vendor | Vendor PN | Our PN | Item Cost | Quantity | Ship/Tax | Total Cost | Date | Description | Location | $0.00 |
| Stock | Best Stainless & | 9R174 | 2101 | $311.00 | 1 | $0.00 | $311.00 | 3/15/2024 | 1" long 9" round 17-4 annealed | 51 | $311.00 |
| Stock | Best Stainless & | 9R174 | 2102 | $311.00 | 1 | | $311.00 | 3/15/2024 | 1" long 9" round 17-4 annealed | 51 | $622.00 |
| Tool | MSC | 97664379 | NA | $106.90 | 1 | $53.50 | $160.40 | 3/15/2024 | Roughing endmill | 51 | $782.40 |
| Tool | MSC | 4354569 | NA | $30.40 | 1 | | $30.40 | 3/15/2024 | Groove finishing endmill | 51 | $812.80 |
| Tool | MSC | 70853304 | NA | $53.82 | 1 | | $53.82 | 3/15/2024 | 1/4 NPT Tap | 51 | $866.62 |
| Tool | MSC | 70853312 | NA | $48.65 | 1 | | $48.65 | 3/15/2024 | 1/8 NPT Tap | 51 | $915.27 |
| Tool | MSC | 7228216 | NA | $4.75 | 1 | | $4.75 | 3/15/2024 | #2 drill for stainless | 51 | $920.02 |
| Tool | MSC | 74130394 | NA | $11.42 | 1 | | $11.42 | 3/15/2024 | 7/16 drill for stainless | 51 | $931.44 |
| Tool | MSC | 7228075 | NA | $3.25 | 2 | | $6.50 | 3/15/2024 | #16 drill for stainless. Qty. 2 | 51 | $937.94 |
| Tool | Monster Jaws | 6RJV622A | NA | $37.90 | 1 | $16.39 | $54.29 | 3/15/2024 | Soft jaws for workholding op 2 | 51 | $992.23 |
| Tool | All Industrial To | 50008640 | NA | $53.71 | 2 | $7.79 | $115.21 | 3/15/2024 | Mitee Bites for workholding op 1 | 51 | $1,107.44 |
| | | | | | | | | | | Total Funds Spent: | $1,107.44 |

# Appendix D – Design Verification Plan & Report (DVPR)

## DVP&R - Design Verification Plan (& Report)

Project: F63 Seal | Sponsor: Solar Turbines | Edit Date: 5/23/2024

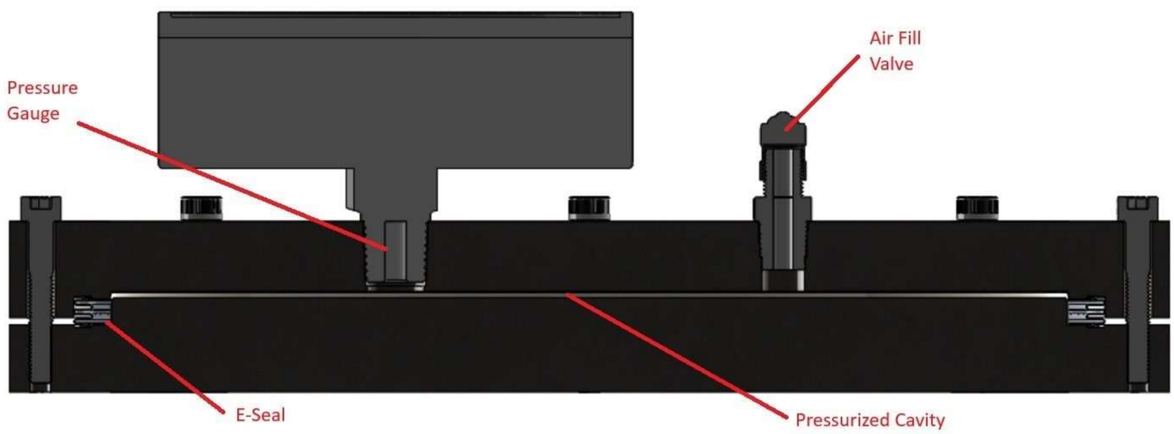
| Test # | Specification | Test Description | Measurements | Acceptance Criteria | Required Facilities/Equipment | Parts Needed | Responsibility | TIMING Start date | TIMING Finish date | Numerical Results | Notes on Testing |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | TEST PLAN | | | | | | | | | TEST RESULTS | |
| 1 | Control Leak Test | Pressure decay test. Test model with a rubber gasket to find control leak values through fittings. | Pressure over time. | Any | Compressed air source | Test rig, rubber gasket | Mason | 5/5/2024 | 5/23/2024 | 0.0002 sccs | Negligible pressure drop relative to seal leak rate. Orders of magnitude lower. Ignoring fitting leak rate for results analysis |
| 2 | Leak Test | Pressure decay test. Test model at initial preload (0.050" shims). Repeat after fatigue test. | Pressure over time. | <10^-3 cc/s | Compressed air source | Test rig | Chris | 5/6/2024 | 5/23/2024 | Pre-Sanding: 13 sccs @ 14 psid<br>Post-Sanding: 3.5 sccs @ 14 psid | Repeated both as machined and after sanding down the sealing surface. |
| 3 | Leak Test | Pressure decay test. Test model at max preload (0.025" shims). Repeat after fatigue test. | Pressure over time. | <10^-3 cc/s | Compressed air source | Test rig | Chris | 5/8/2024 | 5/23/2024 | Pre-Sanding: 7.5 sccs @ 14 psid<br>Post-Sanding: 0.5 sccs @ 14 psid | Repeated both as machined and after sanding down the sealing surface. |
| 4 | Seal Fatigue Test | Test seal to make sure it can survive 5000 cycles of 0.25 inch springback. This test is a reach goal, may not be able to figure it out. | Visual inspection for pass/fail of material failure. Force over time. | No plastic deformation | Load Frame (capable of cycling displacement) | Test rig | Mason | 5/13/2024 | 5/23/2024 | See Excel data in OneDrive | Peak load increased over time. |
| 5 | Leak Test | Pressure decay test. Test model at initial preload (0.050" shims). Repeated after fatigue test. | Pressure over time. | <10^-3 cc/s | Compressed air source | Test rig | Max | 5/14/2024 | 5/23/2024 | Pre-Inspection: 10 sccs @ 14 psid<br>Post-Inspeciton: 20 sccs @ 14 psid | Repeated both with the seal mounts within 5 degrees of how they were cycled in instron and after taking apart and inspecting everything. |
| 6 | Leak Test | Pressure decay test. Test model at max preload (0.025" shims). Repeated after fatigue test. | Pressure over time. | <10^-3 cc/s | Compressed air source | Test rig | Max | 5/16/2024 | 5/23/2024 | Pre-Inspection: 2 sccs @ 14 psid<br>Post-Inspeciton: 3 sccs @ 14 psid | Repeated both with the seal mounts within 5 degrees of how they were cycled in instron and after taking apart and inspecting everything. |

## Appendix E – Test Procedures

Leak Test Procedure

**Team:** F63 Seal
**Test Name**: Leak Rate Test
**Test Number:** 1,2,3,5,6
**Planned Test Date(s):** 5/6/2024 - 5/9/2024, 5/14/2024 - 5/17/2024
**Testing Objective:** To determine a leak rate for a scaled-down and modified test rig to demonstrate proof of function of a potential full-scale sized prototype.
**Scope:** This test will only be evaluating the leak rate through the seal over time.
**Required Test Equipment:**

- Full Test Rig Assembly (Mounts and E-Seal)
- Baseline Test Rig
- Air Fill Valve
- 10-32 Socket Head Cap Screws (SHCS)
- Torque Wrench
- Large Ratchet
- 5/32" Hex Adapter
- Custom 7/8 Crow's Foot
- Pipe Thread Tape
- Pressure Gauge
- Caliper/Micrometer
- 0.025" and 0.050" Shims
- Digital Clock
- Thermometer
- Custom Made Rubber Gasket for Control Testing
- Video recording device




**Hazards:**

- Sharp edges and pinch points that could cause cutting and crushing of limbs
- Pressurized vessel which could cause material yield
- High speed gas from small gaps which could cause eye damage if too close
- Heavy objects which could cause crushing of limbs if dropped

**PPE Requirements**:

- Safety Glasses
- Long Pants
- Closed-Toe Shoes

**Facility:** Mustang 60

**Procedure:**

Initial Steps:

1. Verify that all participants are wearing proper safety equipment as described in the PPE Requirements.
2. Collect the Baseline Test Rig, Leak Test Rig, and other equipment as described in the Required Test Equipment to bring to Mustang 60.

Rig Baseline Test:

1. Place the Bottom Mount on a designated solid flat surface.
2. Place and align the Rubber Gasket into the bottom mount’s cavity.
3. Place and align the Top Mount onto the Rubber Gasket.
4. Slightly lift the Top Mount and rotate it until the bolt holes are aligned on the Top and Bottom Mounts.
5. Place and initially thread each SHCS by hand or with a hex wrench if required.
6. Use the Wrench to tighten each SHCS in a star pattern by 90 degrees, then repeat this process until the two mounts have compressed tightly around the Rubber Gasket.
7. Zero the Pressure Gauge.
8. Apply thread tape to the NPT threads for both the Pressure Gauge and Air Fill Valve.
9. Screw in the Pressure Gauge and Air Fill Valve to the Leak Rate Test Rig threaded holes and torque to specification using the crow’s foot.
10. Start a video of the pressure gauge reading.
11. Slowly pressurize the Leak Rate Test Rig with bike pump through the Air Fill Valve until the Pressure Gauge just overloads (above 30 psi), and then remove the bike pump.
    a. Wait until pressure drops back down to 0 psi.
    b. Stop video recording.

Leak Rate Test:

1. Take a picture of the sealing grooves on the Top and Bottom Mount and make note of any features and measure the diameter and height of the enclosed cavity.
2. Place the Bottom Mount on a designated solid flat surface.
3. Place and align the E-Seal into the bottom mount’s cavity.
4. Place and align the Top Mount onto the E-Seal, coming from above as to not accidentally deform the E-Seal through collision.
5. Slightly lift the Top Mount and rotate it until the bolt holes are aligned on the Top and Bottom Mounts.
6. Place 4 evenly spaced 0.050” Shims around the bolt circle.
7. Place and initially thread each SHCS by hand or with a hex wrench if required.
8. Use the Torque Wrench to tighten each SHCS in a star pattern by 90 degrees, then repeat this process until the two mounts have compressed around the shims (shims cannot move anymore)
9. Zero the Pressure Gauge.
10. Apply thread tape to the NPT threads for both the Pressure Gauge and Air Fill Valve.
11. Screw in the Pressure Gauge and Air Fill Valve to the Leak Rate Test Rig threaded holes.
12. Start a video of the pressure gauge reading.
13. Slowly pressurize the Leak Rate Test Rig with bike pump through the Air Fill Valve until the Pressure Gauge just overloads (above 30 psi), and then remove the bike pump.

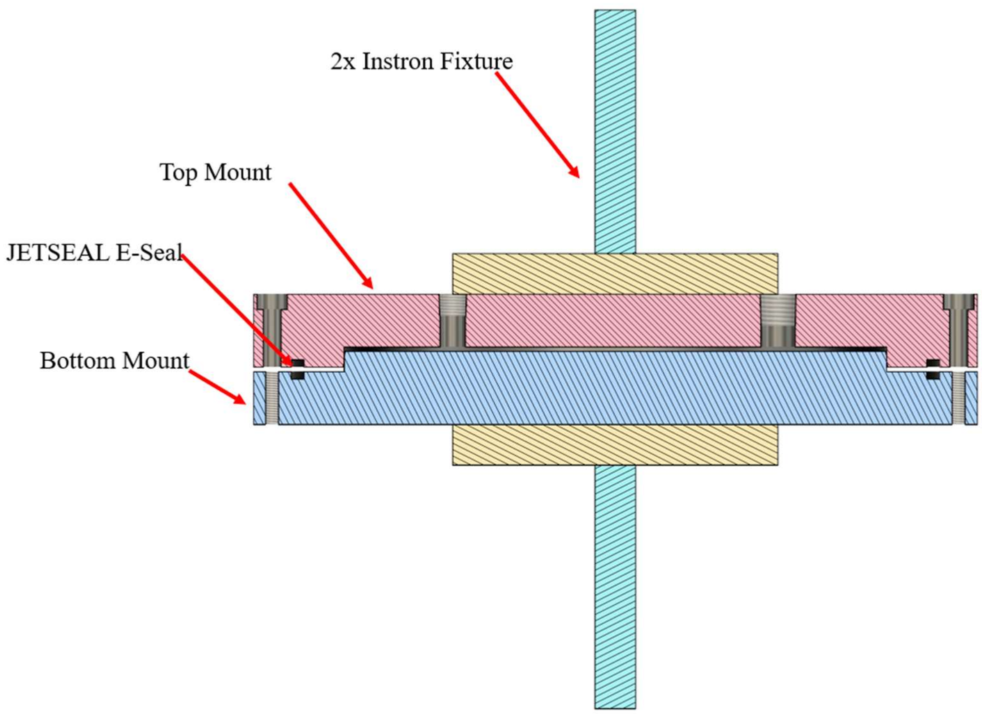
a. Wait until pressure drops back down to 0 psi.
b. Stop video recording.

14. Repeat Steps 12-13 five times.
15. Repeat Steps 1-14, using 0.025” Shims instead of 0.050” Shims.
16. Disassemble the Leak Rate Test Rig.
17. Inspect the E-Seal and the sealing cavity surfaces and note any features or changes.
18. Repeat Steps 1-17 after cycling seal on the Load Frame.

Test Procedure for Load Frame Testing

**Team:** F63 Seal
**Test Name**: E-Seal Cyclic Loading
**Test Number:** 1
**Planned Test Date(s):** 5/16/24
**Testing Objective:** To apply 5000 full-load to no-load cycles on the E-Seal to determine if the E-Seal can survive fatigue loading per the manufacturer's specifications to then retest for the leak rate.
**Scope:** This test will only evaluate the fatigue strength and loading of the E-Seal and not the rest of the test rig.
**Required Test Equipment:**

- Full Test Rig Assembly (Mounts and E-Seal)
- 10-32 Socket Head Cap Screws (SHCS)
- Load Frame Fixture
- Load Frame Fixture 10-32 Hex Head Bolts
- Load Frame Fixture Spacer
- Hex Wrench and Allen Key
- Load Frame with required Programs and Setup




**Hazards:** (list hazards associated with the test)

- Sharp edges and pinch points that could cause cutting and crushing of limbs
- Heavy objects which could cause crushing of limbs if dropped
- Vice pinch points that could cause cutting and crushing of limbs
- Welds/part yielding that could cause the fixture to fall off

**PPE Requirements**:

- Safety Glasses
- Long Pants
- Closed-Toe Shoes

**Facility:** Composites Lab, Bldg. 192-135
**Procedure:**

Initial Step(s):

1. Verify that all participants are wearing proper safety equipment as described in the PPE Requirements.
2. Collect the Full Test Rig Assembly, Load Frame Fixture, and other equipment as described in the Required Test Equipment to bring to the Composites Lab.

E-Seal Cyclic Loading Test:

1. Take a picture of the E-Seal and sealing grooves on the Top and Bottom Mount and make note of any features.
2. Place the Bottom Mount on a designated solid flat surface.
3. Place and align the E-Seal into the Bottom Mount's cavity.
4. Place and align the Top Mount onto the E-Seal, coming from above as to not accidentally deform the E-Seal through collision.
5. Slightly lift the Top Mount and rotate it until the bolt holes are aligned on the Top and Bottom Mounts.
6. Place and initially thread each SHCS by hand or with a hex wrench if required.
7. Place 4 thick shims equally around the diameter of the gaps between mounts.
8. Use the Torque Wrench to tighten each SHCS in a star pattern by 90 degrees, then repeat this process until the top mount has bottomed out on the thick shims.
9. Place the top Load Frame Fixture aligned with the Load Frame Fixture bolt pattern on the Top Mount.
10. Loosely screw in the 10-32 Bolts so that the fixture is flush to the mount surface but can still shift a little.
11. Carefully place the Test Rig on its side, with one person holding it still vertically.
12. Place the bottom Load Frame Fixture aligned with the Load Frame Fixture bolt pattern on the Bottom Mount so that the fin is parallel to the Top Mount's Load Frame Fixture.
13. Loosely screw in the 10-32 Bolts so that the fixture is flush to the mount surface but can still shift a little.
14. Place the Load Frame Fixture Spacers around the bottom Load Frame Fixture fin to be snug against its surface.
15. Have one person carefully lift the Test Rig with the attached Load Frame Fixture into the Load Frame and hold the Bottom Load Frame Fixture's fin in between the bottom Load Frame vice clamps with the flat surface of the Load Frame Fixture and let it down until the bottom of the Load Frame Fixture Spacer is touching the top of the vice.
16. Have another person tighten the bottom Load Frame vice clamps into place on the fin.
17. Lower the top Load Frame vice clamps so that the Top Load Frame Fixture's fin is between its clamps.
18. Have another person tighten the top Load Frame vice clamps into place on the fin, while shifting as necessary so the two Load Frame fixtures align.
19. Once the two fins have slid to be as vertically aligned as possible, use the Hex Wrench to tighten the top and bottom Load Frame Fixtures' Hex Bolts until they are snug.
20. Remove the Load Frame Fixture Spacers.
21. Set the zero of the Load Frame at this point.
22. Loosen the SHCS until there is at least 0.050" of space between the bottom of the screw head and the top of the Top Mount.
23. Recheck that the Test Rig is secured to the Load Frame vices.
24. Set the Load Frame to deflect 0.030" for 5000 cycles.
25. Have one person nearby prepared to E-Stop the program if any failures occur.
26. Wait for the Load Frame to run the full 5000 cycles and make note and take pictures of any large changes in deflection and corresponding loading.
27. Once the Load Frame has run the full 5000 cycles, save the load and deflection raw data.

28. Use the Torque Wrench to tighten each SHCS in a star pattern by 90 degrees, then repeat this process until each bolt is snug.
29. Have one person hold the Test Rig in place while another person loosens the Load Frame vices
30. Remove the Test Rig from the Load Frame and disassemble the Test Rig.
31. Inspect the E-Seal and the sealing cavity surfaces and note any features or changes.

## Appendix F – Raw Testing Results

See Excel provided.

Uncertainty analysis weighting.

| Values | Measured Value | Total Uncertainty | Partial Derivative | (Partial Derivative x Total)^2 |
|---|---|---|---|---|
| Time [min] | 5.00E-02 | 8.33E-04 | -6.55E-01 | 2.98E-07 |
| Pressure [atm] | 2.10E-01 | 2.86E-03 | 3.28E-02 | 8.80E-09 |
| Diameter [ft] | 7.07E-01 | 8.33E-05 | 1.94E-02 | 2.62E-12 |
| Height [ft] | 4.17E-03 | 2.50E-04 | 6.87E-03 | 2.95E-12 |