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Develop Efficient Leak Proof M1 Abrams Plenum Seal

SBIR Phase I: Topic A13-061
Final Technical Report – SubCLIN 001AC

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14. ABSTRACT
Report developed under SBIR contract for topic A13-061. The purpose of this report is to show the feasibility of developing an efficient, leak proof plenum seal for the M1 Abrams. It also shows the need for a newly designed seal based on in-depth research of the performance issues and cost burden of the current production seal. A modeling and simulation approach has been taken to develop a new plenum seal concept and compare its expected performance with that of the current production seal.

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1 Background

A Phase I SBIR contract was awarded to GLSV for the development of a sealing concept that will provide an efficient, leak proof seal between the turbine inlet and air cleaner plenum box on the M1 Abrams. Current production seals are known to leak and allow foreign object debris (FOD) into the engine thus reducing engine life. The objective of the Phase I effort is to develop a seal concept that shows a high likelihood of success when implemented into the vehicle while minimizing changes to the existing hardware. The work performed during this Phase I has resulted in a plenum seal concept that confirms the feasibility of more effectively sealing the turbine to the air plenum box. This effort consists of

- investigation of background information to understand the lessons learned
- definition of the design parameters
- modeling and simulation of current production seal and new seal concepts

An important output of Phase I is the solid modeling and FEA-based simulation that provide a tool for GLSV to completely analyze the sealing performance of new concepts compared to the current seal.

1.1 Problem Description

The seal (plenum seal) that couples the turbine to the air plenum box has been shown to leak causing FOD to enter the turbine resulting in premature and excessive turbine blade wear. This in turn leads to a reduced time interval between turbine rebuilds and an estimated $3-$4 million in repairs annually.

Additionally, the effectiveness of the mission could be compromised when the plenum seal is not performing correctly. Added fuel consumption due to decreased efficiency of the turbine, and an increased risk of failure when high water fording, can put troops into a dangerous position. Those problems can be greatly reduced or eliminated with a more efficient, leak proof plenum seal.

1.2 Phase I Goals

The main goal for the Phase I effort is to develop a feasible concept that will ensure an efficient, leak proof seal between the turbine and the air plenum box. Another goal is to simplify the manufacturing and installation of the seal. A third goal is to determine the technical merit and ultimate cost savings to the government provided by a new and improved seal. At the start of phase I, extensive research was done on the current seal and its shortcomings. The knowledge gained was used to fully define the above-mentioned goals. Modeling and simulation of the current seal and new seal concepts played a major part in working towards the main goal.

1.3 Technical Challenges

The main technical challenge associated with the plenum seal is designing a seal that can absorb large misalignments and still function correctly. The current seal has been designed around the nominal dimensions of the associated components and its shortcomings are quickly realized when the actual fielded equipment approaches the limits of the respective tolerance zones.

The second technical challenge was creating a simulation that accurately represents the current seal and newly proposed versions. The simulation consists of the seal following a trajectory, defined by a CAD motion analysis of the engine installation, and deflection as the seal contacts the plenum lip. This gives an accurate representation of how the seal performs in different alignment conditions. Areas of high stress in the seal material can be measured and analyzed at any point as the seal moves and deflects around the plenum box lip. Contact forces and amount of surface contact made between the plenum seal and plenum box lip are also analyzed. With a functional simulation, time can be well spent trying different combinations of seal profiles and materials to compare their performance.

The simulation can be used to perform design of experiments and optimization of seal geometry features as well as other components that influence the installation trajectory such as engine mounts and chassis brackets. It is also possible to incorporate stochastic simulation into the seal analysis. This allows critical dimensions to be represented by a probability distribution function and then many trials can be run to better understand the statistical likelihood of an acceptable seal at the interface between the turbine and the plenum.

1.4 Literature Review

In depth research was conducted into the history of the plenum seal. Many documents from the Army, General Dynamics and Honeywell were provided detailing the plenum seal past and present.

The original seal was a two clamp design which required a special torquing procedure to tighten the clamps. It also required crawling underneath the tank to look through an inspection hole to verify the correct alignment. While FOD intrusion did not appear to be an issue with this design, it was not desirable to crawl underneath the tank for a visual inspection. It should be noted that the Marines still use this design. Figures 1 and 2 were taken from a leak test performed at Honeywell. The results showed that the seal did allow some FOD intrusion in several conditions as well as allowed water to intrude into the plenum box.

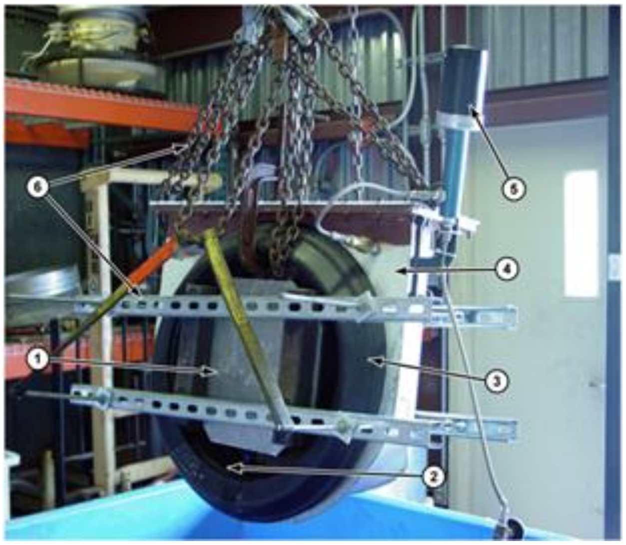


Figure 1: Water immersion test rig at Honeywell (reproduced from Honeywell test report 21-15196)

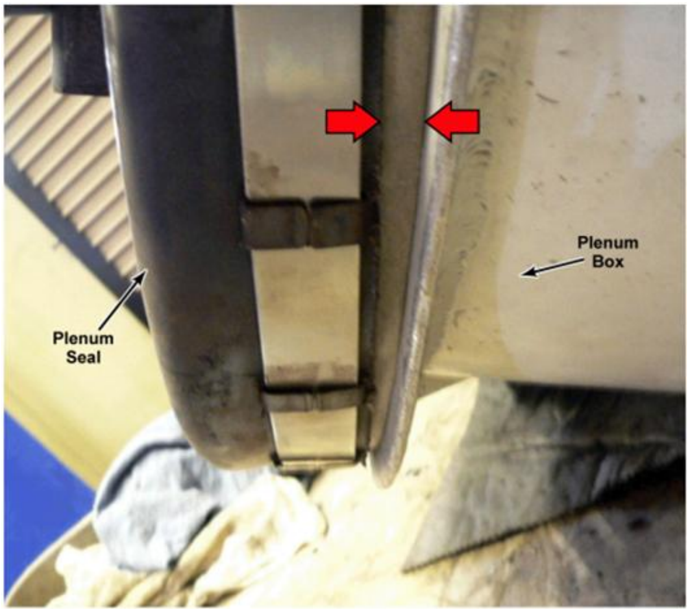


Figure 2: The leakage rate increased significantly when a gap (red arrows) was left between the Dual-Clamp Seal and Plenum Box, as allowed by TM 9-2350-388-23-1-3 WP0266 (reproduced from Honeywell test report 21-15196)

A second seal was designed in an effort to eliminate the need to crawl underneath the vehicle. This is the current seal in the vehicle and once installed on the FOD screen, it is a blind installation process. There has been great concern with the ability of this seal to effectively eliminate FOD into the turbine.

Figure 3: Current production Single Clamp Plenum Seal

Since the completion of the single clamp seal design, leak tests have been conducted on both designs in a lab environment, studies were conducted on the size of the air plenum box, interviews took place with the mechanics installing the turbine and a video was made to help eliminate installation errors. With all of this concern with the plenum seal, it would appear that it doesn't perform up to its initial expectations. Figure 4 shows a comparison of the "as drawn" and "actually fielded" plenum seal in the installed position.

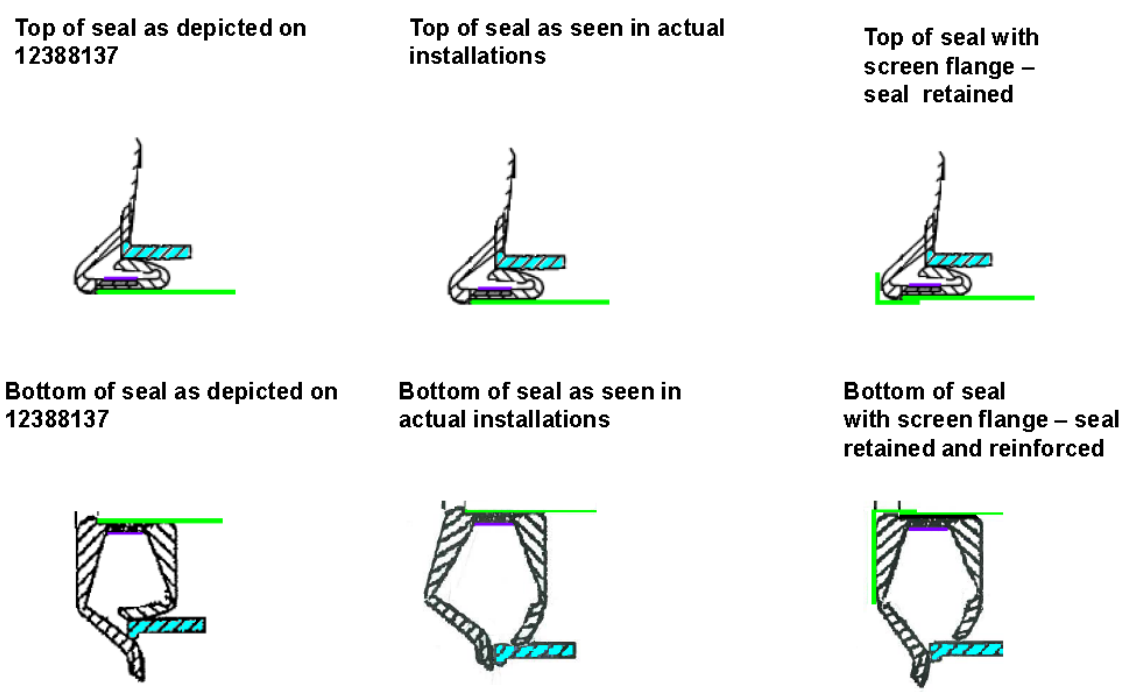


Figure 4: Seal Comparison – As drawn vs. actual installation (reproduced from Honeywell's Plenum Seal Engagement document)

1.5 Design Requirements

A list of design requirements was compiled throughout the literature review process. They are in no particular order;

-Maintain current operable temperature range of -60 to 350 F
-Eliminate need to crawl under vehicle during installation
-Blind installation, sealing occurs as power-pack is seated in hull
-Minimal changes to FOD screen and air box plenum
-Minimize installation time/effort

Misalignment tolerances were taken directly from data provided to GLSV by TARDEC. The overall misalignments the plenum seal must account for are as follows;

-Longitudinal direction = -1.3 inches (engine moves forward) to +.72 inches (engine moves rearward)
-Lateral direction = -.75 inches (engine moves left) to +.79 inches (engine moves right)
-Vertical direction = -.98 inches (engine lower than air box) to +1.01 inches (engine higher than air box)

1.6 Decision Methodology

After a thorough review of available documentation on the background of the plenum seal, GLSV was able to generate several concepts for a new seal design. A list of design criteria and performance characteristics were used to create two trade studies for evaluation and comparison of the concepts. The first study was a performance decision matrix and the second was a cost decision matrix. In both studies the current production seal was used as the basis for comparison. Section 3 goes into further detail about the trade studies.

2 CAD Modeling

CAD models were created of all the associated components that position the turbine in the hull and make up the plenum seal to air cleaner plenum box interface. These CAD models are the building blocks needed to fully understand the interactions between the plenum seal and the plenum box.

2.1 Component Modeling

CAD models were created from drawings and solid models provided by TARDEC. Models were developed to represent the following components:

Turbine
Air plenum box
Current seal
Turbine mounts/guide rails
Chassis interfaces (Turbine guides and mounts)
New seal concepts

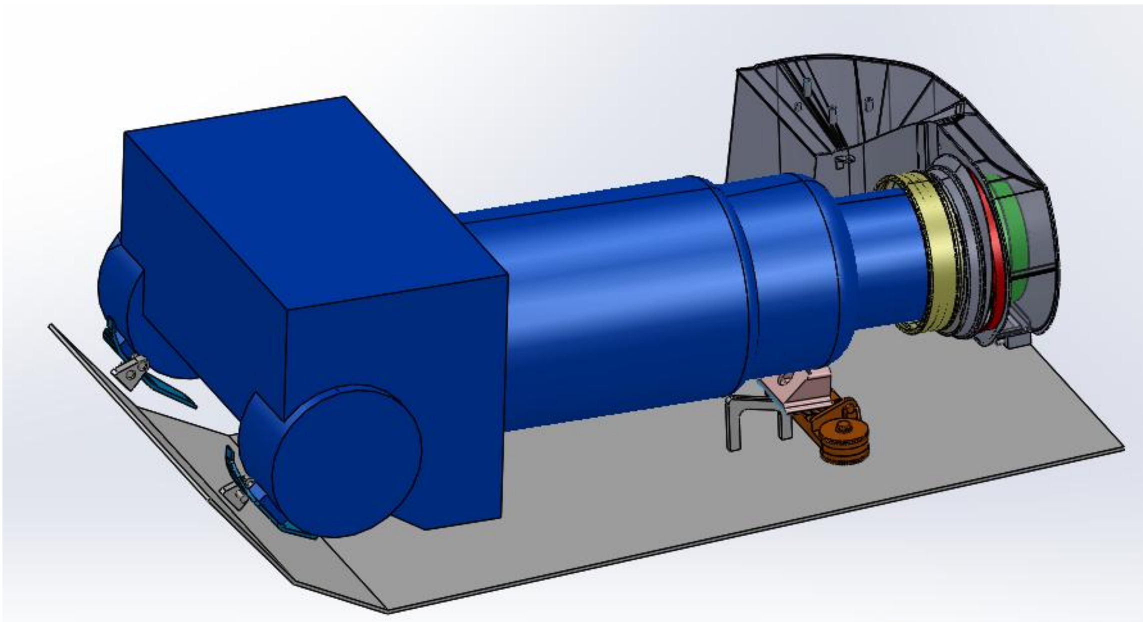


Figure 5: Assembly model of M1 Turbine and related components

These CAD models represent the nominal size of all the components. It is understood that the actual fielded components can vary from nominal sizes by the tolerances on the drawings. For Phase I, these tolerances were assumed to be rolled up into the misalignment numbers previously mentioned.

2.2 Trajectory

Once CAD models of all of the components were created, they were assembled so a trajectory for the seal could be developed. A CAD motion study was built with all of the interfacing components that guide the turbine into its fully seated position. With a working motion model, GLSV was able to trace the path that the seal takes as it mates with the plenum box. A plot of vertical vs. longitudinal motion (Figure 6) was taken from the CAD motion model for use in FEA-based simulations of the seal. This trajectory defines how the seal will interact with the air plenum box and it is important to note it is not a linear path. The vertical motion at the end of the path adds a level of complexity to the overall design.

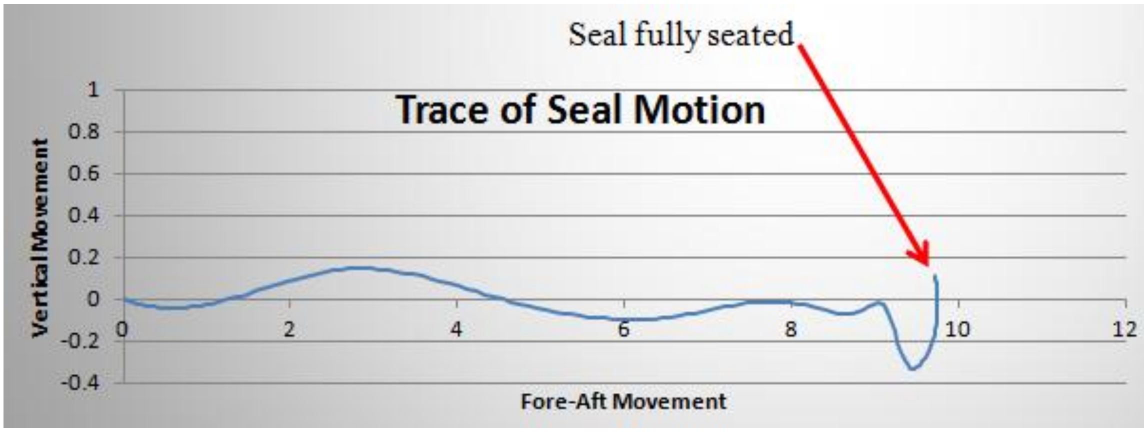


Figure 6: Plot of plenum seal trajectory taken from center point on rear face of current production seal.

There has been considerable disagreement about the actual trajectory. A video was provided that shows the general path, but it wasn't transferred to an X-Y graph. This path is also extremely dependent on the guide components and how close they are to the nominal size.

The Phase II effort would emphasize the importance of this relationship and the proposal will discuss how it will be evaluated. For Phase I, the nominal trajectory was used for the simulation.

2.3 Current Seal

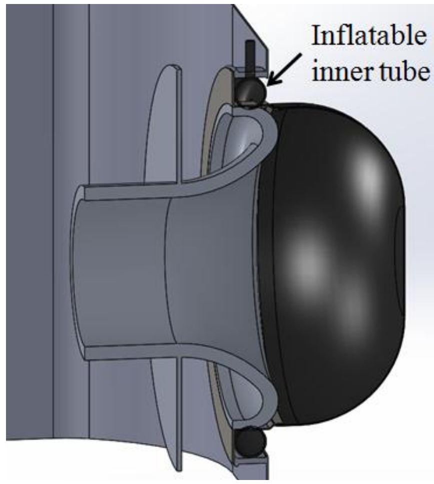
The current seal was modeled to help understand its specific construction as well as its potential short comings. This proved to be a time consuming task as the current seal is asymmetric with a varying cross section. Again, this was drawn in the nominal condition while the fielded seal runs closer to the smaller side of its tolerance range.

2.4 New Seal Design

For Phase I the intent was to develop several different seal designs and down select to the most promising variants. The new seal designs were modeled and compared to each other and to the current production seal. Phase II will be dedicated to refining the most promising designs and developing a final design for prototype and testing.

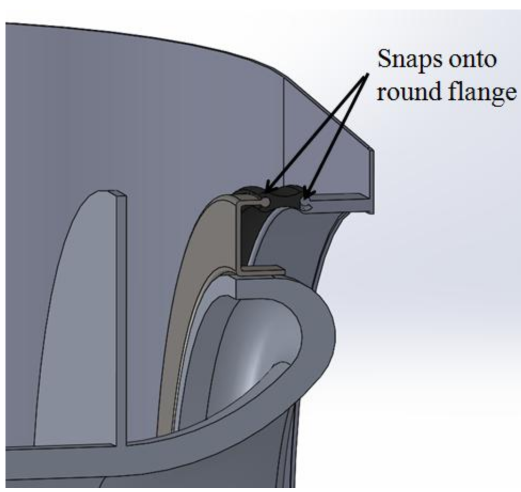
2.4.1 Inflatable

The inflatable seal works much like it sounds. After the turbine is installed, an inner tube is inflated until a positive seal between the intake and the plenum ring is established. A backing flange on the intake side would hold the inflated inner tube inside the plenum lip.



2.4.2 Zipper

A flexible strip of material between the plenum lip and a new flange on the inlet would create a leak proof seal. This would require a new, more direct trajectory of the seal into the plenum or some sort of final seal installation step to secure the seal onto the plenum lip.



2.4.3 V-Band

A flat, flexible seal would butt up to the plenum lip and be fastened securely in place with a v-band clamp. This would require access to the seal after installation to tighten the clamp.

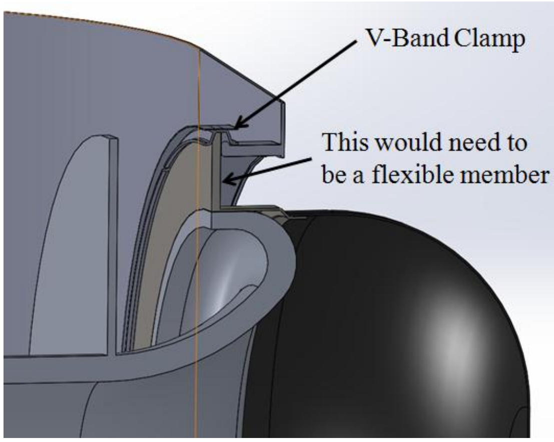


Figure 7: V-Band clamp seal concept

2.4.4 Cartridge

The cartridge clamp would work similar to the way the v-band clamp works. The top half of the clamp would be fixed to the plenum and the lower half would come in with the turbine and mate up with the top side and be bolted in place.

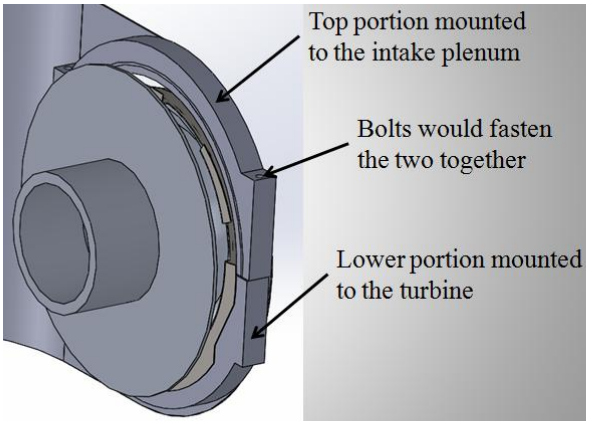


Figure 8: Cartridge clamp seal concept

2.4.5 Magnetic Flat Flange

This concept works much like the name implies. The magnetic flange would fasten itself to a magnet on the plenum upon installation of the turbine. The flexible membrane would absorb all of the motion during installation and operation so that the magnetic connection is never broken.

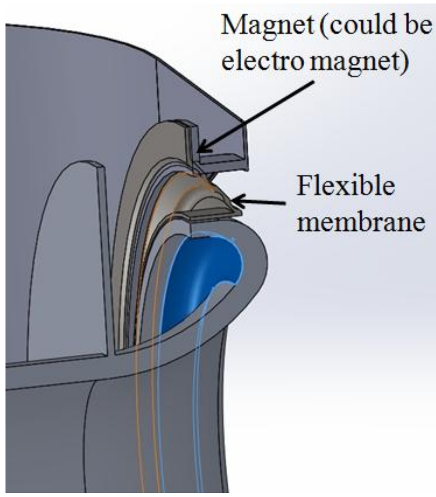


Figure 9: Magnetic flat flange seal concept

2.4.6 BNC (Twist Lock)

The BNC concept refers to a type of electrical connection that involves 2 pins that are received into a female connecter with helical grooves. While this initially appears to have great merit, it was realized early on that the complexity and cost would prevent this concept from being selected. Therefore, the time was not taken to develop a CAD model.

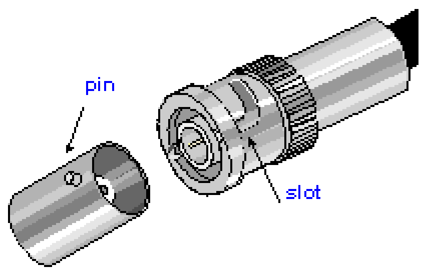


Figure 10: Example BNC connection

2.4.7 Spring Loaded Flap

The spring loaded flap is similar to the magnet design and in fact was the building block for the magnet concept. It would function in a similar way to the magnet except the seal would be made with a spring that once installed would have a "rip cord" that could be pulled to engage the spring. This was also not drawn in CAD as the design evolved quickly to the magnet seal.

2.4.8 Bulb Seal

Bulb seals come in a near infinite array of geometry and can be found in almost all common areas that require a leak proof seal. For example, the auto industry uses bulb seals almost exclusively for sealing the passenger compartment on vehicles, most common household appliances use bulb seals to seal the doors as in a refrigerator or freezer and many other applications. Figure 11 shows some examples of bulb cross sections.

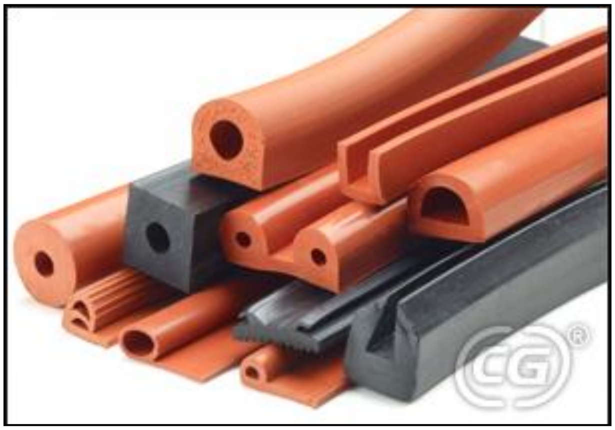


Figure 11: Common bulb seal profiles (www.customgasketmfg.com)

Figures 12 & 13 show the first 2 concepts which are rather simplistic and somewhat replicate the inflatable seal. The bulb seal attached to the air plenum box looks attractive, however it was determined that it would likely see abrasion from the FOD screen when it is installed thereby reducing the probability of success. It was then decided that attaching the seal to the turbine/FOD screen would be the best path forward.

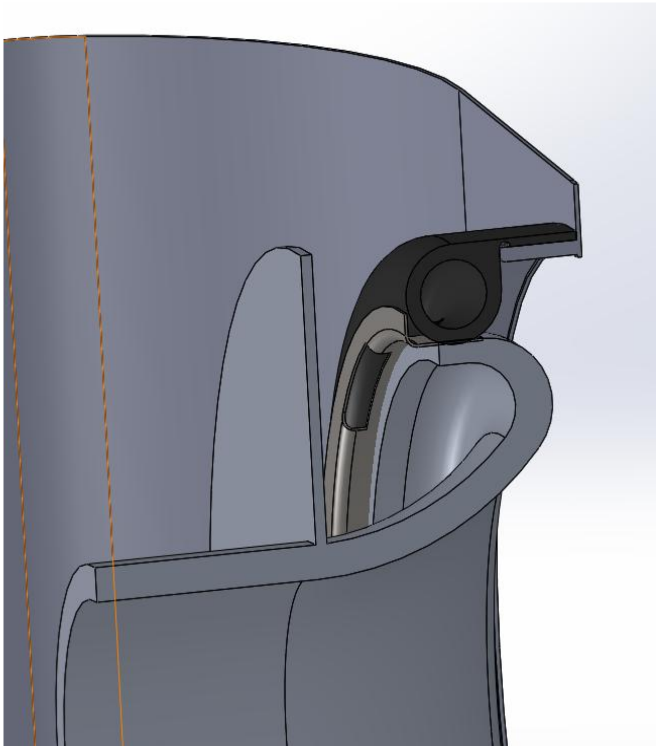


Figure 12: Bulb seal attached to plenum lip

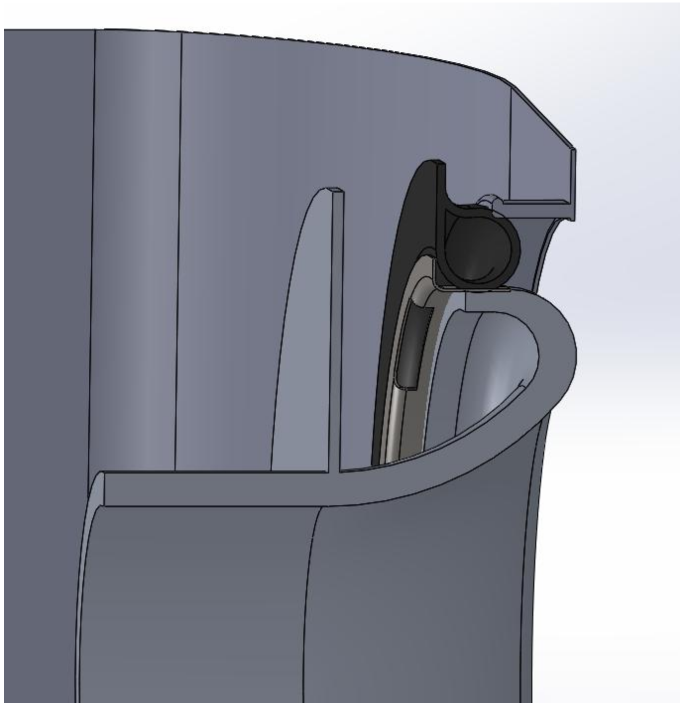


Figure 13: Bulb seal attached to turbine inlet

The final concept developed in Phase I is a hollow, C-shaped bulb fixed to the turbine inlet. As the turbine is installed the bulb wraps around the plenum lip creating the seal. A backing flange ensures that the bulb is pressed into the plenum lip with reasonable force. Figure 14 shows a vertical cross section through the center of the seal as it is about to contact the plenum lip.

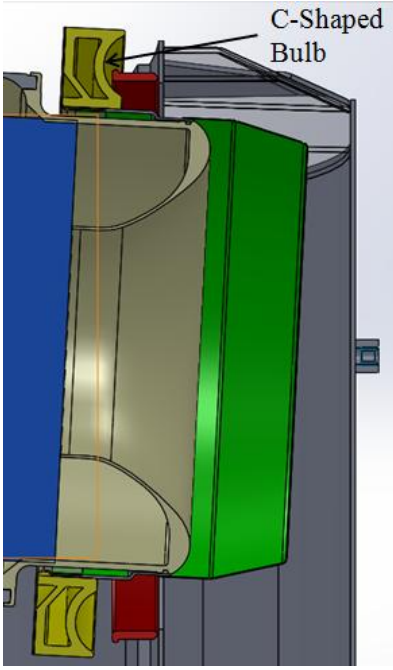


Figure 14: C-shaped bulb seal concept

3 Trade Studies

To down-select from the list of seal concepts that were created, GLSV used two trade studies. The first matrix compares the performance characteristics while the second compares various cost categories. These trade studies were necessary for ranking the concepts as well as comparing them to the current production seal.

3.1 Performance Decision Matrix

The following categories are weighted in order of importance and each concept is given a score of -1, 0 or 1. The current production seal is used as the baseline comparison so a score of -1 is worse than the current seal, 0 is equal, and 1 is better. A higher total score relates to higher predicted performance.

- Cost - The cost for the seal only
- FOD Intrusion - Ability of the seal to keep FOD out of the turbine
- Install Time - Time to install the seal only
- Install Complexity - Risk associated with installing the seal correctly
- Modifications to Plenum - Changes that need to be made to the plenum box in order to integrate the seal

- Modifications to FOD Screen - Changes that need to be made to the FOD screen in order to integrate the seal

- Risk of Failure - How catastrophic the failure mode would be

GLSV Seal Concepts	Cost	FOD Intrusion	Install Time	Install Complexity	Mod to Plenum	Mod to FOD Screen	Risk of Failure	Total
Weighting	2	6	4	3	5	1	7	
Current Seal	0	0	0	0	0	0	0	0
Inflatable	-1	1	0	0	0	-1	-1	-4
Zipper	-1	1	-1	-1	-1	-1	0	-9
V-Band	-1	1	-1	-1	-1	-1	1	-2
Cartridge	-1	1	-1	0	-1	-1	1	1
Flat Flange (magnet)	0	0	0	0	-1	-1	0	-6
BNC	-1	1	-1	-1	-1	-1	1	-2
Spring Loaded Flap	0	0	0	0	-1	-1	0	-6
Bulb Seal	0	1	0	0	0	-1	1	12

Table 1: Performance Decision Matrix

3.2 Cost Decision Matrix

The cost decision matrix follows the same format as the performance matrix.

- Tooling - The cost for tooling to produce the seal

- Raw Material - Cost of the raw material for one seal

- Install Time - Time to install the seal only (labor cost)

- Engine Rebuilds - The reduction of engine rebuilds due to a better seal

- Modification to Plenum - Cost of changes that need to be made to the plenum box to accommodate new seal

- Modification to FOD Screen - Cost of changes that need to be made to the FOD screen to accommodate new seal

- Increased Service Life - Cost savings associated with reduction in man hours spent servicing the turbine

GLSV Seal Concepts	Tooling	Raw Material	Install Time	Engine Rebuilds	Mod to Plenum	Mod to FOD Screen	Increased Service Life	Total
Weighting	4	1	5	7	3	2	6	
Current Seal	0	0	0	0	0	0	0	0
Inflatable	-1	0	-1	-1	0	-1	-1	-24
Zipper	0	-1	-1	-1	-1	-1	0	-18
V-Band	1	-1	-1	1	-1	-1	1	6
Cartridge	1	-1	-1	1	-1	-1	1	6
Flat Flange (magnet)	0	-1	0	0	-1	-1	0	-6
BNC	1	-1	-1	1	-1	-1	1	6
Spring Loaded Flap	0	0	0	0	-1	-1	0	-5
Bulb Seal	-1	0	1	1	0	-1	1	12

Table 2: Cost Decision Matrix

3.3 Trade Study Conclusions

The bulb seal is the highest ranked concept overall. It was the highest ranked in both trade studies individually as well. The results of these studies did not come as much of a surprise. The bulb seal is a very simple, efficient design and shows a lot of promise in the way of life cycle cost savings for the M1. GLSV chose to pursue the bulb seal concept further and used the remaining time during Phase I to improve the design and incorporate it into the simulations.

4 Simulation

Simulations were conducted on both the current seal and the bulb seal concept. The CAD models and the trajectory defined earlier were the building blocks for this task. Running FEA-based simulations with large deformation capabilities has enabled GLSV to see how each seal deflects when it contacts the air plenum box.

The simulations were carried out using the non-linear, large displacement capabilities of Altair Radioss, a finite element solver. The simulation model was set up in Hypermesh. A combination of solid, shell and rigid elements represent the physical geometry of the seal and plenum lip. The trajectory taken from the motion model was used to create a curve for imposing a displacement on the seal. This curve guides the seal into the plenum lip as if all associated components were nominally aligned. An interface between the seal and plenum lip was set up so that the contact between the two would cause the seal to deflect around the plenum lip. The plenum lip is fixed with rigid elements to simulate it being hard mounted in the vehicle.

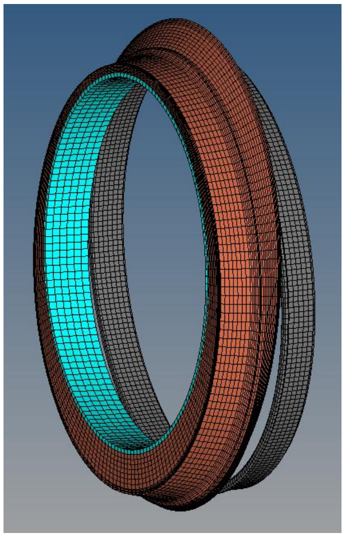


Figure 15: FEA model of the single clamp seal and plenum lip

A particularly challenging task was putting a mesh on the current production seal. The asymmetric and constantly changing profile of the seal made it difficult to apply a uniform mesh. The seal had to be divided up into small sections so an accurate and efficient mesh could be incrementally mapped along the geometry with brick elements. This was necessary for allowing the solver to run in a reasonable amount of time and to get realistic results.

Post-processing of the simulation was done in Hyperview. Stress contours on the seals can be observed to see where there might be potential for tearing or increased fatigue leading to shorter seal life. Contact force between the seal and the plenum lip was also taken from the simulation to evaluate what type of seal profile and material creates the most leak proof seal.

4.1 Current Production Single Clamp Seal

The current seal model was simulated to look at what is actually happening when contact is made with the plenum lip. The ability to zoom in and analyze critical sealing interfaces allows for full understanding of how the seal is behaving during the “blind” installation process. The simulation videos attached to this report show the seal following its installation trajectory starting at the point where it is about to contact the plenum lip and ending when the turbine is fully seated.

In order to run these and all subsequent simulations in a reasonable amount of time, only the seal and plenum lip are shown. It is important to realize that even though the turbine, turbine mounts and interfaces for installation aren’t shown, the path of the seal is still taken from the full motion model.

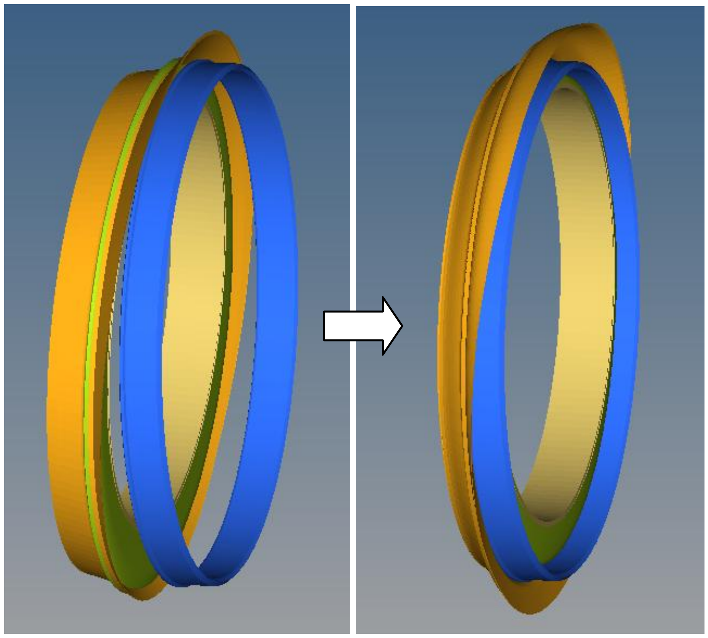


Figure 16: The start and end positions of the seal for all simulations

In Figure 16, the blue ring is the plenum lip, the orange part is the outer seal and the green is the inner seal. It is clear that the inner seal is passing through the outer seal. In practice this obviously does not happen, however, the behavior of each part as contact is made with the plenum lip is accurate. It is possible to add the interface between the inner and outer seal so the tucking of the inner seal prior to installation can be simulated. This task would have greatly increased the setup and run times of each simulation, reducing the total number of simulations conducted. For Phase I it made sense to keep the simulations simple but effective enough to illustrate the critical problem areas.

Figure 17 and Figure 18 show where some short comings of the current seal may be occurring. When the seal goes in at the maximum vertical or lateral misalignment tolerance, gaps between the seal and plenum lip can be seen. While the simulation is not perfect it illustrates the problem areas where FOD and/or water could be leaking into the turbine inlet.

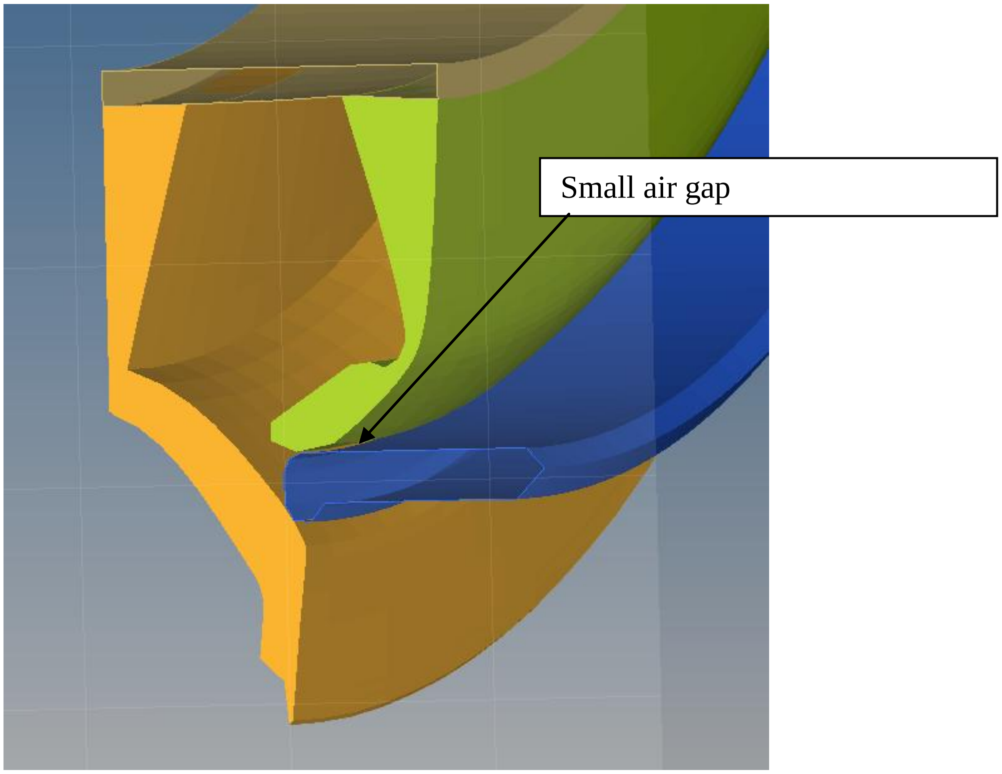


Figure 17: Section view, bottom of seal at max vertical misalignment; engine 1.01” higher than plenum.

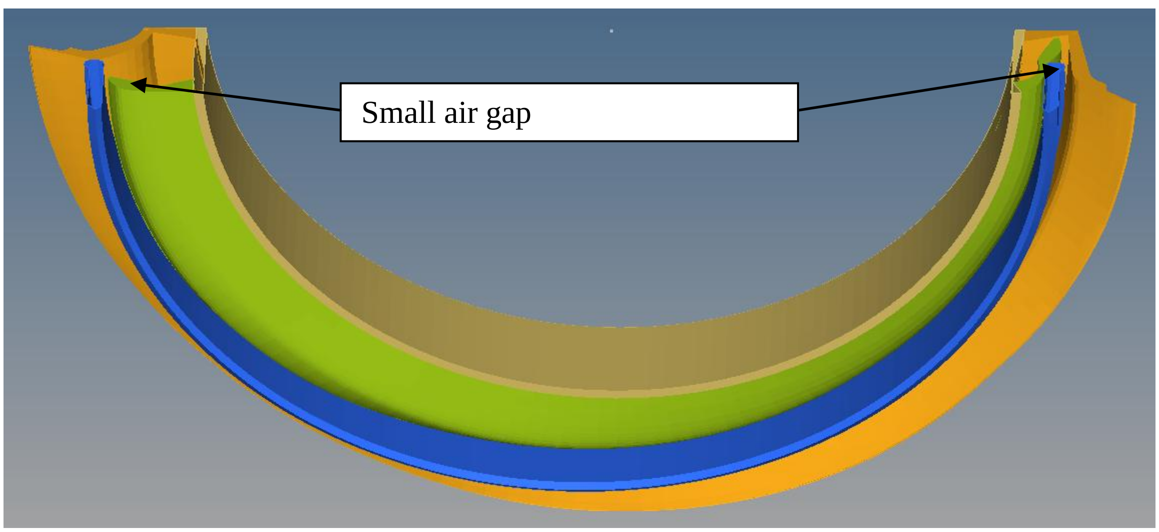


Figure 18: Section view, max lateral misalignment; engine .75" left of nominal alignment.

Figure 19 shows a detailed view of the seal behavior on the right side of the plenum when the engine is misaligned to the left. The outer flap ends up folding back when it is expected to be wrapping around the plenum lip. A very important part of continuing this effort would be to simulate all combinations of turbine to plenum box misalignment and identify these types of issues.

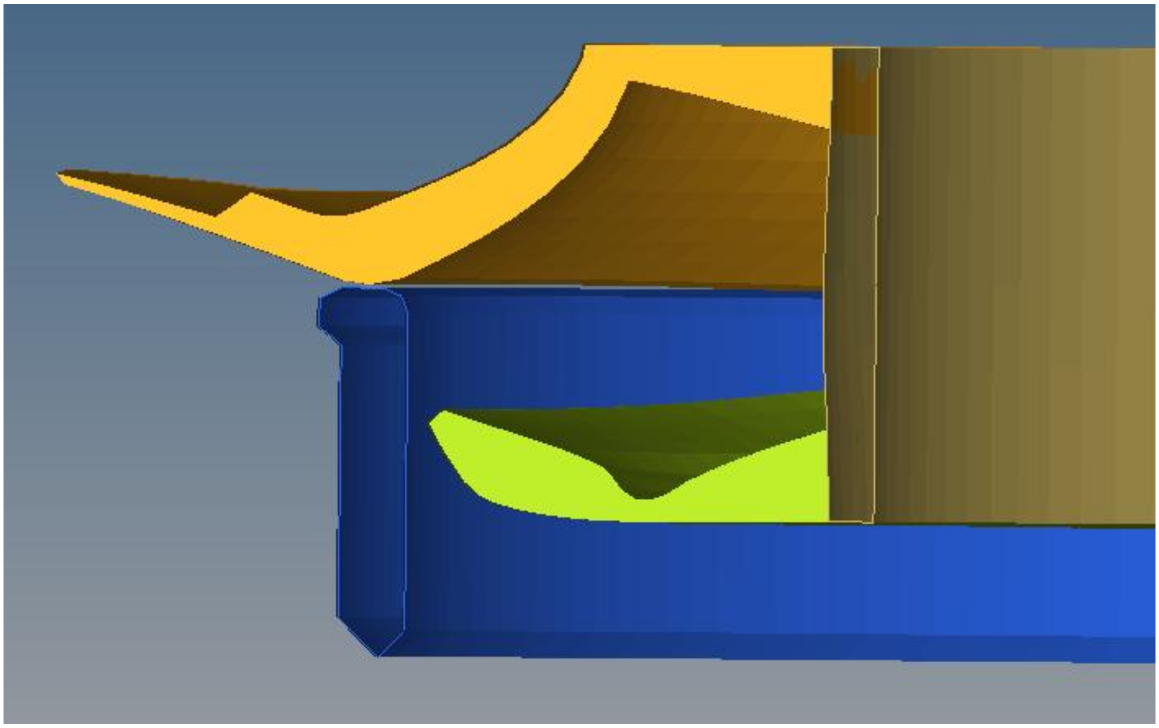


Figure 19: Right side (curb side) of seal to plenum interface

Figures 20 and 21 show stress contour plots of the plenum lip and the seal after it is fully seated. Although there is no history of the seal failing due to weaknesses in the material, this will be a very useful aid in designing the new seal. Failure modes resulting from high stress in the seal material can be identified early on and remedied before the design is complete. Figure 22 shows a contour plot of the pressures seen on the seal and plenum lip. The plenum lip and inner diameter of the seal were created with shell elements to simplify the simulation. They represent the actual geometry and behavior of the components and part of the Phase II effort would be to simulate these parts with a full, solid mesh so that stress and pressure results are as accurate as possible.

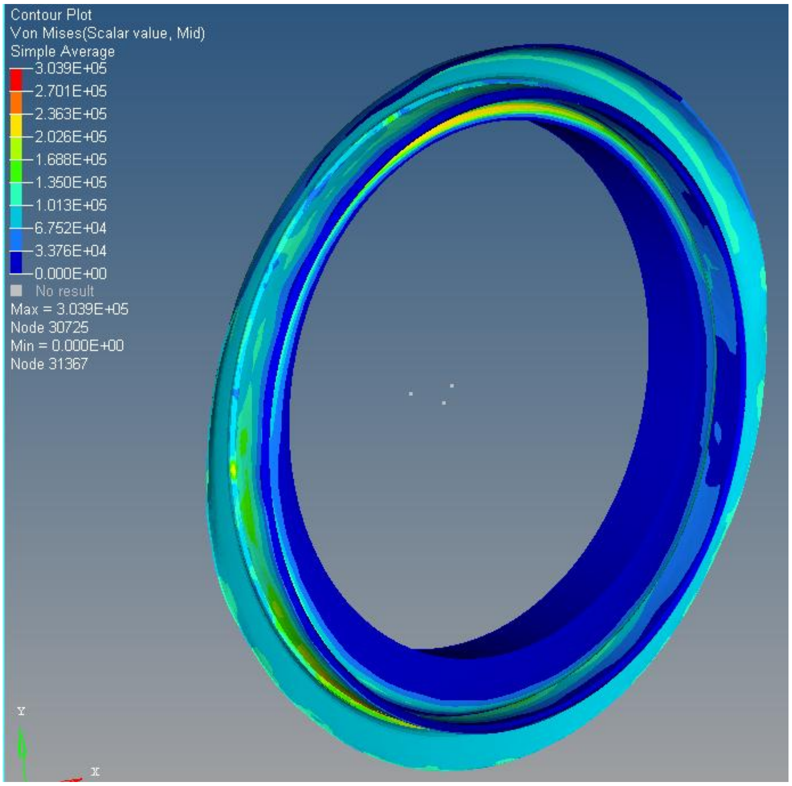


Figure 20: Stress contour plot of current, single clamp seal and plenum lip

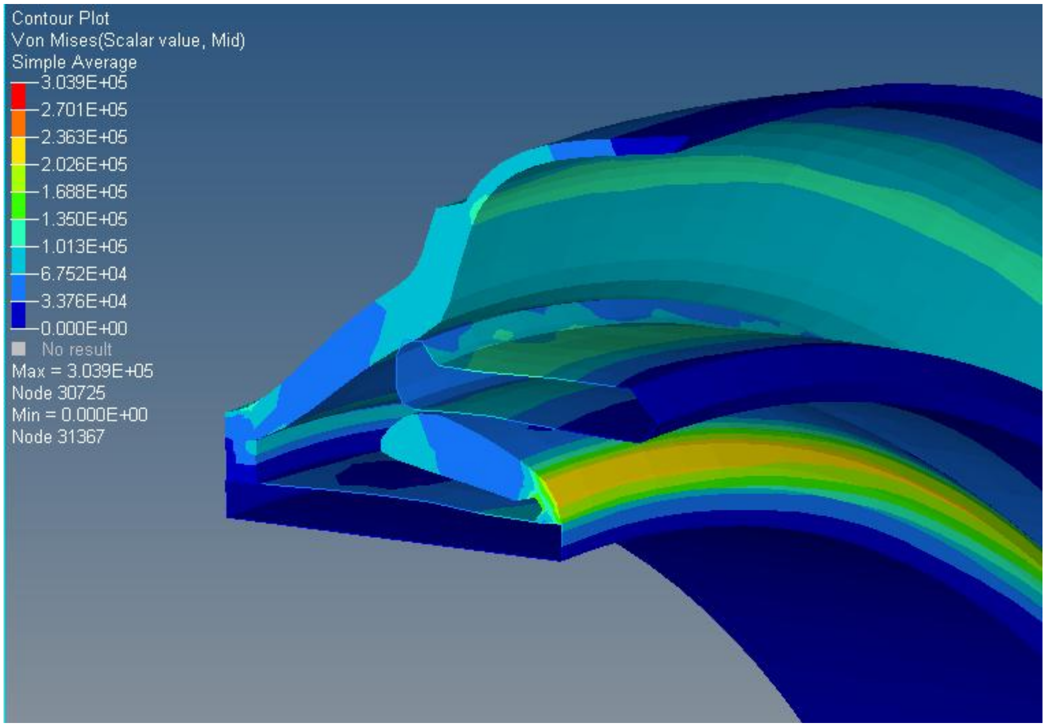


Figure 21: Stress contour plot through cross section near the top of the current, single clamp seal

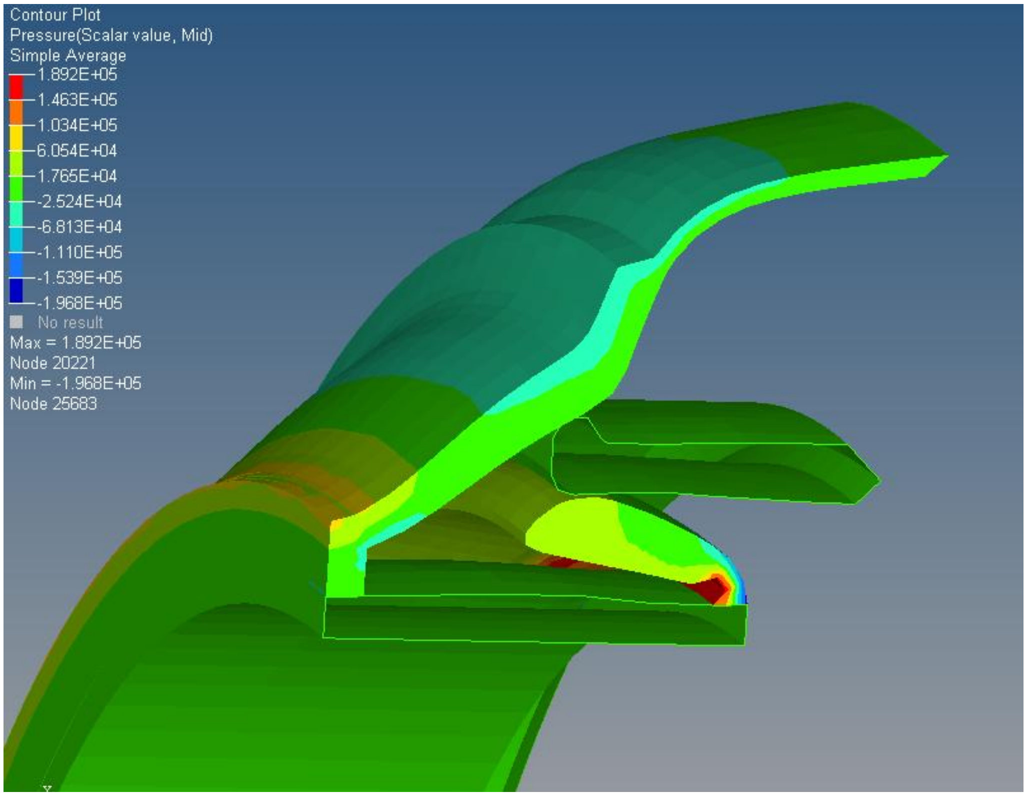


Figure 22: Pressure contour plot through cross section near the top of the current, single clamp seal

4.2 Initial Bulb Seal Concept

The bulb seal concept was put through the same type of simulation as the current production seal. The simulation videos attached to this report show the seal following the same trajectory as the current production seal. GLSV feels the simulation capability will be a great tool for evaluating seal design iterations. Changes in the bulb profile and materials can be easily incorporated and simulated to see their effects on seal performance.

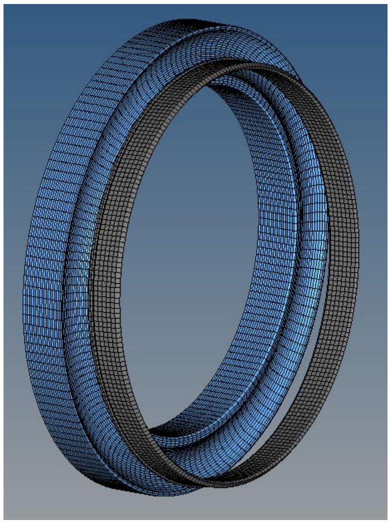


Figure 23: FEA model of the bulb seal concept

The available outputs mentioned at the beginning of this section will help keep the design efforts on target for developing a more efficient, leak proof seal in Phase II. Figure 24 shows the initial bulb seal concept seated on the plenum lip at nominal turbine alignment.

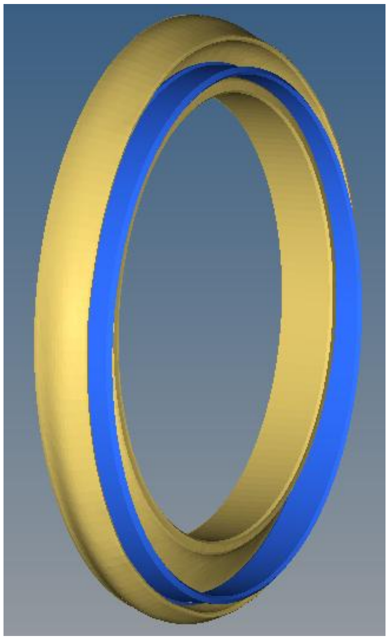


Figure 24: C-Shaped bulb concept seated on plenum lip

The following figures are taken from the bulb seal simulation with the seal installed at nominal alignment. The contour plots were done in the same way they were done on the current seal, providing a useful comparison of seal behavior.

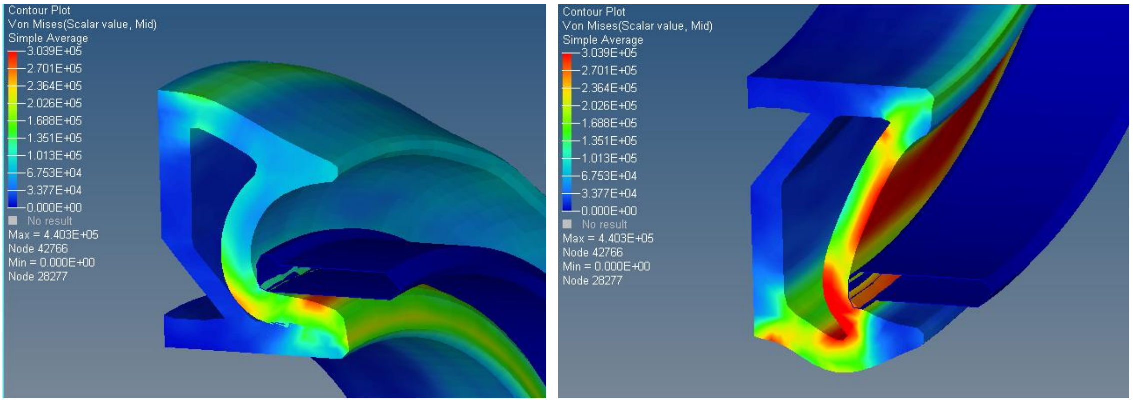


Figure 25: Cross section through top (left frame) and bottom (right frame) of bulb seal concept

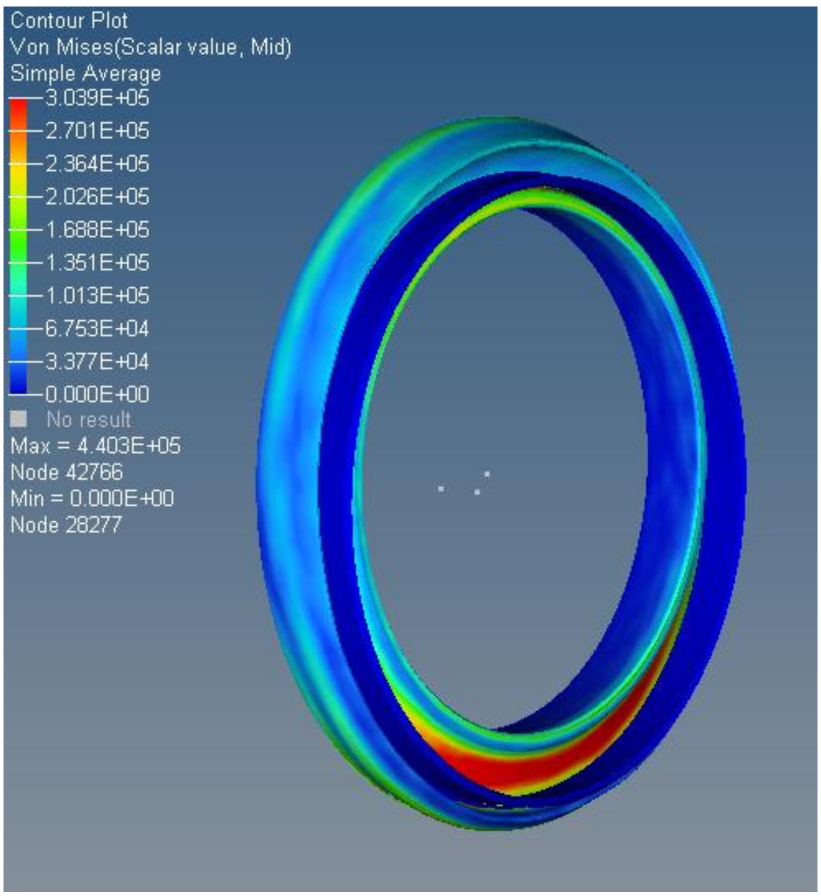


Figure 26: Stress contour plot of bulb seal fully installed

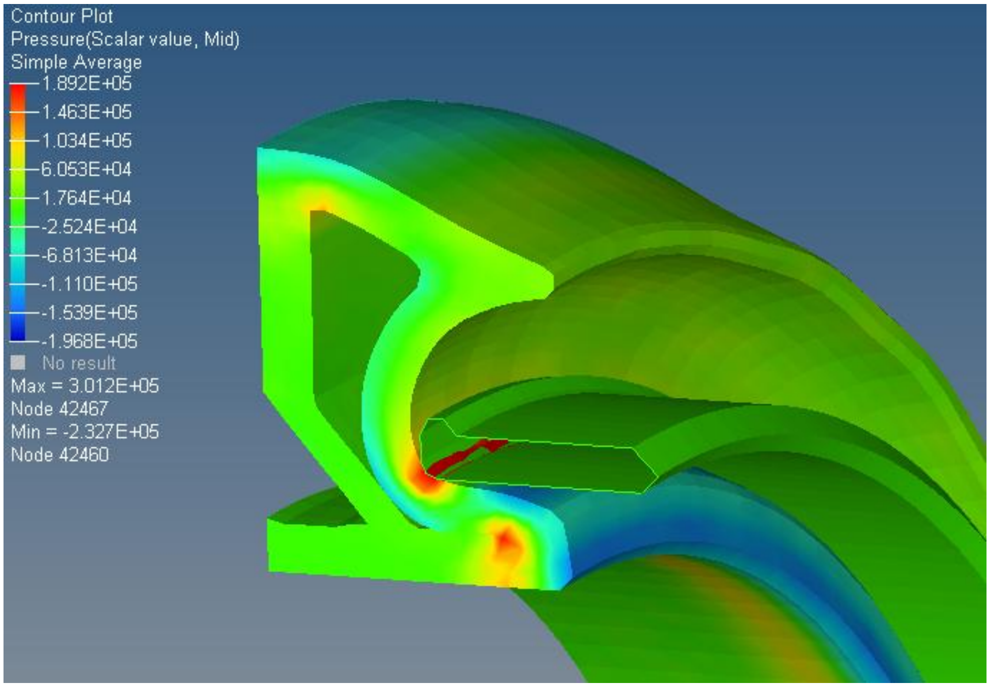


Figure 27: Pressure contour plot near the top of the bulb seal

It can be seen that there are some very high stress areas in the bulb seal. It must be noted that this is an initial concept and future efforts will be required to produce many design iterations to bring down stress levels in the material and raise the pressure applied by the seal on the plenum lip. The results shown here in Phase I are a good example of what can be done with the simulation but don't necessarily show optimized results.

The planned effort for Phase II would include expanding on all levels of this simulation. Areas for refinement include

- Refining the mesh on the seal and plenum lip
  - This would provide better accuracy on the stress and pressure contours and surface contacts between the seal and plenum lip
- Incorporating actual rubber manufacturer's material specs including friction coefficients
- Creating various misalignments that follow the tolerances for all associated components
  - This will allow GLSV to verify seal performance at any turbine to plenum misalignment

5 Materials

A brief study was conducted on different materials commonly used in seal applications. The current seal material is fluorosilicone rubber impregnated with plies of aramid fabric. There is a high likelihood the new seal will be of the same material due to its superior resistance to heat and ability to resist certain chemicals per military standards. This material hasn't been shown to be the source of any issues with the current seal, thus making it a proven and logical choice. Table 3 shows a comparison of some common materials used in various sealing applications. Durometer selection as well as reinforcement and additives may prove to be an important material development activity during Phase II. This provides an opportunity to affect material modulus and friction, which the simulations indicate are important design parameters of an improved seal design. Candidate material formulations should be characterized experimentally for development of an FEA material model as well as chemical compatibility testing during Phase II.

1-Poor 3-Fair 5-Good 7-Excellent	Abrasion Resistance	Acid Resistance	Chemical Resistance	Cold Resistance	Dynamic Properties	Electrical Properties	Flame Resistance	Heat Resistance	Impermeability	Oil Resistance	Ozone Resistance	Set Resistance	Tear Resistance	Tensile Strength	Water/Steam Resistance	Weather Resistance	Total Score
AFLAS (TFE/Prop)	4	7	7	1	5	7	7	7	5	7	7	5	2	4	6	7	88
Butadiene	7	4	4	5	3	5	1	3	3	1	1	5	6	7	4	3	62
Butyl	4	5	7	5	3	5	1	5	7	1	6	4	5	5	5	6	74
Chlorinated Polyethylene	5	3	4	2	5	5	6	5	5	4	7	3	4	5	3	7	73
Chlorosulfonated Polyethylene	5	5	7	4	3	3	5	5	5	3	7	3	5	3	3	7	73
Epichlorohydrin	5	4	5	6	5	3	4	4	6	7	7	2	5	5	3	7	78
Ethylene Acrylic	3	3	4	5	3	3	1	7	7	3	7	5	3	5	2	7	68
Ethylene Propylene	6	5	7	6	6	5	1	7	5	1	7	6	6	6	7	7	88
Fluorocarbon	5	7	7	4	6	3	7	7	5	7	7	6	3	6	4	7	91
Fluorosilicone	4	6	7	6	1	7	5	7	1	7	7	6	3	4	7	7	85
Isoprene	7	4	4	5	3	5	1	3	3	1	1	5	6	7	4	3	62
Natural rubber	7	4	4	5	7	5	1	3	3	1	1	5	6	7	4	3	66
Neoprene	5	4	4	4	3	3	5	5	5	4	6	3	4	5	3	7	70
HNBR	5	7	4	5	6	3	1	7	5	7	5	6	4	7	7	5	84
Nitrile or Buna N	5	3	4	5	6	3	1	5	5	7	1	6	4	6	4	3	68
Perfluorinated Fluoroelastomer	1	7	7	2	3	7	7	7	5	7	7	5	2	4	6	7	84
Polyacrylate	5	1	1	1	3	3	1	7	7	7	7	3	4	3	1	7	61
Polysulfide	1	1	5	5	3	3	1	1	7	7	7	1	1	3	3	7	56
Polyurethane	7	1	4	5	7	4	1	3	5	5	7	3	6	7	1	7	73
SBR or BunaS	5	3	4	5	5	5	1	4	3	1	1	5	4	6	4	3	59
Silicone	1	4	6	7	1	7	3	7	1	4	7	6	1	1	3	7	66

Table 3: Material Decision Matrix

6 Conclusions

Several different designs were presented and the bulb style seal proved to be the most effective based on the trade studies. This seal was then simulated to show its performance with the derived trajectory which is based on the drawings provided. Different misalignments, which were based on information discovered in the literature review, were also investigated. Trajectory and misalignments will be further analyzed in phase II to optimize seal shape and material which will enhance the performance and robustness of the seal.

While the proposed seal design proved to be effective in the given CAD geometry, it has been suggested that the actual fielded hardware is at the edge of the tolerance zone or in fact out of tolerance in some cases. This is one of the focal points for Phase II.

The main takeaway from Phase I is the ability to design a seal, create a CAD model and then run a simulation which follows the correct trajectory and shows how the seal deflects. Not only does it provide a complete understanding of the complex interactions of the plenum seal and the air plenum box but it reduces the number of costly prototypes down to one seal that has a very high likelihood of success. The actual performance of the new seal should match closely to the predicted performance due to the fact that full FEA simulations were used to analyze all aspects of the sealing process.

7 Path Forward

A Phase II proposal has been developed which details the tasks needed to achieve a realizable seal design. The main focus of the proposal relies on the ability to understand the dimensional stack-up of all the components, both in the drawings and in the field. This information is critical to accurately simulating the new designs and ultimately creating an efficient, leak proof plenum seal. M1 life cycle cost savings to the government will also be realized at the successful completion of Phase II.

A seal will then be designed to absorb the new misalignment specification. It is anticipated that this will take many iterations to narrow in on the final design. The performance will be evaluated in 3 different ways. Prior to prototype manufacturing, simulation will verify the sealing ability and stress levels in the objective seal. Several prototypes will be made and then tested in an apparatus that closely represents the geometry and trajectory of the vehicle.

The final step will be to install the seal into an actual tank and verify its performance on a test track and fording pit. This will only be done after conclusive evidence is provided from the mock up tests detailing the success of the seal. Other performance metrics include the ease of manufacturing and installation as compared to the current seal. M1 life cycle cost savings to the government will also be realized at the completion of Phase II.

8 Bibliography

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