Design and Material Analysis of O-ring Seals Within a Collapsible Cup for Hot and Cold Beverages

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1. BACKGROUND AND SIGNIFICANCE

1.1. Background

Within the United States alone, approximately 50 billion paper coffee cups are thrown away each year. From each lone individual who buys just one cup of coffee or tea per day for one year, there are about 23 pounds of waste produced solely due to the disposable cup [1]. According to Starbucks, each one of their paper coffee cups is responsible for a carbon footprint of approximately 0.24 pounds of carbon dioxide emissions [2]. Combining that with the 20 million trees that are cut down each year to manufacture those cups, single use coffee cups are responsible for a significant impact on the environment around us [3,4]. In an effort to help reduce the amount of CO_2 emissions that are produced from non-reusable cups every year while also promoting how simple it can be to introduce and implement a reusable cup into everyday life, a collapsible and reusable cup has been designed. As a main part of that design, several O-rings will be added to create a leak-proof dynamic seal for the liquid contained inside. This literature review will dive into the research and testing of O-ring technology, reliability, and material analysis and how each can be applied to the collapsible cup design.

1.2. Impacts of Collapsible Cup for Hot and Cold Beverages

There are currently thousands of reusable coffee cups on the market ranging from small to large, handle to no handle, or even the duration each cup is able to keep a drink hot or cold. Several large coffee shops are even promoting the use of reusable cups by selling these items within their stores, offering discounts to those who bring their own cup, and even going as far as no longer providing disposable cups to customers. However a common issue when trying to promote the use of reusable cups is that many customers find that they are often inconvenient to carry around due to bulkiness and awkward shape [5]. By implementing the collapsible cup design, users are able to quickly and easily collapse the cup when not in use or extend in order to house their hot or cold beverages. As a main concern of the collapsible cup, O-rings will be added in order to create an impermeable and closed off seal. According to Blum et al. who designed the collapsible cup and found that through the addition of O-rings, a tight leak-proof seal will be created to prevent any leakage from occurring [6]. In doing so, users will have the ability to bring their cup with them everywhere due to its foldable design, making it suitable for pockets, purses, backpacks, and even wallets.

1.3. O-Ring Seal Reliability

The primary concern with the design and implementation of O-rings in the collapsible cup design is ensuring that they not only create a reliable leak-proof seal while in the extended position, but are also able to avoid failure at an early onset. There are numerous properties that may lead to the failure of an O-ring altogether, but the two main factors determined by Liao et al. consist of the deterioration of material as well as random, or inconsistent, loads being applied which increase stresses on the seal material [7]. As time goes on the O-ring, which is most often made of rubber, will begin to degrade resulting in increased compressive stresses and ultimately material failure. A simulation was performed in ABAQUS to examine how these factors affect the overall degradation of the O-ring, utilizing the Mooney-Rivlin model for hyperelastic materials [8]. As expected, the variation in the applied load produces substantial deterioration for the O-ring which could result in an insufficient seal [7]. In order to avoid accelerated failure, two separate studies correlated that if O-rings are placed snugly within the inner surfaces of grooves, there is an increase in contact pressure between the surfaces [9,10]. Taking into account that the O-ring's surfaces must maintain a tight fit within the inner and outer surfaces of the groove as the pressure increases, this will result in higher contact pressure which decreases the opportunity for any leakage to occur [11]. With rubber being a highly elastic material, it will naturally squish as it is being compressed. As long as the proper size of the O-ring is selected, it will be able to fill the entire groove surface area. When the collapsible cup is placed into the extended position, the amount of compression on the O-ring will increase which will result in increased sealing performance due to maximum contact pressure.

In another study performed, Kommling et al. discovered that although O-rings begin to degrade substantially over time, they are still able to remain leak-proof if placed under static conditions [12]. This was verified when an experiment was performed on two different types of rubber, hydrogenated nitrile butadiene rubber (HNBR) and ethylene propylene diene monomer (EPDM). This study was performed in order to determine how long each material would be able to withstand temperatures of 125℃ and 150℃ in a compressed state [12]. The first sign of leakage began to appear approximately 1.5 years after the start of the study, even after material degradation had already begun to take place [12]. Although both of these temperatures are much higher than the average temperature of consumable hot beverages, it is important to note that the O-ring was able to resist such heat. By maintaining a certain compressed position which prevented any increase in material degradation to occur, the seal was able to prevent any significant leakage. However in order to continue safe operation, any O-rings should be replaced prior to this in order to avoid possible leakage that may occur due to vibration, heating, or cooling [13].

1.4. O-Ring Analysis with Varying Material Properties

With there being many options for the types of material that are currently being used for O-rings, it is important to look at the two most common types - metal and elastomer [14]. With the elastomer O-rings not only being very simple but also being very low cost to manufacture, they have become very prevalent in the current market [14]. Additionally, they possess exceptional elastic properties which allow them to easily produce a leak-tight seal. However one of the main drawbacks of rubber are the impacts that aging, load changes, and exterior factors have on the elasticity of the material [15]. Even while being extremely resilient, these factors will begin to break down the rubber material as it continues to age. Liang et al. developed a model to study the sealing performance of an O-ring in a cylinder application and determined that since there could be errors in the machining process of the cylinder, the condensing of the O-ring is not consistent each time the cylinder opened and closed [15]. In this case, the compression of the O-ring is not a constant value but more a random arbitrary variable, similar to the case of the collapsible cup. The different force that will be applied varies from user to user depending on how often they open and close the cup, along with how forcefully they do so. Referring back to the cylinder model, as the inner diameter of the cylinder varies due to inaccurate manufacturing processes, the maximum compressive stress as well as the stress distribution of the O-ring will change [15]. Along with that, the chosen rubber material can have an influence on the overall reliability of the seal due to its material, shape, and load restrictions. Similar to the manufacturing errors produced in the cylinder, the O-ring's material properties may not be constant which increases randomness, affecting the reliability performance of the seal. Even with these varying factors, the elastomer O-ring is still considered to be one of the most viable options due to its compelling ability to create a strong leak-proof seal, the ultimate goal for the collapsible cup.

The second most common type of material used for O-rings is metal. Metal O-rings are most often implemented for high temperature, high pressure, and superconductive uses [16]. In addition to that, they also exhibit greater corrosion resistant capabilities [17]. However, one of the most common setbacks is the rigid structure of the O-ring [18]. In order to improve the elasticity, Kim et al. discovered that by elongating the y-direction of a typical O-ring, made of Inconel 718, while also adding variable thickness, they were able to achieve 31% more elastic energy than typical metal O-rings in experimental and finite element tests [14]. In spite of the increased elastic energy, having limited contact pressure between the metal O-ring and the mounting surface presents its own challenges for seal reliability. However, through this study, it was found that this newfound design will be able to withstand extreme conditions for extended periods of time, making it a huge contender for new market solutions such as the collapsible cup.

1.5. Significance

As carbon emissions continue to rise in the world today, our goal as a population should be to increase carbon neutrality. The first step towards reaching this goal could simply involve introducing this newly designed and innovative collapsible cup which has the potential to keep a beverage hot or cold for 2 hours, while also keeping it tightly sealed inside for safe transport through the implementation of multiple O-rings. Through the references provided within this literature review, O-rings are found to be the most practical option due to their elasticity and resilience over extended periods of time. Along with that, there have been many studies conducted that prove O-rings are the superlative option when it comes to reliable sealing performance. As research on O-ring's continues to develop, determining the most suitable shape and material to increase seal accuracy within the collapsible cup is at the forefront. In promoting this concept, we are each doing our part to preserve the environment and work towards environmental sustainability.

2. OBJECTIVE

The objective of this project is to design and test multiple O-ring seals, all being comprised of varying elastomeric materials, to determine which exhibits the greatest sealing behavior and resistance to excessive deformation while meeting size requirements as defined by the collapsible cup design. A prototype of the collapsible cup will then be built to test the leak tightness of the seals as well as confirm the functionality of the current design of the cup.

3. METHODOLOGY

In order to successfully design, test, and manufacture the collapsible cup, several engineering theories will be applied. The main theory that will be utilized within the finite element analysis process will be the Mooney-Rivlin model. This model aids in simulating the mechanical behaviors of hyperelastic materials, specifically within small to medium strain applications. With rubber O-rings being selected as the primary option for the collapsible cup design, the computational simulation must be performed with the Mooney-Rivlin model applied in order to accurately model the elastic behavior of the rubber as loads are applied. This simulation will also help to demonstrate where the O-ring is experiencing the greatest amount of stress as well as indicate that the material will not tear or yield under applied loads. A laboratory experiment will also be performed once the body of the collapsible cup is built to verify the leak proof seal as provided by the O-rings. This experiment will be used as a final verification step in order to determine that the O-ring selected is the most suitable option for the collapsible cup design.

3.1. FEA Simulation of an O-ring within the Collapsible Cup Design

As a preliminary study, a finite element analysis simulation was performed in order to determine how an O-ring would react to external forces being applied as the cup is transformed into its expanded position. As shown in Figure 1 below, there are four levels to the collapsible cup design. At the upper portion of each level, there is an elastomeric O-ring which is housed within a groove. As the cup is expanded, the inner surface of the upper level pushes on the lower level's O-ring which then drives the O-ring to compress within the groove. As the O-ring is compressed, a leak-proof dynamic seal is then created between the lower and upper level of the collapsible cup.

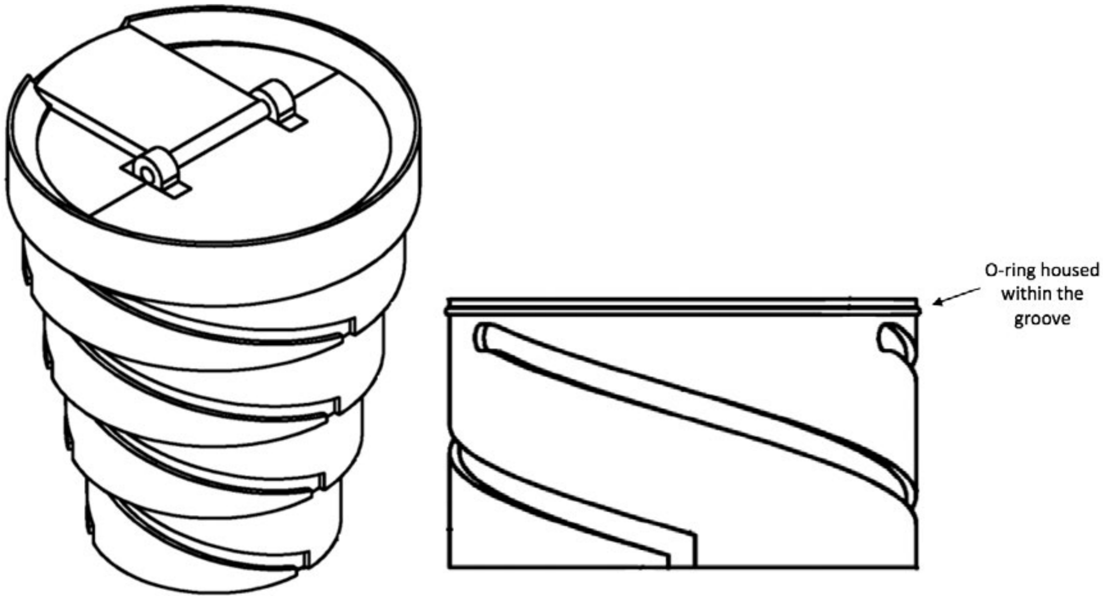

Figure 1: Collapsible cup design which consists of four collapsible levels and one lid [6]. The O-ring is housed within a groove, allowing the upper level to slide down and compress the O-ring which helps to create the seal between the two levels.

In performing this FEA analysis, the displacement of the O-ring as well as the von Mises stresses were calculated using a nonlinear static analysis within SOLIDWORKS (Dassault Systemes, Waltham, Massachusetts, USA). This study has helped to define whether or not the current design of the cup is suitable for O-ring fitment and compression once the upper level is lowered onto the lower level. As shown in the figures below, although this specific O-ring does successfully compress within the groove, it does not completely fill the entirety of the groove space which proves that it may not be the best solution for the current design of the collapsible cup. Thus, the design of the collapsible cup may need to be modified to ensure proper fitment of O-ring seals, such as implementing a more rounded groove. In this solution, an O-ring comprised of FDA silicone rubber with dimensions of $3\frac{1}{2}"\ ID\ x\ 3"OD\ x\ \frac{1}{16}"\ CS$ was used with a durometer measurement of 70 Shore A. As the final design of the collapsible cup is confirmed and the O-ring selection is narrowed, this will allow for more studies to be performed to determine exactly how the model responds to other O-ring sizes as well as durometer hardness. Along with that, this preliminary design study has helped to define whether or not the current design of the collapsible cup should be adjusted so that the O-ring has a greater chance of correctly compressing into the groove.

Due to rubber having a highly nonlinear relationship between stress and strain, it was determined that a nonlinear study would exhibit the behavior of the material most effectively. Since the cup has rotational symmetry, a two degree cross-section of the cup was used to simulate how the O-ring would compress. The O-ring seal was modeled using the Mooney-Rivlin hyperelastic material with a Poisson's ratio of 0.4995, simulating silicone rubber. The Mooney-Rivlin model was selected due to its ability to model the mechanical behaviors of hyperelastic materials, specifically with small to medium strain applications [19]. Both the groove and outer level were modeled using polypropylene plastic, a common material currently used for reusable coffee cups. The groove housing was fixed to replicate the motion of an individual expanding the cup and their hand holding the bottom level stable. The upper level was directed downward in order to simulate the cup being expanded and the two surfaces coming together, ultimately propelling the O-ring into the groove. A fine mesh was selected with high-quality elements in order to ensure a high level of accuracy and more precise solution.

3.2. Displacement Results

As the surface of the upper level is lowered onto the top surface of the O-ring, the O-ring is compressed into the groove located on the lower level of the collapsible cup design. Figure 2 below demonstrates how the O-ring sits when the cup is placed in the collapsible position, with there being a large gap between the inner and outer surfaces of the levels. As the upper level is forced downward onto the O-ring, the O-ring becomes compressed into the groove. The maximum displacement was found to be 1.001mm, located at the upper edge of the O-ring which can be seen in the URES, or static displacement plot, shown in Figure 3. In determining the displacement, it is found that the O-ring experienced the greatest amount of displacement at the top surface. This result proves to be accurate because as the top surface is moved in a downward direction, the upper surface of the O-ring will be the portion that does in fact move the greatest distance. This plot was helpful in understanding how the O-ring compresses as the upper level's inner surface meets the outer surface of the lower level. If the O-ring selected were too large, the two surfaces would not meet which would not allow for a leak-tight seal to be created. When probing a node on the outside surface of the rubber sealing ring and graphing its displacement versus the total integration time as shown in Figure 4, a nonlinear response of the rubber is observed.

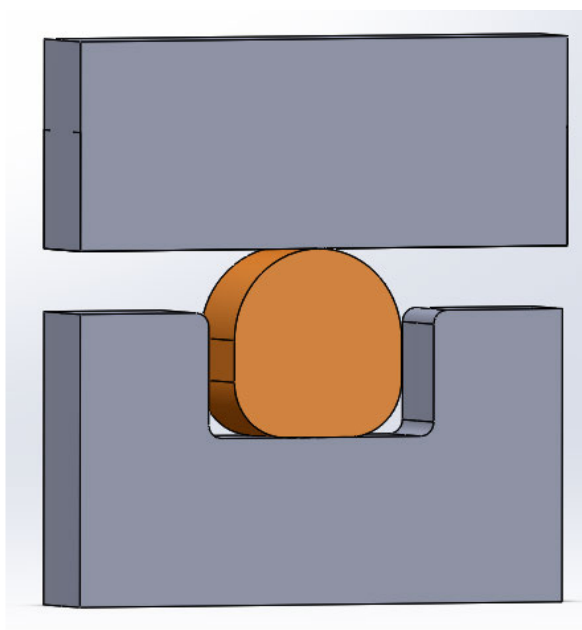

Figure 2: Cross-section displaying the O-ring's placement within the groove of the lower level.

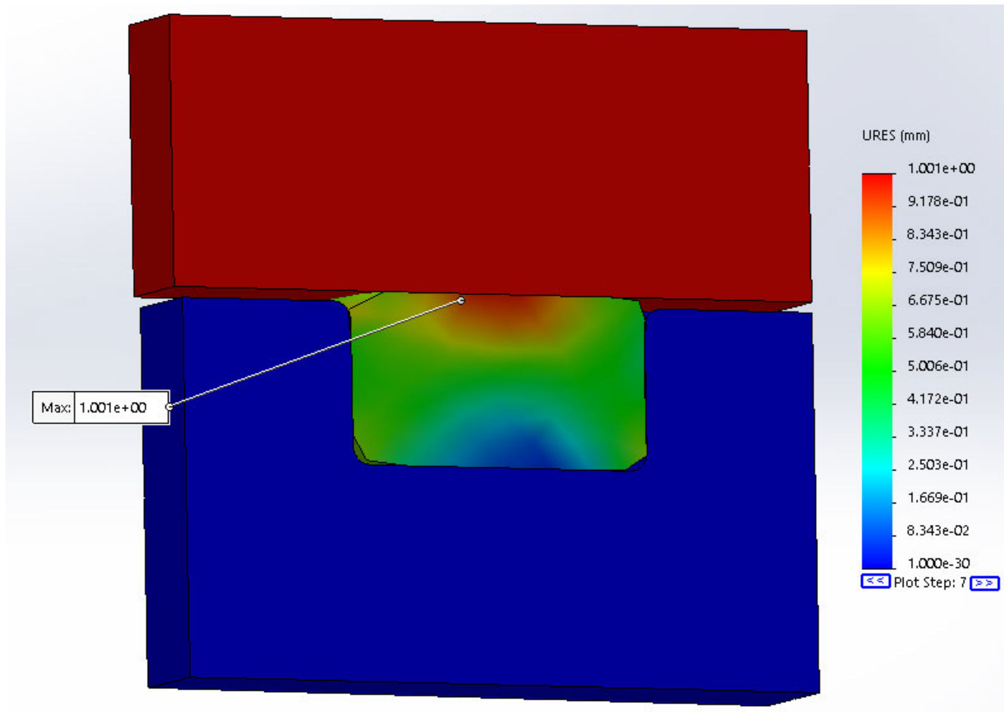

Figure 3: URES (static displacement) analysis results of the O-ring.

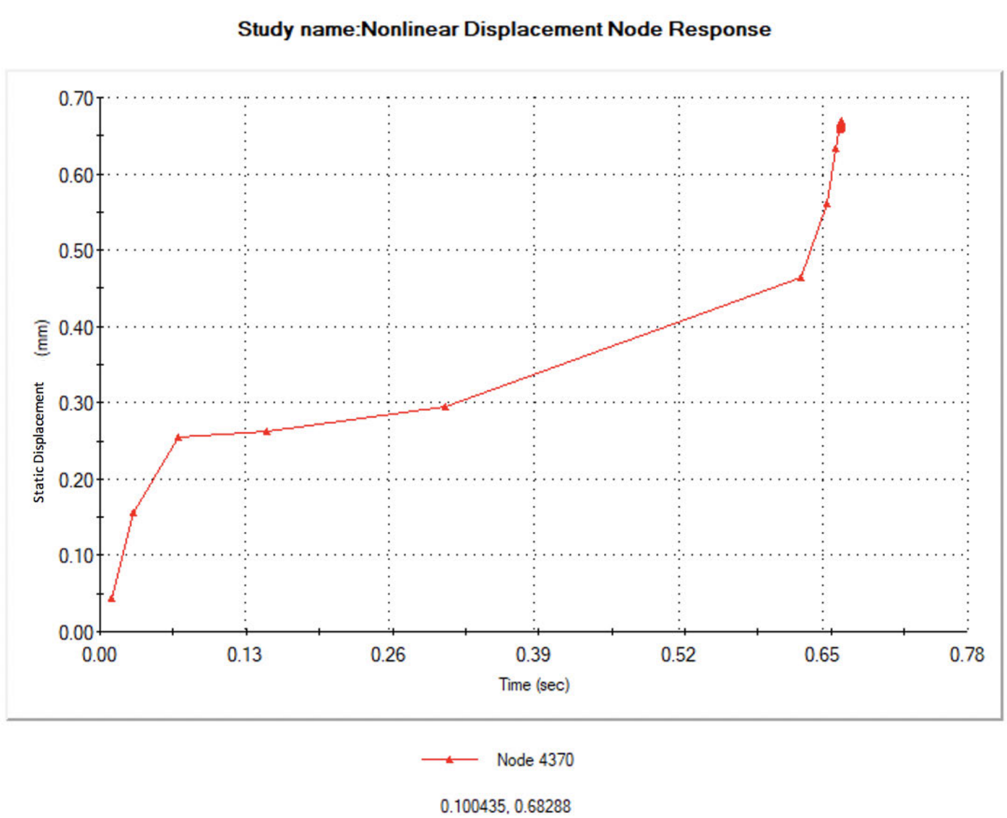

Figure 4: Displacement plot displaying the nonlinearity of the O-ring as it is compressed.
Note: Real material is not piecewise linear.

3.3. Von Mises Stress Analysis Results

The von Mises stresses were calculated in order to determine if the O-ring material would yield when subjected to uniaxial loading. Von Mises stresses were chosen to be analyzed due to their ability to reflect the magnitude of stresses on the cross-section of the O-ring while in working conditions. The greater and more uneven the von Mises stress distribution is throughout the cross-section, the greater the potential for stress relaxation behavior to occur. When stress relaxation occurs in rubber materials, there is a loss of stiffness in the material which can lead to cracking and tearing in the high stress areas [3]. As shown in Figure 5 below, the maximum von Mises stress was found to be $2.917 \times 10^7 N/m^2$ and was experienced on the center-portion of the O-ring. As displayed, this plot agrees with Hertz contact theory which explains that stresses do not appear as prominent on the contact surface, but instead on the inner region.

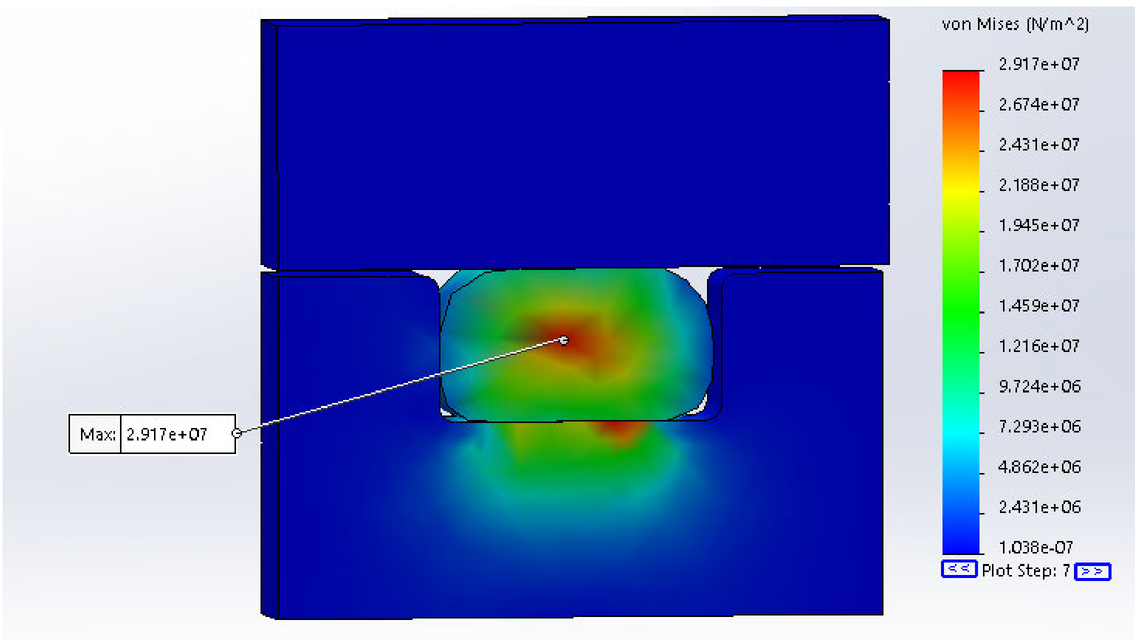

Figure 5: Von Mises stress analysis results of the O-ring.

3.4. Preliminary Material Analysis and Comparison

As the final material for the O-ring has not yet been selected, research was conducted in order to determine the top three elastomeric materials to potentially be used for the collapsible cup design. Using similar applications to narrow down the results, the top three materials were found to be silicone, nitrile, and neoprene. With most of the material properties being very similar as shown in Table 1, there seemed to be a noticeable advantage for silicone rubber due to it already being used within many FDA applications [4,5]. However, one main disadvantage is its resistance to tearing which fell below both nitrile and neoprene. In order to determine which material would be most suitable for the collapsible cup's design, further simulations and experiments must be performed.

Table 1: Comparison of common characteristics of the top three elastomeric materials to potentially be used for the O-ring within the collapsible cup design which was aggregated and compiled from Caserta, Inc. and Frank Lowe commercial webpages [20,21].

	Silicone	**Nitrile**	**Neoprene**
Working temperature range (℃)	-60 to 220	-30 to 120	-35 to 110
Hardness (Shore A)	25 - 80	60 - 90	50 - 80
Tear resistance	Poor	Good	Good
Resilience	High	High	High
Strength properties	Good	Good	Good
Advantages	Heat-resistant; increased flexibility; widely used in many FDA applications; low cost	Highly versatile; increased reliability; low cost; tear resistant; good water resistance	More commonly used for thermal applications; greater fluid resistant properties
Limitations	Poor tensile strength and tear resistance	Limited high temperature resistance	Resistant to silicone oils and greases

3.5. Resources Needed

Table 2: A list of required resources and the corresponding time frames each is needed by.

	Resource	**Time Frame Needed By**
1	SOLIDWORKS license for 3D modeling and 2D drawings	July 2021 - August 2021
2	ANSYS full version (not student version) to complete finite element analysis (FEA) of the O-ring	August 2021 - September 2021
3	Approximately $1,000 to manufacture the body of the cup	December 2021 - January 2022
4	Access to the machine shop within the Engineering building at San José State University	January 2022
5	3D printer to fabricate the lid of the collapsible cup	January 2022 - February 2022

4. DELIVERABLES

Deliverable 1: The 3D CAD files, BOM, and exploded assembly drawing of the collapsible cup design

- Task 1.1: Review the 3D CAD model of the current collapsible cup design and determine the size specifications of the O-ring as defined by the current design
- Task 1.2: Assess the ease of manufacturability for the existing collapsible cup design
- Task 1.3: Generate final 3D CAD files and exploded assembly drawing to prepare for manufacturing process

The first deliverable for this project will be to review the existing 3D CAD model of the collapsible cup design which was created as a part of an undergraduate senior design project course (Adkins, Blum, Hart, and Kiland, San José State University, 2014). In reviewing the design, updates may be made in order to improve manufacturability of the cup as well as ensure that the 'collapsible' feature of the cup will allow it to expand and collapse properly. Once the final design is confirmed and finalized with the principal advisor, the size specifications of the O-ring will be determined and then used for the next step in the project process. The final 3D CAD files, bill of materials (BOM), and exploded assembly drawings will then be generated to prepare for the fabrication process of the collapsible cup.

Deliverable 2: A von Mises stress nephogram, compressive stress distribution nephogram, and contact pressure stress distribution nephogram will be generated to determine which O-ring produces best results under applied loads as apart of the collapsible cup design

- Task 2.1: Complete the preliminary material selection of the O-ring that will be utilized within the collapsible cup
- Task 2.2: Perform the finite element analysis (FEA) simulation of the O-ring seals within ANSYS and generate the stress nephograms

For the second deliverable, multiple stress nephograms will be generated to determine the sealing behavior of the O-ring under varied applied loads. Once the preliminary research of materials is complete and the material selection of the O-ring is narrowed down to the final two contenders, finite element analysis (FEA) will be performed within ANSYS to determine the sealing behavior of the O-rings. A von Mises stress nephogram will be created in order to study the behavior of the internal von Mises stresses and how they distribute throughout the O-ring when in a compressed state. This stress nephogram will also help to demonstrate that the chosen material will not yield or tear under applied loads. A compressive stress distribution nephogram and a contact pressure stress distribution nephogram will also be generated to demonstrate where the O-ring is experiencing the greatest amount of pressure and its ability to conform to the shape of the groove within the collapsible cup. If a large amount of contact pressure is observed, this will also help to confirm that the O-ring will create a leak tight seal within the cup's design. All data found in the stress nephrograms generated within ANSYS will help to determine if the prototype should be manufactured using the initially selected material for the O-ring, or if an alternative material should be considered instead.

Deliverable 3: Physical working prototype of the collapsible cup with the selected O-ring seal installed

- Task 3.1: Manufacture a basic prototype of the cup body
- Task 3.2: Fabricate the lid of the collapsible cup using a 3D printer
- Task 3.3: Compile a table listing all of the components and manufacturing processes used to fabricate the entire collapsible cup design

As the final deliverable of this project, a physical working prototype of the collapsible cup will be built to confirm the overall fitment of the O-ring as well as verify that the 'collapsible' feature of the cup is working properly. Validation testing will be performed by expanding the cup to its extended position, then adding liquid to the internal cavity. If the seal remains tight without any sign of leakage as well as the cup remains locked in the extended position, then the O-ring and the design of the cup will be considered successful for the collapsible cup application. A table will then be created to list each of the components used to build the physical prototype as well as all manufacturing processes used to fabricate the entire collapsible cup design.

5. TIMELINE

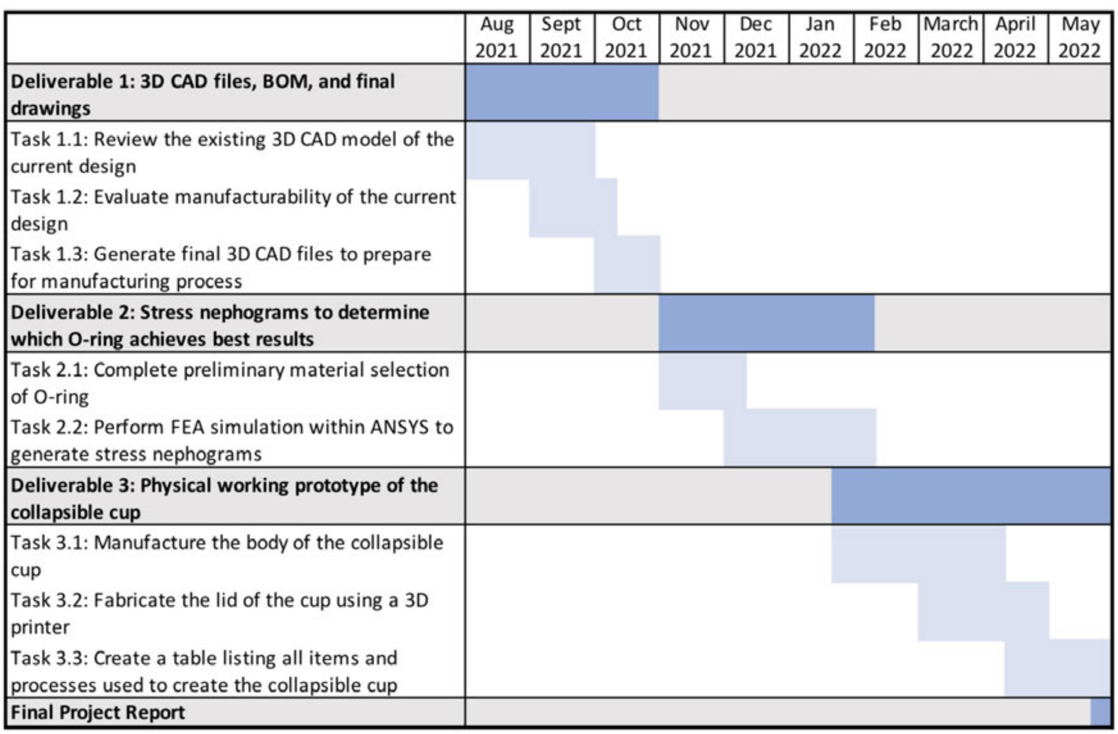

Figure 6: Gantt chart for the collapsible cup project beginning in August of 2021 and concluding in May of 2022.

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