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# Large, Complex Housing

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## Capstone Project Final Report

Honors Project
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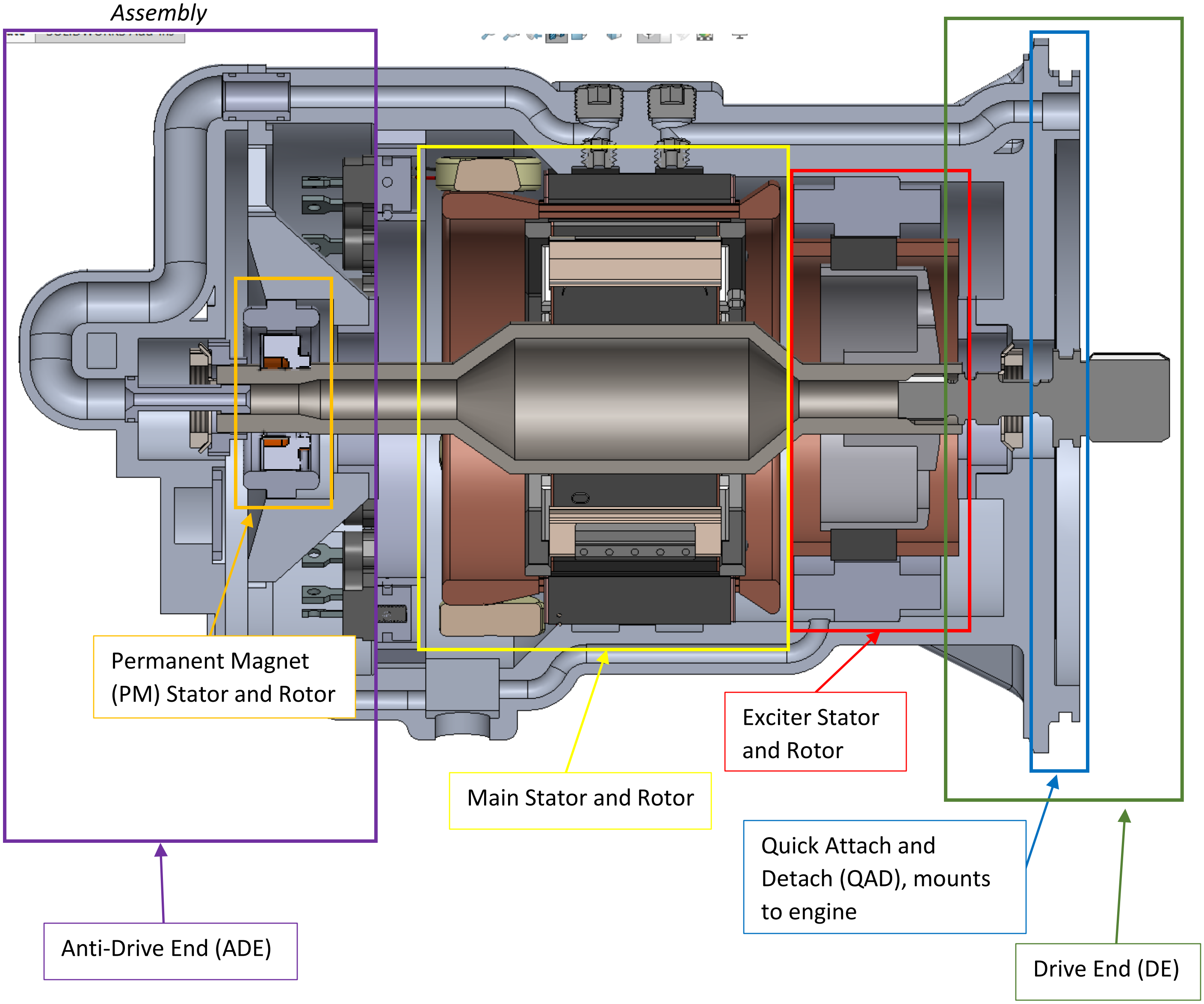
# Contents

## Abstract

The purpose of this capstone project was to develop a design for a High Voltage Direct Current (HVDC) generator housing with built-in passageways for oil to flow through and cool the machine. The machine should be made using advanced manufacturing. A 3D model concept was designed with the use of SolidWorks. The appropriate hand calculations were completed to ensure that the generator housing would contain the components within itself under various environmental conditions.. The model was then 3D printed to produce a prototype that displays the design features within the housing. The next stage of the project will include completing a thermal and stress analysis on the generator assembly to ensure that the oil passageways within the housing sufficiently cool the generator, the internal components will not overheat, and the materials will not fail. This will be completed at Safran Electrical and Power (SEP) within the next year.

For reference and to provide clear understanding of terms used – *Figure A.1: Top Level Machine Assembly*



## 1. Introduction

The Ohio Federal Research Network (OFRN) granted SEP with funding for four different work packages to complete over the next 18 months. This funding is shared between SEP, Youngstown Business Incubator (YBI), Ohio State University (OSU), and Youngstown State University (YSU) for these four work packages. The intention of OFRN providing this funding is to increase the capabilities and workforce in Ohio as well as contribute to the research and development in the aerospace industry and the need for HVDC generators. The senior design project I completed originates from one of these work packages. My senior design project is to help design and produce a large complex generator housing with advanced manufacturing methods (most likely 3D printed castings) with SEP and YBI. This project entails developing the housing model and YBI will own the manufacturability. This housing will be used for a HVDC, 60kVa, oil-cooled generator for future defense aircraft. While these generators don't have much of a difference from traditional alternating current (AC) generators, the development of HVDC generators poses some challenges. One of which is the increasing size needed as the generator's power level and density increase. This requires advancements in the design and manufacturing of the housing that holds together the generator. With these advancements, the generators can operate with an increased power, reliability, and controllability. The goal is to create a model for the advanced manufacturing method and a housing that allows for internal oil-cooling passageways and can be reliably casted and machined. The project has been broken down into phases which are shown in Figure 1.1.

*Figure 1.1 – Block Diagram*


The first phase is the concept design. During this phase, multiple concepts for the housing were proposed and the best solution was chosen to move forward to the next phase. The finalizing design phase is where the design was fully defined, and all the final calculations were made to make sure the housing would meet its requirements. Lastly, this project is for research purposes so a fully functional generator isn't being fabricated as of right now but a prototype casting would be made to ensure that it is manufacturable.

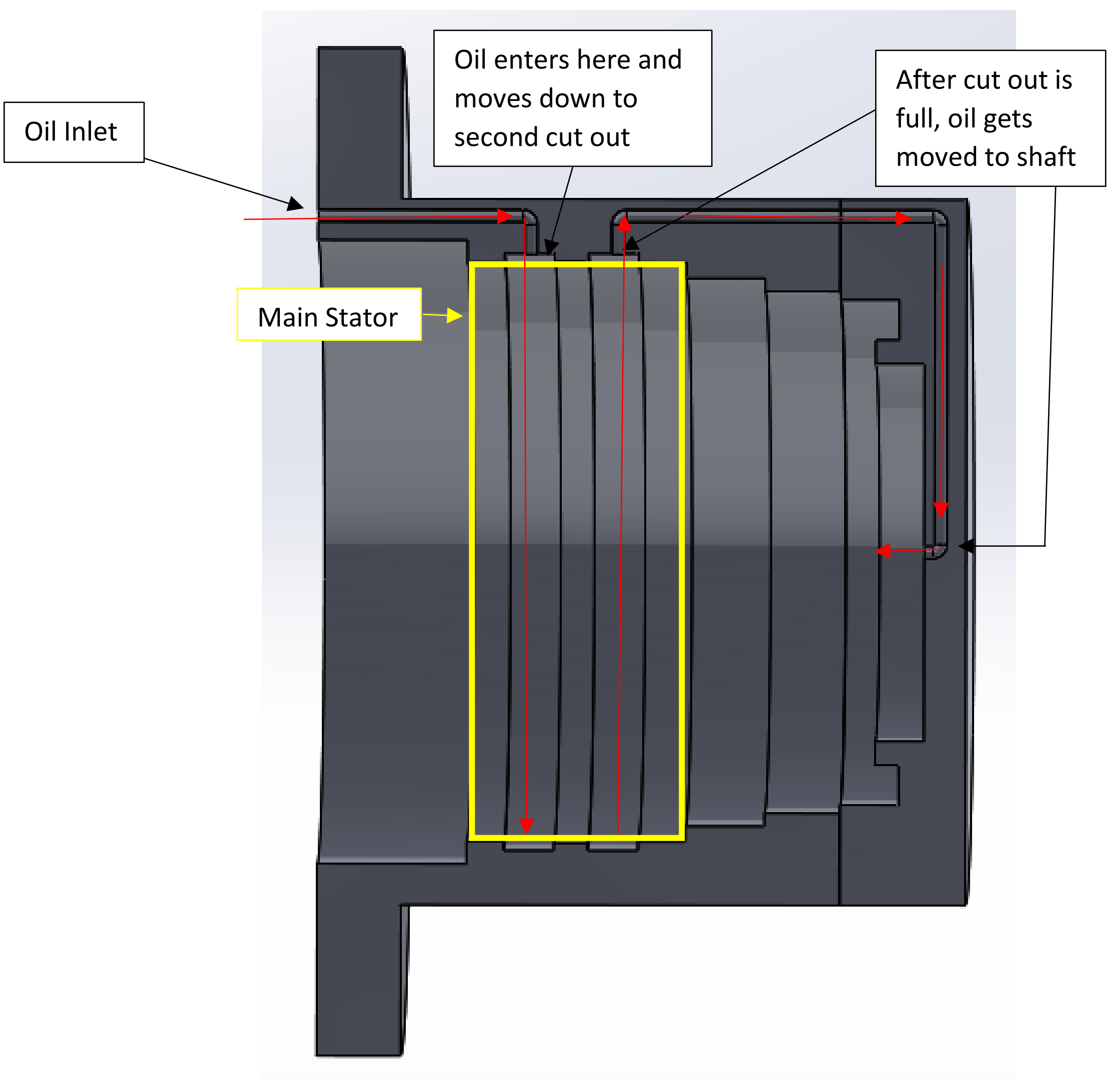
## 2. Design

### 2.1. Design Procedure

The most important design decisions were in regard to the oil passageways through the housing and the end bell placement. The flow of the oil would start by cooling the main stator by flowing around its outer diameter. This is called back iron cooling. Then, the oil would flow into the rotor shaft where it would be sprayed out by the rotational force onto the other phases. The end bell placement would also decide how the stages in the generator would be placed. The main stator within the generator is the hottest component due to electrical losses and needs proper cooling, so I started the design process by coming up with different ways the main stator could be cooled and different placements of the end bell. I started with three different options for the back iron cooling and the end bell placements. Figures 2.1-2.6 are a visualization of those ideas using very simple models.

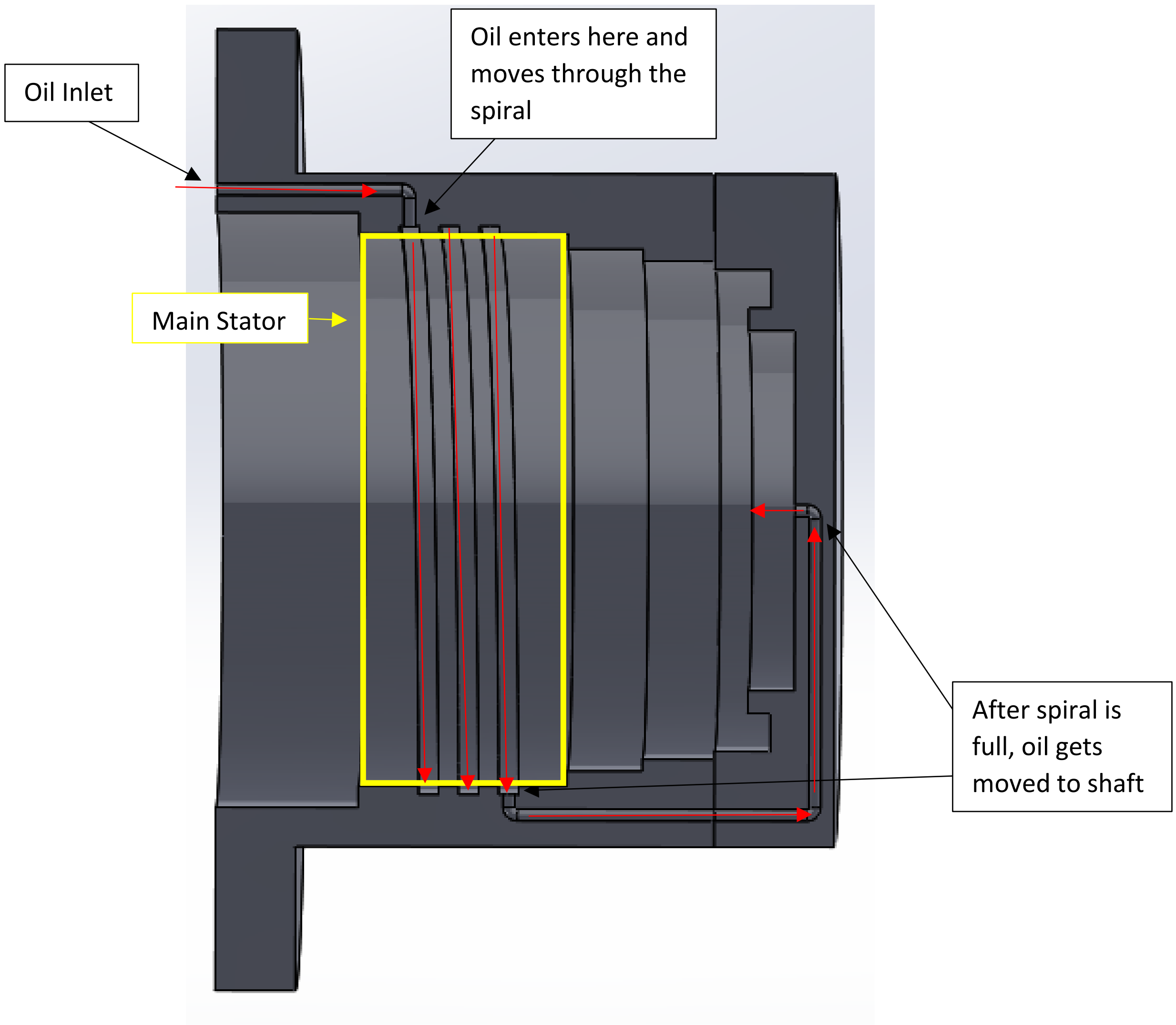
The first option (shown in Figure 2.1) was taken from a past generator in which we have the oil flow in and travel around the stator through a pathway that was cut out. The oil would flow down to a second pathway that was made below the first then would be pushed to the shaft after the passages became full. This idea was chosen for the final design since we have past knowledge that it works, and the symmetry would make it easier to manufacture.

*Figure 2.1 – Very basic model showing oil flow (red arrows) option 1 [SolidWorks]*



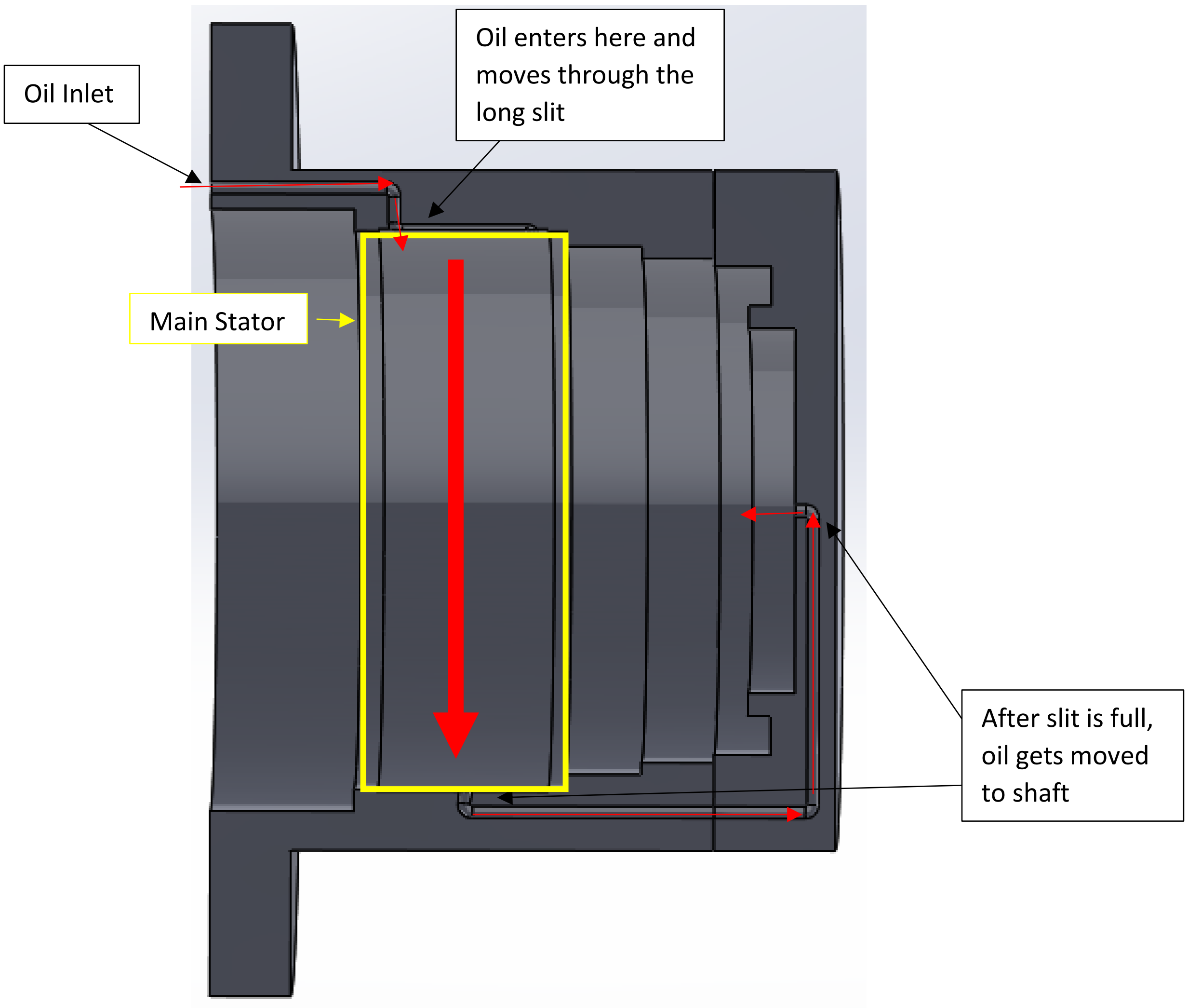
The second option, shown in Figure 2.2, would have the oil flow in and then wrap around the stator through a pathway that was created in a spiral around the stator length, then would flow to the shaft. The pro of this design would be that the oil would flow smoothly and cover the stator evenly, but the con would be since this housing would be casted, it is easier to make things symmetrical.

*Figure 2.2 – Very basic model showing oil flow (red arrows) option 2 [SolidWorks]*



The last option, shown in Figure 2.3, was to have a long slit wrap around the stator and then flow to the shaft. A pro of this option is that it would have been symmetrical, but the con is that it has never been done before so it would require extra calculations and analysis to verify if it worked.

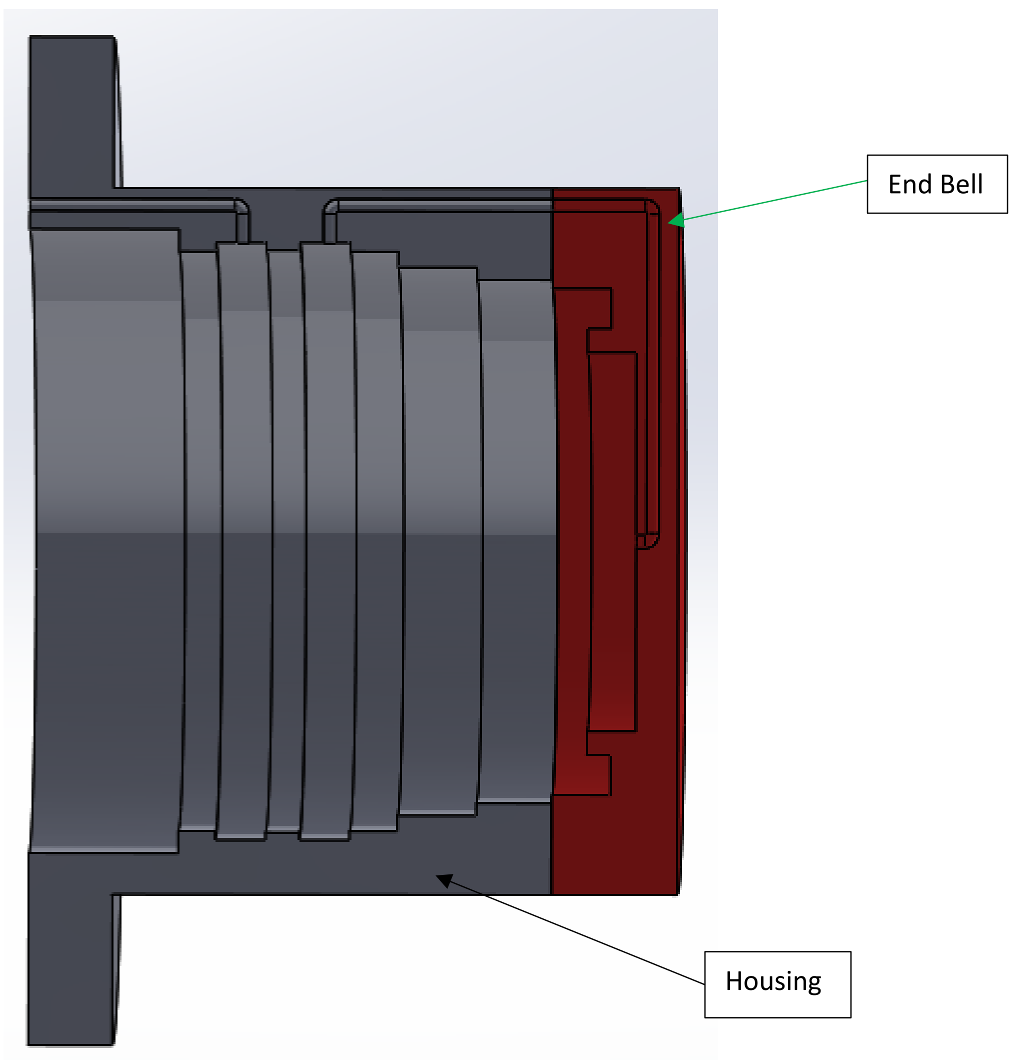
*Figure 2.3 – Very basic model showing oil flow (red arrows) option 3 [SolidWorks]*



The term “end bell” refers to a second part that is attached to the main housing. The placement of the end bell is important because of how the stages are designed. The main stator has the largest outer diameter (OD), then the exciter, and lastly the permanent magnet (PM) has the smallest. All these stators are shrink fit into the housing. If there was no end bell, then the phases must be inserted from smallest to largest. This isn’t a bad design option but having the main stator in the middle of the housing would be more ideal for wiring and overhung moment purposes. This brings out the need for an end bell so there can be multiple options for the order of the stages.

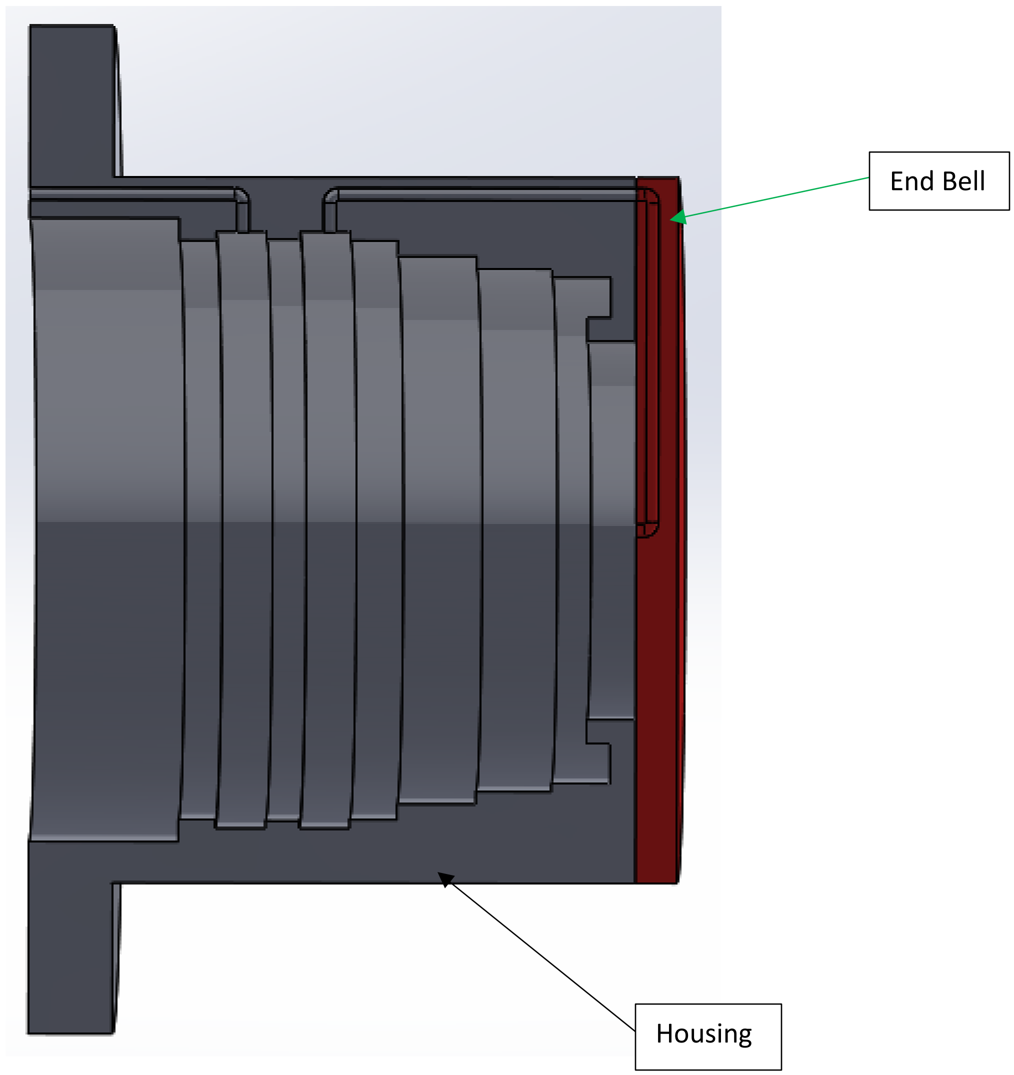
The first option for where to place the end bell (shown in Figure 2.4) would have one stage and the pump attached to it. This is beneficial since it allows the main to be placed in the middle, but problems arise when we try to insert the pump since there is no space that would make for easy access.

*Figure 2.4 – Very basic model showing end bell option 1 [SolidWorks]*



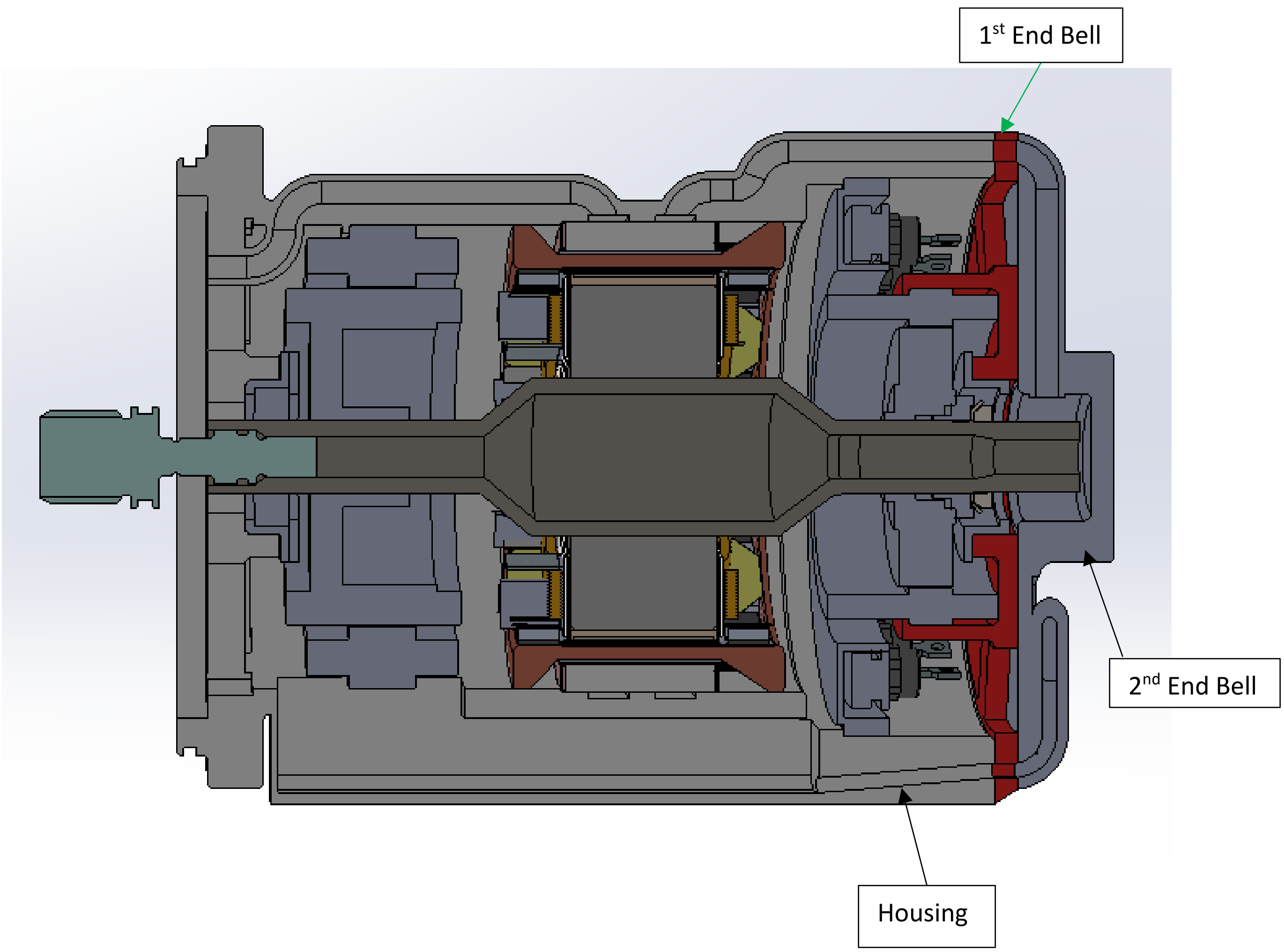
The second option, shown in Figure 2.5, would have only the pump attached to the end bell. The pro of this design is it would make for an easy assembly of the pump into the frame but this eliminated the option of having the main stator in the middle.

*Figure 2.5 – Very basic model showing end bell option 2 [SolidWorks]*



The final option which was selected for the final design, shown in Figure 2.6, was to have two end bells. One that will hold a stator and one to hold the pump. This originally wasn't chosen because the oil must flow through the end bells to get to the shaft and having more end bells increases the risk of spillage but the benefit of having the second end bell which allowed the pump to be easily assembled into the frame outweighed the risk. Figure 2.6 also shows the first iteration of the concept design after the oil flow and end bell placement was decided.

*Figure 2.6 – Model showing end bell option 3 and first concept design iteration [SolidWorks]*



To summarize the pros and cons of the design options, see Tables 2.1 and 2.2.

| **Table 2.1 – Oil Flow Pros and Cons** | | |
|---|---|---|
| **Oil Flow Option** | **Pro** | **Con** |
| 1 (Selected) | Simple, used before, symmetric | |
| 2 | Flow smoothly, cover evenly | Not symmetrical, never done before |
| 3 | Symmetric | Never done before |

| **Table 2.2 – End Bell Pros and Cons** | | |
|---|---|---|
| **End Bell Option** | **Pro** | **Con** |
| 1 | Main can be in the middle | Cannot assemble pump |
| 2 | Can Assemble pump | Main cannot be in the middle |
| 3 (Selected) | Main can be in the middle, can assemble pump | Increased risk of spillage |

Since my project is only on the housing, the main equation that is needed is thermal expansion. This is because the stators are shrink fit into the housing so I must ensure that at the right temperature the stators can fit during assembly and do not come loose during operation. To do this, I used equations (2.1) and (2.2) shown below. Old Diameter refers to the housing's inner diameter at room temperature, CTE stands for the materials coefficient of thermal expansion, ΔT is the change in temperature when the housing is heated, and Stator Diameter refers to the stator's outer diameter at room temperature.

$$New\ Housing\ Diameter = Old\ Diameter + (Old\ Diameter * CTE * \Delta T) \qquad (2.1)$$

$$Clearance = New\ Housing\ Diameter - Stator\ Diameter \qquad (2.2)$$

## 2.2. Design Details

The final design was chosen with the first option for the oil passages and the two end bell option. The dimensions for the housing and both end bells can be found in Table 2.3 below. See Figures 2.7 – 2.10 to see what these values correlate to. Since this is a project I am completing at my internship, I am not able to fully complete it. Right now, we have only finalized the concept design. This means that all the dimensions are nominal and do not have tolerances yet. It also means that these dimensions are what are needed for an interference fit with the stators. See Table 2.2 for thermal expansion results.

**Table 2.3 - Design Dimensions**

| Place | Value | Unit |
|---|---|---|
| A | 14.42 | in |
| B | 8 | in |
| C | 6.86 | in |
| D | 9.88 | in |
| DE Bearing | 2.1 | in |
| Drive Shaft | 1.66 | in |
| QAD | 9 | in |
| Exciter | 6.2 | in |
| Path | 6.5 | in |
| Main | 6.27 | in |
| Diodes | 7.5 | in |
| PM | 2.75 | in |
| ADE Bearing | 1.08 | in |
| Pump | 2.1 | in |
| Shaft | 2.2 | in |
| Sump | 4 | degrees |
| Oil Passages | 0.34 | in |

*Figure 2.7 – Final Concept Model [SolidWorks]*

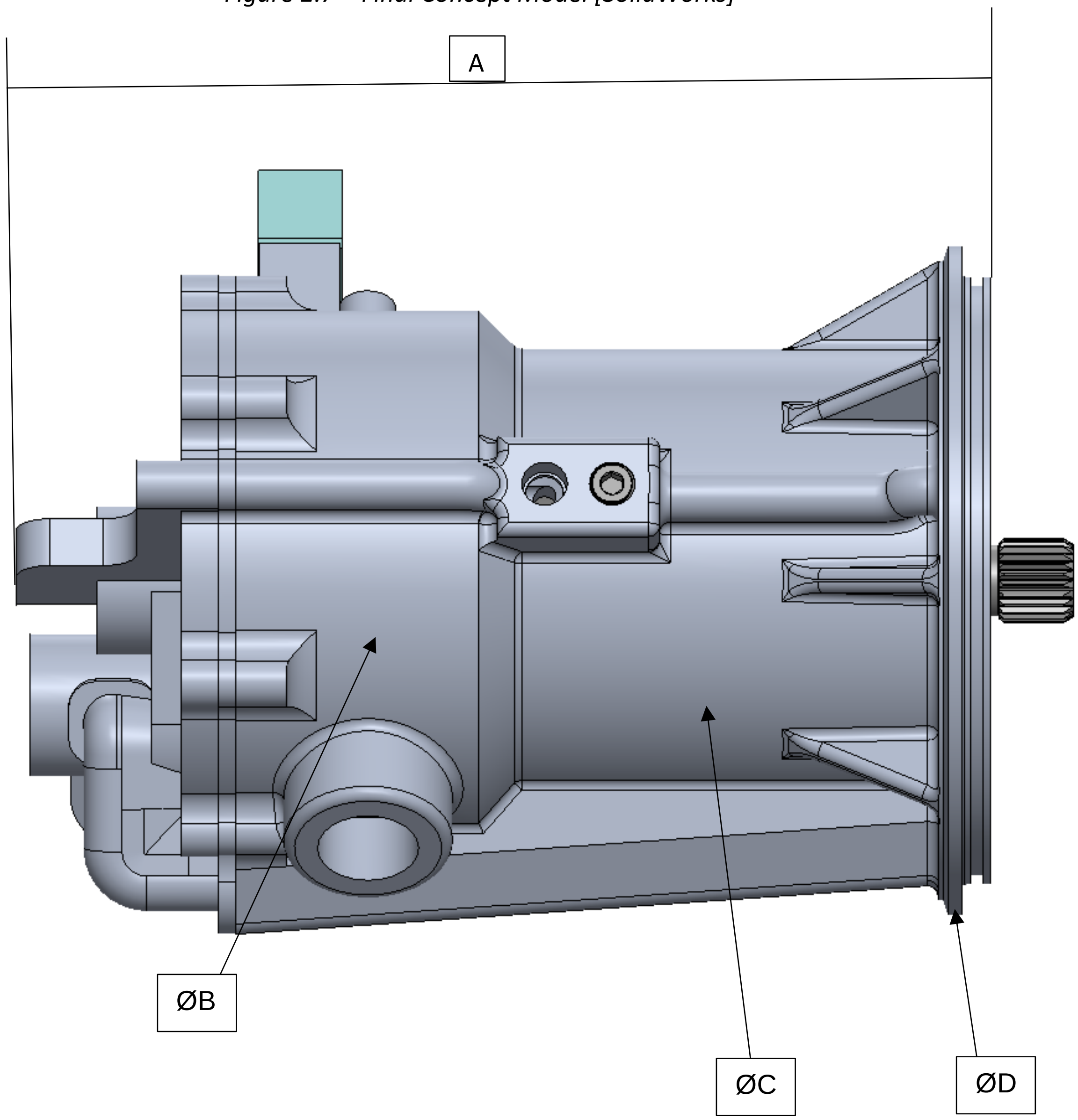


*Figure 2.8 – Final Housing Concept Model [SolidWorks]*

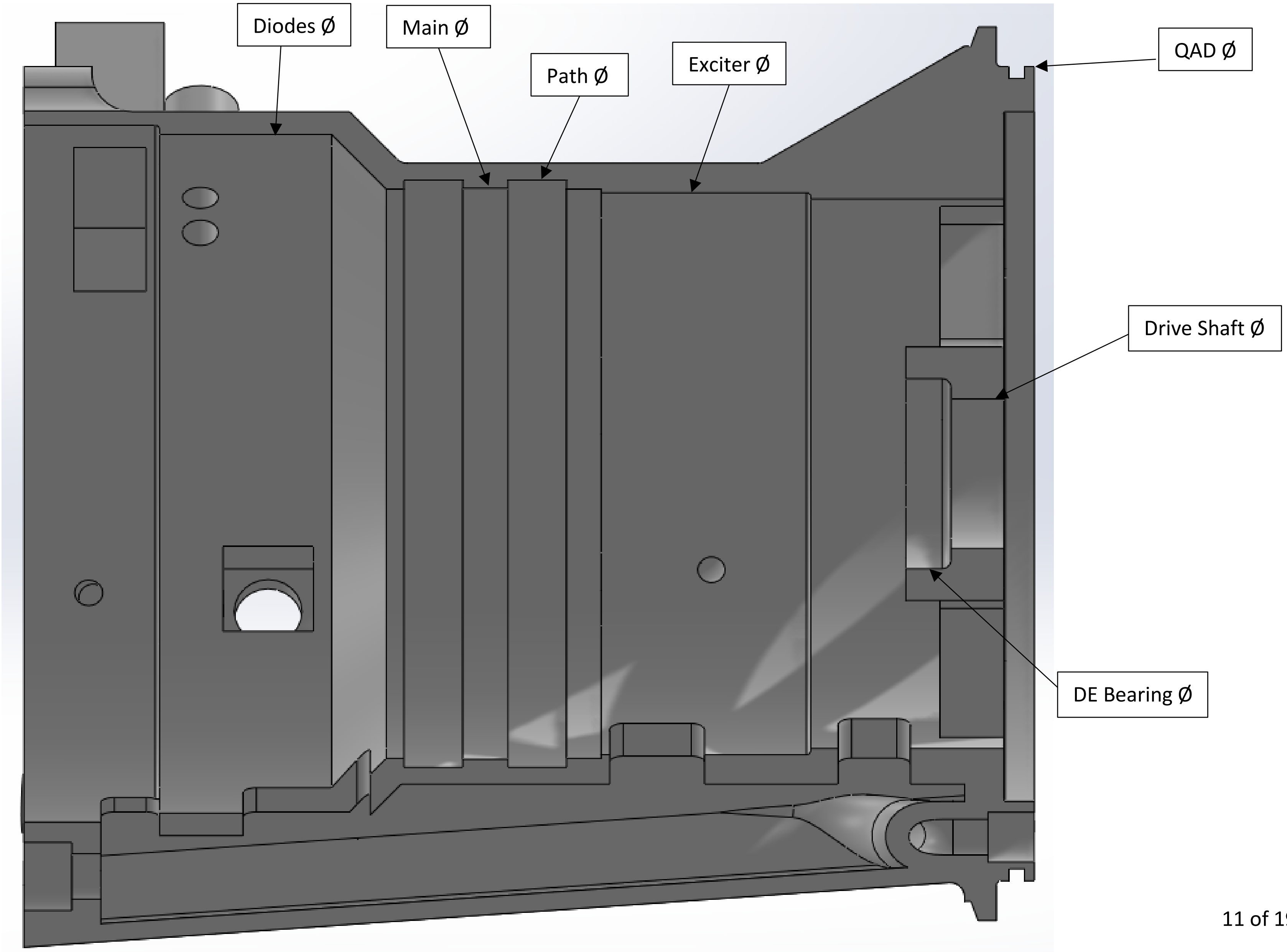


*Figure 2.9 – Final 1st End Bell Concept Model [SolidWorks]*

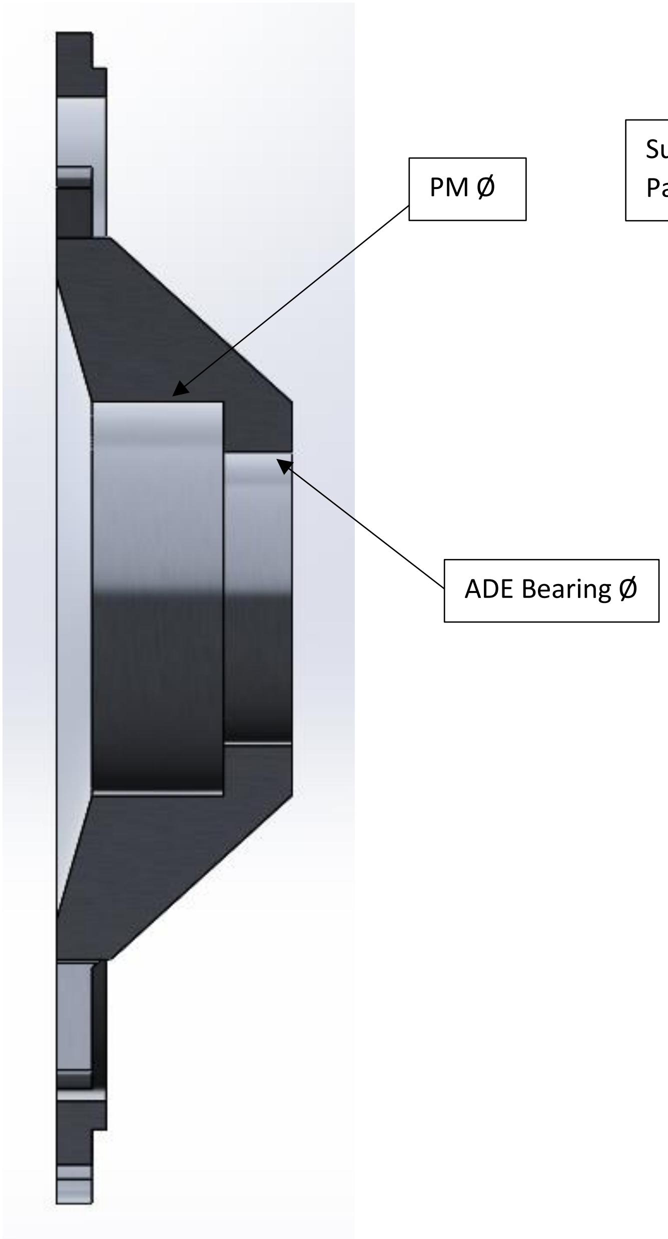
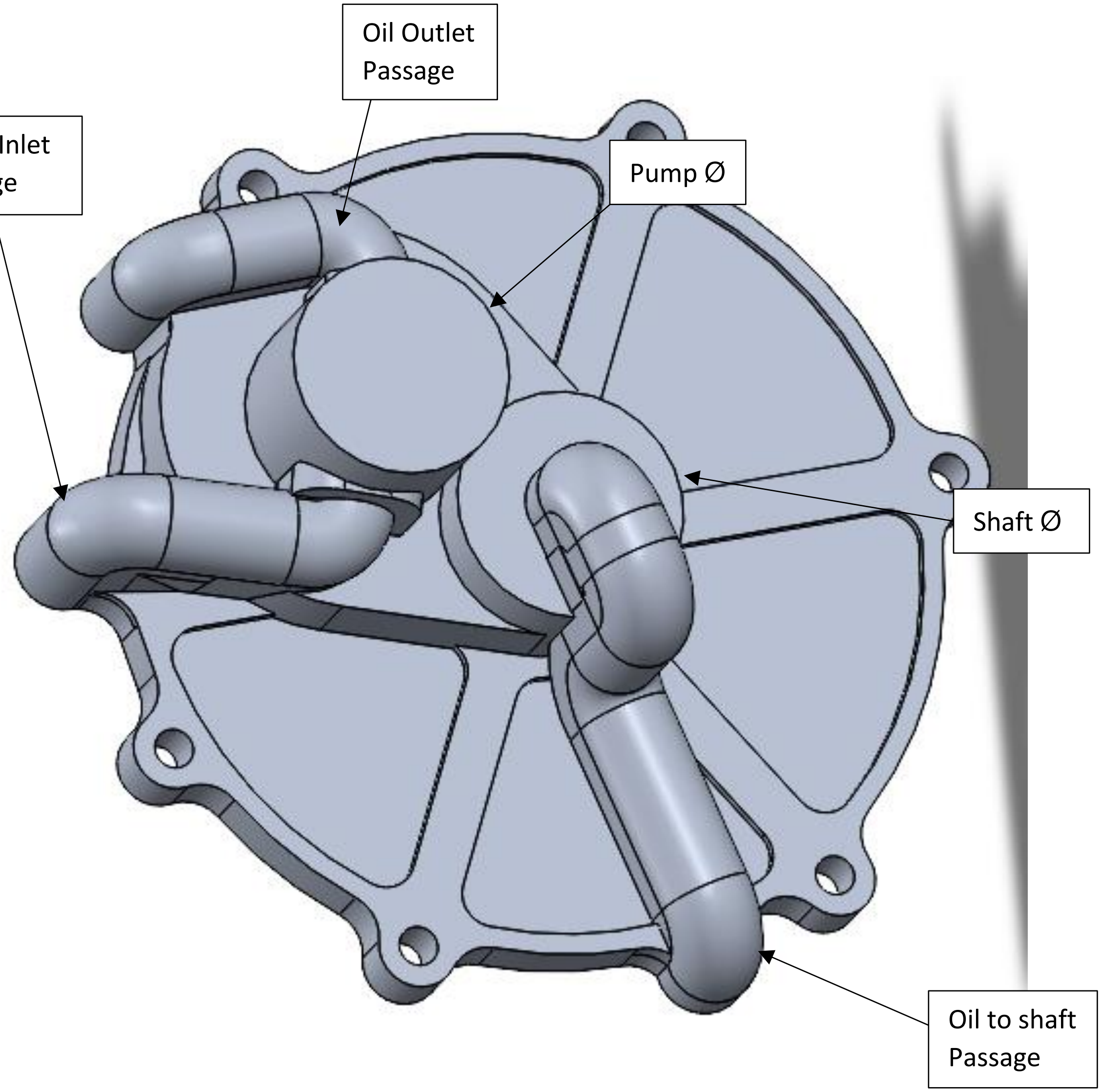



*Figure 2.10 – Final 2nd End Bell Concept Model [SolidWorks]*



The exact passageways that the oil will flow through is shown below in Figures 2.11 – 2.14. The oil will come in from the inlet, cool the main stator, then go to the rotor shaft. The oil in the rotor shaft will spray out to cool the other stages. All the sprayed oil will collect in the sump at the bottom of the generator. The oil then gets pulled to the 2nd end bell by the pump. Finally, the pump pushes the oil to the outlet.

*Figure 2.11 – Final Oil Flow Passages: Inlet and Back Iron Cooling [SolidWorks]*

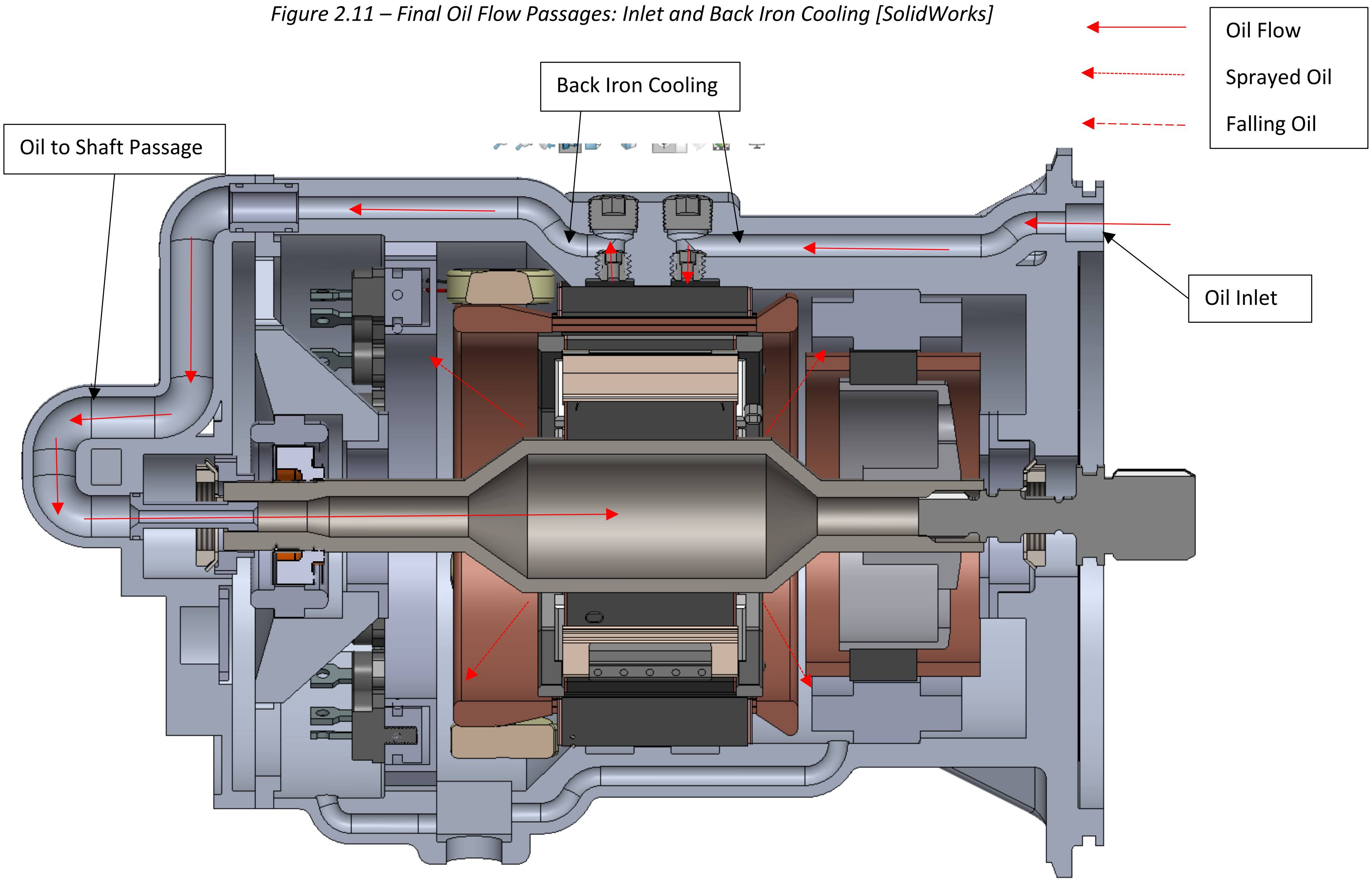


*Figure 2.12 – Final Oil Flow Passages: Sump and Pump [SolidWorks]*

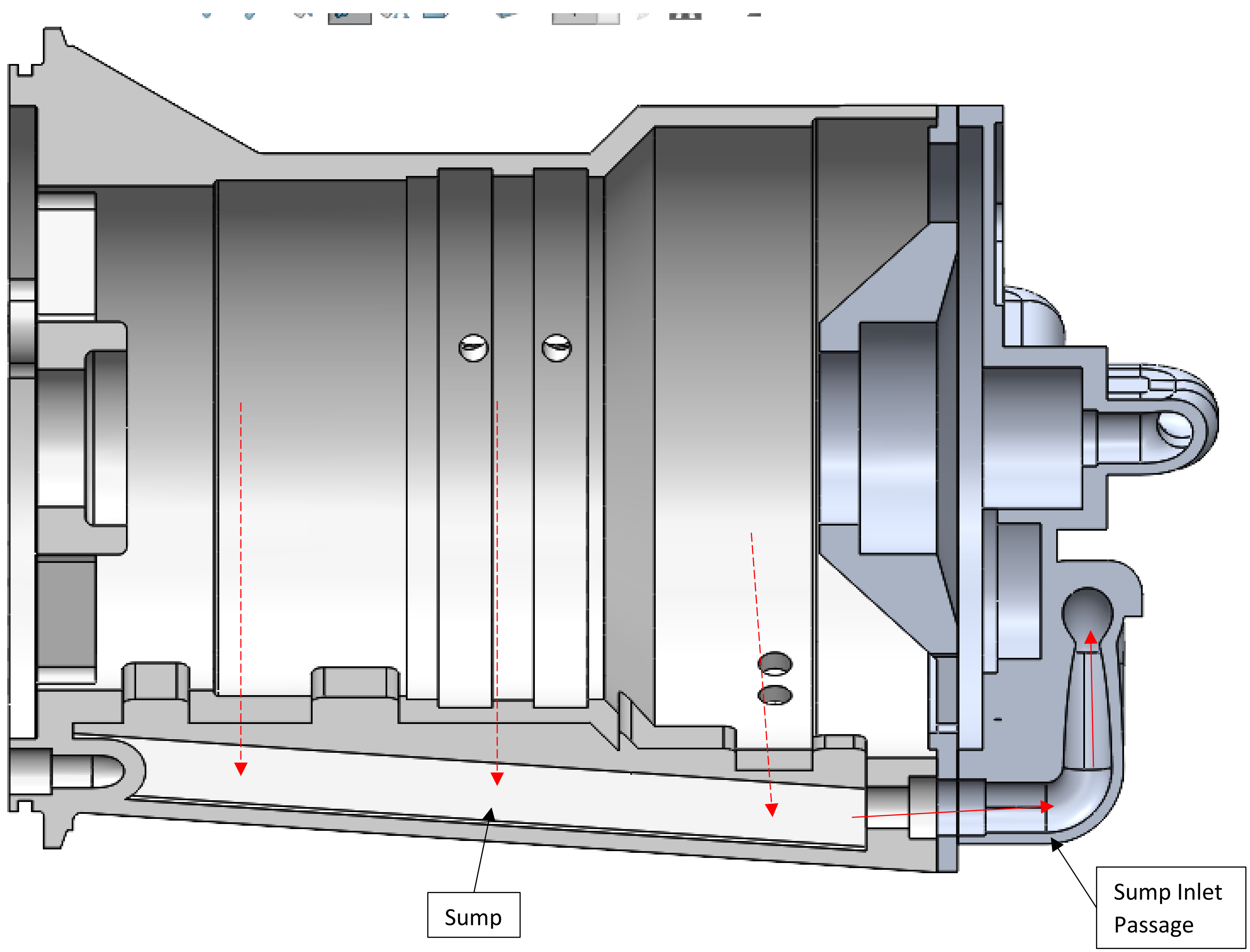


*Figure 2.13 – Final Oil Flow Passages: Sump and Oil Outlet [SolidWorks]*

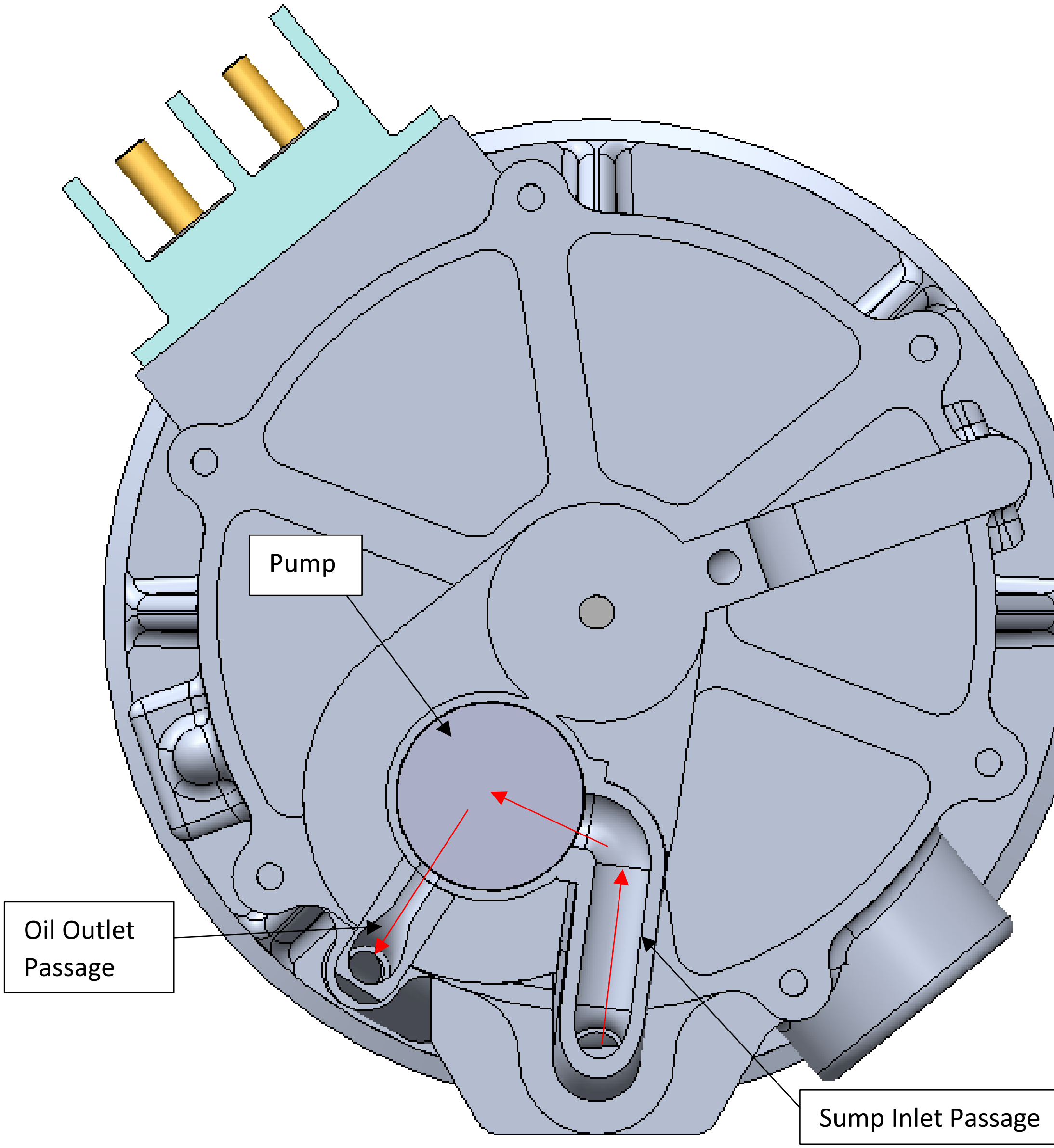
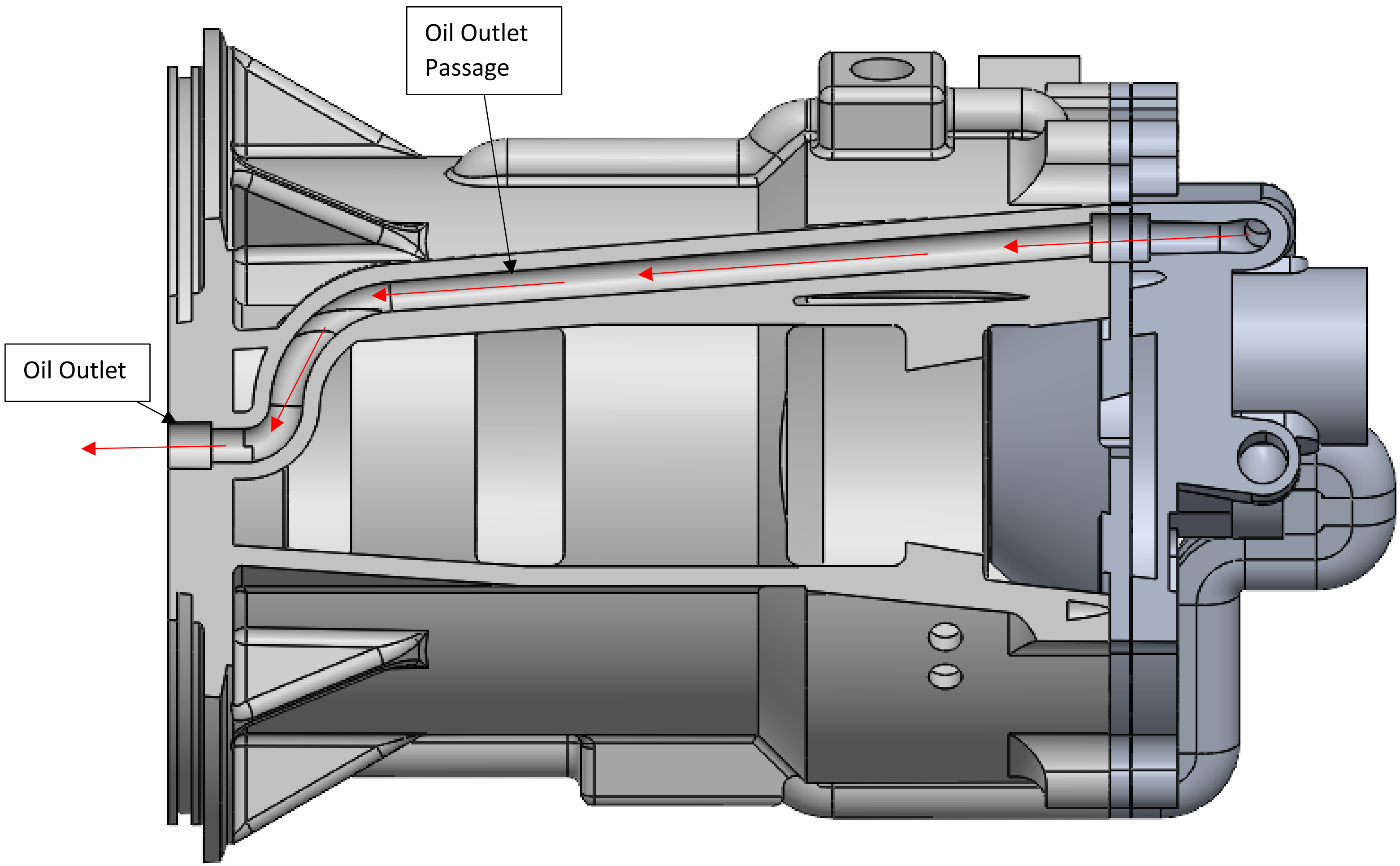


*Figure 2.14 – Final Oil Flow Passages: Oil Outlet [SolidWorks]*



Using equations (2.1) and (2.2), I calculated if when the housing and end bells are heated, will they expand enough to allow the stators to be installed. The results of these calculations can be seen below in Table 2.4. These calculations were made by assuming the housing and end bells were made from aluminum 6061 and the stators were made of hyperco 50. It was also assumed that the housing would be heated up to 350°F and the stators would remain at room temperature. As shown in Table 2.4, if the housing and end bells are heated to 350°F, then they will expand enough to allow a clearance for the stators to be placed inside.

| Table 2.4 – Thermal Expansion Results | | | | | |
|---|---|---|---|---|---|
| **Part** | **Material** | **CTE** | **Dim (in)** | **Temp (°F)** | **Clearance (in)** |
| Housing PM ID | Aluminum 6061 | 1.3E-05 | 2.75 | 350 | 8.7E-05 |
| PM OD | Hyperco 50 | 5.3E-06 | 2.76 | 70 | |
| Housing Exciter ID | Aluminum 6061 | 1.3E-05 | 6.2 | 350 | 0.0127416 |
| Exciter OD | Hyperco 50 | 5.3E-06 | 6.21 | 70 | |
| Housing Main ID | Aluminum 6061 | 1.3E-05 | 6.27 | 350 | 0.00299836 |
| Main OD | Hyperco 50 | 5.3E-06 | 6.29 | 70 | |

## 2.3. Verification

When designing a rotating generator, a large design concern is the electromagnetic components not receiving enough airflow. This can result in overheating and cause the generator to stop performing. Since this project is strictly research and as of right now, a fully functioning machine isn't being made, the thermal analysis could only be theoretical. To ensure that our analysis is as accurate as possible, we analyzed a model for a past generator that we have on site and then tested that generator in real life. By comparing the calculated and literal results, we can see how accurate our analysis is. We can then take the same analysis process and use it on the model we created for this project to get an accurate reading. The generator model that we used for reference was only saved as a step file, so I had to remodel the entire generator for this analysis to start. There will also be a stress analysis done on the machine. Due to time constraints, these tests have yet to be done but will be completed in later months.

## 3. Costs

When calculating my labor costs, I used equation (3.1) shown below.

$$hourly\ rate * hours\ spent * 2.5 \tag{3.1}$$

I spent about 230 hours on this project at a rate of $19/hr. Using equation (3.1), the total labor cost for this project is about $10,925. The cost of having the model 3D printed was about $400. The total cost of this project is about $11,325.

## 4. Conclusions

From the options that were brought up during brainstorming, having the oil flow around the main stator through two passageways and having two end bells would be the most effective way to design the housing. This oil flow has been used before so it builds confidence in this design, but the ultimate determinate of the design will come from the verification testing. Since the design includes two end bells, the assembly will be simple because the pump gets its own end bell, and the stators can be inserted easier. The thermal analysis hasn't been completed yet so it is still uncertain how effective this design will be, but it has a better chance over the other designs.

This product is something that will eventually end up on an aircraft. This means that ensuring safety is the highest priority since a failing aircraft can be highly dangerous. To account for this, the usual aircraft specifications would be referenced. The specific specifications that were used in this design were MIL-PRF-32538, MIL-STD-461 NOTICE 4, MIL-STD-810G CHANGE 1, MIL-STD-704F. These specifications full descriptions are shown below in Table 4.1

**Table 4.1 – Specification Descriptions**

| Title | Description | Author/Publisher |
|---|---|---|
| MIL-PRF-32538 | | DoD/GOV |
| MIL_STD-461, NOTICE 4 | Electromagnetic Interference Characteristics, Requirements for Equipment | DoD/GOV |
| MIL-STD-810G, Change 1 | Test Method Standard for Environmental Engineering Consideration and Laboratory Tests | DoD/GOV |
| MIL-STD-704F | Aircraft Electrical Power Characteristics | DoD/GOV |