Magnetic Gearing for Centrifugal Pumps

Flowserve Presentation – May 14th, 2025

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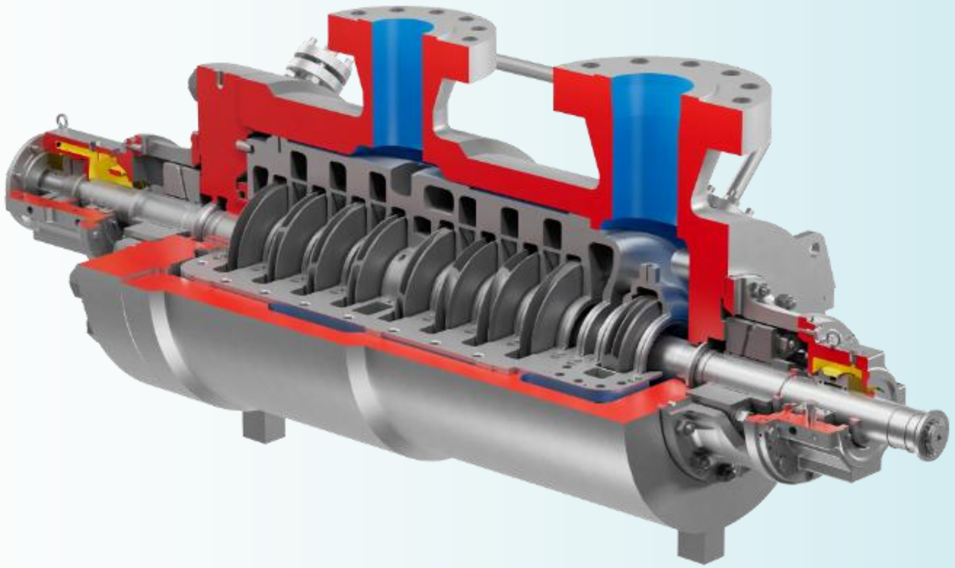
Agenda

- Introduction
- Requirements
- Design & Analysis
- Manufacturing
- Test Results
- Project Results, Summary, & Next Steps

Introduction

Problem: Flowserve is aiming to improve the longevity and efficiency of their centrifugal pumps. These pumps need specific gearing and specialized impellers to reduce cavitation in the fluid. Unfortunately, these designs are complex and expensive.

Flowserve is interested in innovative design concepts that would help reduce these current problems. In particular, Flowserve is interested in Magnetic Gears as a solution to reduce maintenance needs.



Flowserve Byron Jackson Pump

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Introduction

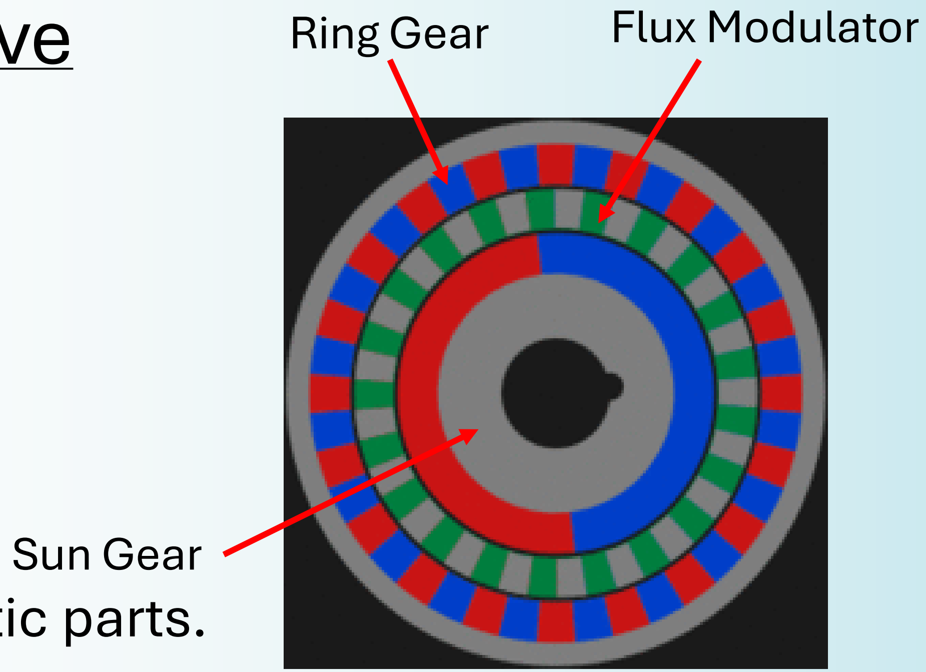
Flowserve has tasked Team 207 to improve upon and finish a previous Senior Design team's Concentric Magnetic Gear (CMG) system, as a proof of concept for their Company.

Value Proposition of CMGs:

Mechanical gear parts replaced with non-contact magnetic parts.

Less lubrication/maintenance required compared to traditional gears.

Reduced noise, friction, and vibration.



CMG animation Diagram

System Level Objectives and Requirements

Description	Objective	Verification
The gear reduction shall be within the threshold of the objective	3:1 - 2:1	Analysis
The gear should demonstrate mechanical efficiency near the objective	95%	Demonstration
The gear should be able to transmit torque matching the objective	~6 N-m	Test
The gear shall be able to operate in temperatures up to the objective	~205° Celsius	Analysis

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Derived Requirements

Legend		
TR	X.1	Functional Requirement
TR	X.2	Performance Requirement
TR	X.3	Technical Requirement
TR	X.4	Specification

INITIAL DERIVED REQUIREMENTS (Scaled Down)			Status
TR 1.1	The gear should have the capability to be able to function in various fluids other than air.	Our physical gear design does not need to itself function in different fluids. However, the research we do should be adaptable to different fluids.	Test
TR 2.1	The gear ratio shall be between a 3:1 and a 2:1 reduction.	The previous team was required to accommodate three different ratios. For simplicity, we will aim for one, to prove the concept's design to Flowserve.	Analysis
TR 3.2	The gear should demonstrate a 95% mechanical efficiency.	We aim to be consistent with the efficiency ranges of a typical Concentric Planetary Gear design.	Demonstration
TR 4.4	The gear should fit within a 177.8-millimeter (7-inch) diameter cylinder with a 215.9-millimeter (8.5-inch) length.	To fit within current Flowserve pump designs.	Analysis
TR 5.1	The gear should be able to transmit 6 Newton-meters of torque.	This is sufficient to gear down the first impeller speed of a current Flowserve pump design at our scaled down model.	Test
TR 6.1	The gear should transmit 5 HP from a test motor at 60Hz and instantly start without decoupling. Otherwise, up to a 20 second ramp-up is acceptable.	We will use the 5 HP test motor purchased by the previous team.	Test
TR 7.3	Max operating temperature of 205° Celsius (400° Fahrenheit).	We need to make sure that the epoxy and magnets operate in this temperature range.	Analysis
TR 8.1	The gear should scale to larger sizes, torques, and gear ratios.	This allows for more ways to test as needed, as well as to present the true potential of the gear.	Analysis
TR 9.3	The gear should reuse already manufactured parts from last year's design team.	This will allow the team to focus more on improving the flux modulator design and the overall efficiency.	Demonstration

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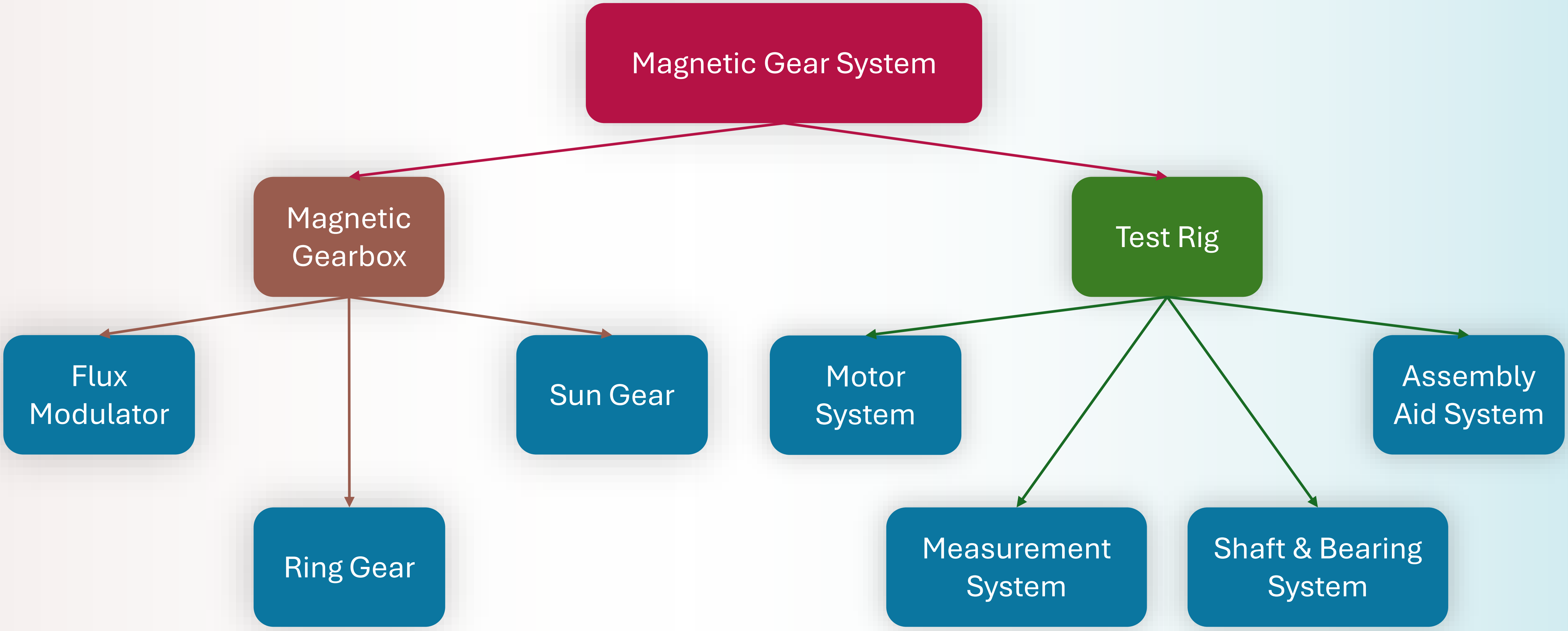
System Architecture



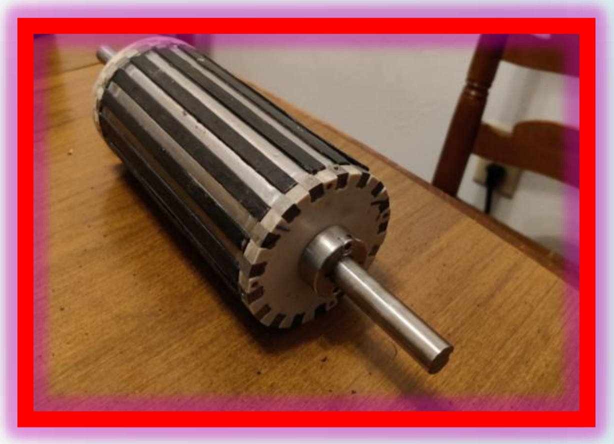
Existing Parts

- Both the Sun and Ring Gears are usable.
- The Flux Modulator requires a complete redesign.
- The Sun Gear is comprised of 6 North/South N50 magnet pole pairs bonded to a low-carbon iron backing.
- The Ring Gear is comprised of 11 North/South N50 magnet pole pairs bonded to the inside of a low-carbon iron backing.

Ring Gear

Sun Gear

Sun Gear



Old Flux Modulator

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Engineering Analysis - Gear Ratios

- Existing sun and ring gear: 6 and 11 magnet pairs respectively
- Number of modulator poles: $N = P_s + P_r$
- CMG gear ratio determined by which rotor is held stationary.
- Input is typically the sun gear
- We chose the 17:6 configuration (~2.83:1) which we are approximating as ~3:1

Output/Input	**Sun Gear**	**Ring Gear**	**Flux Modulator**
Sun Gear $P_s = 6$	1:1	6:11	6:17
Ring Gear $P_r = 11$	11:6	1:1	11:17
Flux Modulator $N = 17$	17:6	17:11	1:1

Rotor Configuration vs. Gear Ratio

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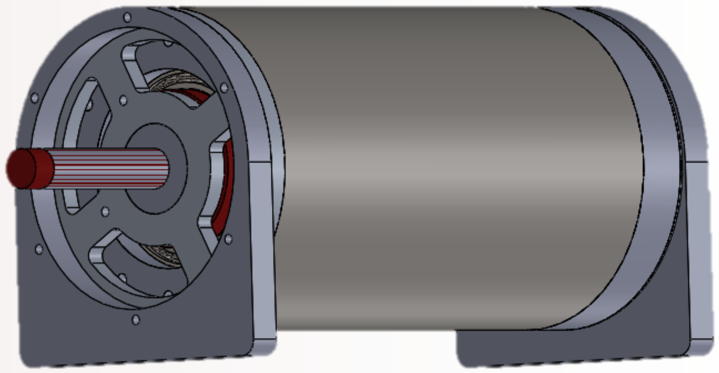
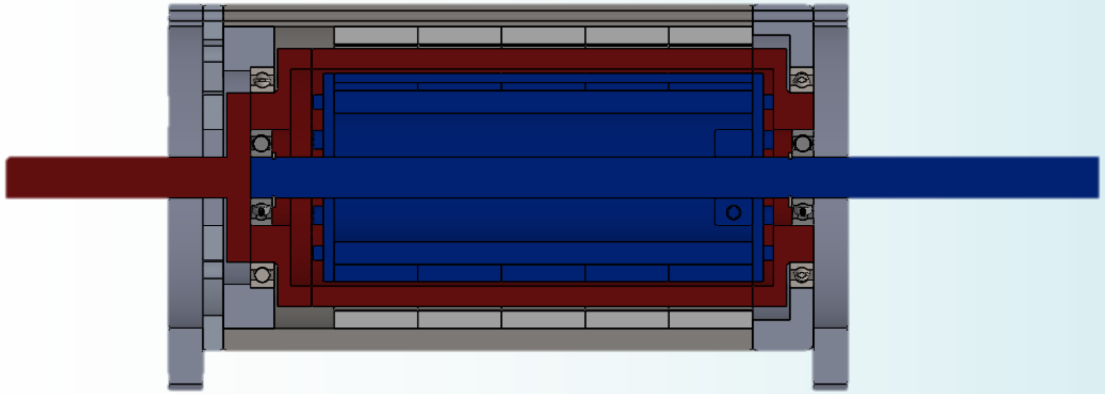
Selected Concept: ~3:1 Fixed Ring Gear



Fixed Ring Gear. Sturdy and easier to build.



Internal layout with fixed Ring Gear.

Risk And Mitigation Plan Summary

Risk ID #	Risk Description	Risk Category	Likelihood	Severity	Risk Level	Owner	Mitigation Plan	Mitigated Likelihood	Mitigated Severity	Mitigated Risk Level	Status
1	Flux modulator material selection above budget	Cost	1	3	4	All	Careful Selection and research before material choice	1	2	3	In Progress
2	Adhesive Overheating Under Load	Technical	2	4	6	All	Reduce Eddy Currents and Shaft friction, better quality adhesive	2	2	4	In Progress
3	Centrifugal deformation of flux modulator	Technical	3	5	8	All	Proper modulator design to promote rigidity compounded with material selection. Mechanical analysis	2	4	6	In Progress
4	Eccentric rotors or modulator causing vibration	Technical	2	5	7	All	Properly balance all rotating assemblies	2	3	5	In Progress
5	Rotor damage due to magnets sticking during assembly	Technical	2	5	7	All	Build an assembly fixture and design an assembly procedure	1	3	4	In Progress
6	Eddy currents generating heat and decreasing efficiency	Technical	3	3	6	All	Perform simulations and design magnetic system to have the least amount of eddy currents possible	2	3	5	In Progress
7	3D printers occupied or failed 3D prints for prototyping	Schedule	1	2	3	All	Plan 3D printing ahead of time and proactively addressing print issues with Library Lab experts	1	1	2	Open
8	Insufficient Rotor support causing vibration	Technical	2	4	6	All	Replace cantilever rotor supports with continuous shaft	1	3	4	In Progress
9	Shaft or bearing mechanical failure	Technical	1	4	5	All	Ensure high quality bearings and shaft machining	1	2	3	In Progress
10	Improper CAD or Ansys Simulation Results	Technical	2	4	6	All	Emergency meeting (possibly with Sponsors) to ensure proper confirmation that dimensions, design, and simulations are accurate	1	2	3	In Progress

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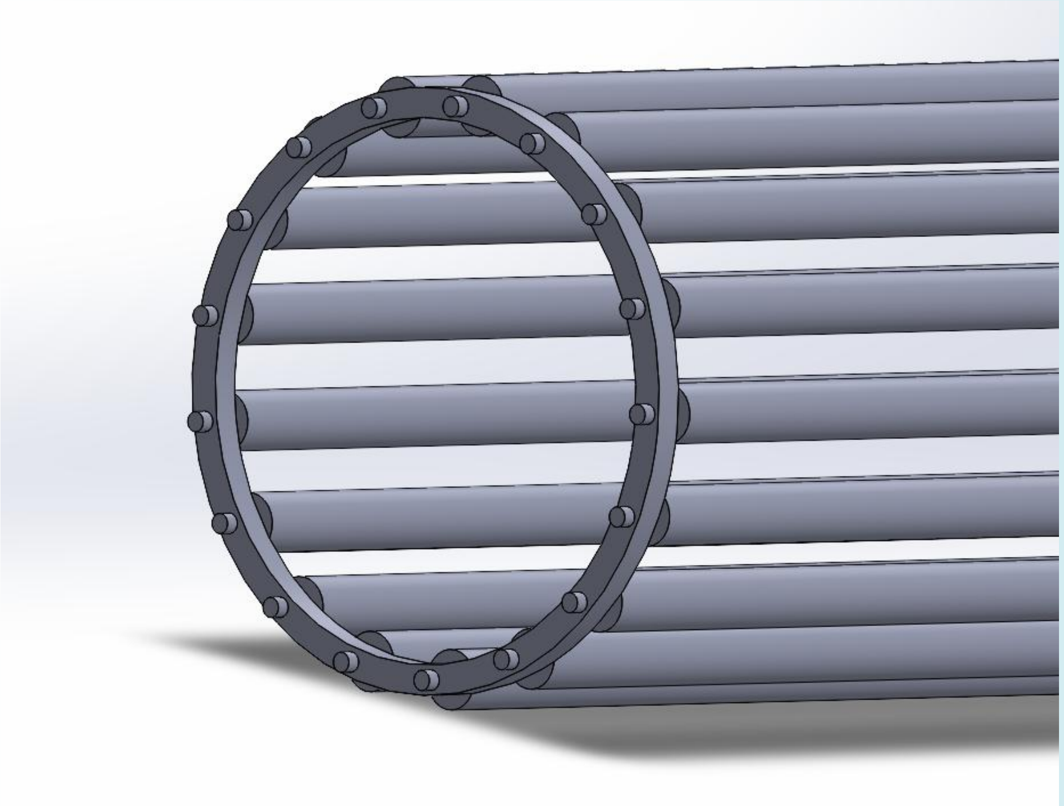
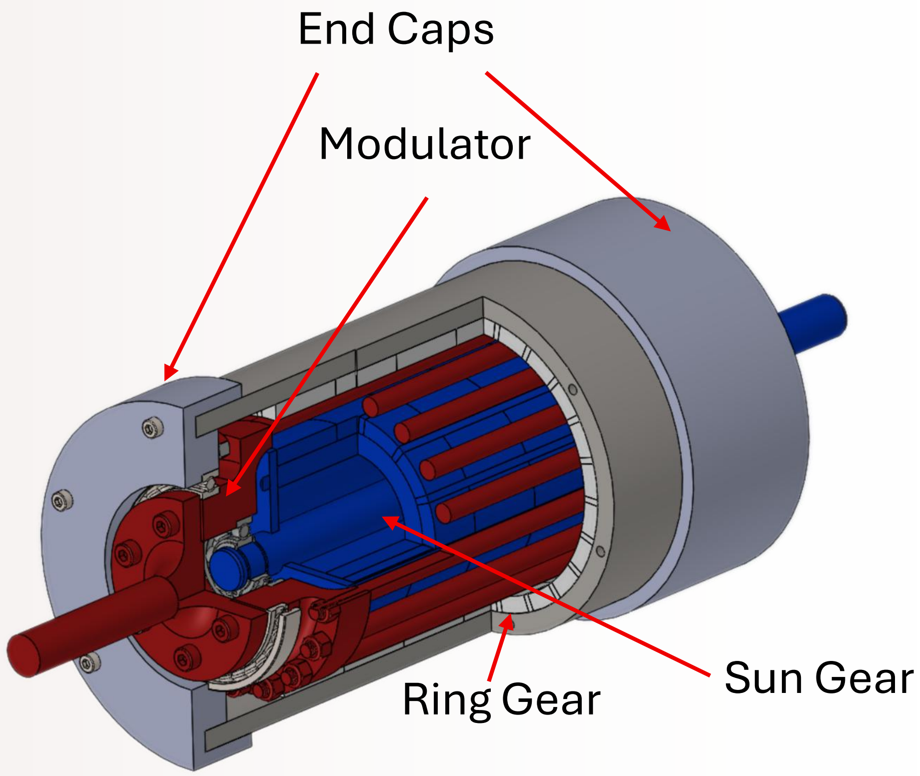
Engineering Analysis - Structural Integrity Hand Calculation

- Simple Centrifugal Force Analysis
- $F_{centripetal} = m_{core} * \omega^2 * r$
- When rotating at 1200 RPM, each flux modulator core will exert ~ 144N on the structure normal to the ring.
- Our design must take this into account for the 17 total cores.



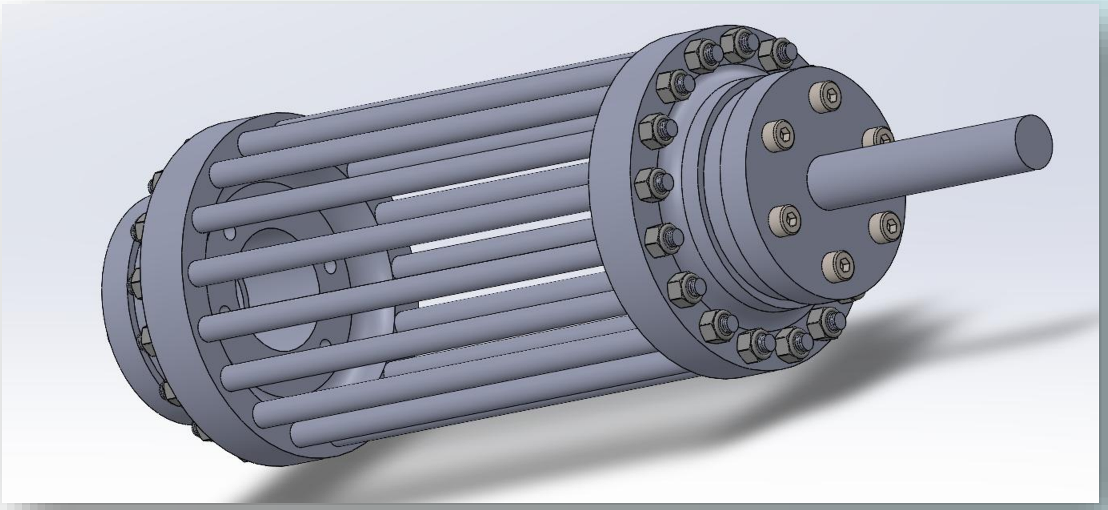
Potential Design: Off-the-shelf parts modulator design with visible cores

Detailed Design



CAD Model of Complete Gearbox

17 Flux Modulator Poles



CAD Model of Skeleton Flux Modulator

Using the previously manufactured Sun and Ring gears as constraints, the Flux Modulator was designed for the best performance given our manufacturing capabilities.

(Engineering Drawings in Appendix A)

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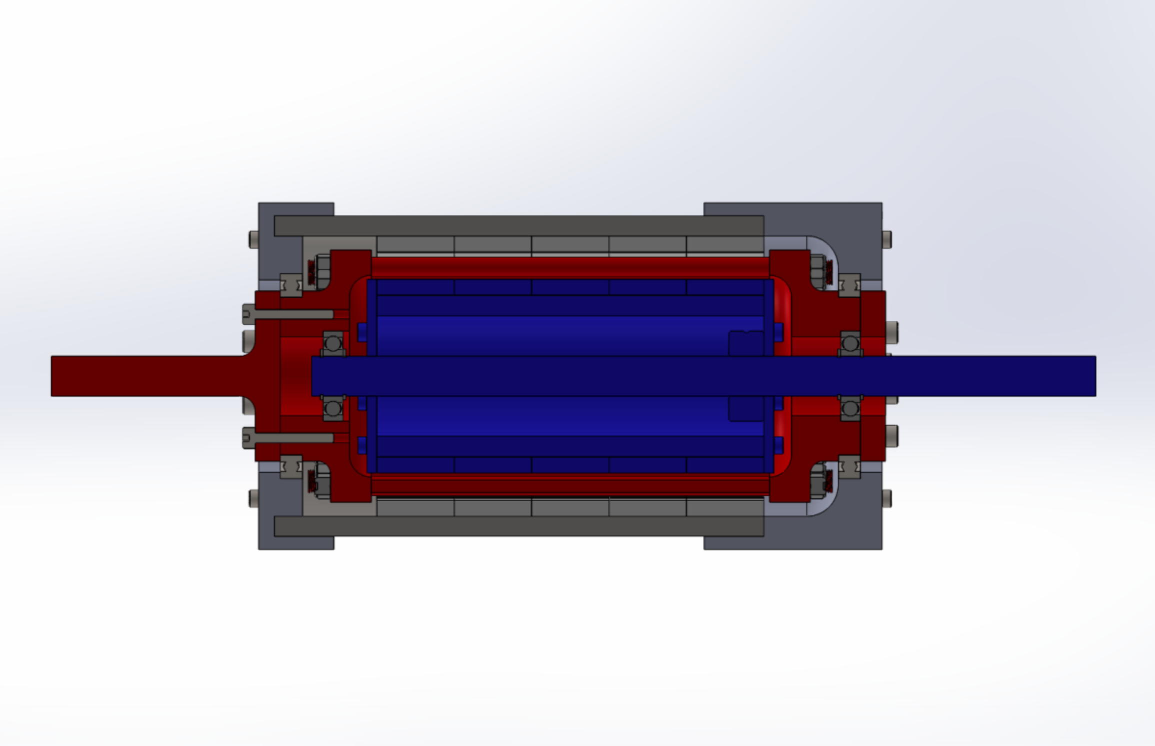
Detailed Design

Blue: Sun Gear
Red: Modulator
Grey: Fixed Ring Gear

Key Features of Design:

- 1 mm clearance rotor clearance
- Materials chosen to withstand large centrifugal forces and temperature ranges
    - 6061 Aluminum was used for the retaining components
    - 1018 Cold-Drawn Steel was used for the Modulator Cores

Designed to meet and exceed the system level objectives and derived requirements.



Cross-Section of Gear System

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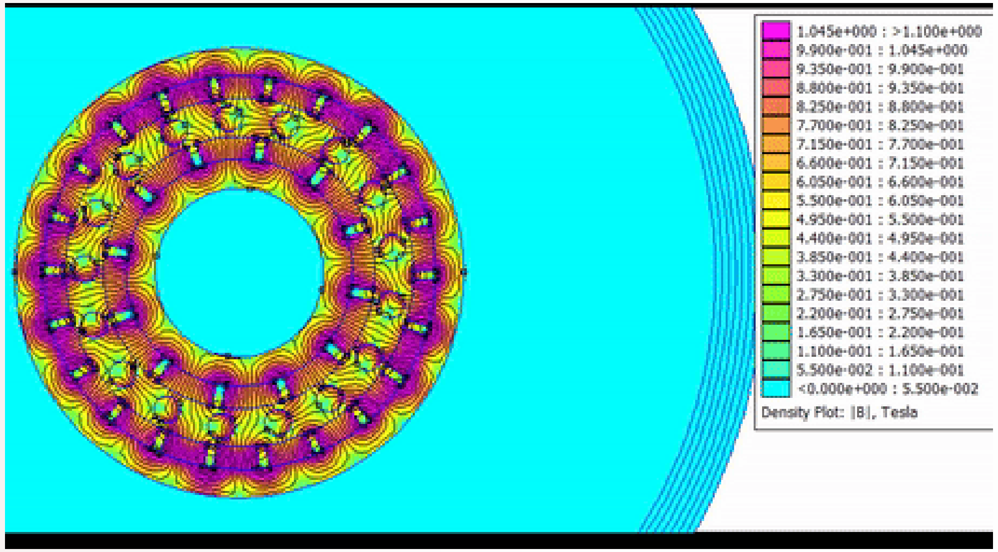
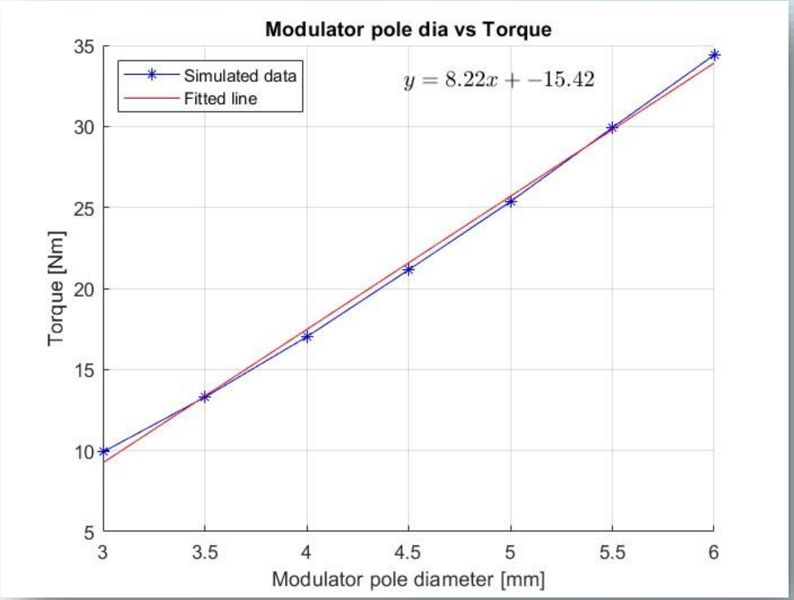
Engineering Analysis – Magnetic Torque



FEMM Magnetic Simulation



Effects of Modulator Pole Diameter on Torque Output

- Using FEMM, we determined that modulator poles of larger diameters provided larger torques.
- We maximized the torque across the gear to **35 N-m** by making our poles as large as possible (6 mm diameter)

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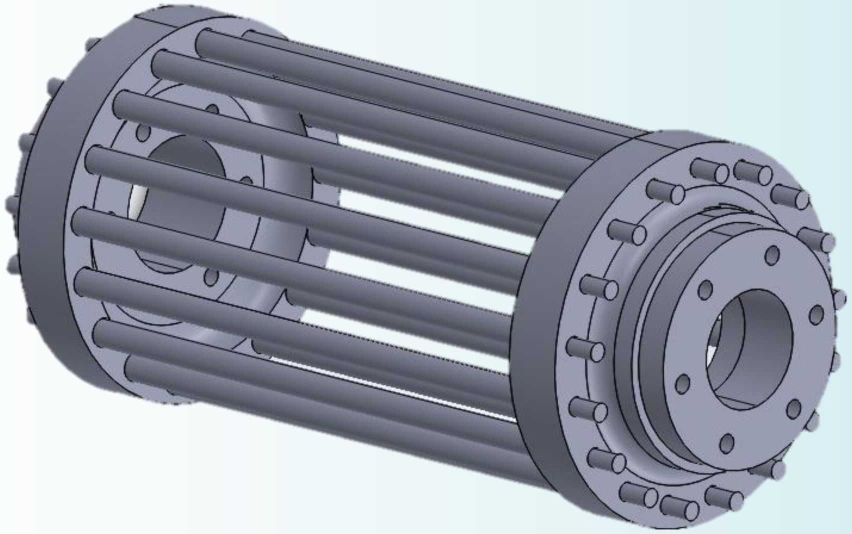
FE Structural Analysis - Loading

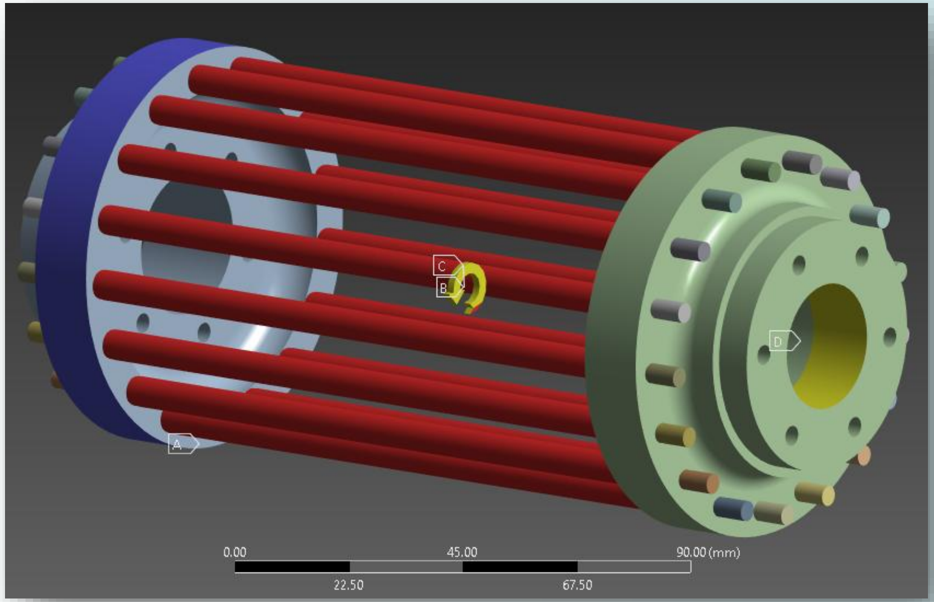
- Loading Scenario
  - Max magnetic 35 Nm moment distributed along the length of the poles.
  - This setup matches the setup of the magnetic forces we are analyzing



Simplified Flux Modulator Design for FEA Simulation

FE Analysis – Boundary Conditions

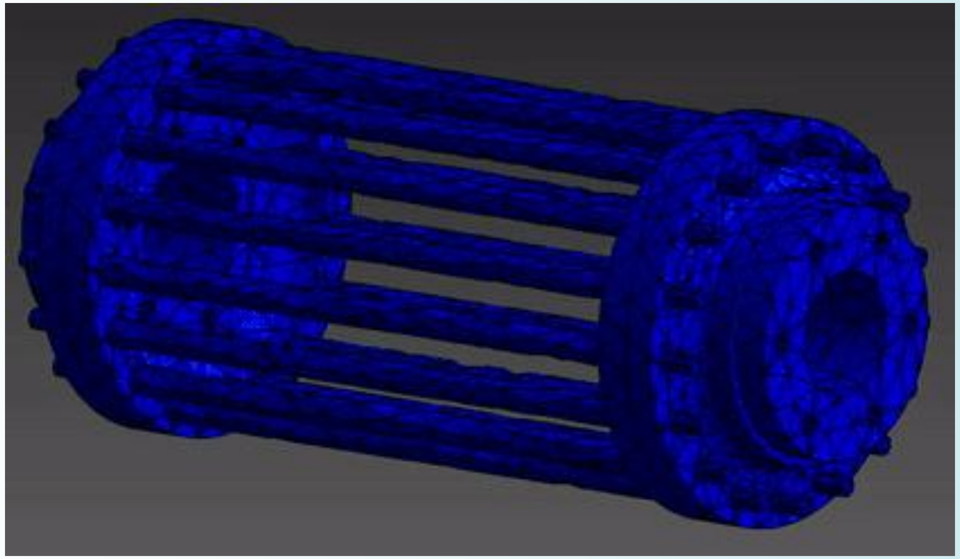
- Left end cap outer face fixed
- Moments due to magnetic flux distributed along the lengths of the 17 poles
- Rotational velocity of 1200 RPM applied to assembly to simulate centrifugal expansion
- Extreme thermal conditions of 204 C (The max allowable temperature requirement)
- Right end cap locked to prevent axial displacement



Loading Applied to Simplified Flux Modulator in Ansys

FE Analysis – Total Deformation

- With 35 N-m torque applied, deformation results converged to a percent difference of ~1.15%
- Max radial deformation of 0.187 mm (1mm clearance)
- Deformation FoS 5.35



Flux Modulator Total Deformation Visualized – (38x scaled)

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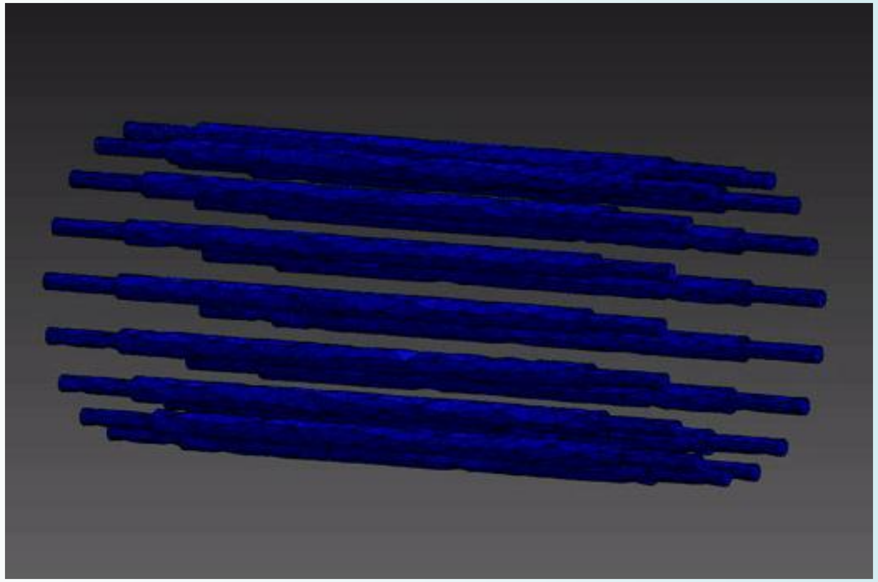
FE Analysis – Max Equivalent Stress (Poles)

- Stress results converged to a percent difference of ~0.197 %
- Max Von-Mises Stress in poles of 91.085 MPa

	Poles		Modulator	
	Combined Stress	FoS	Combined Stress	FoS
Stress	91.085 MPa	4.06	22.02 MPa	12.54



Flux Modulator Poles Equivalent Stress Visualized – (37x scaled)

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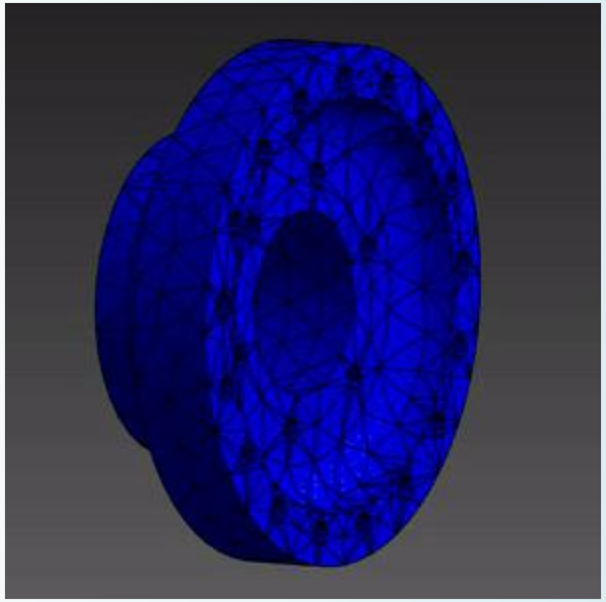
FE Analysis – Max Equivalent Stress (End Caps)

- Stress results converged to a percent difference of ~0.197 %
- Max Von-Mises Stress in end caps of 22.017 MPa

	Poles		Modulator	
	Combined Stress	FoS	Combined Stress	FoS
Stress	91.085 MPa	4.06	22.02 MPa	12.54



Flux Modulator Cap Equivalent Stress Visualized – (39x scaled)

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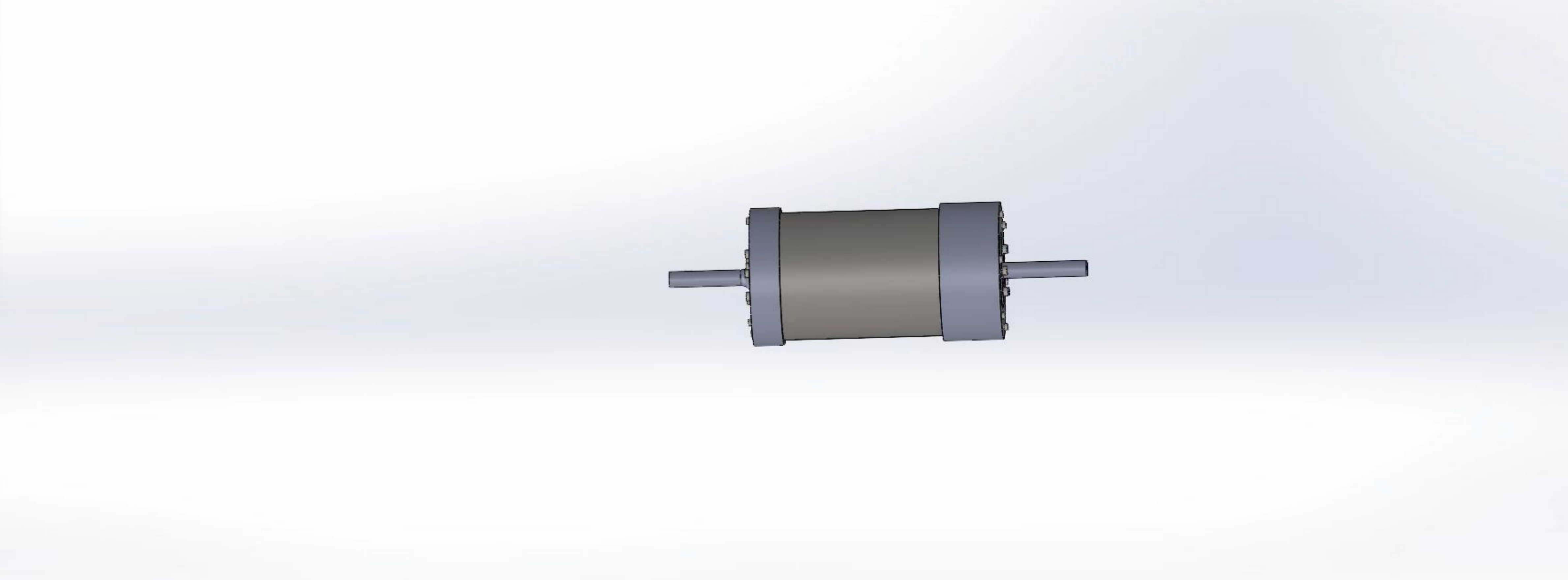
Manufacturing – CMG Breakdown



Manufacturing - Parts

- Modulator and Ring gear end caps outsourced to PCBway (6061-T6)
- Modulator cores machined in Applied lab with stock from Mcmaster (ANSI 1018 CD)
- The existing Ring gear ends were machined slightly to fit easier within the caps, and to ensure concentricity.

CNC machined Modulator caps

Machined Modulator Cores

Ring gear with machined ends

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Assembly

- Assembly of the Modulator was difficult.
- The cores had to be pressed into the cap one at a time as the magnets were pulling them.
- Putting the Sun/Modulator assembly into the Ring gear and caps was not as challenging.

Putting the Modulator around the Sun Gear

Fitting the Ring Caps

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Test Bed

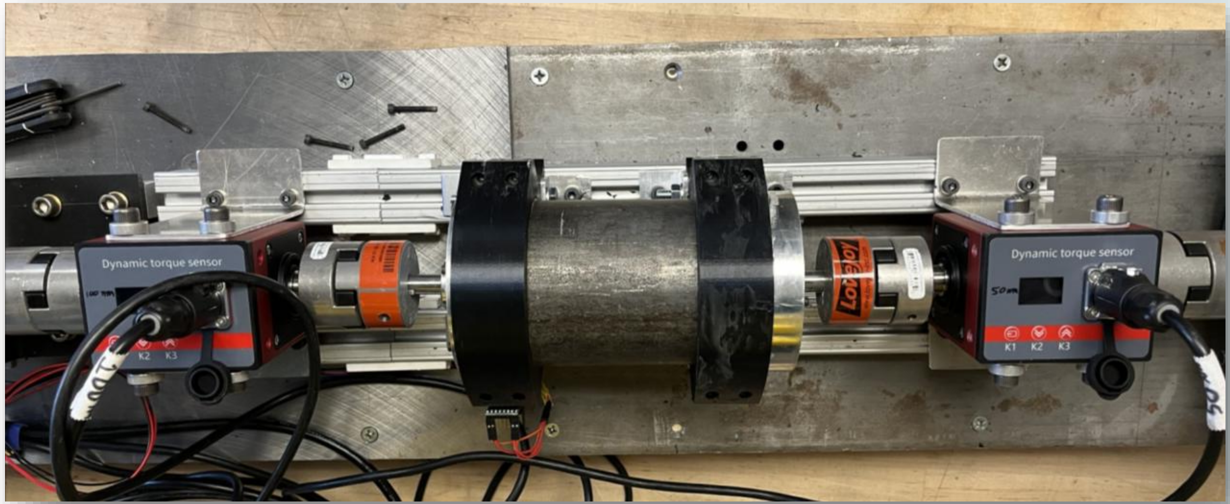
- Test bed sized to accommodate motor, gear, two torque sensors, particle brake, and power supply.
- Brake and torque sensor mounting brackets were manufactured using scrap metal from the Applied lab. CMG mounts were printed in ABS.
- Safety shield

Image of Finalized System

Test Method

- Magnetic Gear must be able to operate in up to ~205° C
  - Tested using Temperature Stickers, Thermal Camera, and Thermocouple
- Magnetic Gear should be able to produce 6 N-m of torque
  - The Rotary Torque Sensors and the Magnetic Particle Brake were used to determine the output torque
- Magnetic Gear shall be a gear ratio between a 3:1 and 2:1 reduction
  - The Rotary Torque sensors display the torque and RPM ratio
- Magnetic Gear should demonstrate a 95% mechanical efficiency
  - Using the Rotary Torque sensors to find the torque and RPM ratio, the product of the two ratios is efficiency

FLUKE Thermal Camera from Flowserve



Torque sensors and CMG

Test Method Procedure

Tests: Torque + Power + Efficiency, Operating Temperature, “Steady State” Temperature, Max Torque Test, Speed Ramp Up Test

For Operating Temperature and Torque + Power + Efficiency Tests:

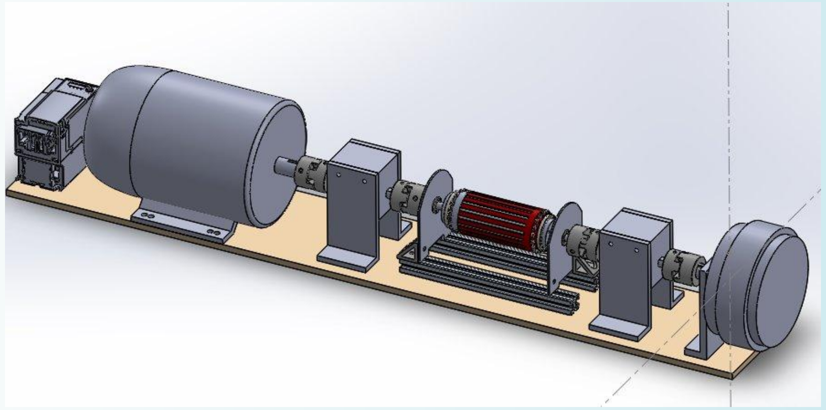
1. Wire and plug in all sensors and motor
2. Ramp-up motor to 250 RPM using the input torque sensor
3. Apply brake load
4. Record input and output RPMs and torques
5. Increase RPM by 250
6. Record the new RPMs and torques
7. Repeat until ~2250 RPM is reached
8. Record shaft and body temperatures using thermal camera
9. Once sufficiently cooled, disassembly record the reading from the temperature sticker

For “Steady State” Temperature Test

1. Run gear at 1000 rpm for an hour and measure external temperature every minute using thermocouple

For Max Torque Test:

1. Apply brake load to maximum
2. Use torque wrench to turn input shaft
3. Record maximum amount of torque before magnet skips



Test Rig Schematic

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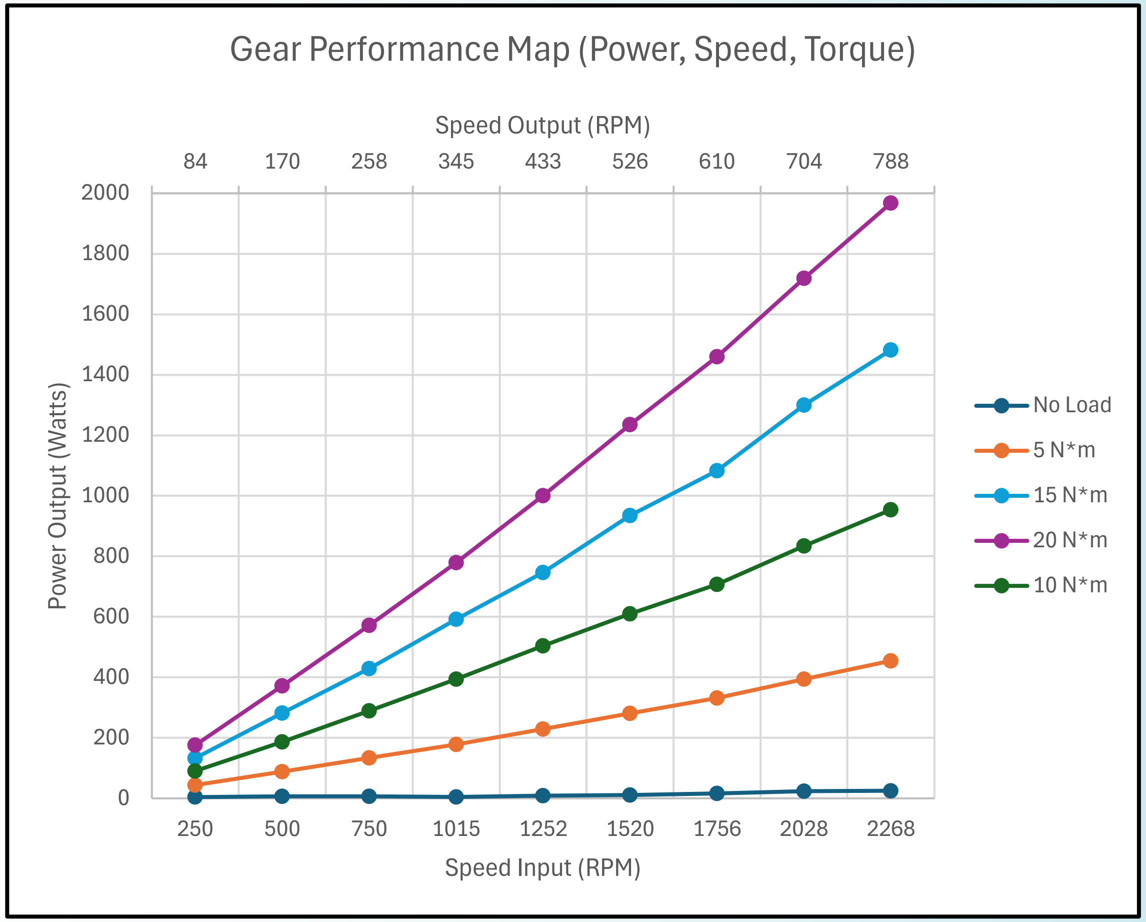
Performance

Torque Output, Speed Input, and Efficiency

Torque Output (N*m) \ Speed Input (RPM)	234	484	736	981	1232	1491	1734	2001	2237
20	89%	84%	80%	78%	77%	75%	74%	73%	73%
15	85%	81%	76%	73%	71%	69%	67%	67%	66%
10	86%	74%	70%	66%	64%	61%	60%	58%	58%
5	68%	56%	49%	45%	42%	41%	40%	38%	38%
0	17%	9%	5%	2%	3%	3%	3%	4%	4%



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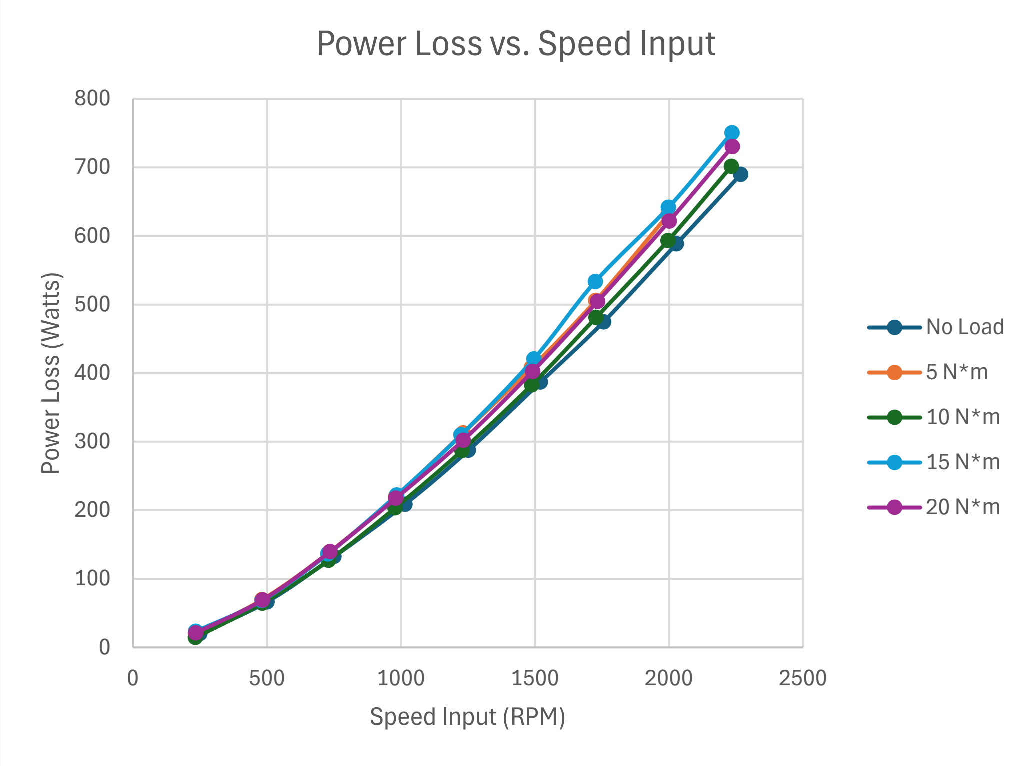
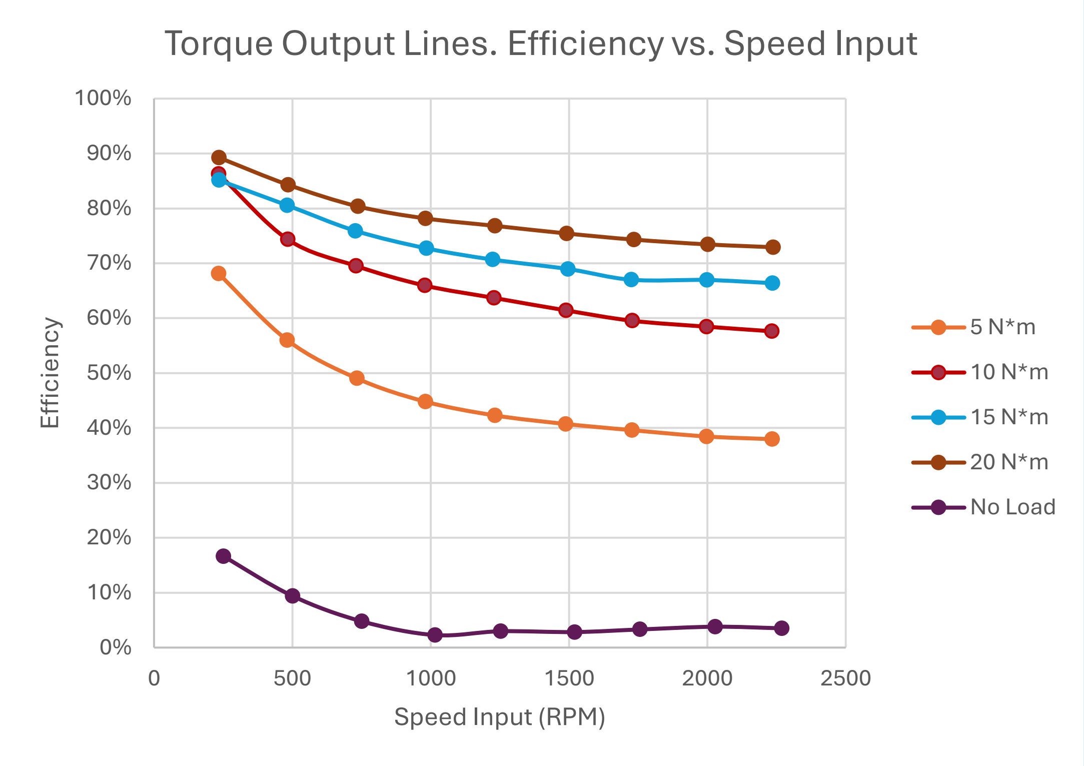
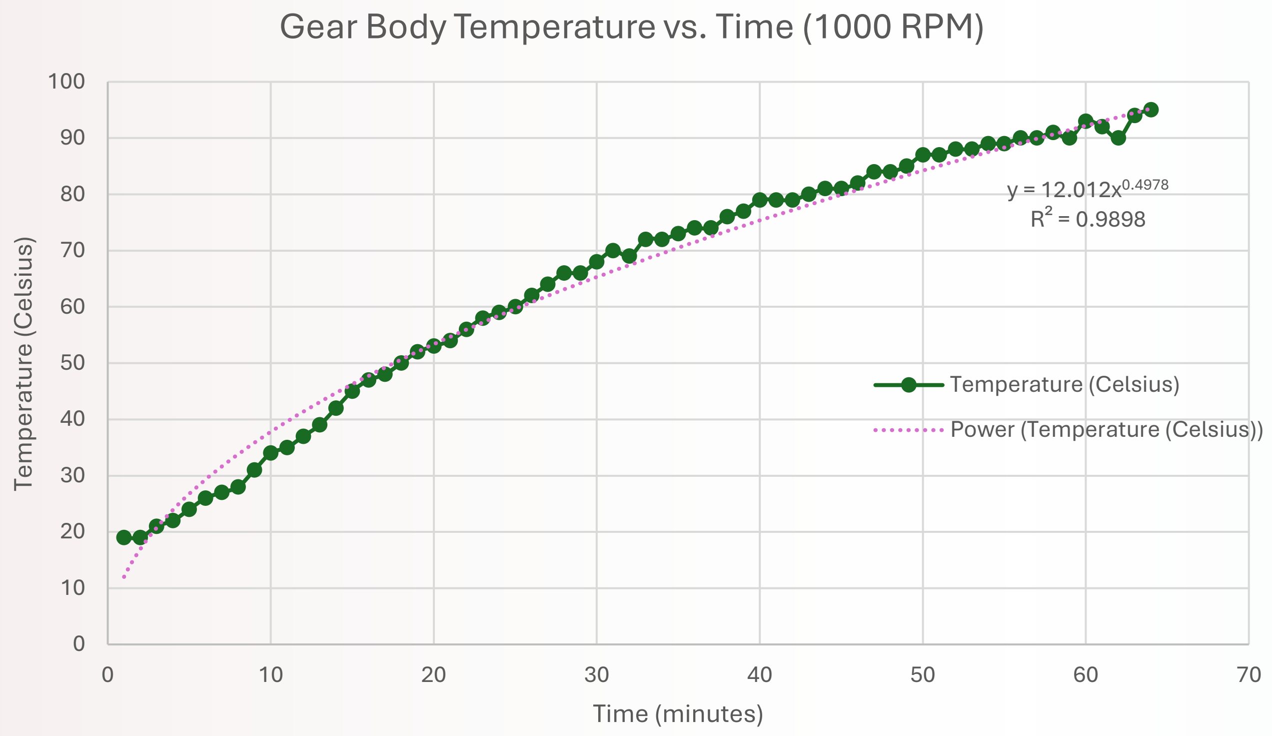
Loss Analysis

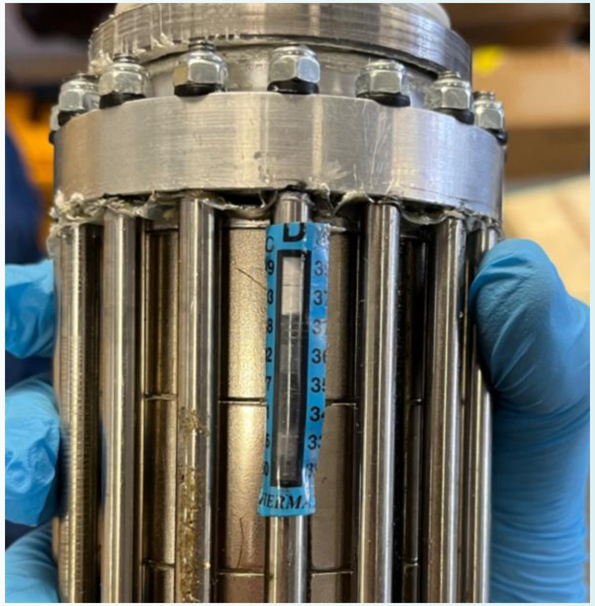




Temperature



FLUKE Thermal Camera in use (max 76° C)



Internal Temp Sticker Results (188° C)

Test Results Comparison

Data	Required	Expected	Result	Status
Input Torque	2.1 N-m	13 N-m	Max ~20 N-m	Achieved
Output Torque	~6 N-m	36.8 N-m	Max ~55 N-m	Achieved
Gear Ratio	3:1 – 2:1	2.83	2.83	Achieved
Efficiency	95%	N/A	Max 89%	**>= 89%**
Temperature	~205° C	N/A	~188° C	Achieved

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Status of Requirements

Legend		
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DERIVED REQUIREMENTS (Scaled Down)			Status
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TR 2.1	The approximate gear ratio shall be between a 3:1 and a 2:1 reduction.	The previous team was required to accommodate three different ratios. For simplicity, we will aim for one, to prove the concept's design to Flowserve.	Achieved
TR 3.2	The gear should demonstrate a 95% mechanical efficiency.	We aim to be consistent with the efficiency ranges of a typical Concentric Planetary Gear design.	>= 89%
TR 4.4	The gear should fit within a 177.8-millimeter (7-inch) diameter cylinder with a 215.9-millimeter (8.5-inch) length.	To fit within current Flowserve pump designs.	Achieved
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TR 7.3	Max operating temperature of 205° Celsius (400° Fahrenheit).	We need to make sure that the epoxy and magnets operate in this temperature range.	Achieved
TR 8.1	The gear should scale to larger sizes, torques, and gear ratios.	This allows for more ways to test as needed, as well as to present the true potential of the gear.	In Progress
TR 9.3	The gear should reuse already manufactured parts from last year's design team.	This will allow the team to focus more on improving the flux modulator design and the overall efficiencies.	Achieved

Status of Requirements

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DERIVED REQUIREMENTS (Scaled Down)			Status
TR 3.2	The gear should demonstrate a 95% mechanical efficiency.	We aim to be consistent with the efficiency ranges of a typical Concentric Planetary Gear design.	>= 89%

Team 207's Magnetic Gear Peak Efficiency hit was 89%, falling **short** of the 95% goal.

Why did efficiency fall short?

- Eddy currents
  - Future testing can quantify how electrical insulation improvements affect efficiency.

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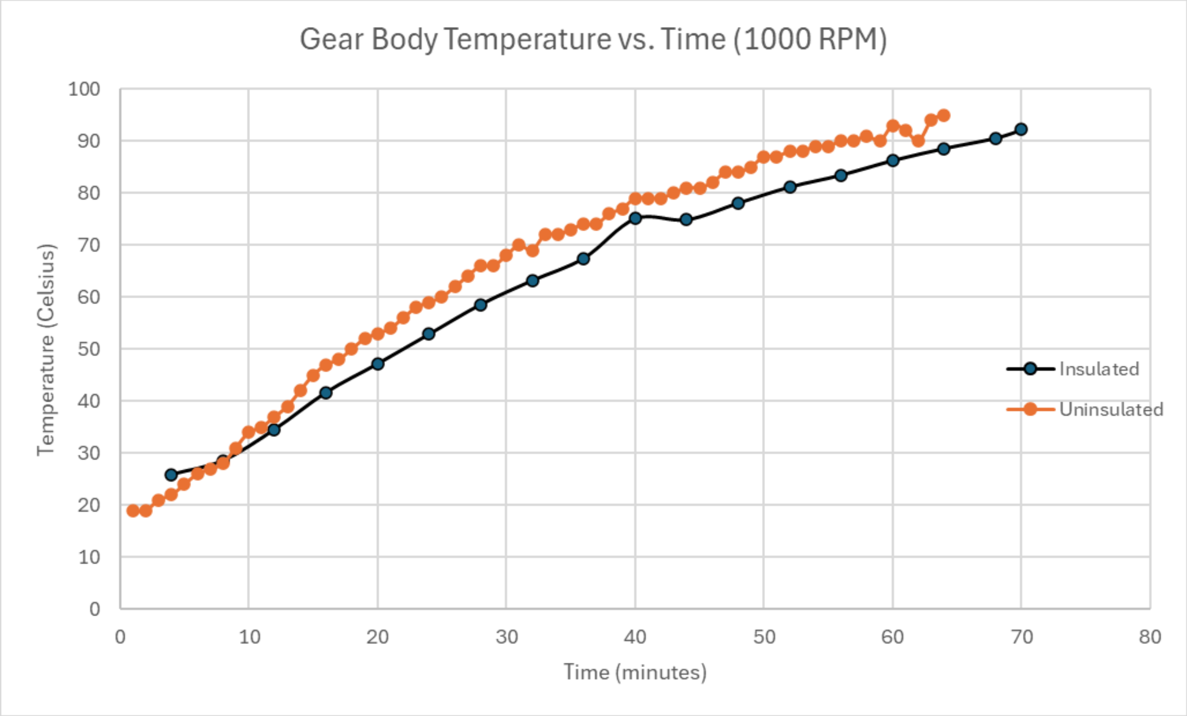
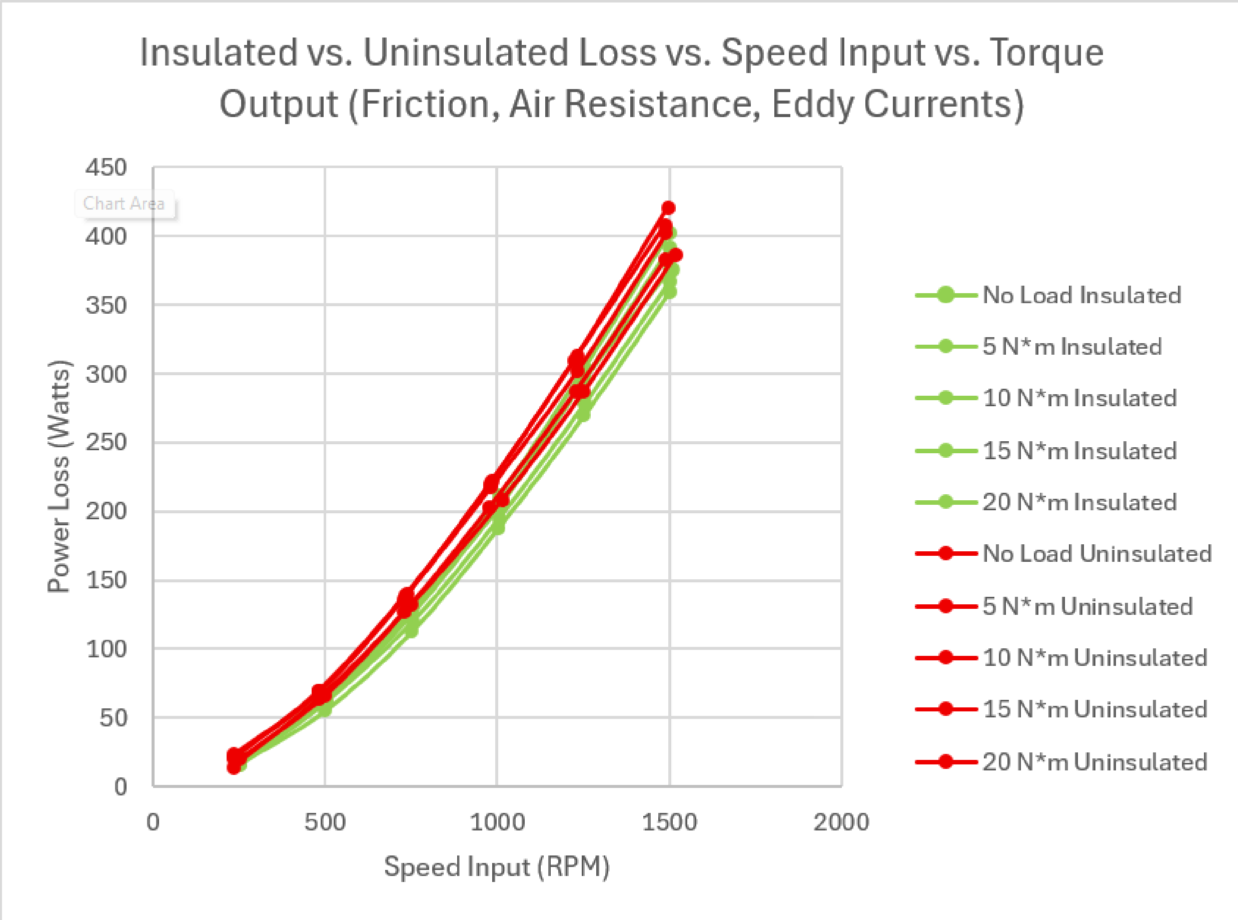
Improvement – Insulated Poles

Performance - Upgraded

Insulated Torque Output, Speed Input, and Efficiency							
Torque Output (N*m)	20	92%	85%	83%	80%	77%	76%
	15	90%	83%	78%	75%	72%	71%
	10	84%	73%	68%	64%	62%	60%
	5	70%	59%	53%	47%	44%	42%
	0	15%	14%	12%	10%	10%	11%
		234	484	736	981	1232	1491
		Speed Input (RPM)					



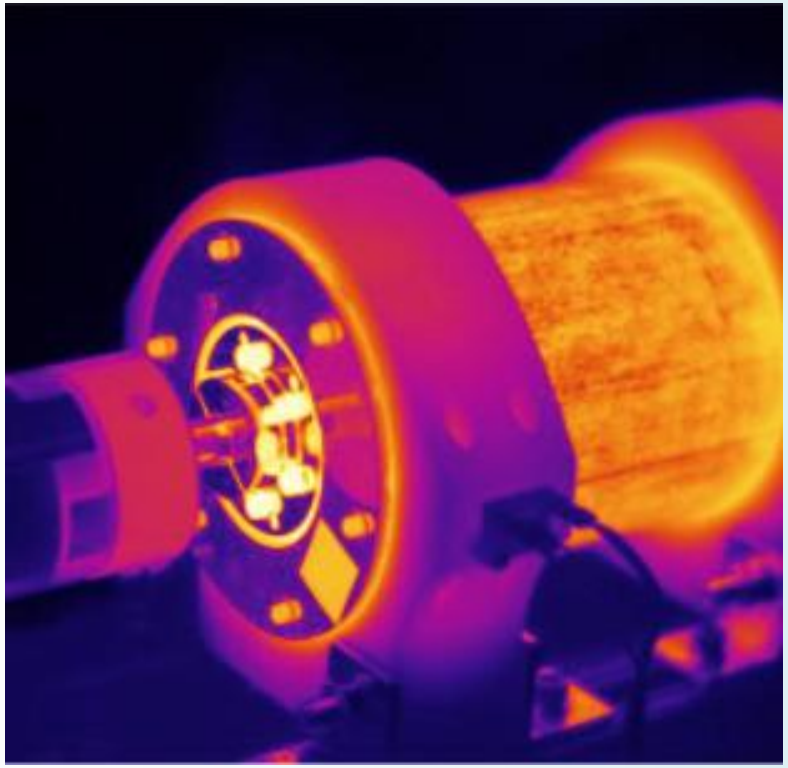
Performance - Upgraded



Breakaway Torque – Unchanged
Max Efficiency 93% @ 40 N*m

Unexpected Outcomes

- The losses appeared to only be a function of speed.
- The heat travelled from the modulator to the ring gear which functioned as a heatsink.
- The initial gear grease boiled
- We observed discoloration most likely due to oxidation or contamination



FLUKE Thermal Camera image (max 93° C)

Conclusions

- Team 207 designed, fabricated, and tested a novel CMG design that surpassed requirements and expectations and remained within the $5,000 budget.
- A balance can be struck between structural integrity and eddy current losses. A structurally sound modulator with aluminum caps and solid cores can operate at useful values of temperature and efficiency.
- Efficiencies between 90% and 95% are attainable at full load with insulated cores.

Conclusions cont.

- Max modulator temperature: **188° Celsius (370° Fahrenheit)**
- Fastest Ramp-Up Speed: **<13 seconds to 3600 RPM (motor constrained)**
- Max Torque Output: **55 N-m**
- Max efficiency: **93%**

Lesson Learned

- Eddy current losses are a real problem and increase with speed.
- At low speeds, useful power output dominates eddy current losses, and efficiency is higher.
- Assembly of a magnetic gear is difficult and requires careful design and planning.
- Thorough testing of a magnetic gear requires measurement of speed and torque at the input and output as well as temperature monitoring.

Future Work – What could be done differently

- Quantify and reduce eddy currents
  - Simulate and quantify
  - Reconcile with thermal and efficiency losses
  - Consider laminated cores and outsource manufacturing
  - Experiment with active cooling
- Improve assembly process
  - Assembly jig
- Reduce drag on flux modulator
- Test gear with higher speeds and larger loads

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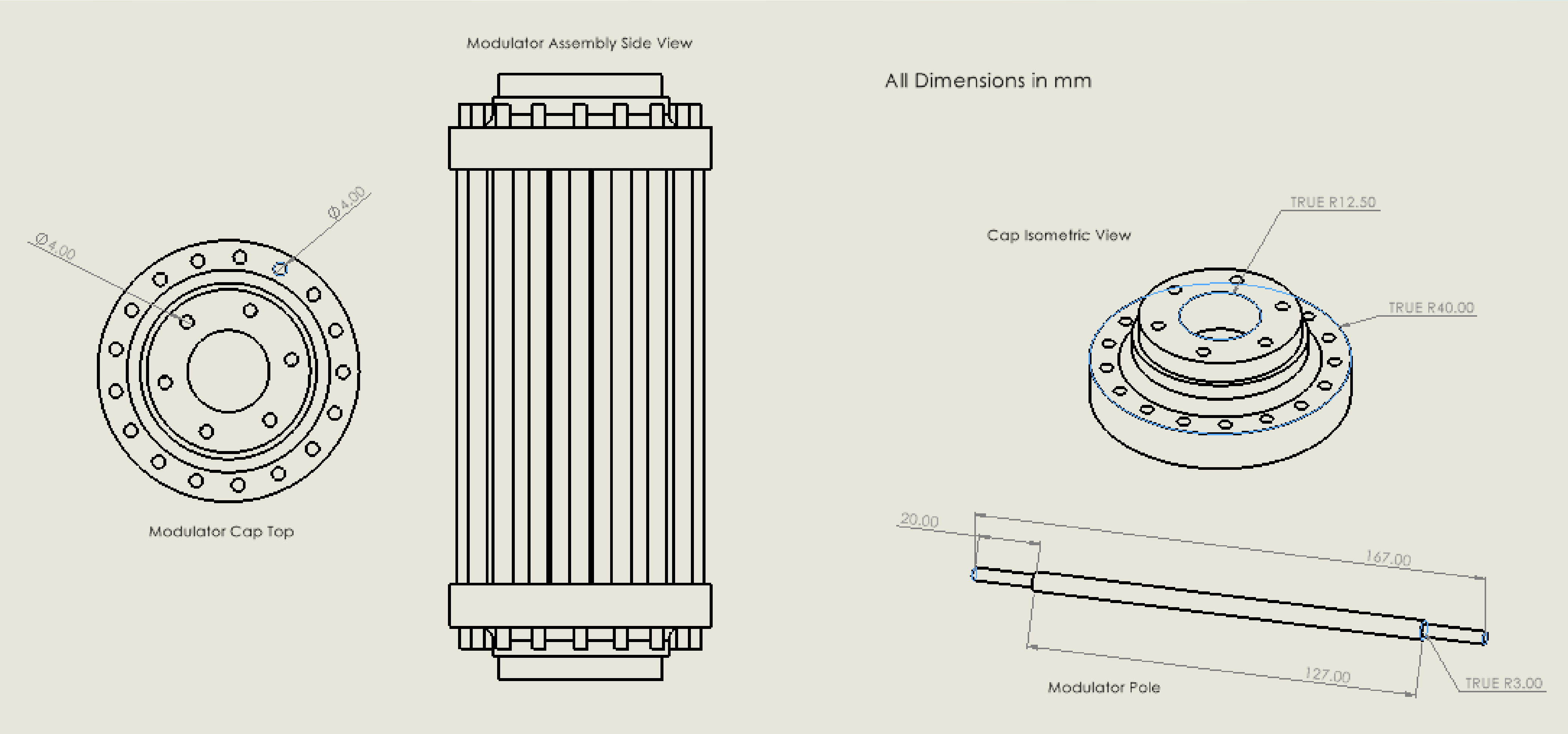
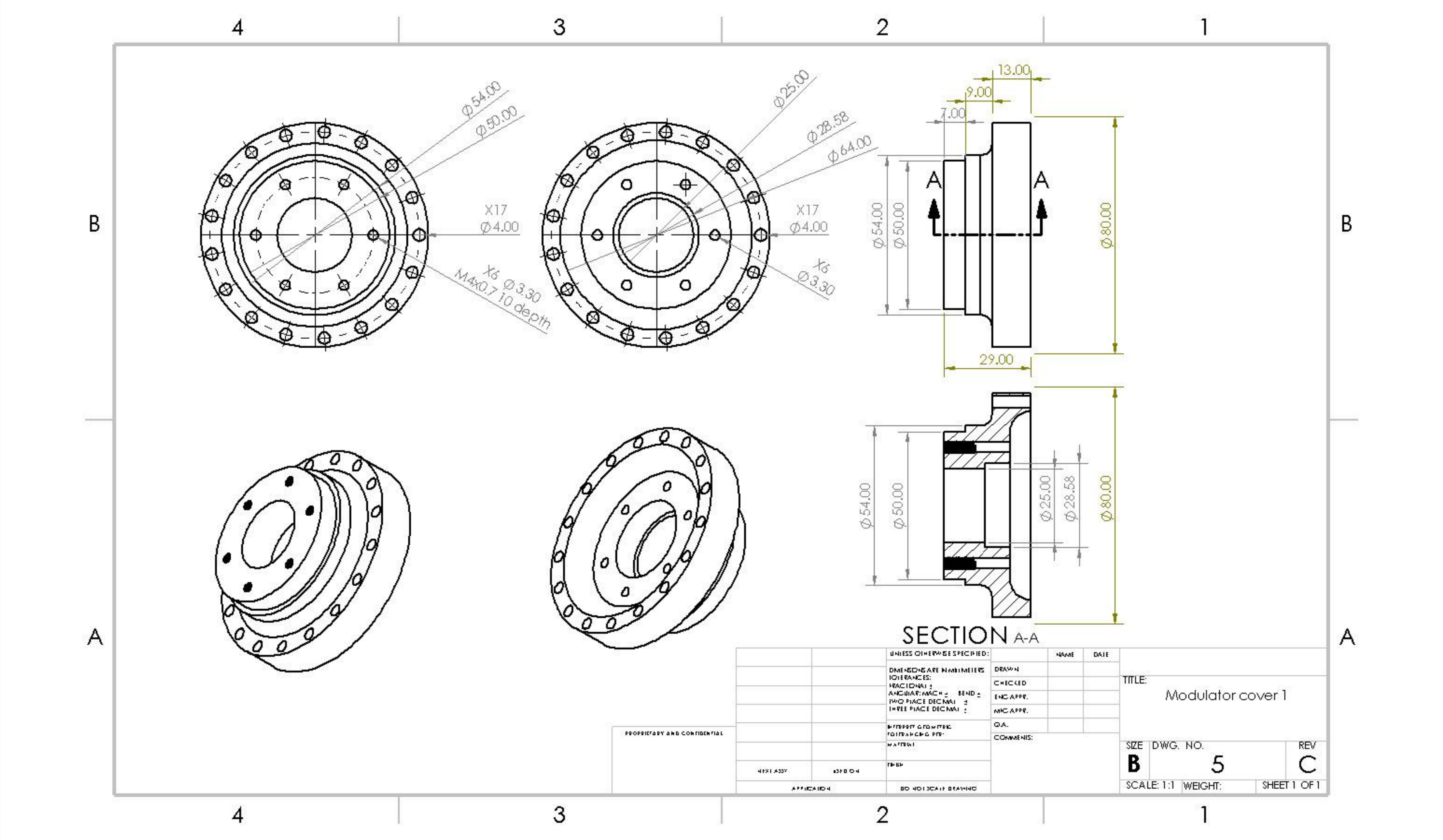
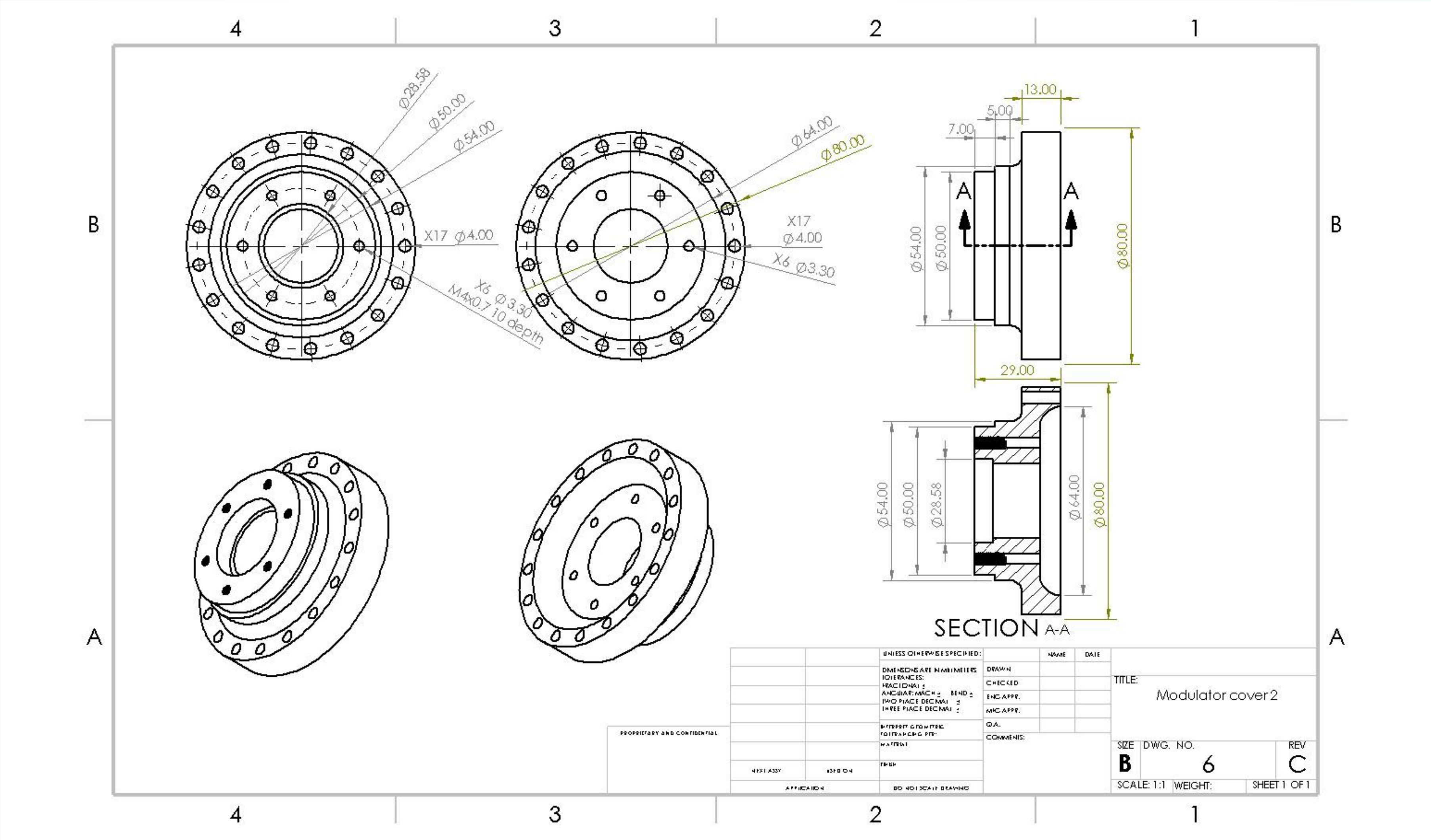
Appendix A – Modulator Engineering Drawing



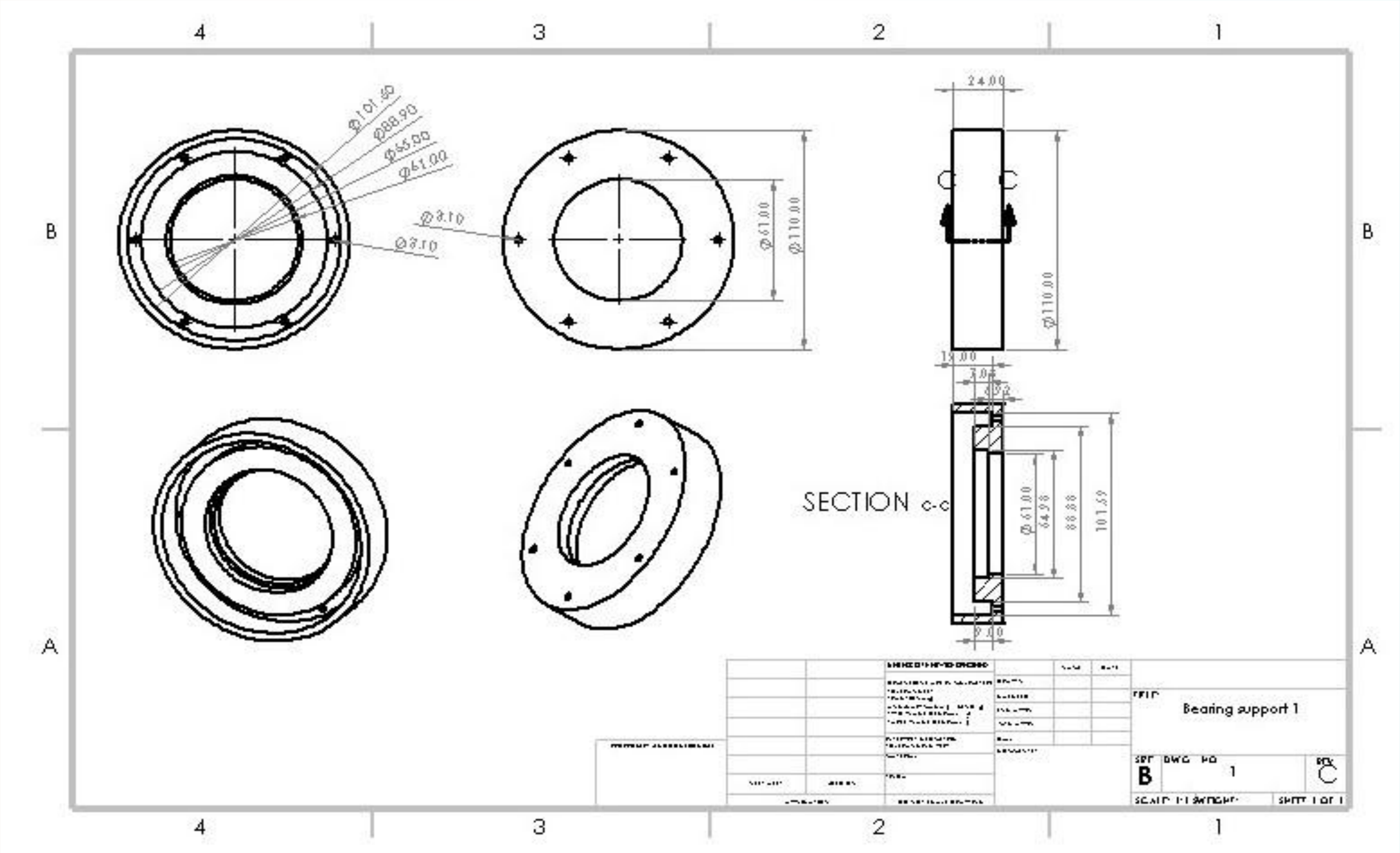
Appendix A – Modulator Cap-1 Drawing



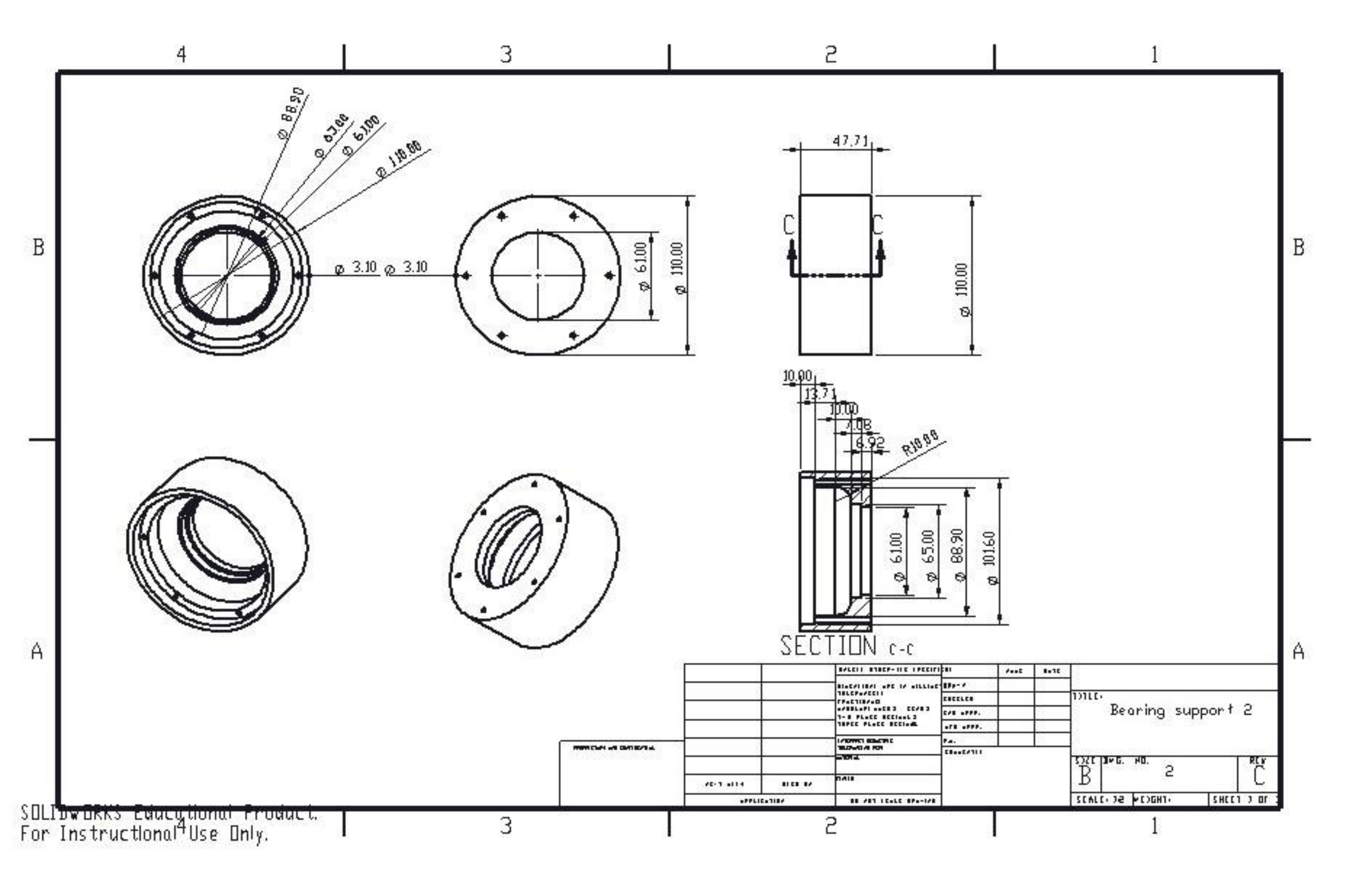
Appendix A – Modulator Cap-2 Drawing



Appendix A – Ring End Housing-1 Drawing



Appendix A – Ring End Housing-2 Drawing



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Appendix A – Insulated Mod-Pole Design