Hydraulic Electromagnetic Magnetostrictive Actuator

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Project Proposal

Document

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Contents

1. Introduction

This report details the project proposal by the Magnetostrictive Actuator capstone team from Northern Arizona University. The project was initiated by Michael McCollum, a Chief Engineer of Pneumatic Controls Technology for Honeywell Incorporated. Mitchell Thune, a recent NAU graduate, is also working with Michael McCollum on this project. Honeywell Aerospace designs valves for airplane air conditioning systems. The client wants to replace an electromagnetic transducer with a magnetostrictive material in the pneumatic control systems used on commercial airliners. The magnetostrictive material for this project is Terfenol-D.

Our team has performed research on various subjects associated with this project including the operation and utilization of solenoids as they pertain to actuation technologies, magnetic shape memory alloys (MSMA), and hydraulic-driven pneumatic actuation. A design solution has been designed utilizing a Terfenol-D core with a piston cylinder style lever. This type of lever amplifies the stroke length via a change in fluid volume as opposed to linear motion translation. The design has been designated the Hydraulic Electromagnetic Magnetostrictive (HEM) Actuator.

The proposal of this design is based on proof of concept experimentation. Dimensions for the proposed design are dependent on calculations that can be seen in the Section 5 of the report, as well as Appendix A. Additional designs have been conceptualized and will be pursued, given the time and resources are available to continue research and development.

2. Project Definition

The definition of the project is broken into the need statement, project goal, objectives, and constraints. The goal is written as a direct answer to the need statement. The objectives list the features to be included in the design. The constraints are the limitations that we must work with in designing this product.

2.1 Need Statement

Currently, there are no operational actuators for aircraft valve systems using the magnetostrictive material Terfenol-D.

2.2 Project Goal

The goal of this project is to develop a viable actuator that incorporates the magnetostrictive properties of Terfenol-D.

2.3 Objectives

After meeting with the client and learning more about the project, the team was able to generate a list of features that will be included in the design. Table 1 shows each objective the team has defined, and how each objective is measured (primarily in English customary units).

Table 1: Project Objectives

Objective	Measurables	Units
Decrease Hysteresis Effect	Magnetic Field Strength	A/m*
Increase Strain	Percent Elongation	in/in
Measure Output Force	Force	lbf
Reduce Operation Time	Time	milliseconds
Maximize Work Per Unit Weight	Work, Weight	ft^2/s^2

* English units for magnetic field are not well-defined.

2.4 Constraints

Along with the objectives and features that the design will include, our team was also given a list of criteria that the design must follow.

- At least 25lb of force exerted
- Need at least 0.03in stroke (based off of 3in length rod)
- Must cost less than $5000
- Must be smaller than 3x5x12in
- Coefficients of thermal expansion must be constant throughout device
- System must be cooler than 212°F
- Greater than 1:10 ratio of input to output distances

Among these criteria, the most complex constraints to achieve are maintaining the input/output ratio with a limited stroke, and keeping the coefficients of thermal expansion constant. For this reason, these constraints should be the starting basis for a design.

3. Proof of Concept Design

Due to lack of the Terfenol-D core the proof of concept involves only the lever and coil. Figure 1 shows the proof of concept designs for both the solenoid and the lever system. The lever shown on the right proves that the small stroke can be amplified with a 15:1 lever ratio. With an input of 75µm (0.003in) the lever system is able to output an ending stroke of approximately 1mm (0.045in). The coil consists of magnetic wire with over 1200-1300 turns and a 12V power supply to produce a magnetic field. Proof of the field is demonstrated by pulling small magnetic materials into the center. The magnetic flux density of the magnetic field with a magnitude of 30 mT was produced by a 2A current running through the solenoid.

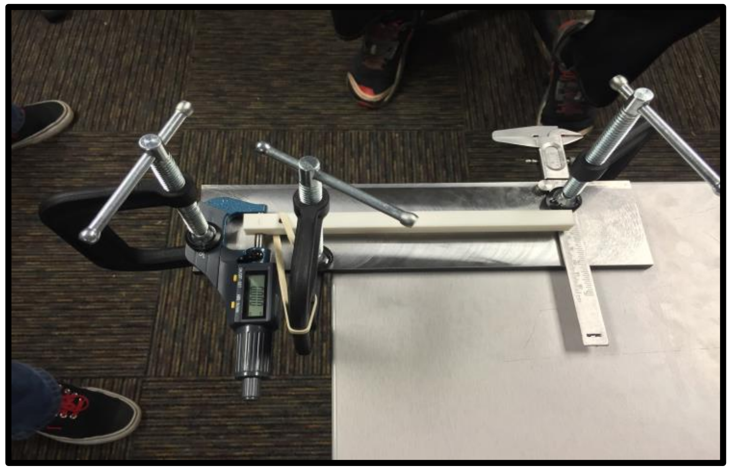

Figure 1: Proof of Concept for the Solenoid (left) and Micromotion (right)

4. Proposed Design

Figure 2 shows the Solidworks CAD model for the proposed design. The device utilizes the Terfenol-D rod in the center, with a sleeve of insulation surrounding it. The sleeve is then wrapped with magnetic copper wire and enclosed in an iron casing in order to redirect the magnetic field to the center (where the Terfenol-D rod is located). The center Terfenol-D rod is connected to a piston that will experience the stroke when the electromagnetic field is applied. This stroke will then move the hydraulic lever from the large hydraulic chamber to the smaller chamber where the actuator piston is located. As the length of the Terfenol-D rod increases and decreases, the smaller piston creates actuation. There are several bolts that span the length between the aluminum end cap and the large piston in order to keep the Terfenol-D rod in a constant state of compression.

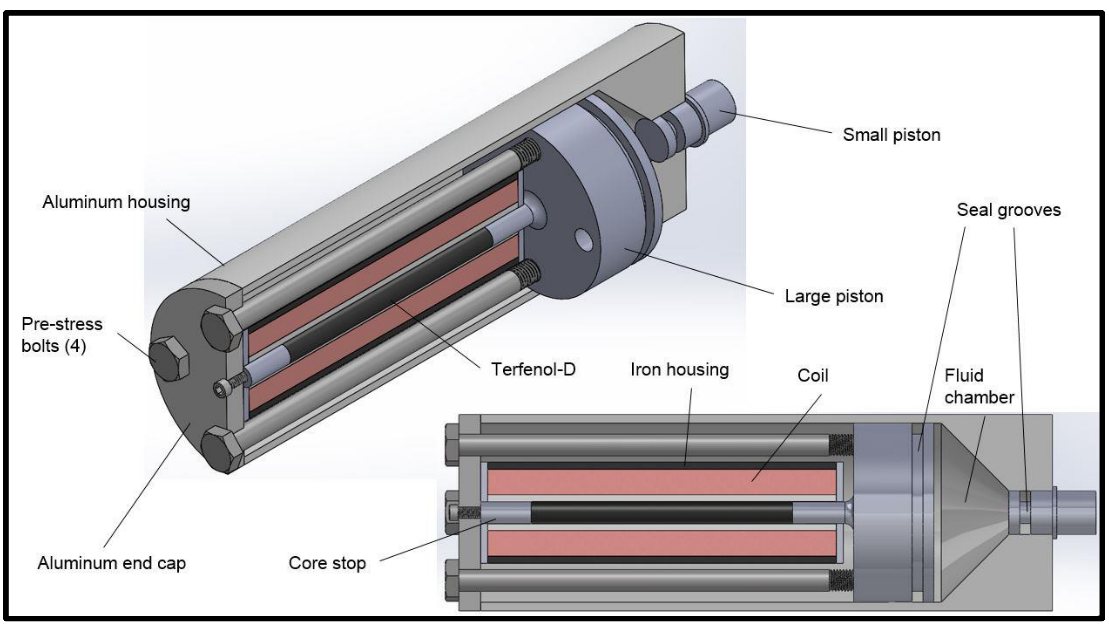

Figure 2: HEM Actuator with Terfenol-D Core, isometric and right view with corresponding labels

Figure 2 shows the proposed dimensions for the device. The largest diameter of the system is 2.25in to accommodate room for the 0.25in bolts to fit in the aluminum housing. The total length of the device is 7.41in from the aluminum end cap to the end of the smaller piston, but this total length can increase as required by the application. The Terfenol-D rod is 0.25in diameter and 3in long. The coil that is wrapped around the core was calculated to have an outside diameter of approximately 0.82in. This means that the iron housing's inner diameter must accommodate this dimension, and in order to keep the device compact, we have chosen the outside diameter to be just short of 1in.

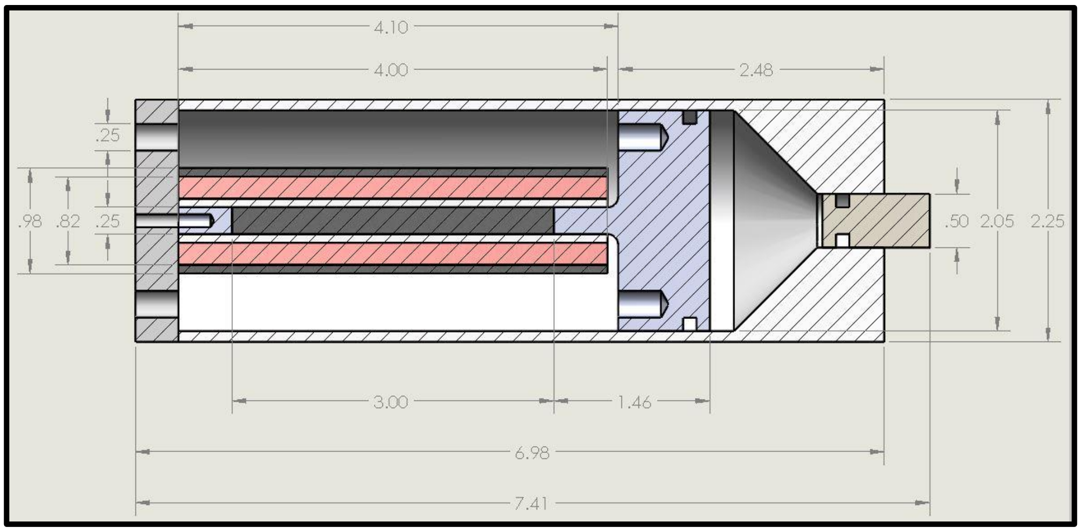

Figure 3: HEM Actuator with Terfenol-D core, drawing and dimensions (in inches), right section view

5. Justifications for Design

The current design of the Hydraulic Electromagnetic Actuator (HEM) comprehensively satisfies the objectives and constraints for the project. Each component has been designed based on the criteria defined in *Section 1*. This section details the justification for each component and respective material composing each component. Every part is designed with a factor of safety of 2 or greater and no component is designed to ever exceed the yield strength of the material used. The materials needed to achieve this factor of safety are discussed in detail in *Section 6*, but will be used to demonstrate the calculations done for each component of *Section 5*.

5.1 Terfenol-D Core

The dimensions of the Terfenol-D cylindrical core are 3in long by 0.25in diameter. This size was chosen based on information from the client for actuators currently in use at Honeywell. In the client's original concept of the design, they used these dimensions of Terfenol-D. In order to verify these dimensions, Team 15 used the constraints defined in *Section 1.3*, which states that the final stroke must be at least 0.03in with a 1:10 lever ratio. The Etrema website shows that an average elongation value is 1%, meaning that the initial length of the Terfenol-D core must be 3in before elongation [1]. To determine if the size of the core is usable as well, Table 2 calculates the factor of safety in using a 0.25in diameter core, the maximum output force of Terfenol-D, and the minimum compressive strength of Terfenol-D [1]. Terfenol-D is extremely brittle, so the compressive strength is used as opposed to the yield strength.

Table 2: Dimension of Terfenol and Factor of Safety

Length	4 in
Diameter	0.25 in
Cross-Sectional Area	0.049087 in^2
Maximum Force Applied	1000 lbf
Minimum Compressive Strength	43500 psi
Pressure Generated	20371.83 psi
Factor of Safety	2.135301

The 0.25in diameter has a factor of safety slightly above 2 when using all of the least risk values for Terfenol-D. The factor of safety will likely be much higher in the actual design, however due to the fact that the core is the most expensive and most difficult component to replace, an excessive factor of safety is desired.

5.2 Required Magnetic Field Strength

The core does not elongate linearly with an increase in magnetic field, and for this reason it is difficult to pinpoint the exact magnetic field strength required. Figure 4, gained from Etrema displays the strain values obtained at different magnetic field strengths [1]. Each curve on Figure 4 represents a different compressive strength value.

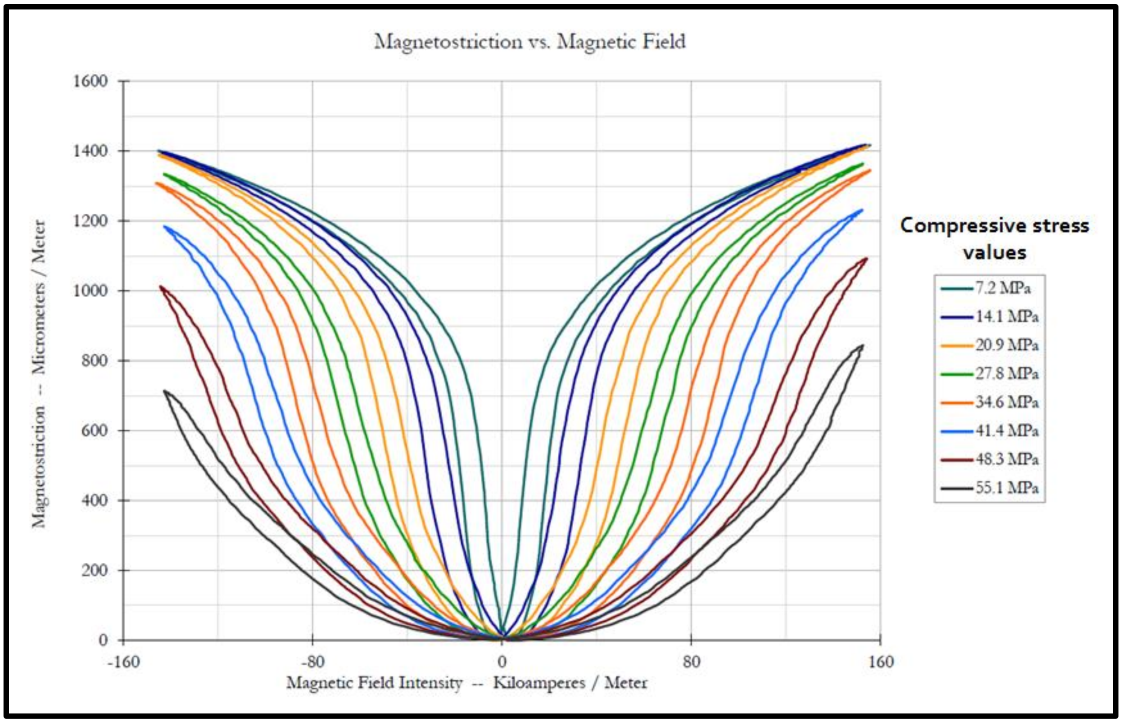

Figure 4: Magnetostriction vs magnetic field at different compressive stresses

The proposed design has adjustable prestress values by altering the tightness of the four compressive bolts, allowing the proposed design to move to the most convenient compressive stress curve on Figure 4. Using the magnetic field strength and strain values at the maximum and minimum compressive strengths shown, Table 3 and Table 4 have been generated to provide a general magnetic field strength target.

Table 3: Strain and Elongation at 7.2 MPa

Magnetic Field Intensity [kAmp/m]	[mT]	Strain	Elongation [in]	Final Stroke Distance [in]
10	12.536	0.00055	0.00165	0.0264
20	25.072	0.00082	0.00246	0.03936
30	37.608	0.00093	0.00279	0.04464
40	50.144	0.00102	0.00306	0.04896
50	62.68	0.00108	0.00324	0.05184
60	75.216	0.00113	0.00339	0.05424
70	87.752	0.00118	0.00354	0.05664
80	100.288	0.00122	0.00366	0.05856
120	150.432	0.00134	0.00402	0.06432
155	194.308	0.00142	0.00426	0.06816

Table 4: Strain and Elongation at 55.1 MPa

Magnetic Field Intensity [kAmp/m]	[mT]	Strain	Elongation [in]	Final Stroke Distance [in]
10	12.536	0.000001	0.000003	0.000048
20	25.072	0.000005	0.000015	0.00024
30	37.608	0.000015	0.000045	0.00072
40	50.144	0.00003	0.00009	0.00144
50	62.68	0.00006	0.00018	0.00288
60	75.216	0.00009	0.00027	0.00432
70	87.752	0.00011	0.00033	0.00528
80	100.288	0.00018	0.00054	0.00864
120	150.432	0.00043	0.00129	0.02064
155	194.308	0.00084	0.00252	0.04032

The range is between 10-160kA/m and 12.5-194.3mT. With a low prestress value, the required magnetic field strength for the minimum 0.03in stroke is 16mT, and with a high prestress value the required magnetic field strength is 46mT. All of the prestress values begin to converge around the 200mT range, for this reason a 200mT magnetic field is the target value for the solenoid design. With such a high magnetic field strength, there will be many more options for the usable prestress values providing greater opportunity for optimization of the prestress values.

5.3 Solenoid

With a magnetic field strength value in mind, the solenoid design is dependent on the wire gage, number of turns, and the number of amps running through the wire. The amperage capacity for different wire gages at varying temperatures is obtained from coonerwire.com, the wire diameters are obtained from [2]. In order to get uniform magnetic field lines running through the 3in core, the solenoid needs to have a larger length and have the core positioned towards its center. The selected length to accommodate the increased solenoid length is 4in. Based off of the length of the solenoid and the diameter of the wire, a specific number of turns is available per layer of wiring. The number of layers can then be increased until a usable magnetic field strength is obtained. The solenoid was initially designed for a 22 gage magnetic wire, 10A, 11 layers, and a 0.995in outer diameter (calculation Table 5 shown below).

Table 5: Initial calculations for the proposed device

Magnetic Field Required	200 mT
Permeability (air core)	1.25664E-06 H/m
Number of passes	11
Thickness of Plastic Spool to Wrap Wire On	0.08163 mm
Wire Gage	22
Ampacity (for 105 °C)	10
Wire Diameter	0.0267 in
Number of Turns Per Pass	149
Number of Turns Total	1639
Magnetic Field Generated	202.72mT
Final Outside Diameter	0.995 in

However, the team is unable to find a purchasable thin iron shell with a 1in inner diameter to surround this solenoid design (discussed in *Section 5.4*). For this reason a new design has been generated to match the inner diameter of an available iron casing at 21mm (0.039in) [3]. The new design also produces 200mT, but uses a smaller gage wire with more turns. The finalized solenoid dimensions are shown below in Table 6.

Table 6: Revised calculations for the proposed device

Magnetic Field Required	200 mT
Permeability (air core)	1.25664E-06 H/m
Length	4 in
Number of passes	18
Thickness of plastic spool to wrap wire on	1.5875 in
Wire Gage	30
Ampacity (for 105 °C)	2.5 A
Wire Diameter	0.0109 in
Number of Turns per Pass	366
Number of Turns Total	6588
Magnetic Field Generated	203.71 mT
Final Outside Diameter	0.767 in

5.4 Power Source

According to a quote from ccoils.com, the resistance for the solenoid dimensions specified in *Section 5.3* is about 100ohms. The amperage capacity of 30 gage wire is 2.5 amps, so to provide this amperage, a voltage of 250V is needed. A North American wall outlet only runs 120V, however a voltage converter can be purchased relatively inexpensively to step the voltage up to 250V. With this type of power converter, a wall outlet can be used as the primary power source.

5.5 Hydraulic Pistons

The difference in area between hydraulic pistons is necessary to increase the stroke of the magnetostriction of Terfenol-D. The minimum lever ratio is 1:10, but a lever ratio of 1:16 will provide a beginning and ending diameter with standard values and will also exceed the expectations of the design. The volume displaced by the input piston is equal to the volume displaced by the output piston because the hydraulic chamber is sealed. In order to increase the stroke by a factor of 16, the area of the output piston must be 16 times less than that of the input piston. A minimum diameter for the output piston is 0.5in in order to accommodate the piston's seal notches which must be cut to maintain an airtight seal.

The stress concentrations in the pistons are at the shoulder where a radius of curvature is needed, and at the notches required for installing a seal on each of the pistons. The radius of curvature for the piston shoulder is selected as 0.05in because it is a standard radius of curvature value, but this radius can be increased without weakening the design if needed. The stress concentration factors for each of the problematic areas are gained from *Shigley's Mechanical Engineering Design, 9th Edition* [4]. Using Aluminum 2011-T3 with a yield strength of 43000psi the resulting dimensions and stresses along with their stress concentrations are shown in Table 7 and Table 8 [5].

Table 7: Large piston calculations with Aluminum 2011-T3

Force	1000 lbf
Large Diameter	2 in
Slot Depth	0.125 in
Slot Length	0.125 in
Radius of curvature	0.05 in
Material Yield Strength	43000 psi
After-Notch Diameter	1.75 in
r/t	0.4 in*
a/t	1 in*
Stress Concentration Factor	3.7
Stress on inner diameter	415.7517 psi
Stress in notch	1538.281 psi
Factor of Safety	27.95328

*values obtained from [4]

Table 8: Small piston calculations with Aluminum 2011-T3

Lever Ratio	16
Pressure After Losses	318.3 psi
Slot Depth	0.125 in
Slot Length	0.125 in
Radius of curvature	0.05 in
Material Yield Strength	43000 psi
Large Diameter	0.5 in
After-Notch Diameter	0.25 in
r/t	0.4 in*
a/t	1 in*
Stress Concentration Factor	3.7
Stress on inner diameter	1273.2 psi
Stress in notch	4710.84 psi
Factor of Safety	9.127884

*values obtained from [4]

5.6 Lever Pressure and Wall Thickness

The input force from the plunger induces a pressure within the fluid. A constraint from *Section 1.4* specifies that the output force must be 25lbf; meaning that the input force must be over 400lbf to achieve a lever ratio of 1:16 (chosen in *Section 5.4*). The maximum amount of force that can be output by the input piston is 1000lbf when the core is at magnetic saturation. If a larger output force is desired then this value can also be used to determine a new internal pressure. The internal fluid pressure resulting from these forces is shown in Table 9.

Table 9: Input Force Relation to Average Pressure in Cylinder

Input Force (lbf)	Average Pressure (psi)
400	127.3
1000	318.3

Using the highest possible pressure within the lever and the Aluminum 2011-T3 material, Table 10 shows the required wall thickness using the equation for hoop stress within a pressurized vessel [6]. The longitudinal stress is not a concern, because the wall thicknesses in the longitudinal direction of the lever are many times greater than in the hoop stress direction.

Table 10: Hoop Stress Aluminum 2011-T3

Yield Strength	43000 psi
Stress Concentration Factor	1*
Minimum Factor of Safety	2*
Internal Pressure	127 psi
Internal Diameter	2 in
Minimum Wall Thickness	0.005907
Accepted Wall Thickness	0.08 in
Actual Factor of Safety	13.54331

*values obtained from [4]

The required wall thickness is too small to machine, even when considering the highest possible stress within the cylinder and a factor of safety of 2. For this reason, the wall thickness has been increased to 0.08in (2mm) in order to make it viable to machine. Increasing the wall thickness only reduces the amount of material removed during machining, so the cost of obtaining the lever dimensions is not drastically affected.

5.7 Compressive Bolts

The two common standard sizes that can fit between the 25mm (0.98in) iron solenoid casing and the 2in inner casing diameter are 0.25in and 0.125in bolts. The bolts must be positioned around the center so in order to maintain a uniform compressive stress on all sides, 4 bolts will be used and tightened in unison. Finely threaded bolts will be used to reduce the diameter decrease from threading and to reduce the required thread engagement lengths (reference Figure 5). The diameters of each of these bolts after threading (minor diameter) can be calculated and used to determine the tensile stress on each of the bolts Figure 6.

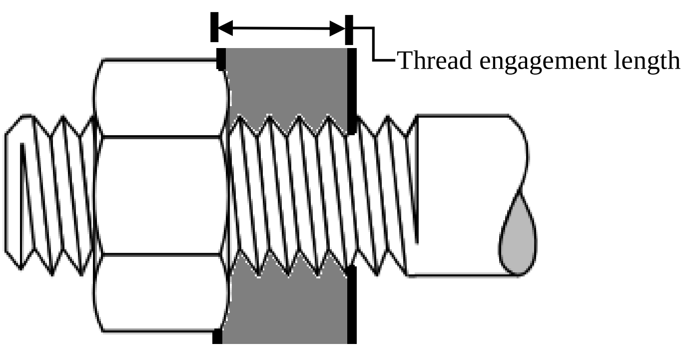

Figure 6: Threaded length [7]

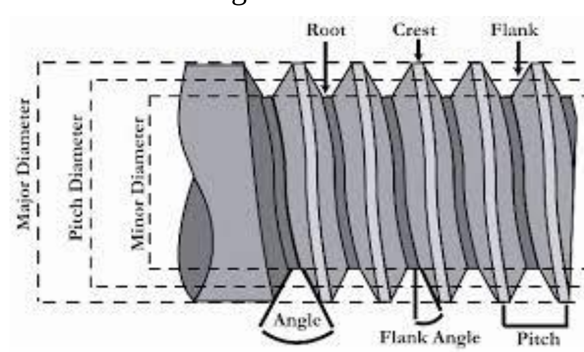

Figure 5: Threading Diameter [8]

Another concern is the length of threaded bolt that must be engaged in order to resist shearing when the tensile force is applied. The required thread engagement length along with the factors of safety for a tensile loading on the austenitic stainless steel 18-8 bolts are shown in Table 11.

Table 11: Thread engagement length and Yield Strength with 250lb per bolt

Bolt diameter	0.25 in
Threads per inch	28 1/in
Tensile stress area	0.032 in^2
Area of screw thread	0.036374 in^2
Stress on threads	6873.06 psi
Stress on bolt	7812.5
Thread Engagement Ratio	0.697674
Thread Engagement Length	0.204198 in
Bolt material	303A
Yield strength	30000 psi

The 0.125in bolts fail under tensile loading when inserted into Table 11, meaning that 0.25in bolts are required and their thread engagement length must be 0.4in to maintain a factor of safety of 2. This thread engagement length requires that the length of the upper shoulder of the input piston from *Section 5.4* is increased to a length of 0.86in to accommodate both the seal notch and the threaded distance into the piston.

5.8 Endplate

The endplate is loaded with 4 bolts and the core stop. The 4 bolts are positioned around the center and placed in tension when the Terfenol-D compresses the core stop. The core stop creates a bending stress and a shear stress outward from the center [9]. The stress values using the yield and shear strength for Aluminum 2011-T3 show that the determining factor is the bending stress generated, shown in Table 12.

Table 12: Al 2011-T3 Endplate stresses and factor of safety

Center Force	1000 lbf
Number of bolts	4
Diameter of core stop	0.25 in
Plate thickness	0.25 in
Center Pressure	20371.83 psi
Distance from center to piston bolts	0.75 in
Max bending moment	187.5 lb*in
Max bending stress	18000 psi
Max shear stress	5092.958 psi
Material	Al 2011-T3
Yield strength	43000 psi
Shear strength	32000 psi
Factor of Safety	2.388889

In order to maintain the factor of safety of 2, the endplate thickness must be about 0.25in.

5.9 Lever Fluid

The determination for the lever fluid is based primarily on cost. After calculating the head loss for SAE J1703 brake fluid using Table 13, it was found to be negligible when using a 45° angle and a fluid with a low viscosity such as the brake fluid selected. The calculations assume the movement of the plungers are done over 0.5s, and that the flow is at steady state during that movement.

Table 13: Fluid properties and pressure loss for the desired component

Density	2.076 slug/ft^3
Kinematic Viscosity	1550 in^2/s
Input Force	1000 lbf
Output force	62.5
Large Plunger Movement	0.003 in
Small Plunger Movement	0.0048 in
Reynold at Large Plunger	3.519055
Reynold at Small Plunger	14.07622
Length of Pipe	0.25 in
Loss Coefficient for Nozzle	0.19*
Friction Factor at Large Plunger	18.1867
Friction Factor at Small Plunger	4.546676
Angle from Horizontal	45
Pressure Change	0.001626 psi

*obtained from [10]

6. Material Selection for Design

Material for the proposed design was chosen based on the constraints and general engineering design factors considered for their respective components. These design factors include material properties, dimensions, stress concentration, price, and positioning. Calculations for the design plan were made by comparing and contrasting the advantageous properties of different material options available to the team, then using their strength values of selected materials to identify which of them maintain an adequate factor of safety.

The housing, endplate, and pistons will all be made out an aluminum 2011-T3. This material was chosen because it fit all of the criteria needed for these 3 designs. This type of aluminum has a high yielding point at 43kpsi, is easy to machine with typical mills and lathes, and has a low magnetic permeability (meaning it will neither affect or be affected by the generated magnetic field). Another advantage to using this material for all 3 designs is that it will reduce material cost and machining cost by only having one piece of stock to cut parts from.

The solenoid casing material was chosen to be 99.5% purity annealed iron. This type of iron has a high magnetic permeability and will vastly strengthens the magnetic field that the Terfenol-D experiences. This pure iron material does not have strong mechanical properties, but the proposed design does not require this component to support any forces.

The prestress bolts will be made from stainless steel grade 18-8 which has a low magnetic permeability and a high yield strength.

The solenoid wiring was chosen at 30 gage magnetic copper wire to accommodate the current flowing through the system because this gage wire has a small enough diameter to achieve the number of turns without a large increase in diameter for the coil. The downside to using a small diameter wire is that it will require a higher voltage to function properly, however this has been taken into account by selecting a voltage converter to attach to the power source.

The hydraulic fluid selected is SAE J1703 brake fluid. This fluid has been chosen because of its incompressibility, low viscosity, and very low price.

The plastic seals for each piston are to be made from Teflon. Some hydraulic fluids have negative reactions to certain types of rubbers, but Teflon is can create an airtight chamber without reacting to the fluid [11]. Teflon seals are common as well, so it will be easier to obtain than many other types of seal materials.

7. Bill of Materials

The bill of materials for this design is shown in Table 14. The total cost of the first prototype comes to $698.99 (not including the cost of the magnetic coil because the team has yet to receive a quote for the magnetic wire). The most expensive component of the device is the Terfenol-D core with a price of $447.00. The only company that produces Terfenol-D is Etrema, meaning that searching for less expensive alternatives is not an option. This cost includes the manufacturing expenses associated with the specific dimensions. Table XX shows the price of each individual item and the quantity required for the design. Table 14 shows the price of the individual item and the quantity required for the design.

Table 14: Bill of Materials

Component	Manufacturing Cost ($)	Purchasing Cost ($)	Qty.
Terfenol-D core	Included with Purchase	447.00 [1]	1
Soft iron casing	Included with Purchase	138.00 [7]	1
Aluminum rod	1.31	48.74 [5]	1
Magnetic coil	Included with Purchase	TBD	1
0.25in bolt	N/A	5.59 [12]	4
0.125in bolt	N/A	0.51 [12]	1
Hydraulic fluid	N/A	4.99 [13]	TBD
Teflon seal	Included with Purchase	15.00 [11]	2
250V USA Power Plug adapter	N/A	6.08 [14]	1
Total	698.99		

8. Project Planning

The Fall 2015 Gantt chart has been updated to include all progress and completed tasks throughout the semester and is shown in Figure 7. This time period begins 08/31/15 and ends 12/17/15. The tasks that have guided the team throughout the project are listed, and important milestones are noted below. The black bars denote tasks that have been completed and the black diamonds denote milestones that have been reached.

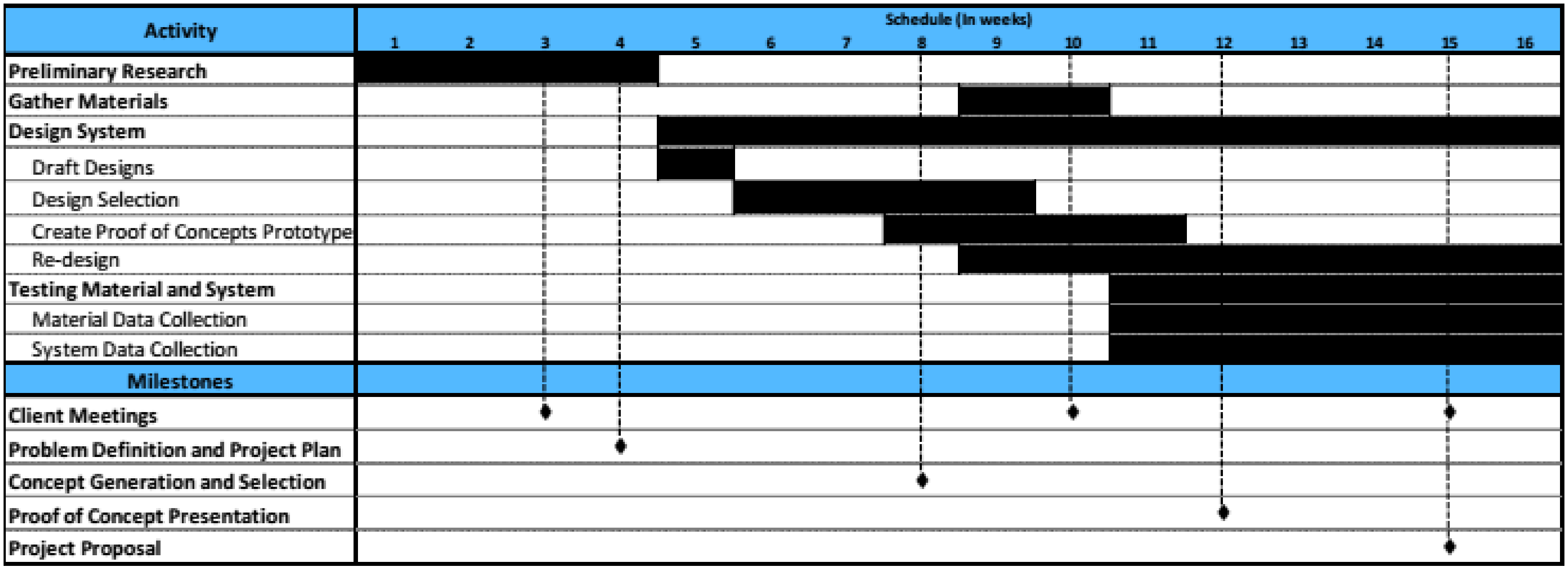

Figure 7: The updated Gantt chart for the Fall 2015 semester

The design team has constructed a preliminary Spring 2016 Gantt chart (located in Appendix A) in advance to organize the tasks and deliverables for the second semester. The majority of Spring 2016 semester will be developing multiple prototype stages. The time period for this semester will be 1/19/15 through 5/12/15.

9. Risk Assessment and Contingencies

Malfunction and unpredictability are an inherent part of the engineering process, and they must be accounted for in the design. Although several modes of failure have been identified in order to prevent malfunction in the design, it is possible that failure may occur in other aspects of the design process. The following list outlines possible risks and contingency plans for each component of the device.

- Solenoid does not produce sufficient magnetic field strength
    - Increase number of turns of wire, and therefore overall diameter of solenoid
    - Purchase silver wire solenoid, thus increasing the cost of the device
- Terfenol-D does not produce desired stroke
    - Increase magnetic field through alternative solenoid design
    - Adjust amount of prestressing placed on Terfenol-D
    - Strengthen material to reduce deflections
- Hydraulic system does not function properly
    - Replace with mechanical lever system
- Hydraulic seals do not function properly
    - Increase width of plungers
    - Lower tolerances between plunger and housing
- Fluid chamber contains air bubbles
    - Outsource chamber pressurization to hydraulic manufacturer with proper equipment
- Working fluid does not function properly
    - Consider different fluids with different criteria based on reason for failure
- Operating temperature exceeds 212°F
    - Incorporate cooling system and/or insulation
    - Reevaluate fluid material
    - Use temperature resistant materials
- Tolerances of dimensions can not be achieved at the Northern Arizona University machine shop
    - Outsource manufacturing of component to private machine shop that specializes in close tolerances
- Materials fail due to stresses or temperature changes
    - Reiterate design with higher factors of safety
    - Consider different materials
    - Reuse materials that have not been damaged

10. Design Alternatives

The alternatives are based on possible innovative concepts and can be used as potential contingency plans. Innovative concepts are practical enough to prove or disprove with testing.

A Class 1 lever system will work for the purposes of this project if other options are proven to not work, or performs less efficiently than expected. Class 1 levers are a thoroughly proven design concept so there is very little risk of them failing.

A design idea that could combine the core and lever components is to create a hydraulic lever using ferrofluid. The fluid would have powdered Terfenol-D suspended within an incompressible fluid and act as both the piston and the lever. This is an idea that has not been utilized in any known Terfenol-D applications, but through testing, the team can determine the potential possibilities of this idea.

There are several innovative concepts that could be used to control the magnetic hysteresis that the Terfenol-D experiences. Such design alternatives are: using a vibrating wire to affect the magnetic bias, iron filings suspended in the previously mentioned ferrofluid to act as miniature magnets once the field is applied, and randomizing the magnetic field to realign the crystals within the Terfenol-D rod.

The design team will also consider an alternative method for prestressing the Terfenol-D. In the current design, the Terfenol-D is prestressed with four bolts fixed symmetrically around the solenoid. These four bolts may be replaced with a single bolt passing through the center of the Terfenol-D. This requires ordering a new specimen of Terfenol-D manufactured with a longitudinal hole. This concept would provide more space between the solenoid and the aluminum housing, allowing for a larger coil if necessary, but it would also require a large cost commitment to test.

In order to increase the strength of the magnetic field applied to the Terfenol-D, the team will consider placing permanent magnets between the Terfenol-D and the solenoid coil. This magnetic field will create a magnetic exchange bias for the core.

11. Conclusion

The Northern Arizona University Magnetostrictive Actuator capstone team is proposing the design of a Hydraulic Electromagnetic Magnetostrictive Actuator as one solution to the problem defined by Honeywell Aerospace. This HEM Actuator meets the needs as defined by Honeywell, offering a theoretical output force greater than 25lbf, a stroke equal to or greater than 0.03in., a development cost less than $5,000, a unit cost of less than $1000, dimensions that fit within the proposed space, maximum temperature under 212°F, and a variable input to output stroke ratio that can match or exceed 1:10. The coefficients of thermal expansion have not been found for all components. Hysteresis control has also been theorized, and will be tested to determine its effect.

This design will be prototyped and tested during the Spring 2016 semester at Northern Arizona University. Once the final design is completed, the team hopes to attach it to an actual butterfly valve to demonstrate the true application of the device.

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Appendix A: Spring 2016 Gantt Chart