

Computer Aided Design of A
Magnetostrictive Actuator

by

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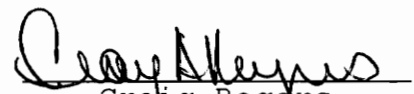
in

Systems Engineering

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(ABSTRACT)

There is a present need in many industries for miniature actuators that can supply large forces and relatively small linear displacements. Actuators incorporating magnetostrictive materials show promise in filling this need. Magnetostrictive materials expand when exposed to a magnetic field. Currently available commercial magnetostrictive actuators are not capable of meeting the requirements of most applications because they are not optimized for those applications. Optimization of a magnetostrictive actuator is presented using the latest computer aided design tools. Priority is placed on designing the actuator to maximize performance, reliability, and to a lesser degree, minimizing life cycle cost. Further, relationships between all design dependent parameters are derived. The two main investigations deal with optimizing the magnetic field within a magnetostrictive actuator. First, it is shown that making the induction coil the same length as the magnetostrictive element results in a 12% weight savings with only a 5% decrease in a average

magnetic field intensity from the baseline design. Second, it is shown that a thin magnetic circuit may be incorporated into the baseline design that increases the average magnetic field intensity by 34% while increasing the weight of the actuator by 0.16 pounds.

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CHAPTER 1

SYSTEMS ENGINEERING APPROACH

1.1 Definition of the Problem

The need for high performance mini-actuators exists in many fields - aerospace, commercial production, defense, automobile, and medical, to name a few. Presently, there are serious actuator performance deficiencies (stroke, displacement, energy density) in short stroke applications such as precision drilling machinery vibration control, precision positioning, and "smart" control of large optical devices, such as laser arrays [2]. Long stroke versions of these actuators are needed to replace actuators currently in place such as hydraulic and pneumatic actuators. The current systems are lacking in reliability, energy density, design simplicity, and frequency response.

As an example, there is no actuator currently available that will satisfy the requirements of next generation artificial hearts. Today, more than 35,000 patients who need heart transplants go without because of lack of donors. Despite heavy funding and high public visibility, modern artificial heart research has not produced a design that is reliable for more than a few weeks. The main reason is that the requirements and operating environment for the heart's actuator are extremely difficult satisfy. The actuator must

supply sizable displacements and forces with low input power, and must fit into a 3.5 cubic inch package. The requirements are shown more quantitatively in **Table 1**. Complex actuators with many moving parts are not allowed as no maintenance is allowed after implantation. This automatically eliminates omnipresent hydraulic and pneumatic actuators. Life cycle cost is a secondary consideration but will become more important as the technology becomes capable of satisfying the performance requirements. A completely new actuator concept is needed to fulfill these requirements.

The widely varied markets for new actuators has led to recent development of actuators incorporating electroactive elements. Magnetostrictive material is a type of electroactive material. However, most research to date on magnetostrictive actuators has been on demonstrating feasibility in a certain application, not optimizing the design dependent parameters for that application. The program that this Project is a part of is attempting to develop a much improved actuator over the commercial actuators currently available.

This Project deals mainly with optimizing the magnetic field within the actuator. A strong magnetic field is the most critical parameter in getting the most energy output from a given volume of magnetostrictive material. Also,

Table 1: Artificial Heart Requirements

Output	
<i>Max. Pulse Rate</i>	160 bpm
<i>Min. Pulse Rate</i>	60 bpm
<i>Force Delivered</i>	27 - 31 lbs
System Endurance	
<i>Cycles</i>	1 year - 8.4×10^7
<i>Reliability</i>	95% at 95% confidence
<i>Maintenance</i>	None Possible
System Power	
<i>Required. Output</i>	3 W
<i>Max. Input</i>	21 W
Thermal Management	
<i>Max. Tissue Heat Flux</i>	0.04 W/cm^2
<i>Max. Tissue Contact Temp.</i>	42° C
Size	
	See CCF Drawing 2805
Environment	
<i>Humidity</i>	100% Relative Humidity
<i>Temperature</i>	37° C
<i>Pressure Changes</i>	14.7 psi - 9.6 psi
<i>Noise</i>	Device may not create > 60 dB
<i>Vibration</i>	Device may not create > .1 g ² /Hz

making the magnetic field as uniform as possible ensures that all of the magnetostrictive material is working to its capability.

Analytical techniques do a fair job of estimating the maximum field intensity at the centerline of the coil, but do not offer insight into the distribution of the magnetic field. They also do not include geometric and material effects of the actuator caps and case. The magnetic field can increase or decrease towards the ends of the coil, depending on the materials surrounding the coil.

Even experimental measurements are not enough to fully optimize the magnetic field. The measurements are difficult to make and published data points frequently are not at close enough intervals throughout the space. In fact, the displacement vs. field intensity curves offered by the Terfenol-D manufacturer are based on a field measurement at a single point within the coil [6].

What is needed is a magnetic field analysis in which the magnetic field intensity can be monitored at many specific locations within the magnetostrictive material. The best tool for this analysis is one of the many commercially available tools using the finite element method or boundary element method to solve the basic equations of electromagnetism at a large number of locations. However, such an analysis was not found in the literature. Even if

there were results available for general design guidance, it would still be worthwhile to perform the analysis for the actuator design at hand to have complete control over the input values and the approximations used in solving the equations.

1.2 Project and Report Objectives

This Project and Report is a small part of a research and development program for the U.S. Government. The precise program goals can be summarized as:

Output Displacement: 0.032 inches

Displacement Amplification : 75:1

Output Force: 100 pounds

Length: 3 inches

Diameter: 2 inches

Input Power: 600 Watts

Failure Rate: 1 failure per 1000 hours of continuous
operation at 25 Hz.

There are no specific life-cycle cost requirements for the program. However, to make the actuator viable in the commercial sector, the life cycle cost will have to be competitive with competing technologies. In the case of the artificial heart, the entire life cycle cost is based on the

design and fabrication of the heart - there are no opportunities for scheduled or unscheduled maintenance. Also, the high degree of reliability required will push the R&D and testing costs up. For a typical actuator application, such as in a high speed industrial valve, the problem is more complex. The materials cost of a magnetostrictive actuator will always be high because of the magnetostrictive material itself. For example, the 1.5 inch long, 0.9 inch diameter rod studied in this program costs close to \$1000. If the actuator is meant for aerospace applications, the lightweight material costs will add to this.

On the current actuator design, the sliding parts and electronic controller will have the highest failure rates. A full analysis is required to determine if it is better to replace or repair these parts at scheduled and unscheduled maintenance. This depends on many variables such as the number of actuators in the field, the cost of replacement parts, the cost of setting up repair shops, and a myriad of others as described in [9].

Heavywalled bench test units have already verified the basic operation and performance of the baseline actuator design. This Project is part of the effort to optimize design dependent parameters to push later actuator designs

to their performance limits. The goals for the program are not attainable by any available electroactive actuator.

The specific objectives for this Project are to:

1. Identify relationships between all design dependent parameters and actuator performance parameters.
2. Analyze geometrical effects of the baseline actuator design.
3. Investigate the effects of different actuator case materials on the magnetic field intensity in the magnetostrictive material.
4. Recommend design changes to meet the overall program objectives mentioned above.

This Project implements specific elements of the Systems Engineering Process as described in Section 1.3.

1.3 Systems Engineering Approach

This Project, and the overall research program, fit into several slots in the life-cycle development of a magnetostrictive actuator system. The life cycle systems engineering process is presented in **Figure 1**. In **Figure 1**, the shaded boxes are those that are addressed in the overall program.

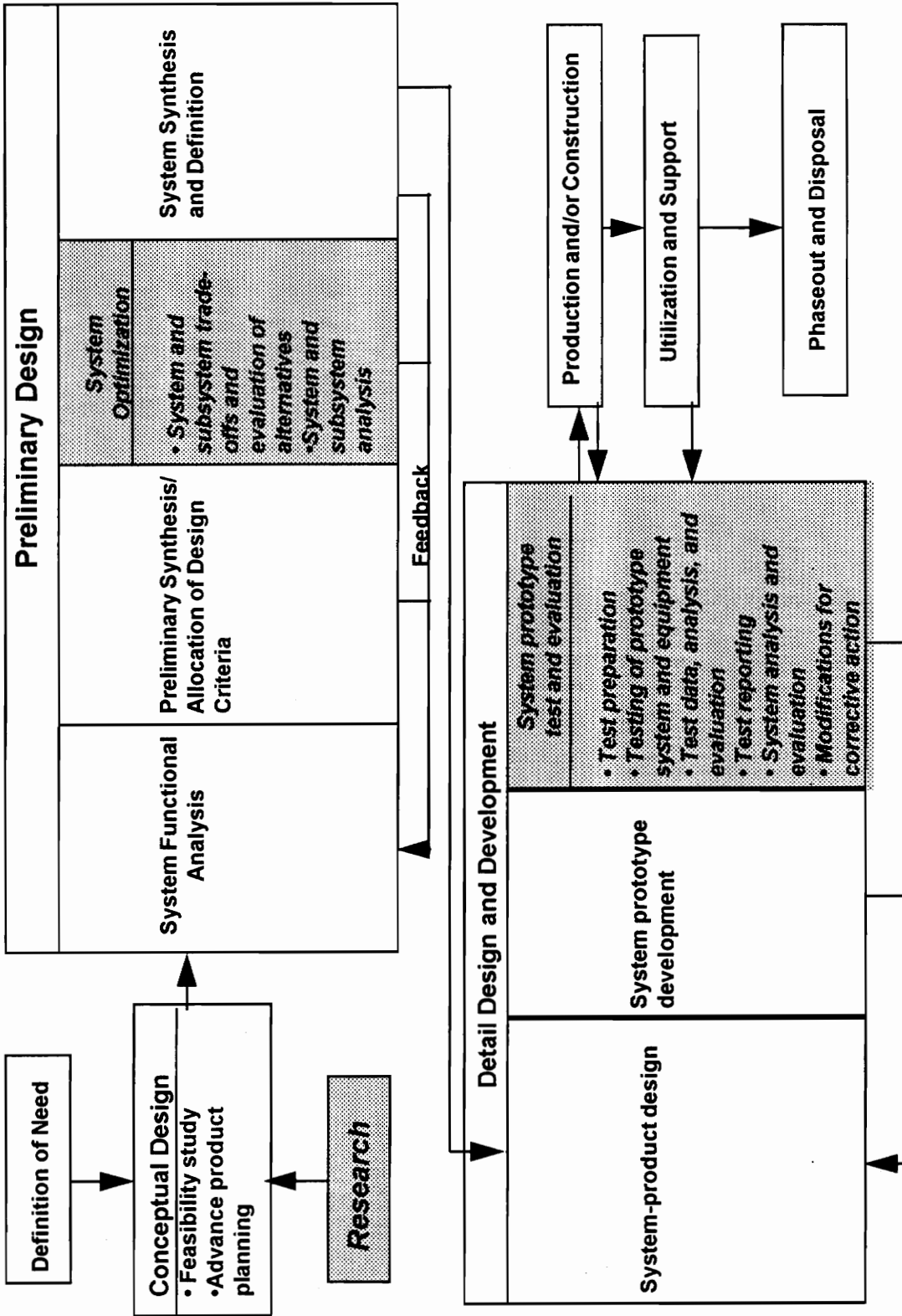


Figure 1: System Life Cycle Process (Adopted from [9])

The research program that this Project is a part of is not to be considered in the classic product development life cycle, however. **Figure 2** is a flow chart showing the program tasks as they actually exist. The shaded box "Optimize/Analyze Actuator Design" is the task of which this Project is a part. A heavywalled baseline actuator has been fabricated and tested to demonstrate functioning of the actuator and control system design. The objectives of the program are concerned solely with the performance and reliability of the system. It is a true research and development program in which new design approaches and techniques are being employed. In terms of the life cycle, the program could be considered to be in the System Optimization and System Synthesis and Definition phases. On the other hand, practically none of the steps before these in **Figure 1** have been completed. There is no maintenance concept, and a functional analysis has not been completed.

This Project falls under the Systems Optimization slot in the development life cycle. In general, this step consists of evaluating different combinations of design dependent parameters to optimize certain system performance parameters. In the order of evaluation parameters (see **Figure 3**), this Project deals with the optimization of fourth order parameters: actuator weight, input power, reliability, output displacement, and output force. This is

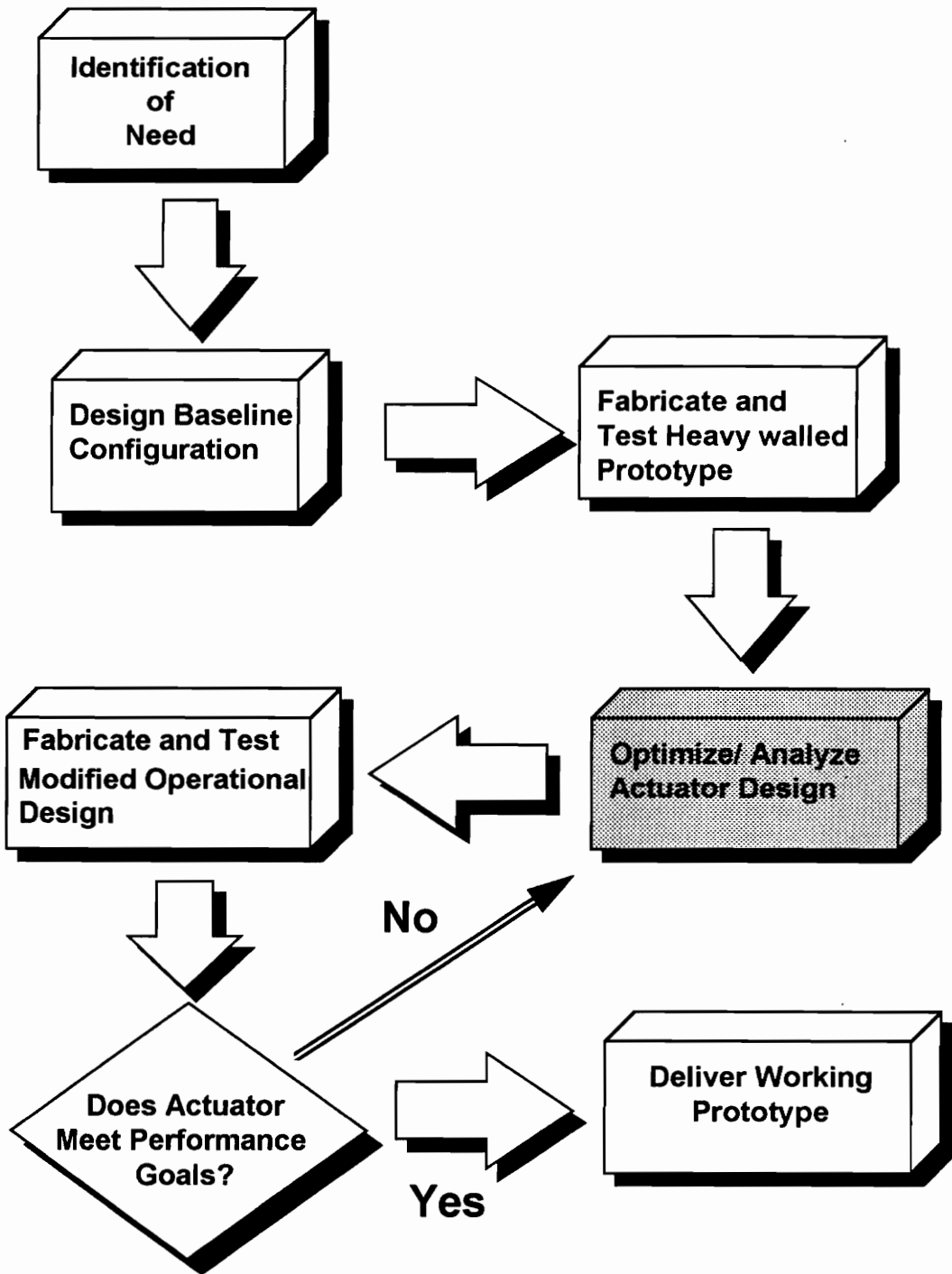


Figure 2: Actual Research Program

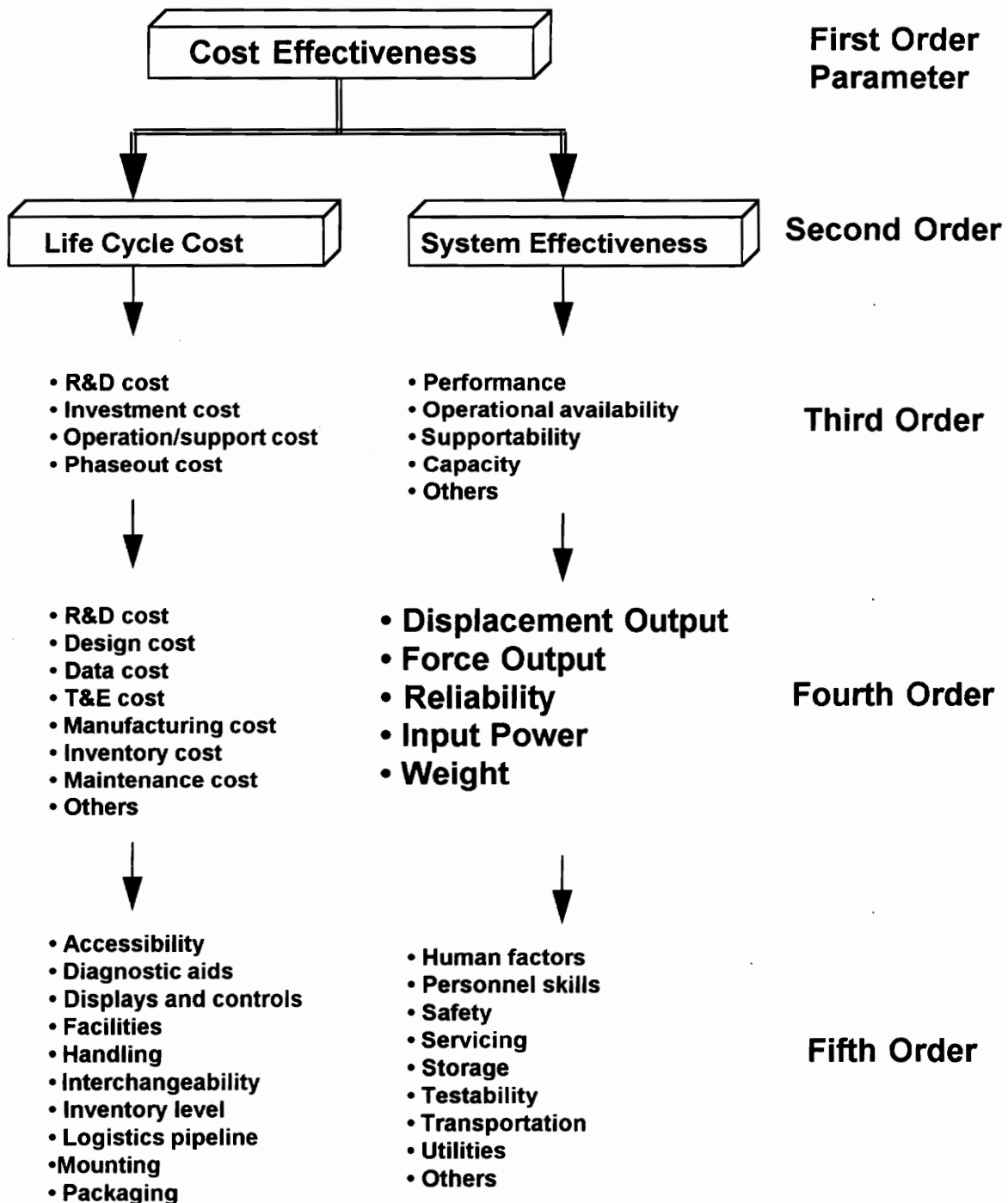


Figure 3: Order of Evaluation Parameters
(Adopted from [9])

accomplished by manipulating fifth order parameters. Maximizing the magnetic field intensity for a given configuration will maximize the output displacement.

Defining the relationships between the design parameters for magnetostrictive actuators is a fairly complex task. Using the casual diagram method [19], **Figures 4 and 5** present the qualitative relationships between design parameters. In the causal diagram, all design variables are listed. The fourth order parameters are in the shaded boxes in the figure. Arrows denote a relationship between two parameters. The plus or minus sign accompanying each arrow further qualifies the relationship, by predicting whether a parameter will increase or decrease based on an increase in the independent parameter. For example, in **Figure 4**, an increase in the current results in an increase in the magnetic field intensity. Thus, this relationship is represented by the arrow from "Current" to "Magnetic Field Intensity," with a plus sign. On the other hand, increasing the coil resistance decreases the coil current, with all other variables constant. This relationship is denoted with a minus sign in the causal diagrams.

Causal diagrams are useful for several reasons: (1) They concretely define the system's relationships in an easy-to-see format; (2) They offer insight into indirect relationships that are not obvious, and one can follow the

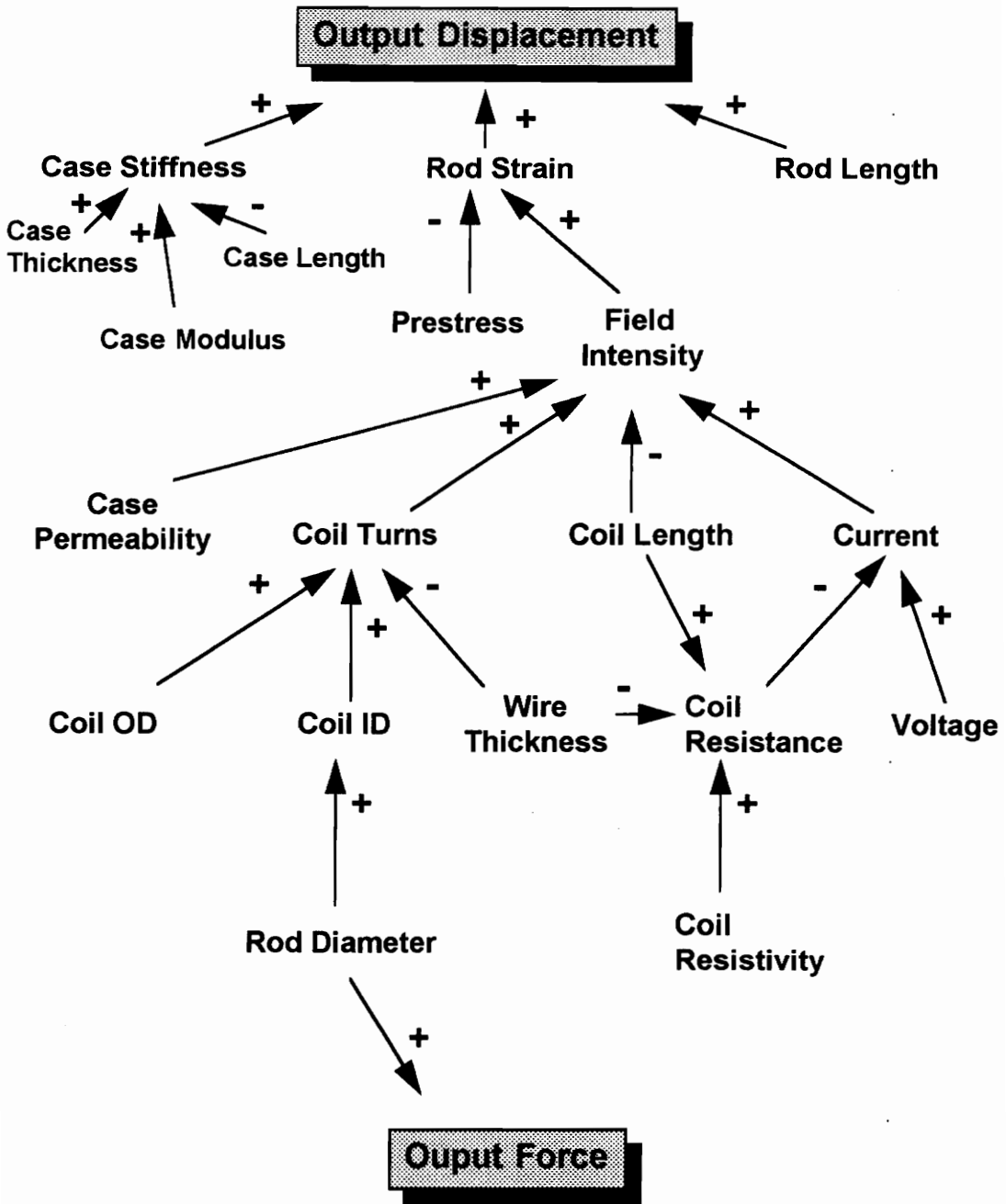


Figure 4: Causal Diagram For Design Dependent Parameters

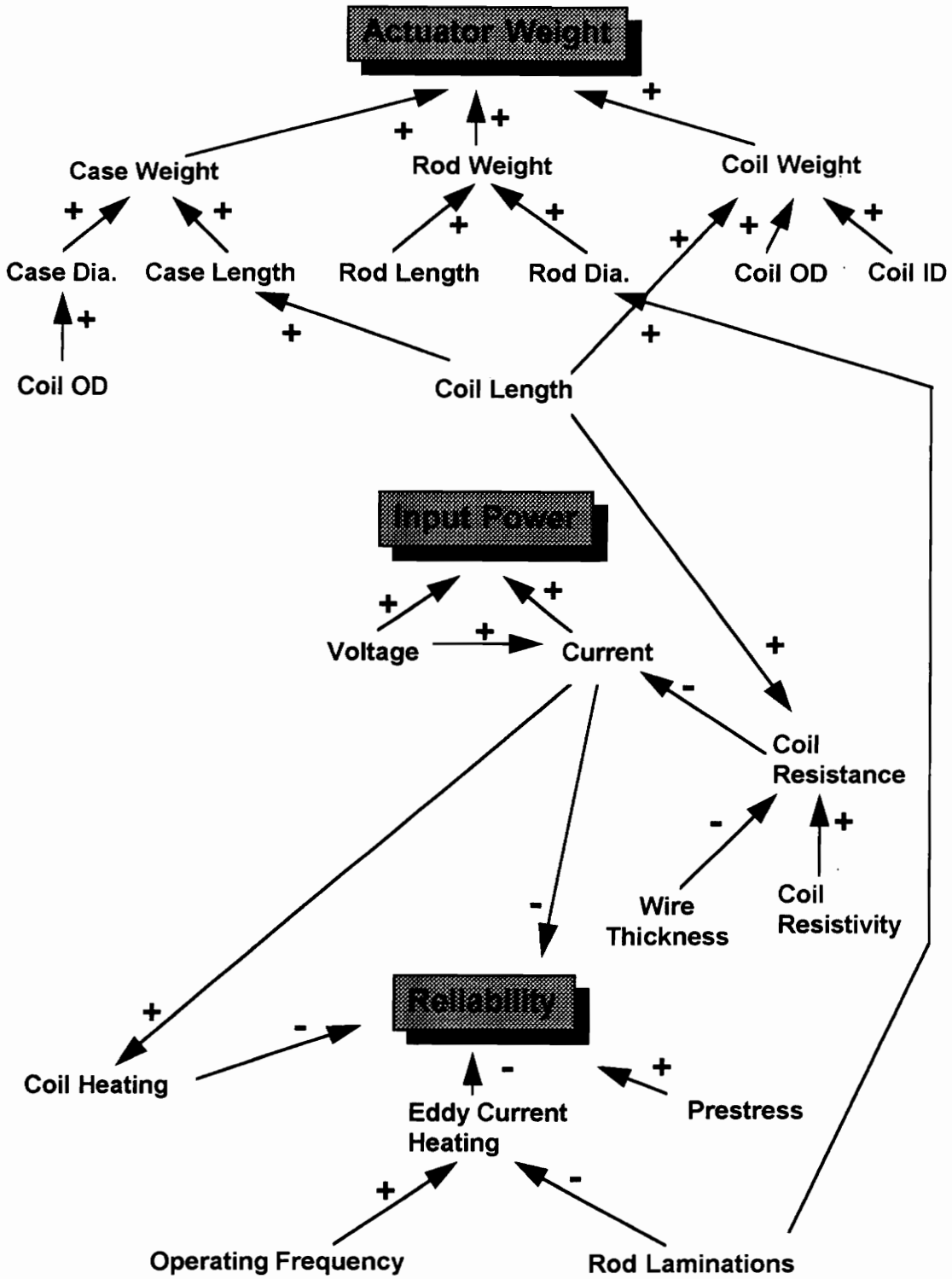


Figure 5: Causal Diagram For Design Dependent Parameters

ripple effect of changing a parameter to the desired level. For example, a design factor that was thought to be quite important before completing the diagram turned out to not have an effect at all - the wire thickness. It was reasoned that by simply decreasing the wire diameter and squeezing more coil turns into the allotted coil volume, a greater magnetic field intensity could be realized. After completing the diagram, the inverse relationship between wire thickness and coil resistance was plain to see. So, if the wire thickness is decreased, the coil turns increase. But, rippling the coil resistance upwards, the current in the coil is less for the same voltage because of the higher resistance. The relationships are linear, so the field intensity is the same for all wire thicknesses, for a given voltage and coil geometry.

This Project utilizes an important systems engineering tool for the optimization process - Computer Aided Design (CAD). CAD has revolutionized conceptual design because many system configurations can be modeled before selecting a final configuration. CAD combines the processes of mechanical packaging and engineering analysis. It can reduce costs by reducing or eliminating the need for costly physical models and prototypes. Also, keeping an integrated, up-to-date electronic model ensures that all designers are working with the same representation.

One reason that a computer tool was required for this Project is that solving the proper magnetic field intensity equations for each point in the geometry is very computationally intensive. The solutions are approximations of the famous Maxwell equations:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\mathbf{B} = \mu(\mathbf{H})\mathbf{H}$$

where \mathbf{H} is the magnetic field intensity, \mathbf{J} is the current density in the coil, \mathbf{B} is the magnetic flux, and μ is the magnetic permeability. The permeability will be discussed in more detail in the next chapter.

The computer tool used in this Project implements the Boundary Element Method (BEM) to solve Maxwell's equations. The BEM is a variation of the moment methods [10]. The dimensionality of the problem is reduced by one, from the finite element equations, without sacrificing the accuracy. This accuracy is, in general, superior to that of the finite element method [11].

For this time limited Project, however, the main reason that BEM software was selected is that it is easier to use than FEM software because generating a mesh is not required.

The user must only define nodes around the interesting boundaries in the problem. Geometries and nodes may be altered easily, allowing more alternatives to be evaluated. Another advantage of the BEM is that open areas of air or vacuum need not be meshed or defined geometrically, as in the FEM models. These open areas play an important role in electromagnetic analysis (e.g. the air gap in electromagnets), and it is not time efficient to redefine the open area mesh for each geometry change. Finally, in the BEM, potentials and fields can be obtained at any point with the same degree of accuracy. Therefore, zooming into a particularly interesting region does not decrease the accuracy of the solution. In the FEM, zooming into a particular element yields interpolations from the nodal values of that element.

The software chosen for this Project also utilized one of the most important features of Computer Aided Design - model portability. The original baseline model for the analysis was imported from a three dimensional solid modeling package. The configuration alternatives were changed in the geometry model of the electromagnetic software. Then, any of the alternatives could be exported back to the solid modeling software for realistic visualization. Thus, throughout the analysis, a configuration database was kept up to date and was available

for import into the solid modeling packaging software and the electromagnetic software. This is important when several people need to be sure that they are working on the same baseline design.

CHAPTER 2

HISTORY AND BACKGROUND

2.1 Magnetostrictive Materials

Magnetostrictive materials are those that change shape when exposed to a magnetic field. James Joule discovered the magnetostrictive effect in nickel in 1840, and cobalt, iron, and their alloys were later found to show magnetostrictive effects [1]. Before the magnetic field is applied to the magnetostrictive material, small magnetic domains within the material are perpendicular to the direction of expansion. However, the domains rotate and align themselves with an applied magnetic field, causing expansion of the material. As the magnetic field intensity is increased, more domains rotate and the strain of the material increases until saturation, when nearly all of the domains are aligned with the magnetic field.

Application of the magnetostrictive effect in actuators and transducers began with nickel as the working material in the 1950's [2]. However, the maximum strain of nickel is only 50 parts per million (ppm). So, a ten inch nickel rod can only increase in length by 0.005%, or 0.0005 inches.

In the 1960's and 1970's, researchers at the Ames Laboratory of the U.S. Department of Energy and at the Naval Ordnance Laboratory (now the Naval Surface Weapons Center)

in Silver Spring, Maryland, made a series of developments in materials with "Giant" magnetostrictive strains [1]. A combination of Terbium, Dysprosium, and Iron called Terfenol-D ($Tb_xDy_{1-x}Fe_2$) can give strains of more than 2000 ppm at room temperature. The exact stoichiometry of the material can be varied to achieve different performance characteristics.

This large strain, along with high frequency response and other properties, makes it an attractive material for use in many applications where short stroke and high forces are required. Two other types of "electroactive" materials, piezoelectric (PZT) and electrostrictive, are similar to magnetostrictive materials in that they change shape in response to electrical input. PZT materials expand or contract in proportion to the voltage applied to them. They have been around since 1946 [3] and have replaced almost all nickel based magnetostrictive actuators. Electrostrictive materials expand in proportion to the square of the electric field applied to them.

Table 2 compares some parameters of Terfenol-D, piezoelectric, and electrostrictive materials. Piezoelectric materials are desirable for their extremely short response times and the fact that virtually no power is required to keep them in their extended position. Their strain characteristics are not very sensitive to

Table 2: Comparison of Electroactive Materials

Parameter	Piezoelectric	Electrostrictive	Magnetostrictive
Coefficient of Thermal Exp. (ppm/°C)	1.6	5	12
Compressive Strength (Kpsi)	72.5	72.5	101.5
Energy Density (Btu/ft ³)	0.026	?	0.38-0.67
Maximum Strain (ppm)	800	825	2100
Response Time @25°C (micro-sec)	5	100	Determined by Coil
Tensile Strength (psi)	1500	1760	4100
Use Temperature (°C)	75	40	100
Young's Modulus (mpsi)	10.5	16	3.6

temperature, but PZT ceramics suffer from high hysteresis effects. Electrostrictive materials offer high compressive stress resistance and slightly higher displacement output than piezoelectric material. They display much less hysteresis than piezoelectrics, but have a limited temperature operating range. Terfenol-D has an extremely high energy density and displacement capability. Each material is suited for specific applications. One major difference is that piezoelectric and electrostrictive actuators rely on laying up many ceramics on top of one another to produce a reasonably sized element, while Terfenol-D is a solid, one-piece construction. In general, piezoelectrics are suited for intermittent duty situations [4], where space and response time are design drivers. Magnetostrictive materials are better for medium force, high displacement applications on a continuous duty cycle where reliability is at a premium.

2.2 Magnetostrictive Actuators

A current application of the materials described in the last section is miniature linear actuators - devices that supply linear forces and displacements. Until recently, electroactive materials were only used for gross movements, such as acoustical generators, or, in reverse, for mechanical/electrical conversion. However, many researchers

and developers have realized the utility of these materials for precision positioners and actuators. These mini-actuators are generally smaller, lighter, faster, and provide less force and displacement capabilities than the omnipresent hydraulic and pneumatic actuator systems. However, linear actuators incorporating electroactive materials as the working elements are not without their deficiencies. The exploitation of the actuation capabilities of these materials is still in the early phases. **Table 3** lists some of the applications and deficiencies of current linear actuation systems.

There is a need to develop actuators that utilize electroactive materials. These materials are sometimes called smart materials because they can be quickly and easily adjusted in response to their environment. For example, piezoelectric actuators are being investigated for use in controlling the motions and stresses of computer equipment during earthquakes [5]. However, the implementation and design of electroactive actuators is not mature, especially magnetostrictive actuators. In fact, there is currently only one supplier of Terfenol-D magnetostrictive actuators in the U.S. [6]. These actuators can multiply the displacement of the TFD material by a factor of three (with a corresponding decrease in the output force), but the applications are still limited to those

Table 3: Current Linear Actuation Systems

Actuator Type	Applications	Advantages	Deficiencies
Hydraulic	Large scale actuation - heavy machinery, brakes, aircraft control surfaces, cherry pickers, cranes,	Large force and displacement capabilities, "stiff" actuation	Complex design, requires fluid and associated plumbing, high maintenance, leak prone, many moving parts, difficult to miniaturize, pump required for closed cycle, slow response times
Pneumatic	Medium scale actuation - air nail guns, gas piloted valves, drills	Large force and displacement capabilities, gas supply is portable	Complex design, high pressure plumbing, frequent leaks, requires pump or bulky pressurized feed, "mushy" response, slow response times
Electric motor/ ball screw	Medium scale actuation - missile thrust vectoring, linear positioning, heavy machinery	Accurate positioning, all electric operation, power stroke/retract	Bulky construction, many moving parts, heat generation, difficult to miniaturize, weight, system reliability, frequency limited
Piezoelectric	Small scale actuation - vibration control, laboratory shakers, valves	Extremely fast response times, remain extended with no power addition, all electric	Extremely small displacement capabilities, brittle ceramic construction, high failure rates, excessive heating at high frequencies, high voltage required, hysteresis
Electrostrictive	Small scale actuation - optical equipment, fuel injection, electrical switches, laser gyros	Low hysteresis, high force, good stress/strain	Low frequency, small operating temp. range, small displacements, brittle ceramic construction
Magnetostrictive (TFD)	Small scale actuation - inch worm motors, sonar drivers, vibration suppression, miniature pumps	Large displacements and energy density, high reliability, all electric	Medium response time, high power, heating encountered at high frequencies, limited design database.

requiring very small displacements. The off-the-shelf technology available makes little attempt to minimize weight or volume, both of which are critical in aerospace and miniature applications.

Figure 6 shows a simplified block diagram of a magnetostrictive actuator, and **Figure 7** gives a brief statement of the function of the most important actuator elements. As mentioned in section 1.1, the TFD rod expands in proportion to the magnetic field intensity induced in the rod. The response time of the Terfenol-D rod is exceptionally fast, but coil induction limits the system response time. **Figure 8** shows a typical strain versus magnetic field curve for TFD. The field can be generated in a number of ways, but the most common way is to pass a current through a wire coil wrapped around the TFD rod. **Figure 9** illustrates the direction of a magnetic field for a given current direction in a coil.

A magnetostrictive rod within the coil will expand whether the current is positive or negative as shown in **Figure 8**. Thus, a magnetostrictive actuator is power extend only, unless a permanent magnet is used to bias the rod. In this case, the permanent magnetic field extends the rod to some intermediate position short of its saturated length. Then, as a positive current is introduced into the coil, the magnetic fields add constructively, and the rod

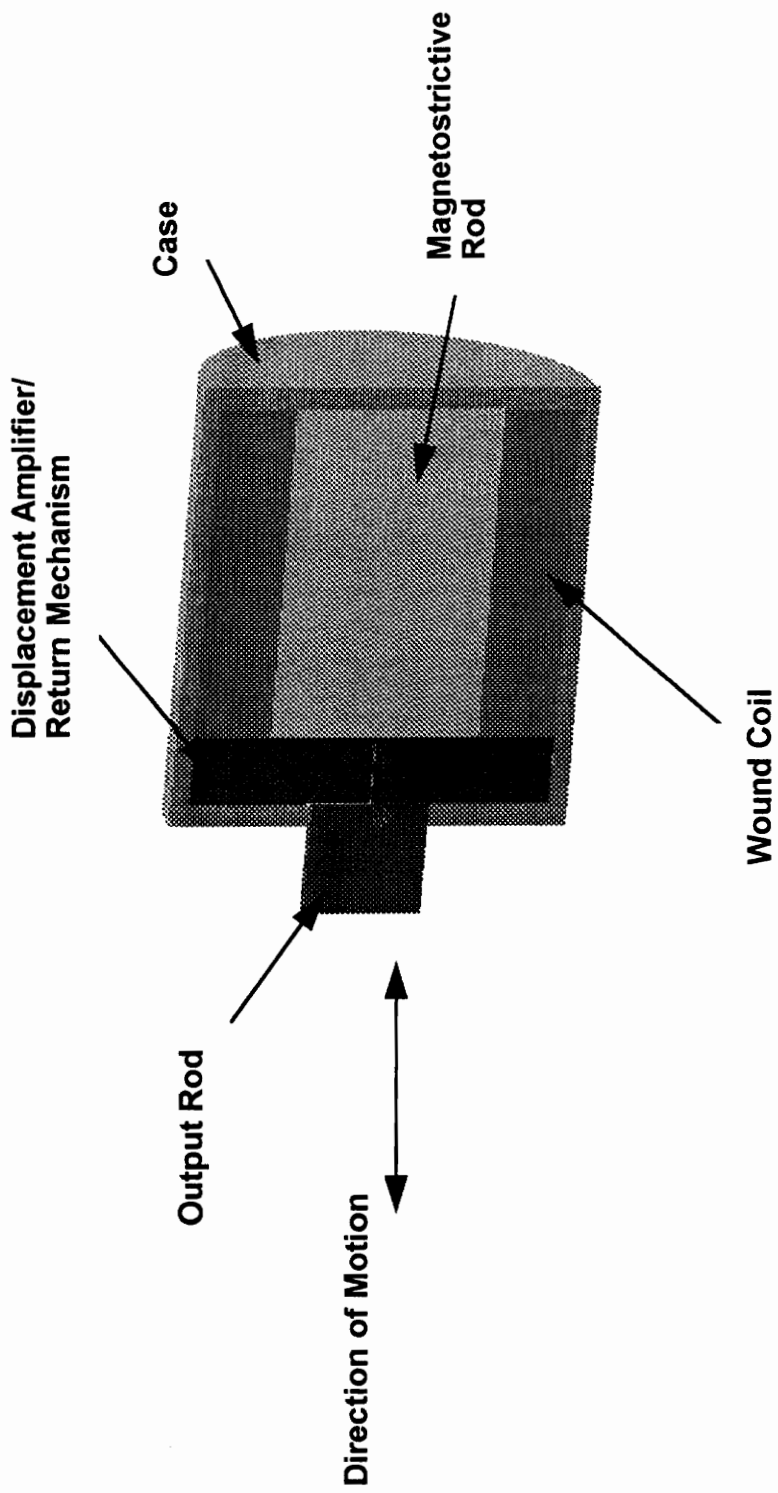


Figure 6: Simplified Actuator Cutaway

**Energy
Flow**



Control Electronics

- **Generate Actuation Signal**
- **Amplify Signal**

Coil

- **Convert Input Electrical Energy to Magnetic Energy**

Magnetostrictive Rod

- **Convert Magnetic Energy to Mechanical Energy**

Case

- **Provide Structural Stiffness**

Displacement Amplifier

- **Convert Force - Displacement**

Output Rod

- **Deliver Mech. Energy to Load**

Figure 8: Actuator Element Functions

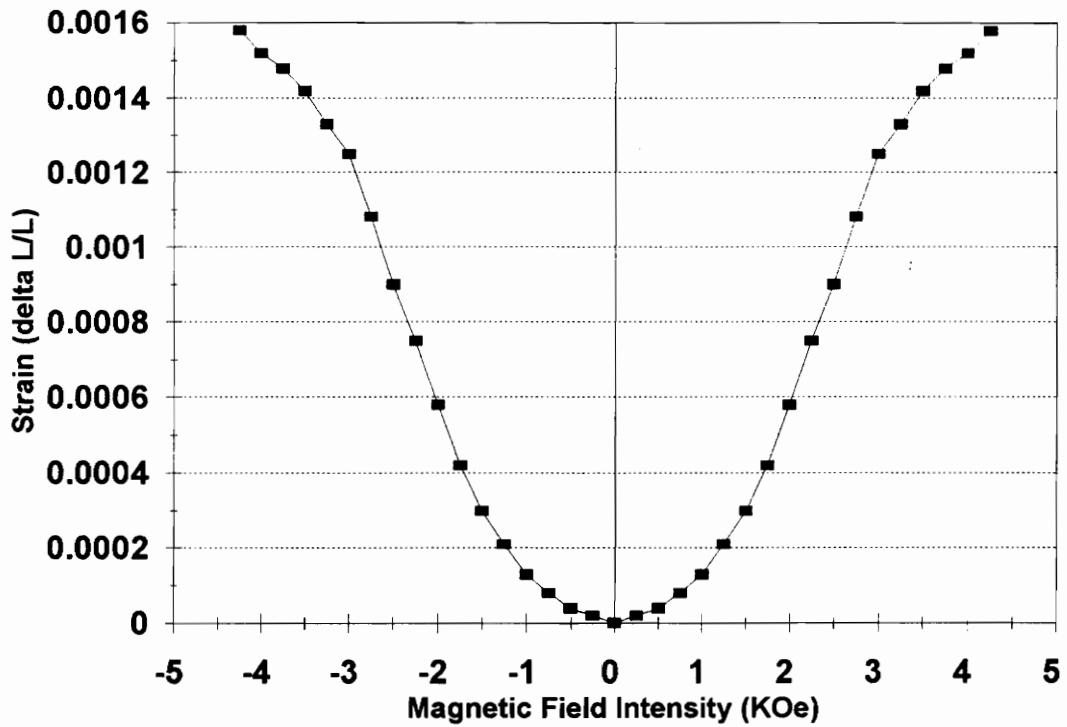


Figure 8: Typical Strain vs. Magnetic Field Intensity for TFD

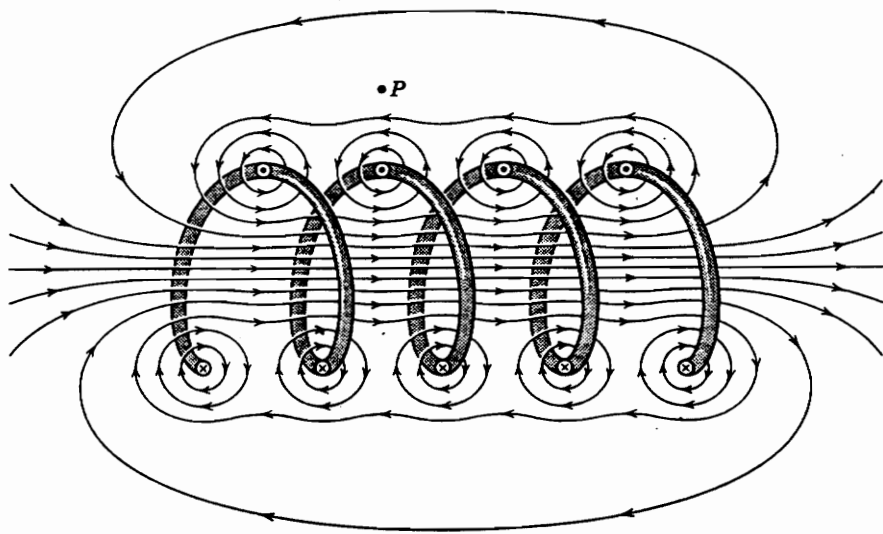


Figure 9: Magnetic Field Generation

may extend further. If the current is reversed, the magnetic fields add destructively, and the rod retracts to its natural length. Terfenol-D is also quite sensitive to the prestress applied to the rod. In general, as the prestress increases the displacement capabilities of the rod increase. However, more current, and magnetic field, is required to bring about the displacement. The force output of the element is proportional to the cross-sectional area.

2.3 Basic Relations

Preliminary sizing of magnetostrictive actuators is a fairly complex undertaking because of the large number of variables. As a start, one determines a desired displacement, force, and volume and finds the magnetic field required for this condition from the curves in **Figure 10**. How to get the magnetic field is the next question. As a first approximation the relation

$$H = nI/L \quad (1)$$

where H = magnetic field intensity
 n = number of coil turns
 I = current in the coil
 L = coil length

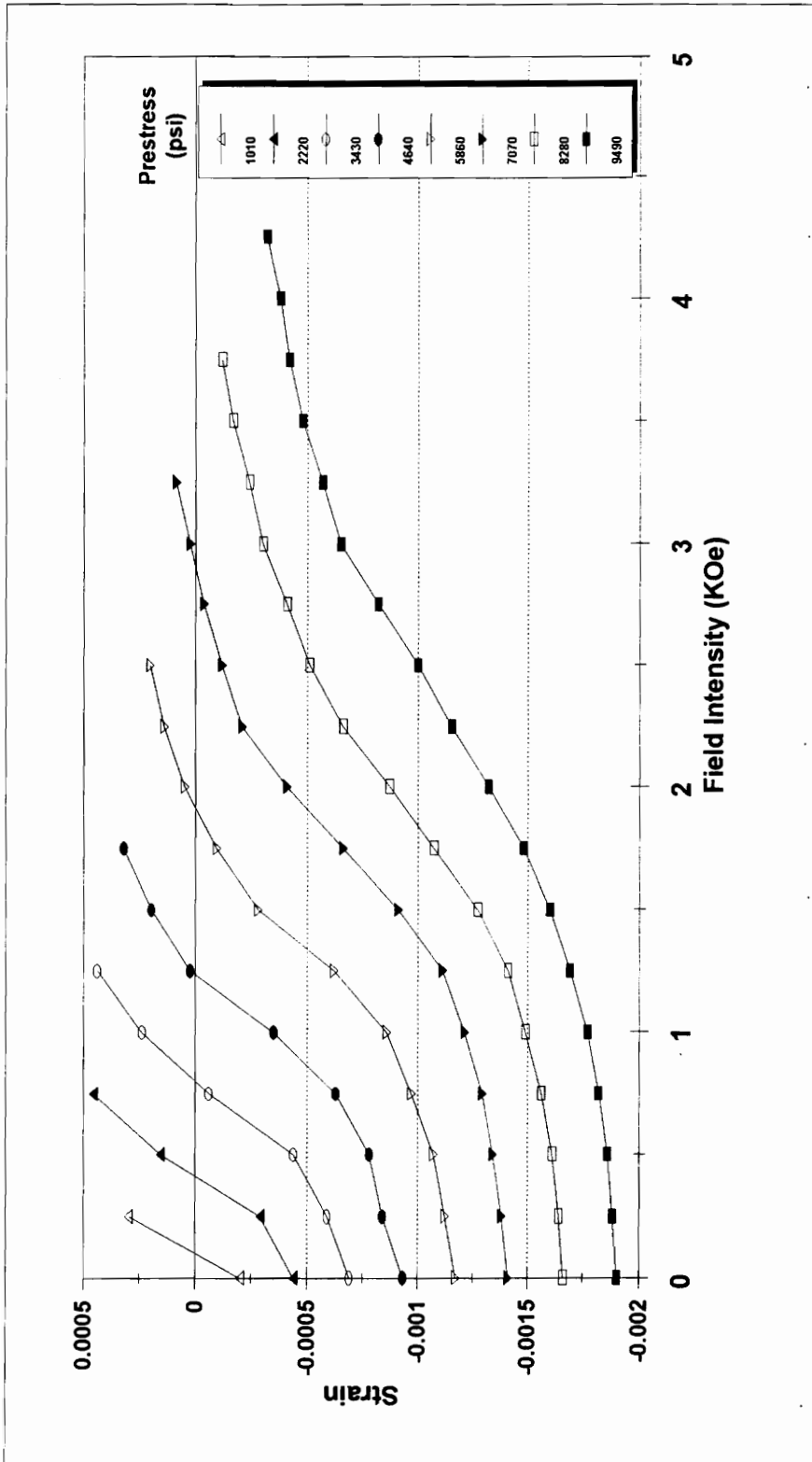


Figure 10: Prestress Effects On TFD Response

can be used. It approximates the maximum field intensity at the centerline of the coil for an infinitely long coil.

Using geometric relations, equation (1) expands to

$$H = \sqrt{\frac{P(OD - ID)}{4\rho\pi L(OD + ID)}} \quad (2)$$

where P = input power (Watts)
 OD = coil outside diameter (cm)
 ID = coil inside diameter (cm)
 ρ = coil wire resistivity (ohms/cm)
 L = coil length (cm)

There are also more sophisticated equations for magnetic field approximation [8]. However, they all estimate the field at the centerline of the coil, and do not lend any information on the distribution of the field throughout the magnetostrictive rod. Furthermore, none of the simple equations include environment geometry and material effects. To optimize the magnetic field for magnetostrictive actuators, computer based design is necessary. This is the foundation of this Project and Report.

CHAPTER 3

METHODOLOGY AND TECHNICAL RESULTS

3.1 General Approach

This chapter discusses the Project's methodology and results together because the approach was modified as the Project progressed. The approach was modified as I learned more about the electromagnetic modeling and design process and as data was being collected on the heavywalled actuator in the lab. Still, all of the work in this Project was geared toward optimizing the magnetic field by investigating the effects of alternative geometries and materials.

3.2 Baseline Design

The baseline actuator design, as it was modeled in the BEM software, is shown in cross section to scale in **Figure 11**. The model is symmetric about its centerline (the left side of the figure), and only half of the cross section is shown. Using the centerline symmetry yields the same solution as the full model and keeps the model development and solution time down. Also, if the number of nodes is limited by the software, a half-model allows more precise simulation by concentrating all of the nodes in the half-

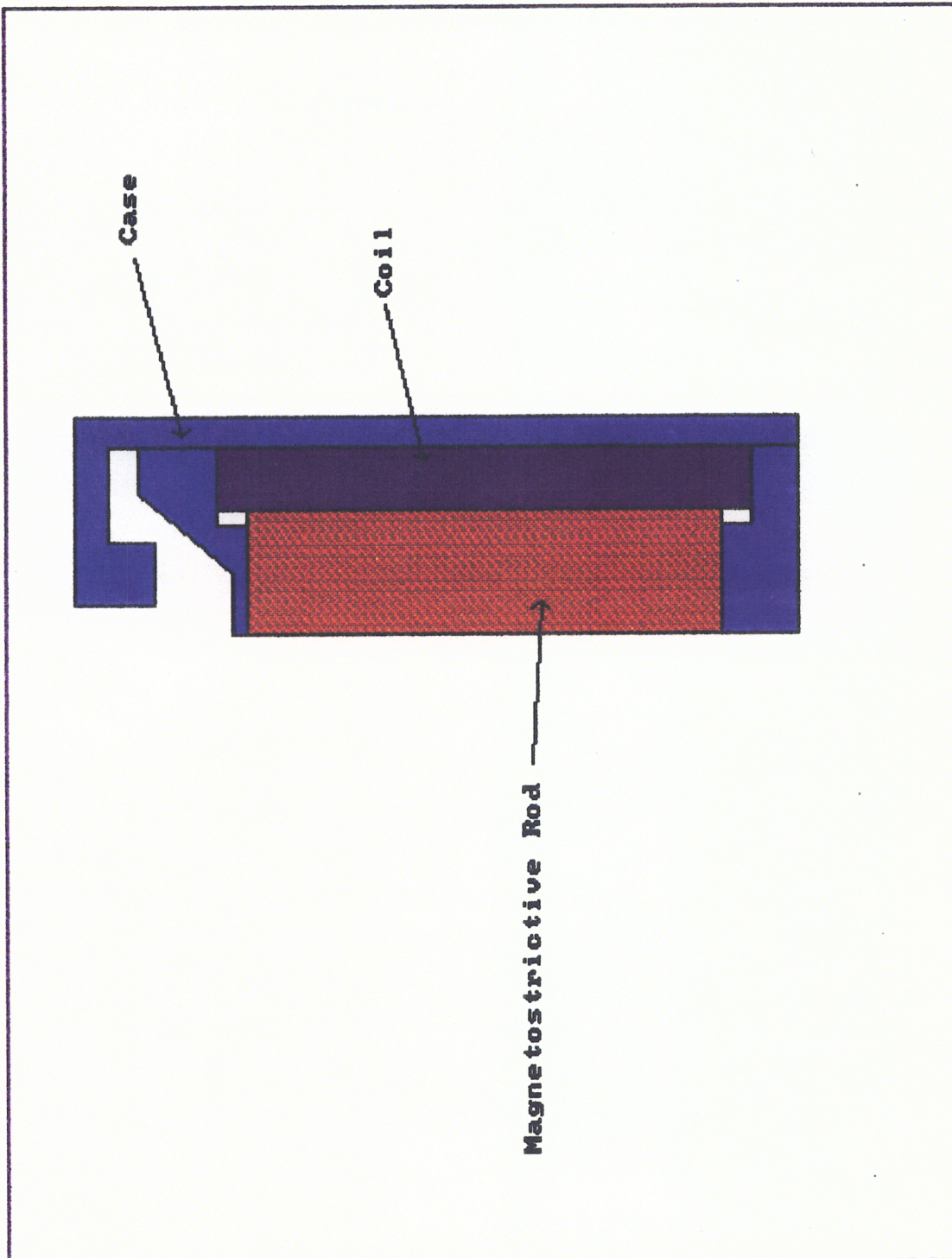


Figure 11: Baseline Actuator Model

geometry instead of spreading them about a full model. Furthermore, the model only includes the "magnetic" portion of the actuator. That is, only the coil, magnetostrictive rod, and other parts in close proximity to the coil are included. By only including the parts that would affect the magnetic field, the problem could be more accurately defined and computational time was cut considerably. For example, the displacement amplification section and the output rod were not included in the model. It was later discovered that their absence does not affect the solution at all because of the material properties.

The baseline design uses a cylindrical magnetostrictive rod 1.5 inches long and 0.9 inches in diameter. The coil's ID is 0.92 inches, and its OD is 1.5 inches. In the baseline model, the coil "overhangs" the magnetostrictive rod by 0.1 inches on each end. The 1.7 inch long coil uses a wire thickness so that there are 870 turns from end to end. The rationale for the overhang was that it would provide additional magnetic field to the ends of the rod, increasing its strain. The effect of the overhang on other system parameters was investigated first in this Project. The analysis will be discussed in the next section.

The baseline case and endcap material for the final prototype is beryllium. It has an excellent stiffness/weight ratio that makes it widely used in

aerospace applications. The bulk materials procurement and machining are expensive and time consuming, however, so using CAD methods to evaluate the design before production is especially useful. The heavywalled actuator for path finding experiments replaces the beryllium parts with stainless steel.

The preliminary sizing calculations for the baseline actuator were based on a current of 10 Amperes through 870 coil turns which gives a current density of 8700 amp-turns. Equation 1 predicts a maximum magnetic field intensity of $8700/1.7 = 5118$ Oersted. Other approximation methods [8] predict 2050 Oersteds. Again, neither of these estimations include geometry and material effects of the surrounding actuator.

3.3 Coil Length Investigation

The objective for this analysis was to determine if having the coil overhang the magnetostrictive rod is advantageous in terms of magnetic field intensity, coil weight, and input power. The methodology was to vary the coil length and check the average magnetic field intensity along the centerline of the magnetostrictive rod¹. All

¹The average magnetic field intensity along the center of the rod is readily available in the BEM post-processing software. It was used throughout the Project as a technical performance parameter for comparison between different configurations.

other physical parameters were kept constant - coil ID and OD, rod size, and coil current density.

Keeping the coil current constant as the coil length increases means increasing the input power because the coil's resistance increases with length. The causal diagrams in Chapter 1 show these relationships. But, it would be ridiculous to increase the coil length if the input power is kept the same (with the coil ID and OD kept constant), because the magnetic field intensity would decrease (see equations 1 and 2), and the coil weight would go up - a lose-lose situation.

Also, it was assumed that the coil would not be shorter than the magnetostrictive rod to save volume or power. Preliminary simulations showed that the ends of the magnetostrictive rod would barely be energized if the coil were shorter than the rod. Also, volume would not be saved because the actuator must be long enough to accommodate the magnetostrictive rod and wide enough for the coil OD.

So, in the simulation runs, the coil length ranged from the magnetostrictive rod length, 1.5 inches, up to 2.5 inches. The number of coil turns was scaled linearly with the coil length. At each length, it was assumed there was enough power to deliver 10 amps. The current density was calculated as $(10 \text{ amps}) * (\text{number of coil turns})$.

Figures 12 and **13** compare the increase of the magnetic field intensity with the increase in coil weight and coil heating respectively. Obviously, if input power and actuator weight are not concerns, it pays off to make the coil as long as possible. **Figure 12** shows, however, that the law of diminishing returns is in effect for magnetic field intensity increases - the curve is becoming flat. This signifies decoupling of the magnetic field from the magnetostrictive rod. The same result will be realized if the coil OD is increased indefinitely. Eventually, the extra turns available at the outside of the coil are so far removed from the magnetostrictive rod that their magnetic fields are not realized at the center of the coil.

Another argument that can be made is that for a given coil length, why not make the magnetostrictive rod the same length and maximize the available volume of working material? Increasing the magnetostrictive rod length, or decreasing the overhang, will increase the output displacement of the actuator. One circumstance that would merit an overhang is for a given application, the magnetic field requirement leads to a coil length, and the actuator performance and weight requirements lead to a magnetostrictive rod length shorter than the coil.

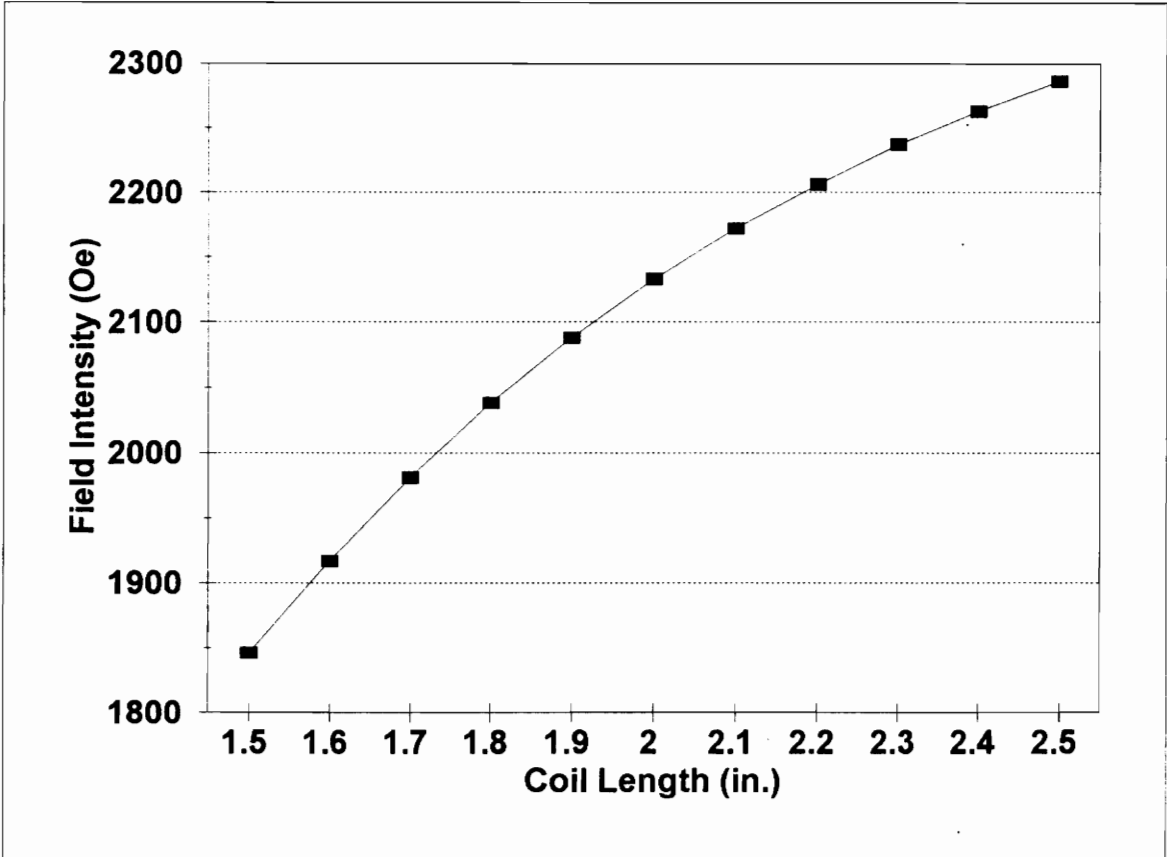


Figure 12: Field Intensity vs. Coil Length

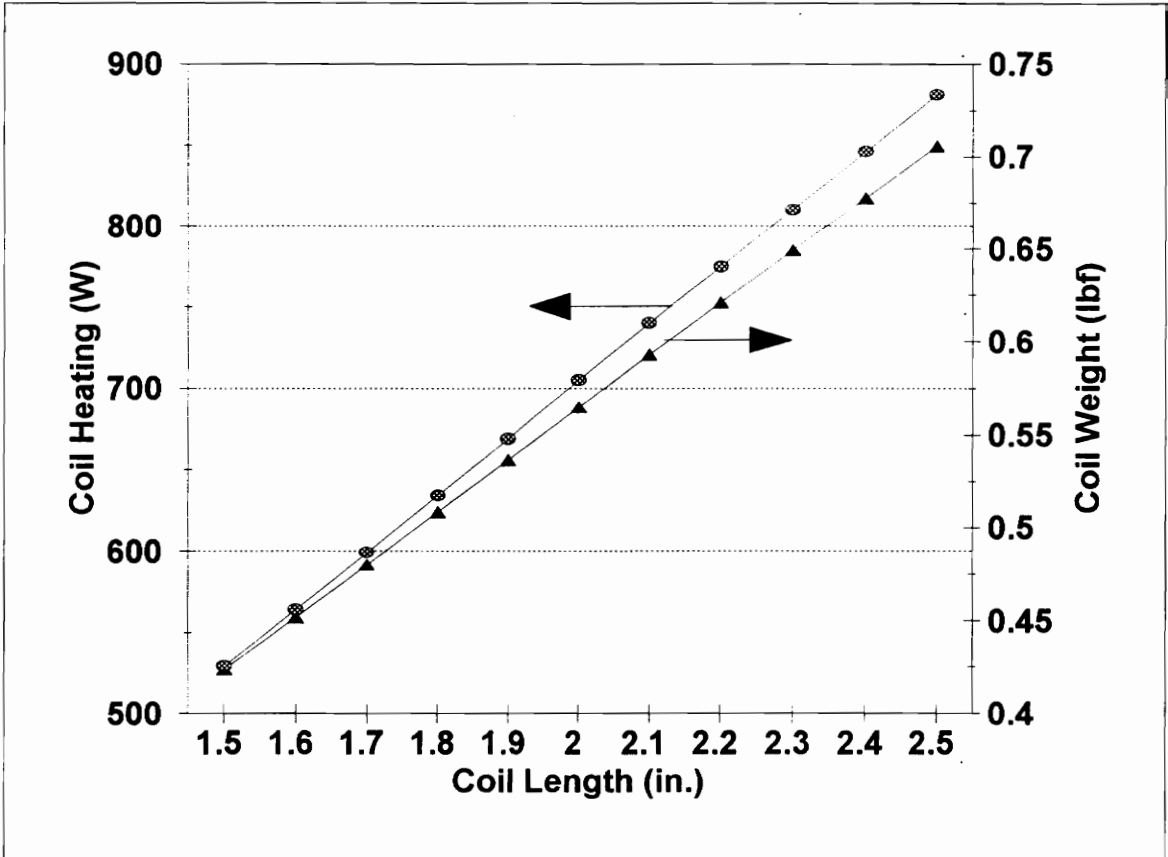


Figure 13: Coil Heating and Coil Weight vs. Coil Length

A few design guidelines can be gleaned from the analysis:

- Determine the length and diameter of magnetostrictive material for a given application. This often requires the use of simulation codes to investigate the effects of prestress and return mechanisms.
- Determine the magnetic field intensity required to satisfy the performance requirements.
- Starting with a coil the same length as the rod, increase the coil's OD until the resulting field intensity is satisfactory or until a limiting diameter is reached.
- Adjust the coil length, if necessary.

If the coil is made longer, consider increasing the magnetostrictive element length unless weight or configurational restrictions take precedent.

For our research program where power and weight are to be minimized, it is recommended that the coil be shortened to 1.5 inches, the length of the magnetostrictive rod. **Figure 14** is a plot of the magnetic field intensity along the centerline of the magnetostrictive rod for the coil lengths of 1.7 and 1.5 inches. From the average values in **Figure 14**, and assuming that the coil weight and resistance vary linearly with length, shortening the coil from 1.7 to 1.5 inches results in a 5% reduction in magnetic field intensity, and a 12% reduction in coil weight and power input. The actuator case can also be made shorter and

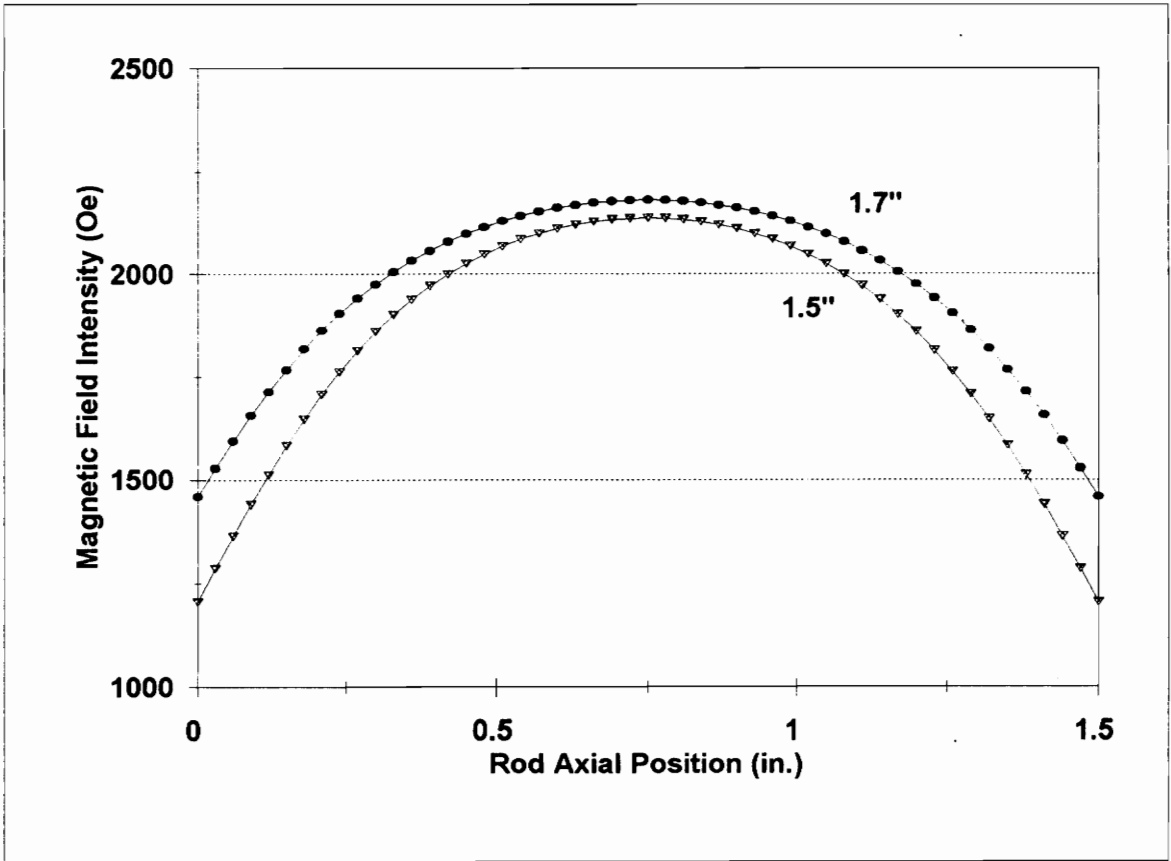


Figure 14: 1.5" and 1.7" Coil Length Field Distributions

lighter to accommodate the shorter coil, so the weight savings over the baseline configuration for the actuator system would be expected to be in the 20% range.

3.4 Geometry and Materials Investigation

The objective of this analysis was to determine if the magnetic field intensity could be increased and made more uniform across the magnetostrictive element by using materials and configurations other than those in the baseline design. **Figure 15** shows the baseline magnetic field intensity contours, and **Figure 16** is the same plot for the actuator with a 1.5 inch coil. Again, the baseline case and other structural parts are to be made of beryllium, the coil is copper, and the magnetostrictive rod is Terfenol-D.

In a magnetic fields analysis, the most important material property is the permeability of the material. The magnitude of the permeability is proportional to the "magnetic conductivity" of the material. A high permeability material provides a path of low resistance to flux field just as a 1 ohm resistor provides the path of least resistance if it is in parallel with a 100 ohm resistor. Therefore, for an applied magnetic field, the highest magnetic flux will be found in the material with the highest permeability. Usually, the permeability is given as

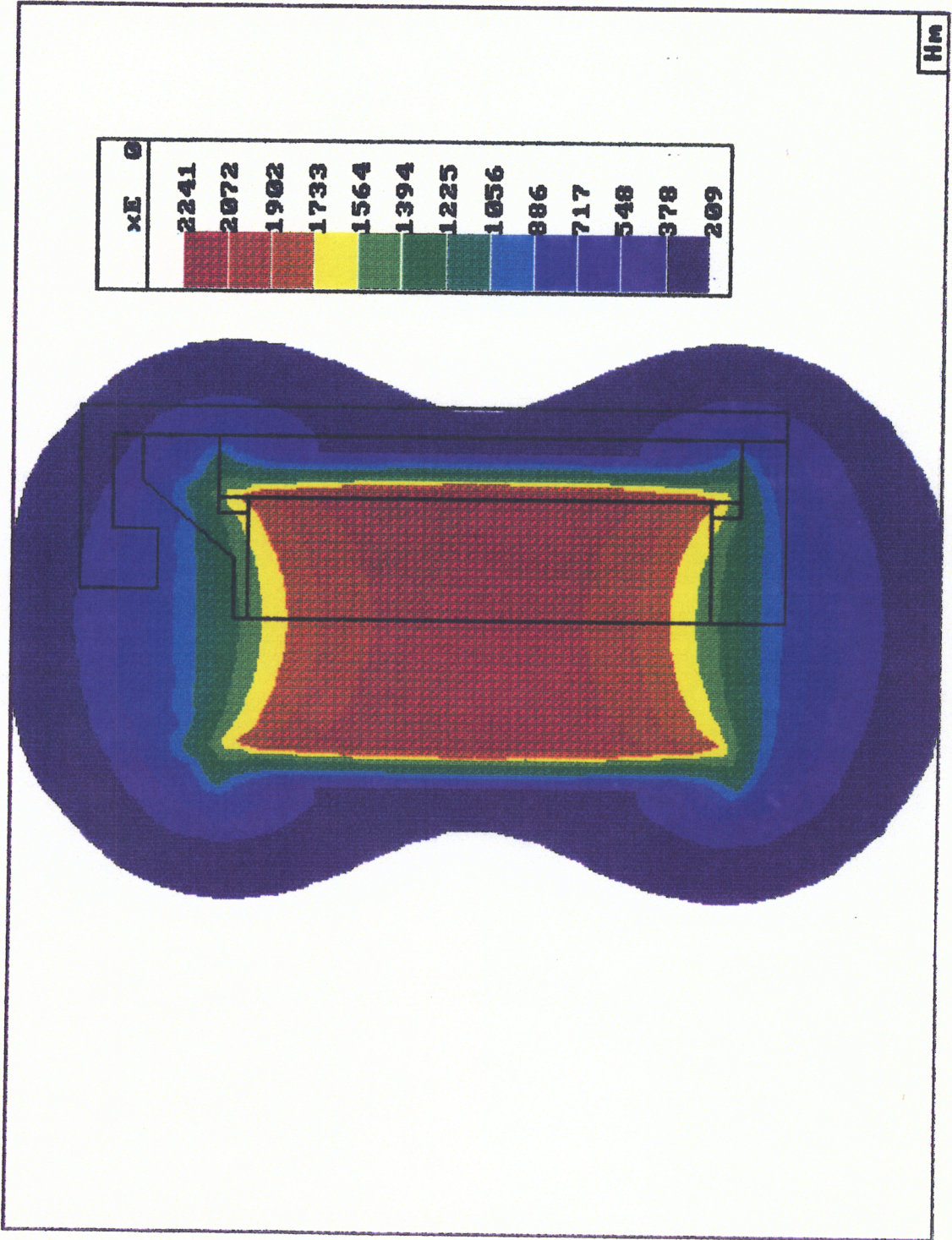


Figure 15: Baseline Field Intensity Contours

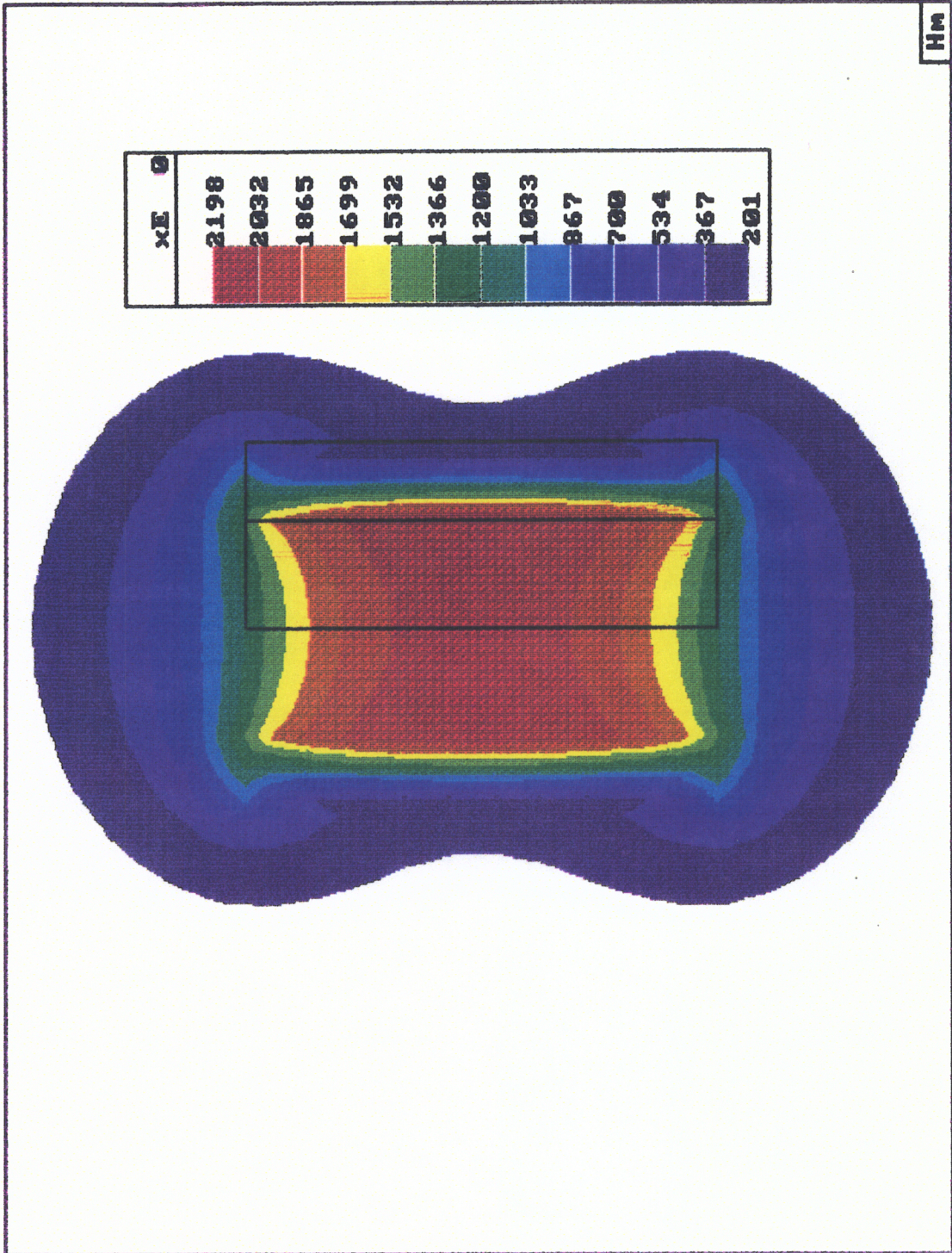


Figure 16: 1.5" Coil Field Intensity Contours

a relative value to air. **Table 4** gives some sample relative permeability values for common materials.

A high permeability material has internal magnetic fields that add constructively with the external (applied) magnetic field. Therefore, the internal field intensity in these materials is actually higher than the applied field. Most materials have no effect on the applied field and are referred to as non-magnetic. These materials have relative permeability's close to 1.0, air's value. Therefore, non-magnetic materials do not affect the magnetic distribution at all. If they are left out of the analysis, the field intensity would be the same at every point in the solution space.

Beryllium is a non-magnetic material. Its permeability is just slightly greater than 1.0, so the beryllium case and parts could be left out of a magnetic field analysis without affecting the approximate solution. However, in most magnetic coil applications, there is a **magnetic circuit** provided for the flux to return from the coil back to the core material in the center of the coil. This magnetic circuit is made of a high permeability material and provides a path of least resistance for the flux. The goal is to reduce the magnetic *leakage* flux out of the actuator case. Back in **Figure 16**, all of the flux which is not returned to the rod is considered leakage flux. It essentially circles

Table 4: Relative Permeability of Common Materials

Material	Relative Permeability
Wood	.999999
Aluminum	1.0000065
Beryllium	1.0000079
Nickel	50
Permalloy 45	2500
Carbon Steel	30000
Supermalloy	100000

the coil/rod system and is not available to be converted to mechanical energy by the rod. For an infinitely long rod, all of the flux would be returned to the rod.

In most common magnetic applications, such as in terrestrial transformers, weight is not a concern. In these applications, the entire case and endcaps surrounding the coil are made of a high permeability steel or iron. For the actuator at hand, the magnetic field intensity in the magnetostrictive rod could be greatly increased by making the entire case and endcaps out of a high permeability material, such as carbon steel. Such a model is shown in **Figure 17**. The magnetic field contours for the all steel model is shown in **Figure 18**, and the distribution along the centerline of the rod is compared to the all beryllium model in **Figure 19**.

One interesting result is that for the all steel design the magnetic field intensity is higher at the ends of the magnetostrictive rod than at the center, which contrasts with the all beryllium model. This is because all of the leakage flux from the beryllium model is being returned to the ends of the rod in the steel model. Also, the magnetic field intensity distribution is much higher in the steel model - the average value is 35% higher than in the beryllium model.

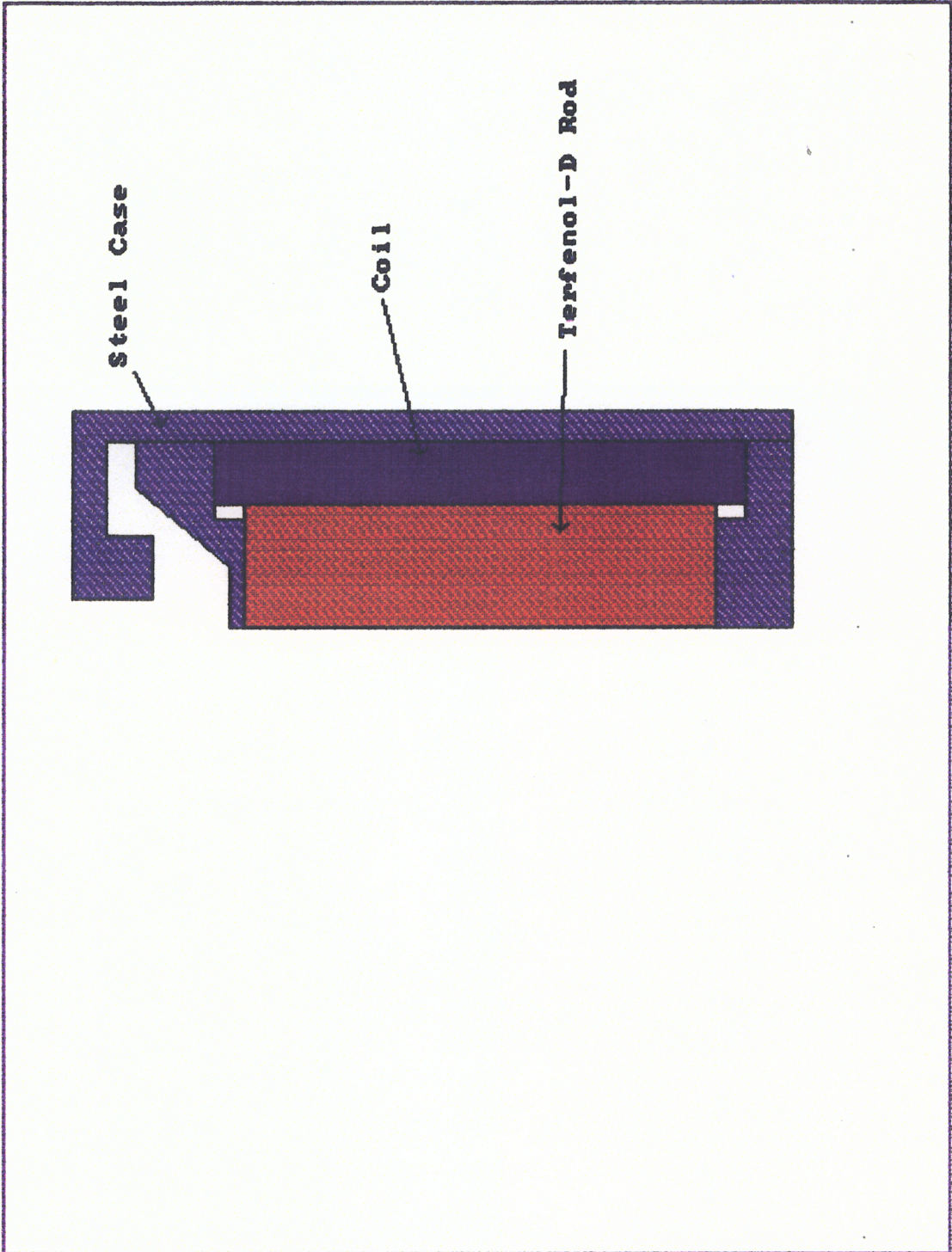
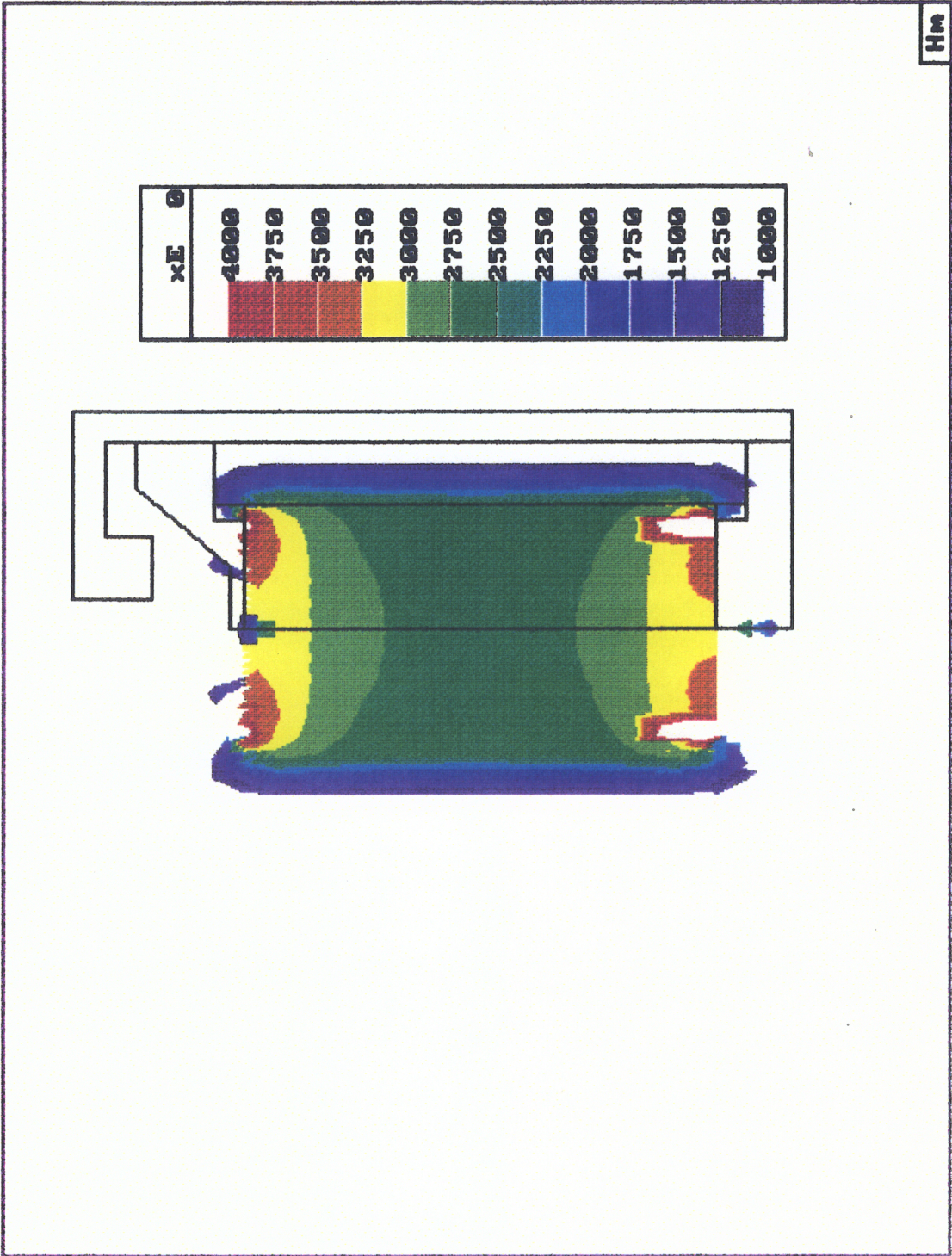


Figure 17: Actuator Model With Carbon Steel Case and Endcaps



Hm

Figure 18: All Steel Field Intensity Contours

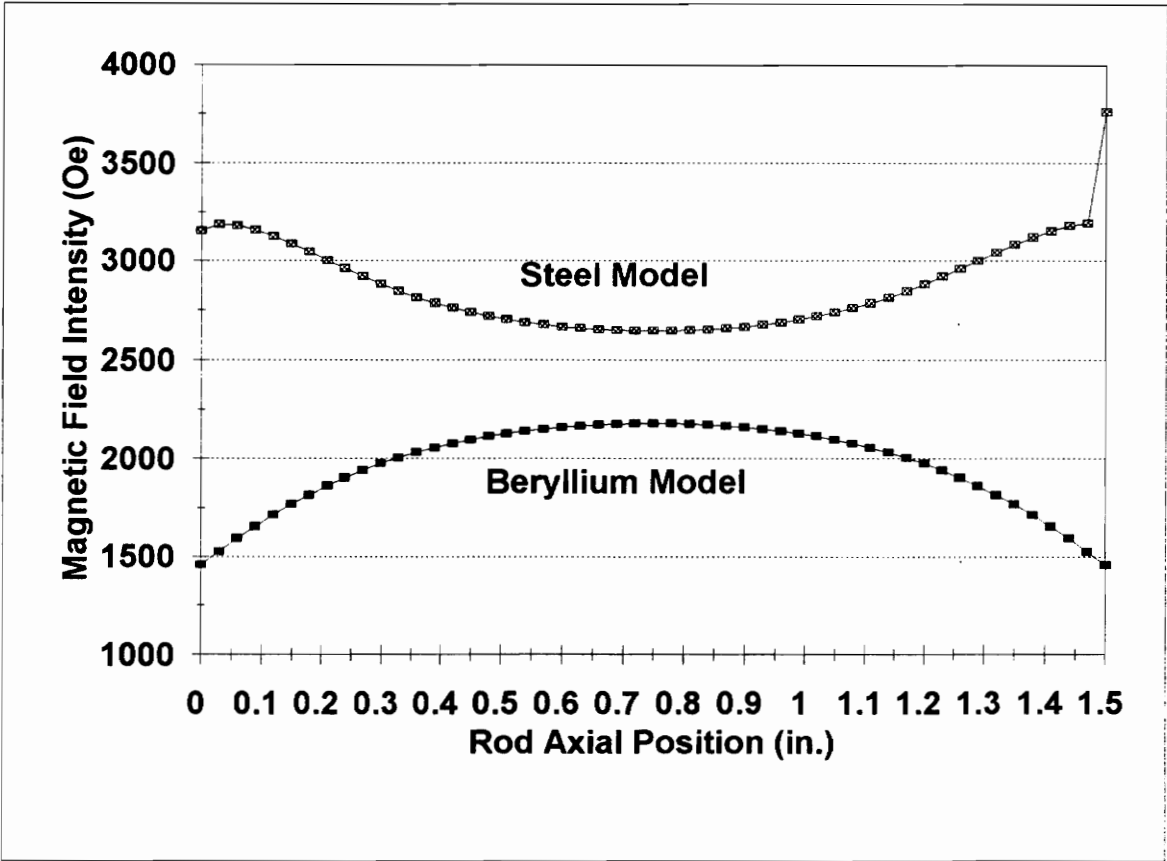


Figure 19: Steel vs. Beryllium Field Distributions

distribution In this actuator, however, weight should be minimized. That is why beryllium was chosen for all case materials. It provides 50% more stiffness than steel at one-fourth the weight. If it could provide a suitable magnetic circuit for the actuator, it would be the ideal material. But this is not the case.

The approach taken to solve this problem was to provide a magnetic circuit with only a thin layer of high permeability material around the coil and rod. The bulk of the case would still be beryllium. A solution was sought that would minimize the weight increase of the actuator, would maximize the flux return, and would be easy to implement in a prototype model. Of course, these are conflicting requirements, so the best combination was sought.

Three designs were considered: (1) The **Full** configuration, shown in **Figure 20** as it was modeled, uses a layer of high permeability material around the entire coil, including the ends. The magnetic circuit contacts the magnetostrictive rod at both ends. This design would require multiple pieces, as moving parts have to slide against stationary parts. The small gap between sliding parts was assumed to be small enough to neglect in the model. (2) The **Can** configuration uses a layer of high permeability material around the entire coil and only the

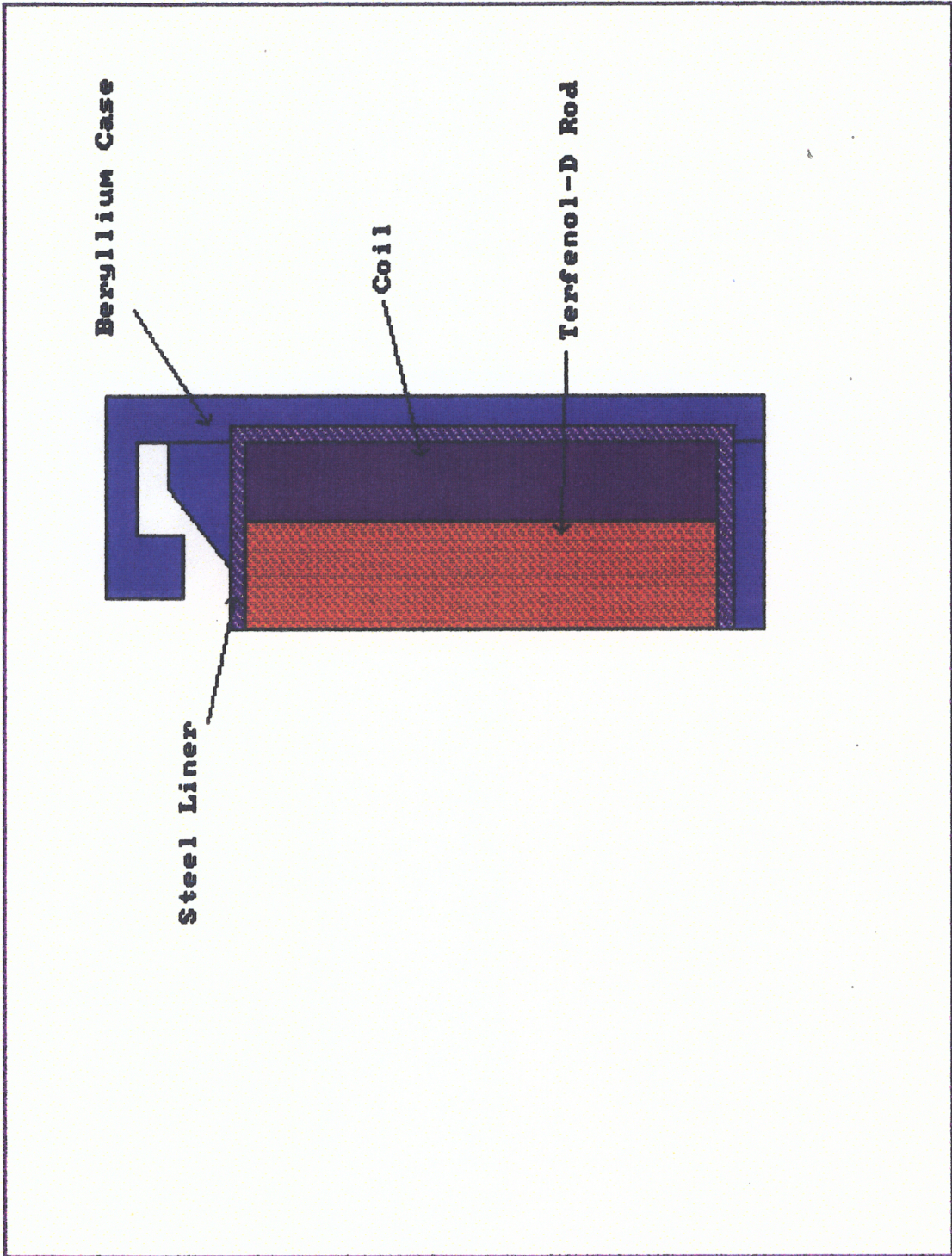


Figure 20: Full Magnetic Circuit

stationary (bottom) end of the coil and rod. The axisymmetric model is shown in **Figure 21**. Picture it as an empty soda can with the top cut out. This design should be lighter than the *Full* design and would not require sliding parts. However, the magnetic circuit will not be as effective. (3) The final design, **Wrap**, is simply a cylindrical shell of high permeability material. As shown in axisymmetric cross section in **Figure 22**, it is like an empty soda can with both ends cut out. This design is not a complete magnetic circuit - neither end of the magnetostrictive rod touches the circuit, but it is lighter and simpler than the first two designs.

The technical performance parameters for the trade-off study were the average magnetic field intensity along the centerline of the magnetostrictive rod, the distribution of the magnetic field along the centerline, and the weight of the magnetic circuit.

The methodology was to set up all three configurations in the electromagnetic analysis software and solve for the magnetic field distributions. This process was repeated for several magnetic circuit thicknesses, starting at 0.05 inches down to 0.00625 inches. The hypothesis was that the thinner circuits would not be as effective magnetically, but would be lighter.

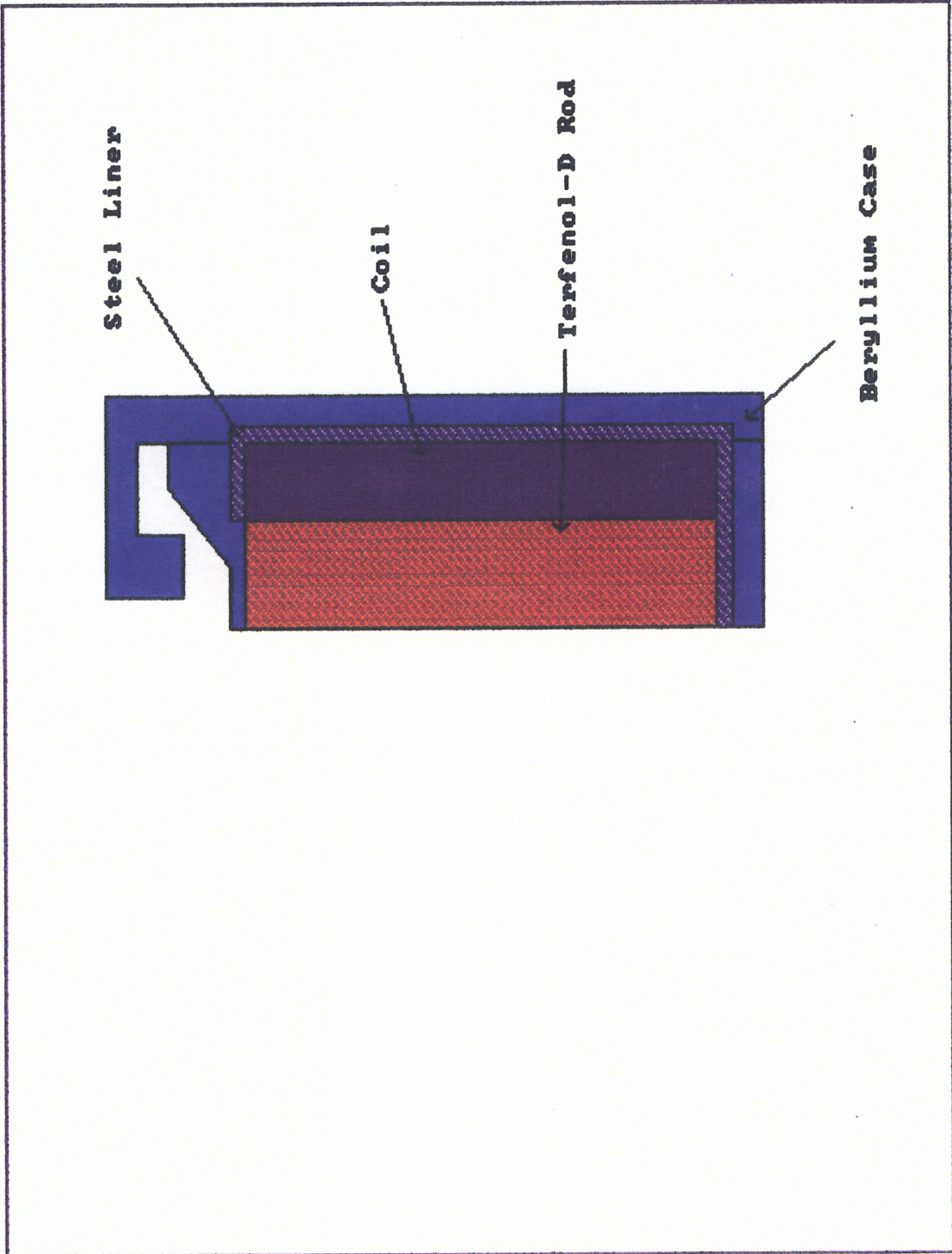


Figure 21: Can Magnetic Circuit

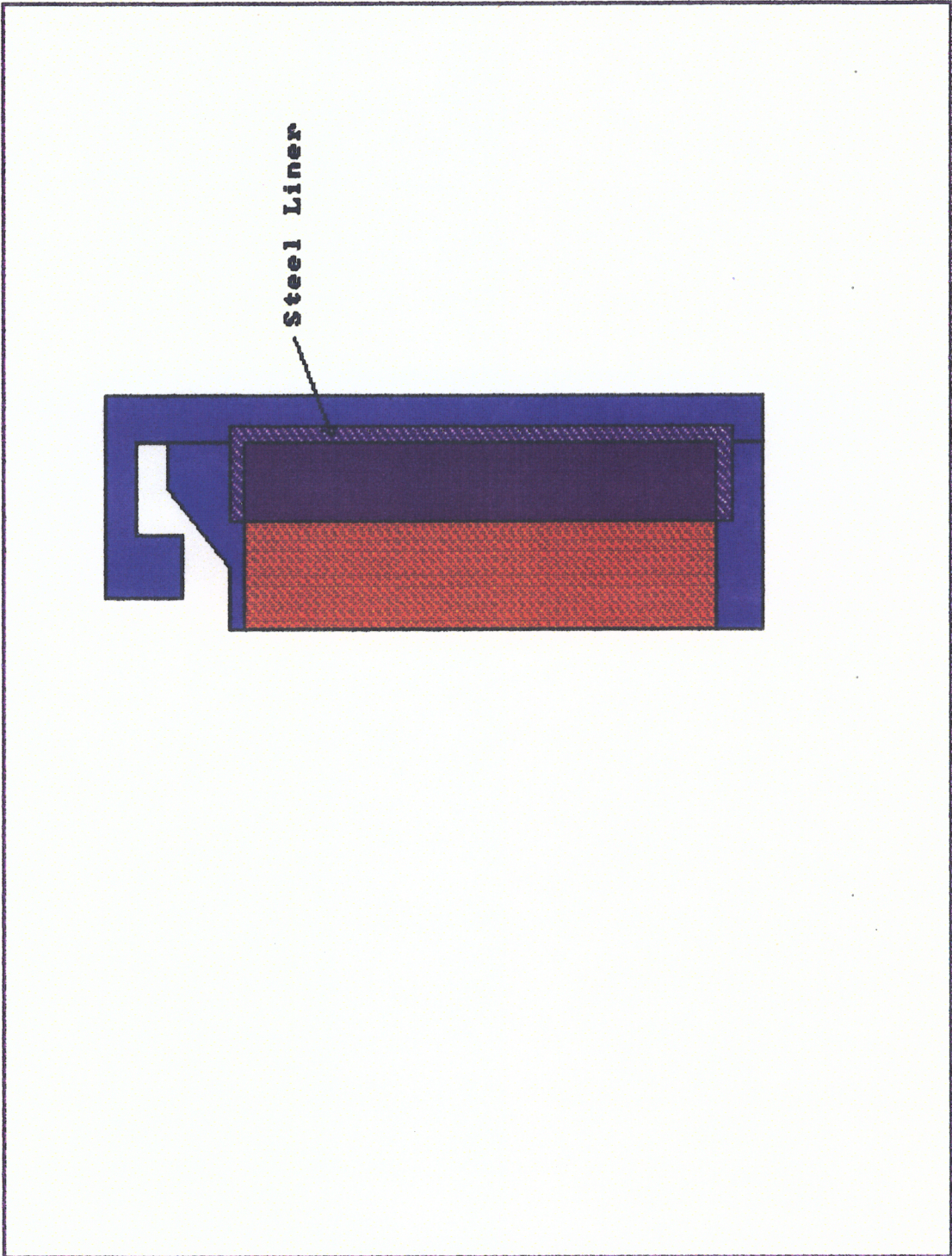


Figure 22: Wrap Magnetic Circuit

Carbon steel was used for the magnetic circuit material in all runs. Its relative permeability is 30,000, and it is relatively cheap and readily available in many sheet thicknesses. The model for this analysis used a 1.5 inch long coil and magnetostrictive rod, based on the analysis reported in section 3.3. The input current density was 7676 amp-turns, or 10 amps and 767.6 coil turns. This value was scaled from the 8700 amp-turns used with the 1.7 inch coil.

3.5 - Materials and Geometry Results

This section gives the results of the analysis described in Section 3.4. **Figures 23, 24, and 25** show the contour plots of the magnetic field intensity for the **Full, Can, and Wrap** configurations, respectively, all with 0.050 inch thick magnetic circuits.

In the *Full* plot, all field intensities above 2533 Oersteds and below 2517 Oersteds are in white, so that the resolution across the magnetostrictive rod would be better². **Figure 23** demonstrates how a magnetic circuit can reduce the leakage from the coil. In comparing **Figure 23** with **Figure 16** from section 3.3, it can be seen that the magnetic flux is returned to the magnetostrictive rod much

² The white areas around the outside edges of the magnetostrictive rod in **Figure 23** are due to solution problems that the Boundary Element Method has around sharp corners. These singularities can be reduced by replacing the corners with small radii curves. This was not done in this study to save computational time, and because the corner effect has minimal bearing on the centerline solution.

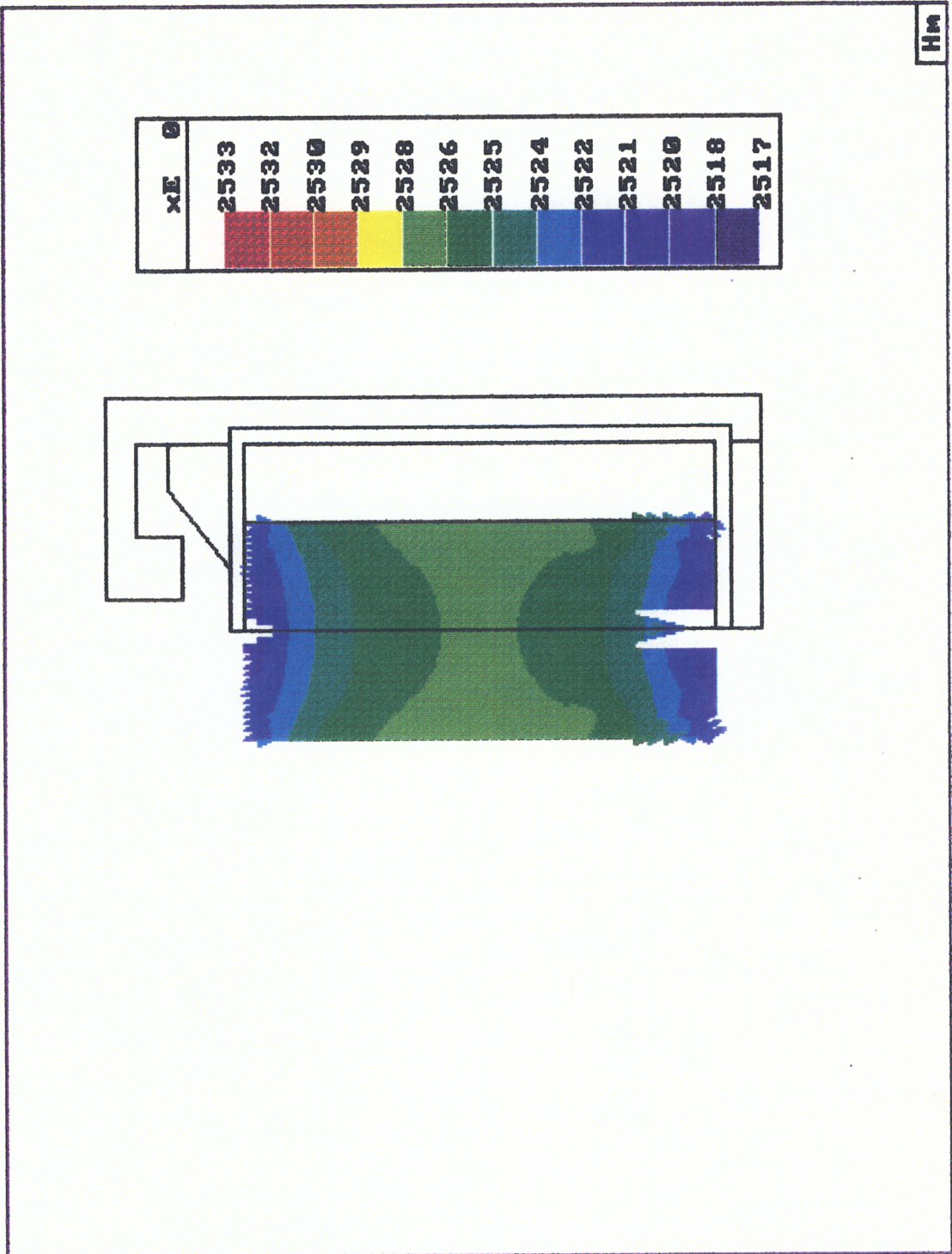


Figure 23: Full Field Intensity Contours

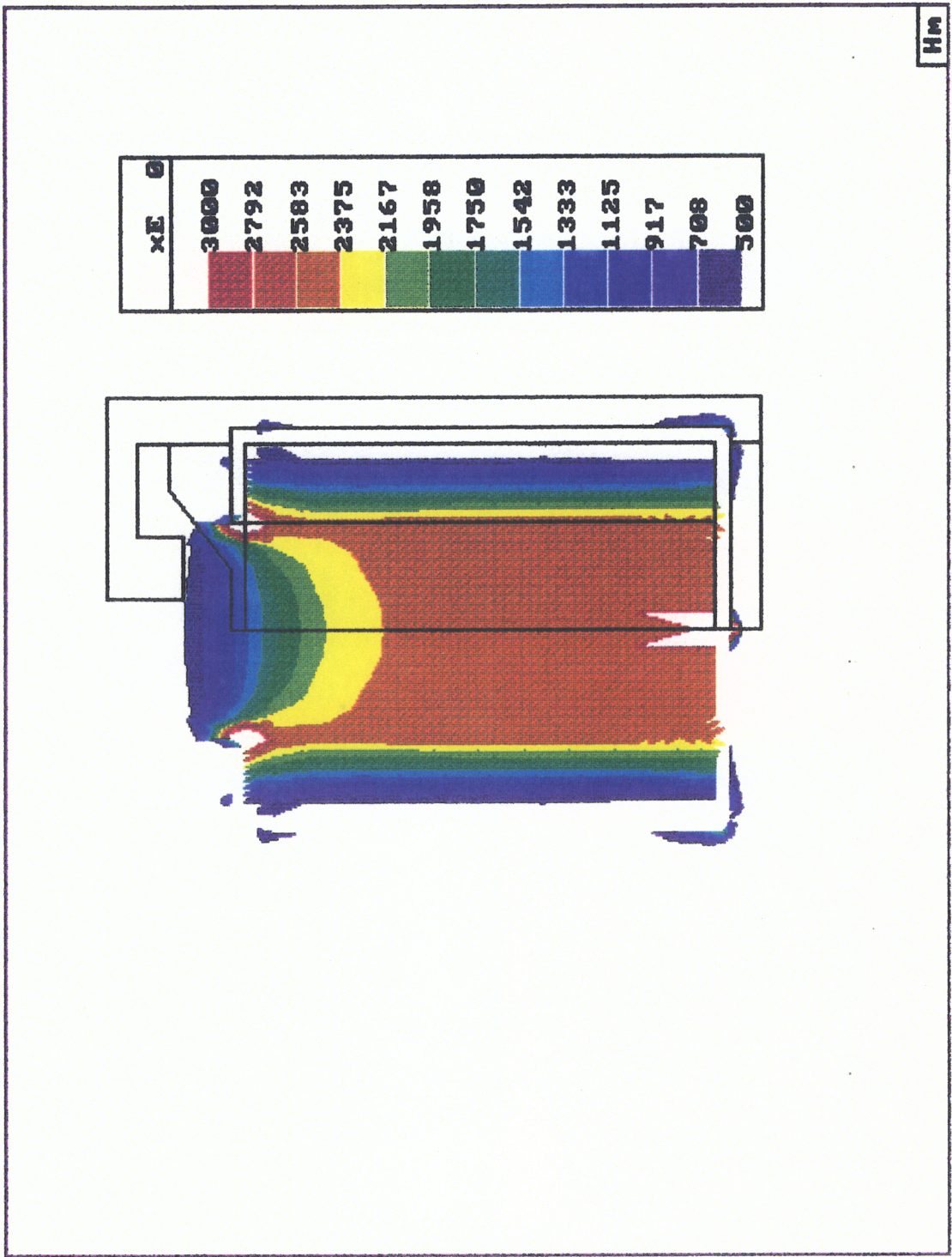
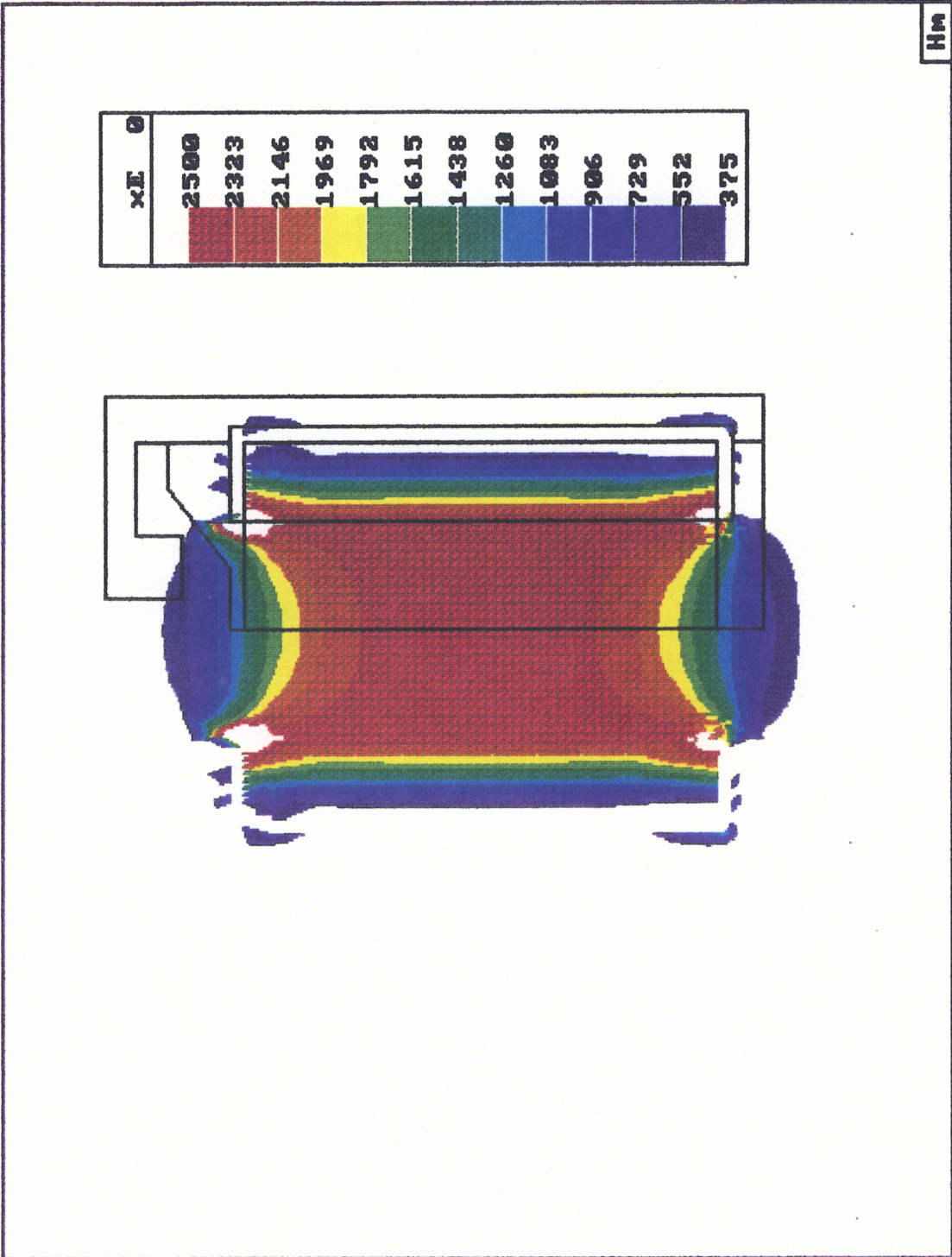


Figure 24: Can Field Intensity Contours



mm

Figure 25: Wrap Field Intensity Contours

more effectively than in the baseline model. The magnetic field intensity outside of the circuit (the leakage) is much smaller with the magnetic circuit in place. More importantly, there is an increase in the average centerline magnetic field intensity from 1876 Oersteds to 2525 Oersteds. This is effectively increasing the efficiency of the actuator since more input electrical energy is available for conversion to mechanical energy.

Figure 26 shows the results of varying the thickness of the magnetic circuit on the average centerline magnetic field intensity. As expected, the effectiveness of the field decreases with thickness, but not much. At 0.0625 inches, the smallest commercially available sheet thickness, the average intensity at 10 amps is 10.4% greater than with no shield at all. **Figure 27** shows that the field intensity is very "flat" across the magnetostrictive rod. This is desirable since the entire rod is working near the maximum magnetic field intensity.

Figures 24 and **25** show the contour plots for the *Can* and *Wrap* configurations, respectively. Again, in both figures, the white areas have magnetic field intensities either less than the lowest value on the scale (outside the actuator) or greater than the highest value on the scale (around sharp corners). In both figures, flux leakage is seen around at the ends without a magnetic circuit endcap.

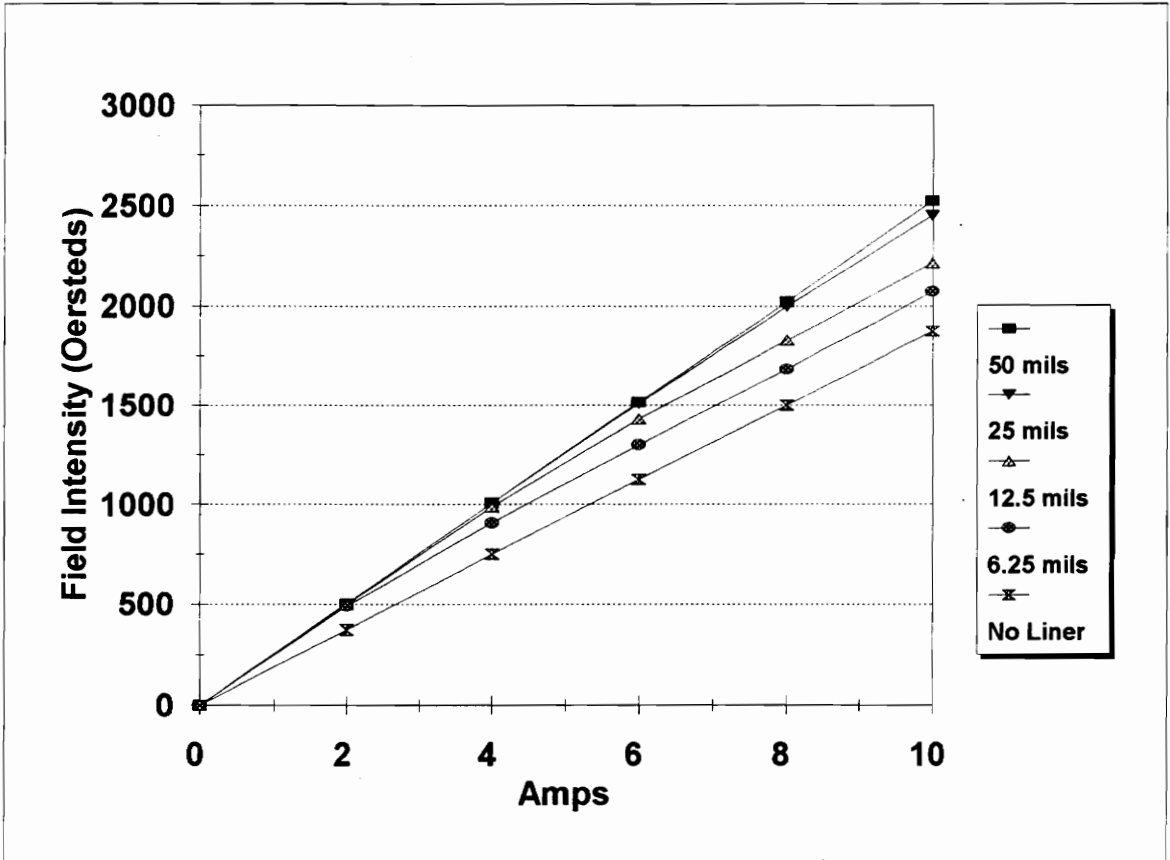


Figure 26: Thickness Effects On Full Circuit

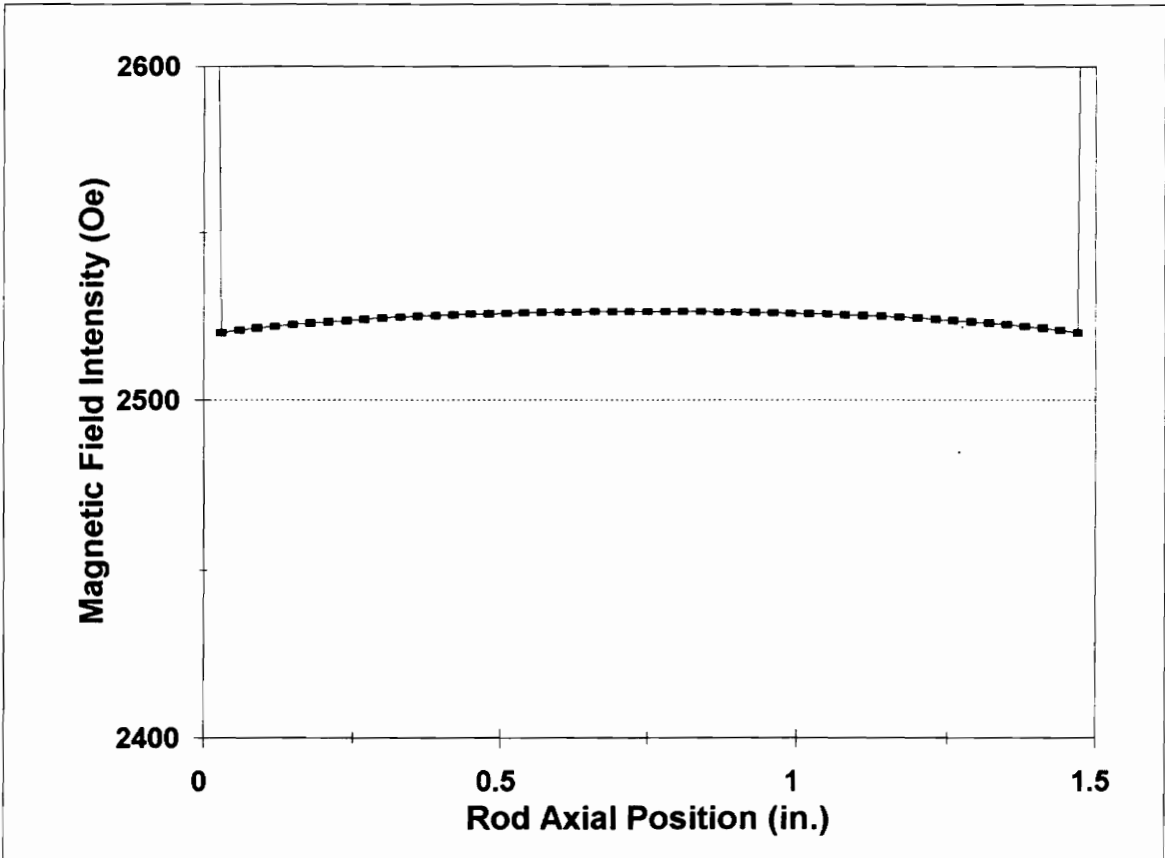


Figure 27: Full Circuit Field Distribution

However, referring to **Figures 28** and **29**, these designs also provide more magnetic field at the magnetostrictive rod centerline than the baseline design. **Figures 30** and **31** show the interesting distributions of magnetic field intensity along the magnetostrictive rod centerline.

As was stated earlier in the chapter, weight is a major concern for this actuator system. Replacing a certain volume of structural beryllium with a steel magnetic circuit will certainly increase the weight of the actuator. The graph in **Figure 32** shows the estimated weight increases due to the magnetic circuit for the three designs.

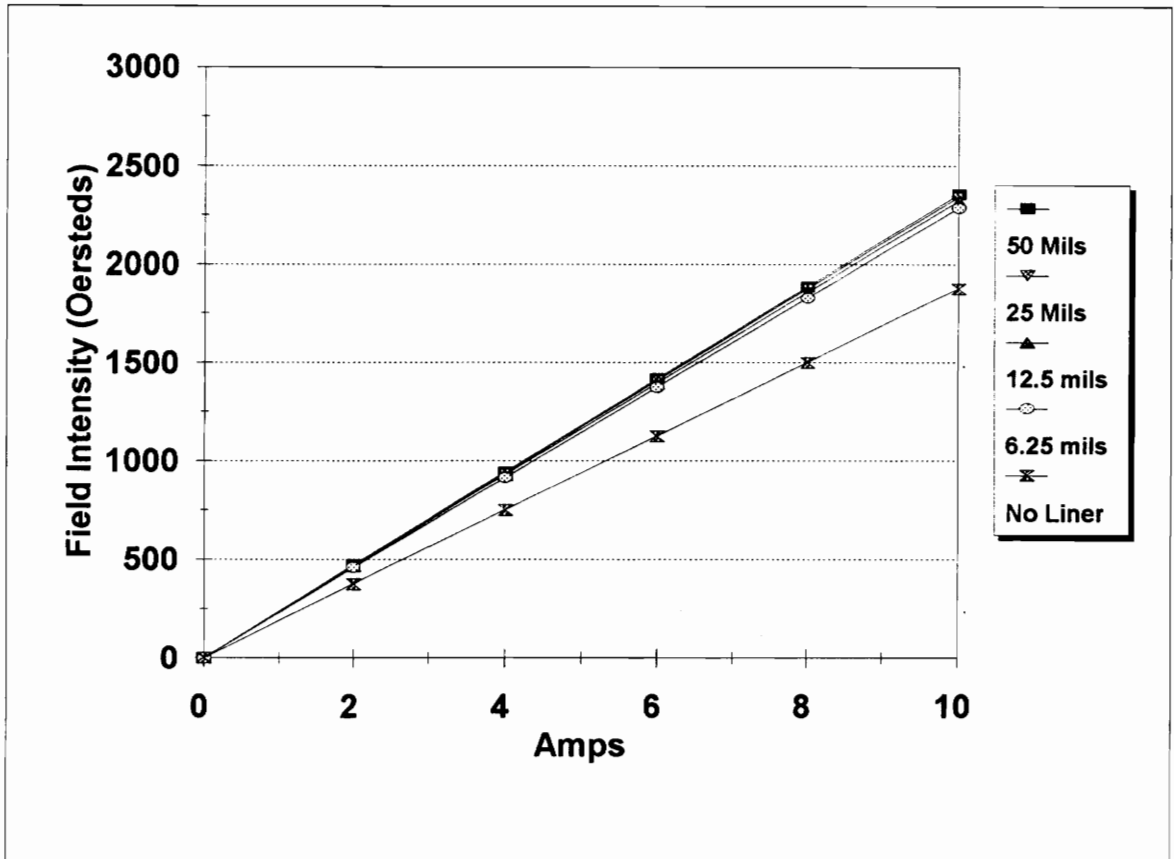


Figure 28: Thickness Effects On Can Circuit

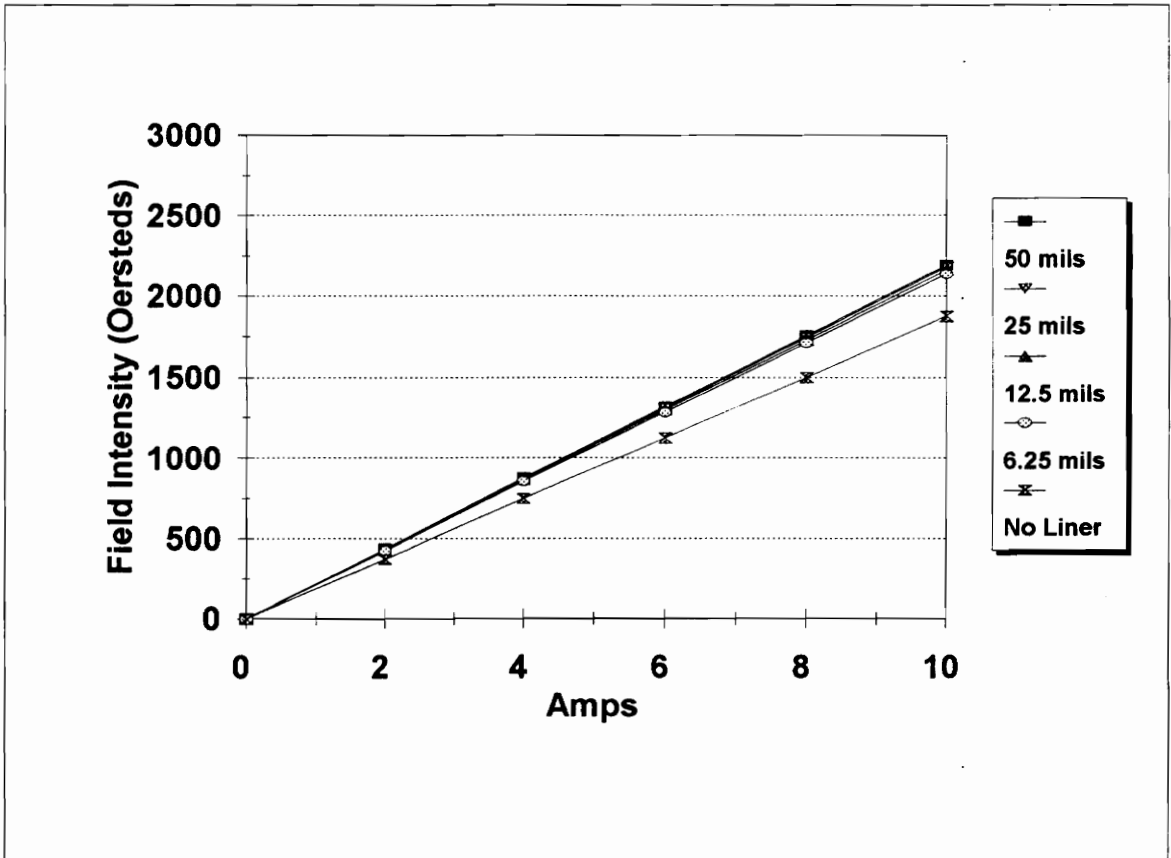


Figure 29: Thickness Effects On Wrap Circuit

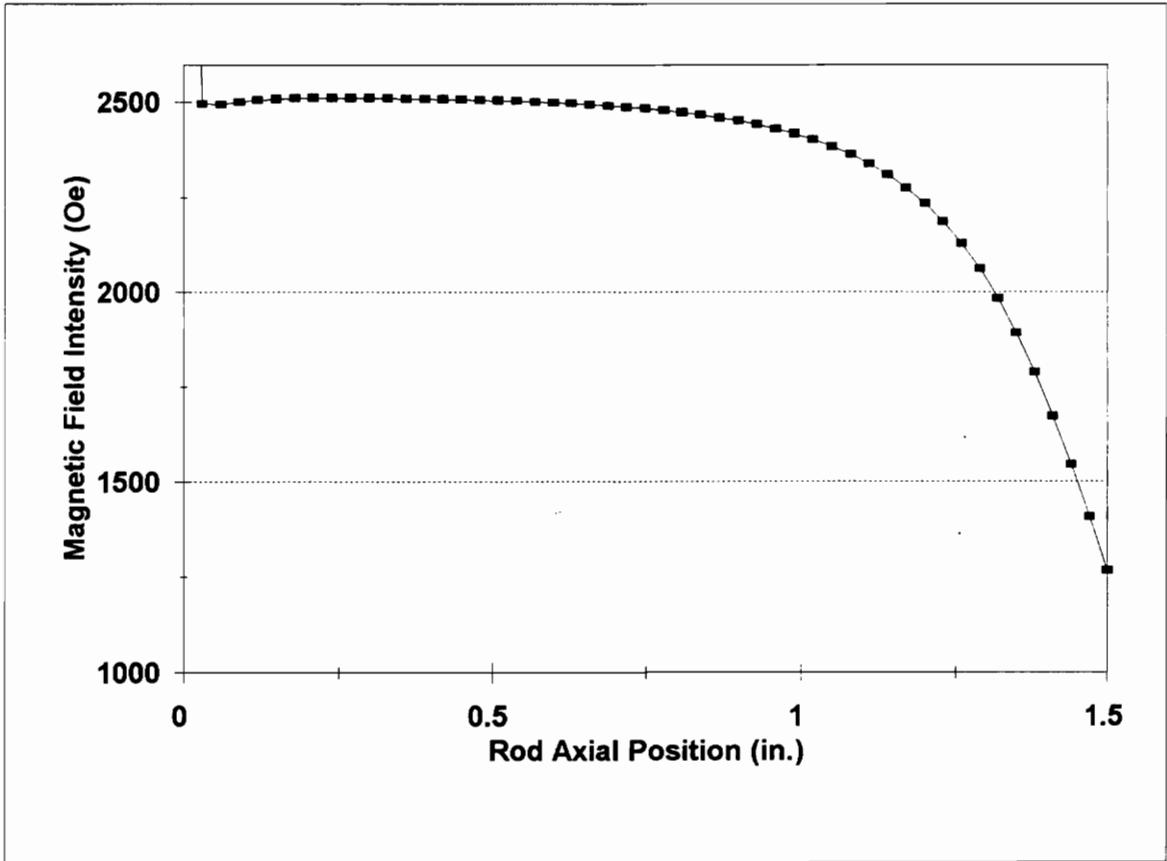


Figure 30: Can Circuit Field Distribution

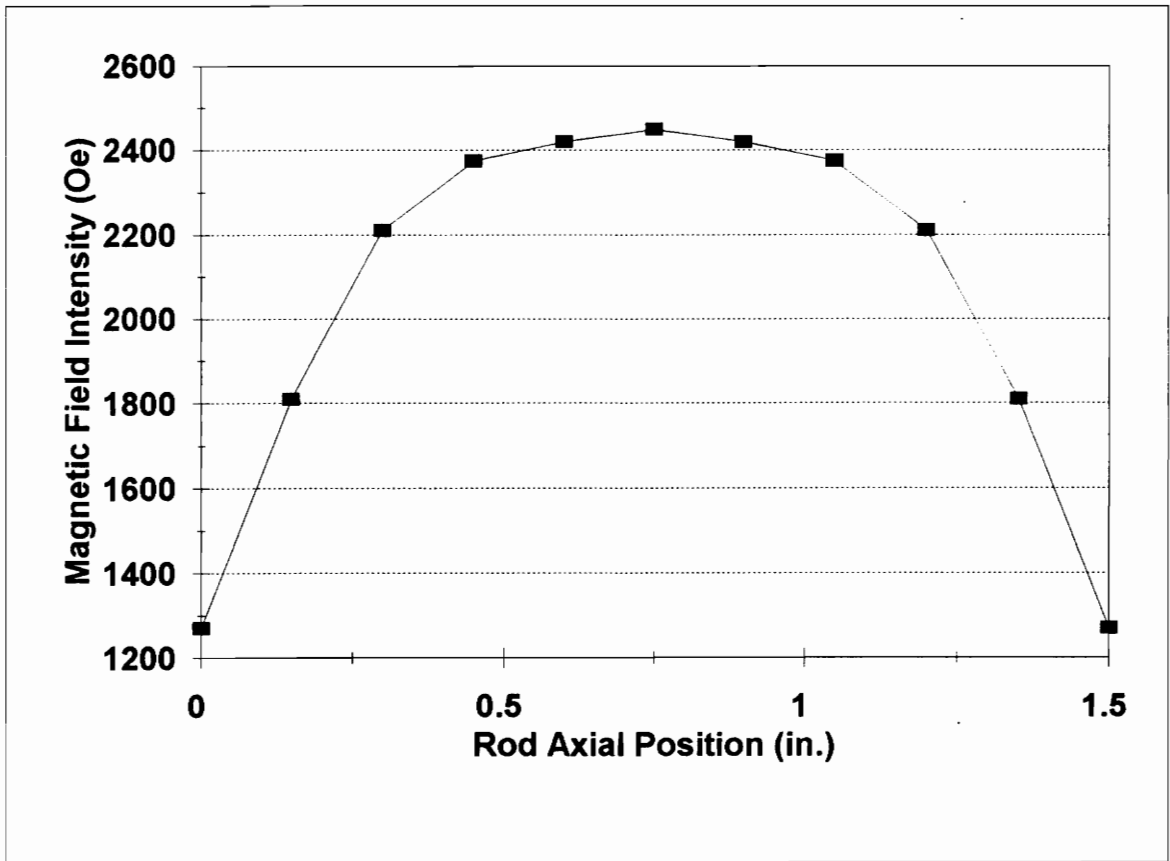


Figure 31: Wrap Circuit Field Distribution

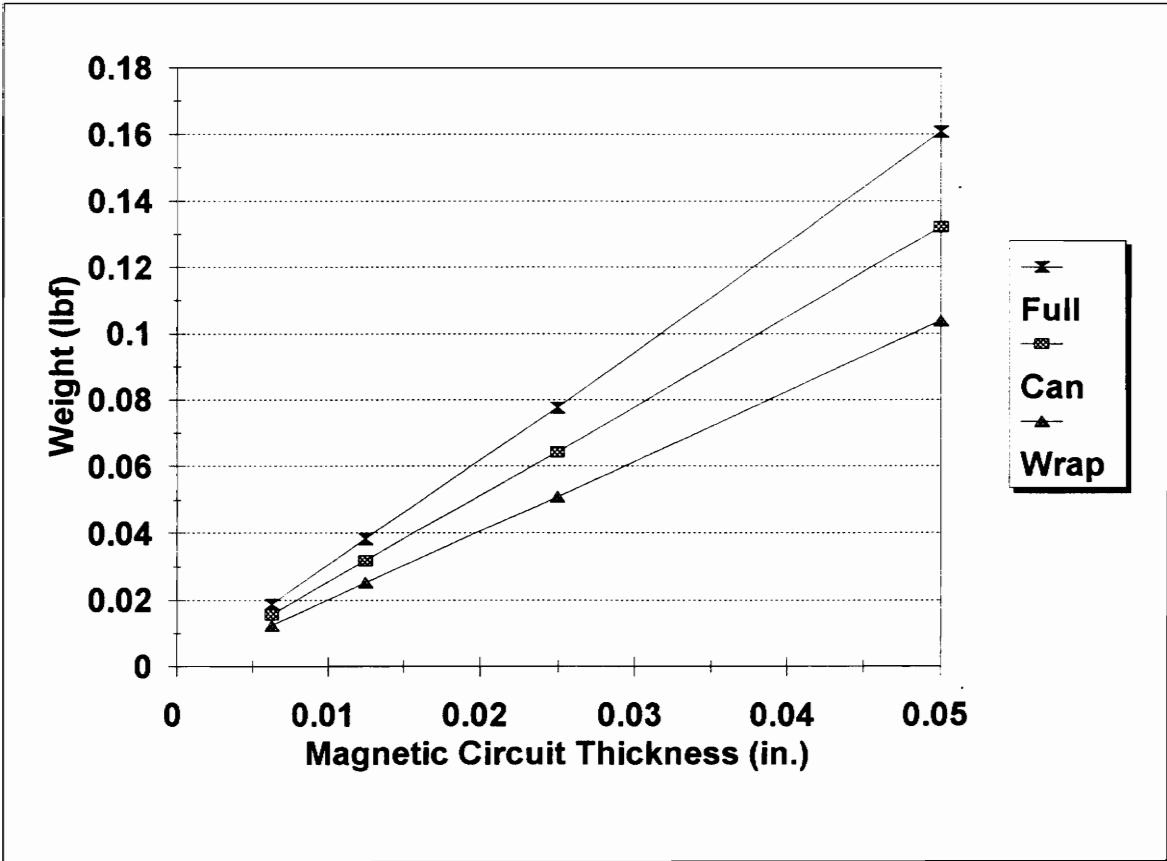


Figure 32: Magnetic Circuit Weights

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Based on the analysis presented in Chapter 3, several conclusions can be made about the optimization of the baseline actuator. First, it is clear that the baseline actuator was not optimized for weight or magnetic field intensity. Second, the optimum magnetic field intensity to electrical coil weight ratio is realized when the coil is the same length as the actuator. Third, it is simple to increase the magnetic field intensity in the magnetostrictive rod by including a magnetic circuit about the electrical coil. Fourth, three designs were examined in the analysis. The choice of a design should be based on field intensity, weight, cost, and complexity requirements.

4.2 Recommended Design Changes To Baseline Actuator

In Section 3.3, the recommendation was already made to shorten the coil to the length of the magnetostrictive rod - 1.5 inches. This was based on the fact that the coil and case weight savings outweigh the magnetic field intensity decrease. Furthermore, in light of the magnetic circuit analysis presented in 3.4 and 3.5, the magnetic field intensity for a 1.5 inch coil with a surrounding magnetic

circuit is higher than the intensity for the baseline 1.7 inch coil only.

A magnetic circuit is recommended for this actuator. **Figure 33** compares the various configurations considered in this study in field intensity distributions. **Table 5** compares the three magnetic circuit designs based on percentage increase in magnetic field intensity and weight increase. Because of weight constraints, it is recommended to implement the magnetic circuit with a highly magnetic material as a thin layer about the coil and magnetostrictive rod. The *Full* configuration gives the greatest flux return capability, but the *Can* design gives nearly the same performance without the need for a sliding part. This consideration is important from a life cycle cost perspective. The main reason is that another sliding part decreases the reliability of the actuator. In particular, failure modes such as the sliding part hanging up or increasing the sliding friction of the stroke are possible. This increases the life cycle cost of the actuator by increasing the downtime per operational time ratio. Another consideration is that the *Can* configuration can be fabricated in one piece. This requires less design, fabrication, and testing resources (both material and labor) than the *Full* design with at least two pieces.

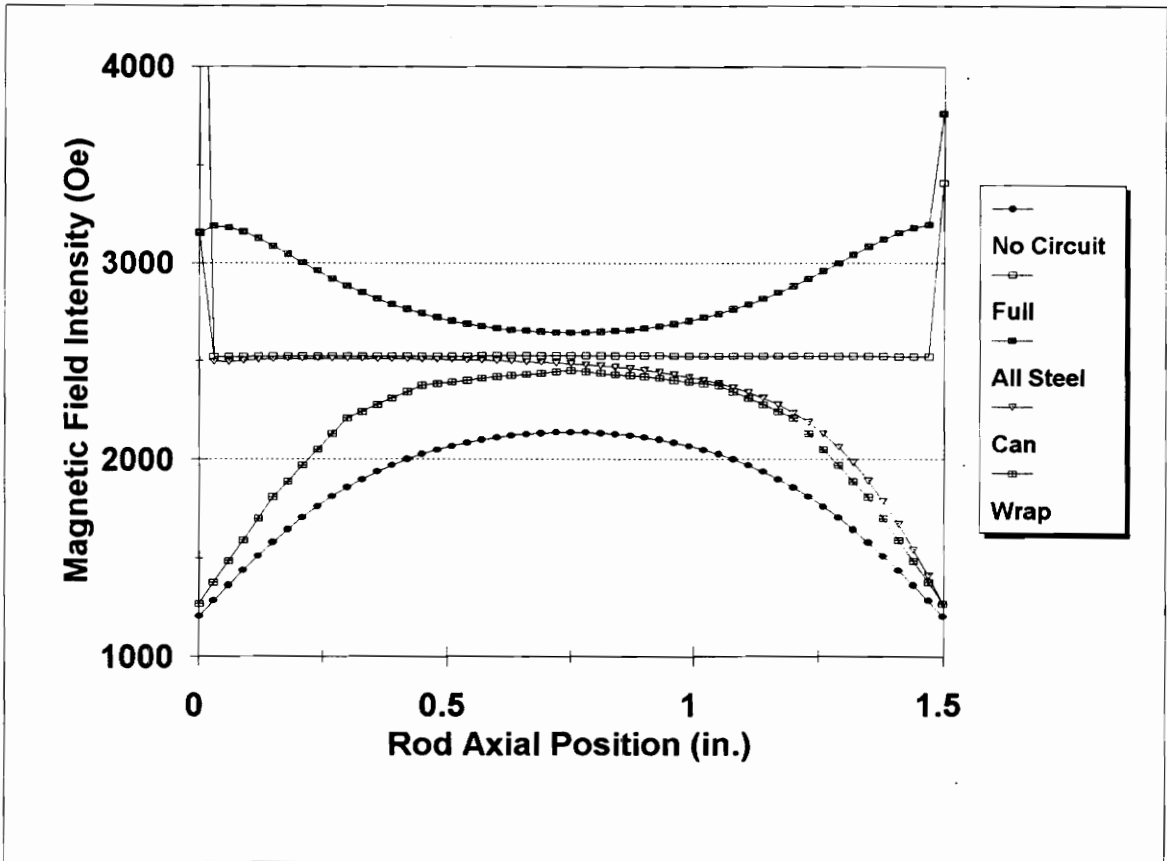


Figure 33: Field Distribution Comparison

Table 5: Analysis Results Summary

	Full		Can		Wrap	
Thickness (in.)	Field (%)	Weight (lbf)	Field(%)	Weight (lbf)	Field (%)	Weight (lbf)
0.05	34.52	0.1608	25.68	0.1323	16.99	0.1037
0.025	33.24	0.0778	24.97	0.0644	16.27	0.0510
0.0125	26.49	0.0383	23.81	0.0318	15.36	0.0253
0.0625	18.07	0.0190	21.95	0.0158	14.01	0.0126

Field Numbers Are Average Increases Over The 1.5" Coil Baseline Design From 2-10 Amps.

The weight increase is minimal with the Can configuration. At 10 amps, a 0.050 thick circuit increases the magnetic field intensity by 26% and only increases the actuator weight by approximately 0.1323 pounds.

Feedback from the actuator electronic controller developers also makes the use of a magnetic circuit attractive. During the course of this Project, the developers discovered that finding electrical components to switch the baseline 10 amps at the required frequency (thousands of cycles per second) would not be easy. Any reduction of the current requirement would be a welcome design change. The magnetic circuit will make it possible to realize the same magnetic field intensity at a lower current than in the baseline design. For example, referring back to **Figure 26**, a field intensity of 2000 Oe can be obtained with a 0.050 inch thick magnetic circuit at 8 amps - a 20% reduction. This will reduce the heat rejection by 36% and the input power by 20% for the same supply voltage. Also, the reliability of the electronic components will increase at the lower current. This will allow the use of derated components to increase the reliability of the actuator.

The circuit should be well insulated from the coil to prevent a short circuit from developing. Also, a circuit

material with a low electrical conductivity would be desirable to reduce eddy current losses at high frequencies.

4.3 Recommended Future Research

The first set of recommendations deal with issues that have become apparent during the course of this study that should be addressed during the prototype development of the generic development.

(1) **Investigate the effects of eddy currents on the actuator's performance.** Eddy currents, or induced currents, arise in electrically conductive materials in a changing magnetic field. The energy dissipated to create and sustain eddy currents is not available for conversion to mechanical energy, so the actuator's efficiency suffers. Eddy currents also affect the reliability of the system as eddy current heating can cause the magnetostrictive rod to thermally expand, decreasing its output capability.

The critical frequency when eddy currents become important for Terfenol-D magnetostrictive material has been investigated [1], and **Figure 34** shows that it is dependent on the diameter of the magnetostrictive rod. In this case, for a 0.9 inch diameter rod, the critical frequency is approximately 300 Hertz, well below the design requirement. Laminated magnetostrictive rods, in which insulating material is interspliced with magnetostrictive material, are

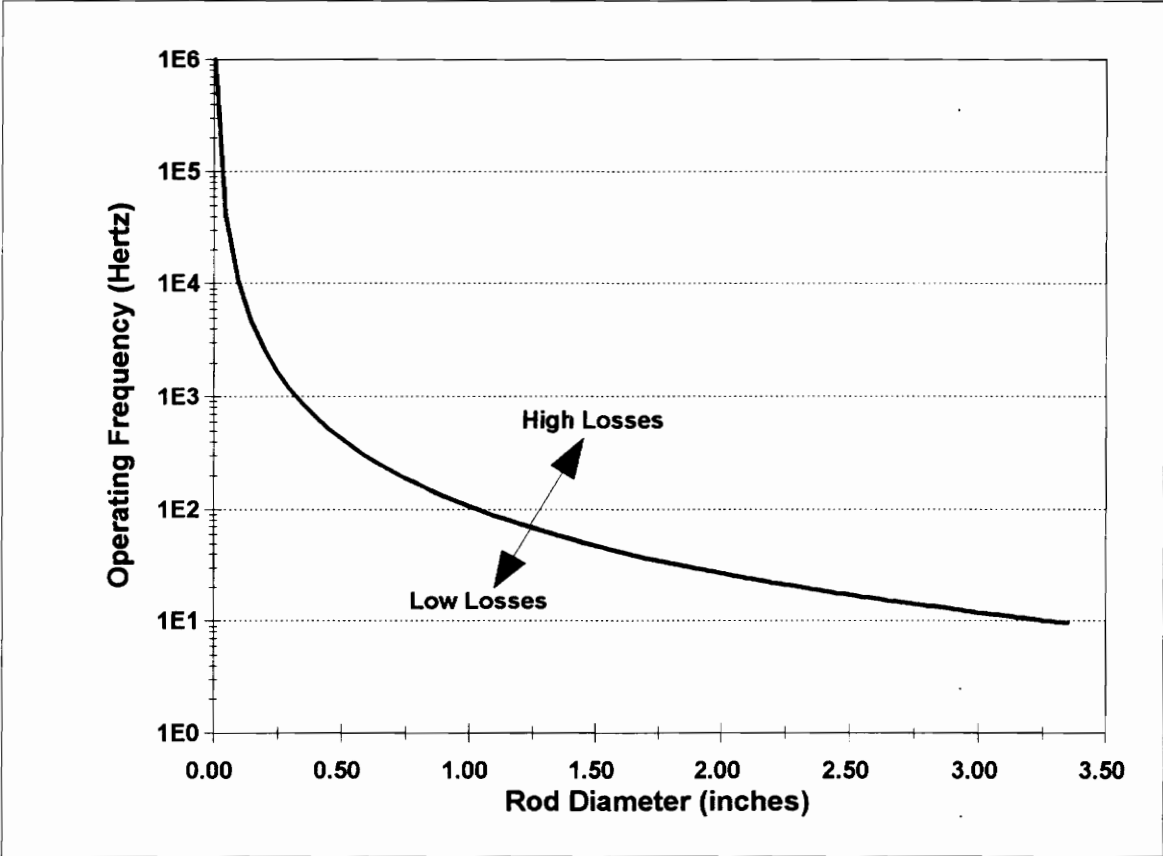


Figure 34: Terfenol-D Critical Frequency

available. These rods are more expensive and are larger than the nonlaminated rods but may prove necessary upon further inspection.

(2) Investigate all high permeability materials for the magnetic circuit. There are ultra-high permeability materials available that would increase the flux return capability of the magnetic circuit. These materials should be compared based on cost, compressive strength, weight, and available sheet sizes.

(3) Investigate using thermoelectric transducers on the coil surface to convert waste heat into usable electrical energy. Waste heat management will be a serious problem in applications where the heat absorption limits of surrounding materials is low. Also, it is always desirable to increase the efficiency of the system. This approach has not yet been implemented or even investigated. Packaging may prove to be a major hurdle.

(4) Investigate low resistance coil materials. Coil resistance has been the major performance limiter in coil applications. Silver's resistance is 7% less than copper's, but it is much more expensive. A comprehensive survey of government, private labs, and universities to determine the prospects on low resistance wire materials should be completed. High priced wire may be justified in critical

actuator location. Low resistance wire will reduce the input power requirements and heat rejection of the actuator.

Once the generic actuator development has been successfully completed and actuators for special applications are being developed, there are more recommendations.

(1) Reliability prediction should be completed. This will entail reliability allocation and ultimately, a full Failure and Effects Analysis (FMEA). In short, the FMEA describes all possible failure modes, the effects of the failure, and preventive measures [9]. The focus of the reliability prediction will focus on the electronic controller. The electronic controller must reliably switch high current at high frequencies and is a prime area for failure. Other critical areas for failure will be in sliding parts, displacement amplifier, and the return mechanism. The magnetostrictive material shows almost no aging effects and its reliability is considered to be excellent [1]. The FMEA will also have variables introduced based on the operating environment, especially temperature.

(2) A human factors analysis should be completed for applications that involve human interaction. The analysis should produce safety precautions for working around and maintaining the actuator. The analysis should also include

identifying design features that inhibit required maintenance. Finally, the human factors analysis will be important in the packaging of hand-held applications. An example may be a hand held power drill. The actuator must be packaged so that it fits into a user-friendly shape and weight. Waste heat should also be considered.

TECHNICAL REFERENCES

1. Butler, J.B., Application Manual For The Design Of Etrema Terfenol-D Magnetostrictive Transducers, EDGE Technologies, 1988.
2. Goodfriend, M., *Material Breakthrough Spurs Actuator Design*, Machine Design, Vol. 63, 1991.
3. Claeysen, F., *Characteristics of PZT Materials*, Journal of the Acoustical Society of America, Vol. 67, 1809-1811, 1980.
4. Anderson, C.W. et al, *Miniature Hot Gas Thruster Research*, PRI-91-104, November 1991.
5. Telephone Conversation with Professor Craig Rogers, Virginia Polytechnic Institute, 11 April 1994.
6. Telephone Conversation with Toby Hansen, ETREMA Products, Inc., 23 February 1994.
7. Tannehill, R. H., and Toole, P. L., Modern Physics, University of Pittsburgh Press, 1971.
8. *ETREMA Terfenol-D Magnetostrictive Actuators* catalog, ETREMA Products, Inc., 1993.
9. Blanchard, B.S., Fabrycky, W.J., Systems Engineering and Analysis, Second Edition, Englewood Cliffs, Prentice-Hall, Inc., 1990.
10. Harrington, R.F., *Field Computation by Moment Methods*, Reprinted by R.F. Harrington, R.D. 2, West Lake Road, Cazenovia, N.Y. 1968.
11. Yildir, Y.B., *Computer-Aided Field Analysis of High Voltage Apparatus Using the Boundary Element Method*, Proc. Of The International Coil Winding Conference, Rosemont, Illinois, Oct. 5-8, 1987.
12. Yildir, Y.B., *Computer-Aided Magnetic Field Analysis Using The Boundary Element Method*, Proc. Of The International Coil Winding Conference, Cincinnati, Ohio, Oct. 3-6, 1988.

13. Cole, Wade(IBM), Chai, H.D. (San Jose State University), **An Assessment Of Various Magnetic Simulation Tools**, Proc. Of The 18th Annual Symposium on Incremental Motion Control Systems and Devices, Champaign, Illinois, June 20-22, 1989.
14. Yildir, B.Y., Klimpke, B.W., Prasad, K.M., **Magnetic Analysis of Brushless DC Motors Using the Boundary Element Method**, Presented at the PCIM'91 Conference, Universal City, CA, September 24-26, 1991.
15. Galvangni, J., **Electrostrictive Actuators and Their Use In Optical Applications**, Optical Engineering, Vol. 29, 1389-1391, 1990.
16. Teter, J.P., **Characteristics of Electrostrictive Materials**, Journal of Applied Physics, Vol. 56, 1856-1858, 1984.
17. Savage, H.T., Abbundi, R., and Clark, A.E., **Permeability, Magnetomagnetic Coupling, and Magnetostriction in Grain-Oriented Rare Earth Iron Alloys**, Journal of Applied Physics, Vol. 50, 1674-1676, 1979.
18. Hayt, W.H., **Engineering Electromagnetics**, McGraw-Hill, 1989.
19. Drew, D., *Class Notes - Applied Systems Engineering*, 1992.