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THESIS

**AN INVESTIGATION OF SLIDING ELECTRICAL
CONTACT IN RAIL GUNS AND THE DEVELOPMENT OF
GROOVED-RAIL LIQUID-METAL INTERFACES**

by

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December 2001

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AND THE DEVELOPMENT OF GROOVED-RAIL LIQUID-METAL
INTERFACES

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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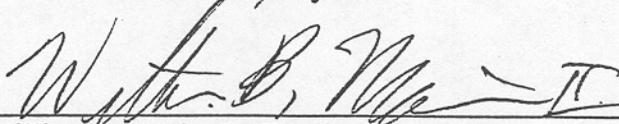
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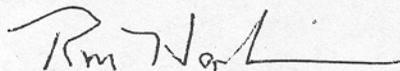


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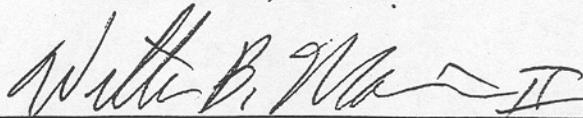
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ABSTRACT

The barrel life of a solid armature rail gun is a critical issue. Arcing along the barrel pathway at the interfaces between the armature and the rails produces severe damage. The ability to protect the rails and yet provide sufficient electrical contact to sustain arc-free high-current flow is desirable. This thesis investigates the use of liquid metal as an interface material between the sliding electrical contact surfaces of the armature and the barrel rails. Experiments were conducted with the Naval Postgraduate School's 4-inch Rail Gun and liquid metal interface coatings were applied to the armatures. Results indicated that the liquid interface protects the rails and projectile surfaces for static electrical contact. Apparatus has been design to investigate sliding electrical contact between armature and rails in a controlled manner. New rails with a novel Adamy-Maier grooved rail design were fabricated to facilitate coating rails. Various groove patterns have been designed to control the current flow through the rails and across the interface surfaces, while maintaining lateral stability and interface integrity. These experiments are still in progress at the time of this writing.

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I. INTRODUCTION

This thesis investigates the liquid metal interface between the armature and rails of solid armature Electromagnetic (EM) Rail Guns. Experimentation was conducted using the NPS 4-inch rail gun with quick-change rails, and liquid metal interface coating was applied to projectiles and rails.

The results obtained in these experiments led to the development of a novel grooved rail design, and the 4-inch EM gun was modified to permit the mechanical acceleration of armatures in the barrel prior to triggering the power supply.

The rest of this chapter is dedicated to providing the reader an insight into the attractive features electromagnetic rail guns offer to naval warfare, some of the problems this technology faces, and the motivation behind this thesis. Chapter II will explain the experimental approach and the modifications to the NPS 4-inch gun. The results of experimentation will be revealed in chapter III followed by a discussion of those results in chapter IV. Finally, chapter V will provide my summary.

A. NAVAL RAIL GUNS

The suitability of Electromagnetic (EM) Rail Guns to naval warfare has been well-documented [1,2]. There are also numerous benefits to naval surface ships with respect to safety, logistics, volume, and maintenance of a rail gun system when compared to conventional propellant gun systems [2,3]. Of the many benefits rail guns offer, increased range is arguably the primary appeal to Naval Surface Warfare [1, 2, 4].

Conventional *chemical-propelled* gun systems, such as the Navy's 5-inch gun, have muzzle velocities of approximately 800 m/s. Researchers in the field of Electro-Thermal-Chemical (ETC) launch are attempting to dramatically increase the muzzle velocity of similar chemical propelled guns. It is estimated that ETC could nearly double the muzzle energy of current 5-inch guns from 11MJ to 20MJ [2]. Much of the ETC research is focused on using a plasma jet as an igniter to enhance the burn rate of conventional propellants. Electrical energy is used to develop the plasma jet and this

feature is how EM launch and ETC launch are related. While it has not been explicitly stated what range ETC and EML technology would bring to future weapon systems, the EM launch community expects ranges in excess of 300 nautical miles for future EML systems [1, 2, 5, 6].

An ability to fire a projectile over 300 nautical miles would revolutionize Naval Warfare. Outfitting EM rounds with precision guidance packages would create an awesome strike synergy with the two main weapon systems currently used to reach distant targets; *carrier aviation* and the *tomahawk missile*. Firing EM projectiles within this range, would help mission planners match, more appropriately, a weapon commensurate with the target.

This dramatic increase in firing range would also allow surface combatants to increase their target set. This benefit alone revolutionizes the Naval Surface Force's presence in a particular theater. It would lessen the need for combat troops ashore to carry artillery pieces thus facilitating a highly maneuverable force against the enemy [7]. It would also permit surface ships to influence events ashore by bringing a quick strike, long-range weapon into a region to dissuade an adversary from taking offensive actions.

The increased range would also boost the Navy's ability to fulfill its current mission roles. Answering calls for fires from U.S. Marines ashore is significantly impaired when there is an expectation that the littorals are fortified with mines. Increased ranges would create a substantial increase in force protection measures to the surface fleet, while conducting this vital mission.

B. BACKGROUND

Rail guns operate on the principle that a *sliding contact* armature completes the conduction path between two conducting rails. When current flows through the rail gun shown in Figure 1.1,

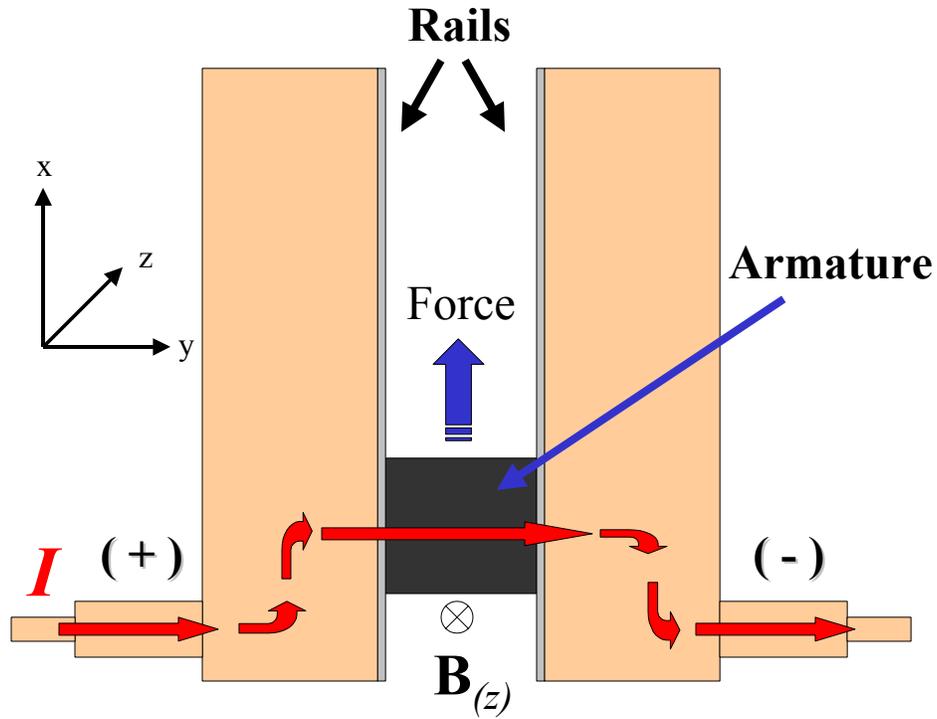


Figure 1.1 Schematic of EM Gun rails and armature.

the electrical current path I creates a magnetic field, $B_{(z)}$. The current I through the armature interacts with the magnetic field $B_{(z)}$ to produce the Lorentz force

$$d\mathbf{F} = I \times \mathbf{B} dw \quad (1)$$

where dw is element of length along the current path through the armature. It can be shown that the magnitude of this force is given by

$$F = \frac{1}{2} L' I^2 \quad (2)$$

and is directed along the X -axis. The term L' is the inductance gradient of the rail gun and is fixed by the geometry and construction of the rails in the barrel [8] while the term I is the total current. For more thorough derivations of rail gun equations and subsequent meanings, see works completed by other Naval Postgraduate students Beach [3], Lockwood [9], Gillich [8], Juanche [10], Feliciano [11] and Gurhan [12].

The number of shots that can be fired from a set of rails before the rails need to be reconditioned or replaced is a critical issue [5]. Whether the lifetime of a set of rails needs to be comparable to the longevity of barrels in conventional chemical propellant

guns is open for debate. Nonetheless, rail life needs to be more understood to facilitate intelligent discussions about the future design of a Naval Rail Gun System.

C. BARREL WEAR

The science of projectile motion can be broken down into two primary disciplines *interior* and *exterior ballistics*. Exterior ballistics is concerned with controlling the projectile once it leaves the bore of a gun. With the substantial increase in projectile velocity and the ranges rail guns offer, exterior ballisticians will need to concentrate on smart projectile technology capable of surviving high-g acceleration.

Interior ballistics concentrates on the motion of the projectile in the bore of the gun. Gun barrel designers must be intimately familiar with this discipline to ensure that projectile exits the barrel with the appropriate velocity. Rail guns introduce new problems to both the ballisticians and the barrel designer. The ability to achieve high velocities projectile motion has, to date, come at the expense of rail degradation, which ultimately affects *barrel life*.

There are three major categories of rail damage: deposition, erosion, and gouging. The damages caused by these three effects are directly related to the condition and type of construction used to maintain the sliding electrical contact between the armature and the rail. There are also other wear mechanisms influencing rail life. Stresses and strains are present in rail gun barrels, which may ultimately affect the lifetime. A fourth category may evolve as a result of these stresses and strains and may be termed, rail flexing, or rail bending damage due to the magnetic pressures produced by the Lorentz force in the barrel.

D. INTERFACE

The contact area between the armature and the rails is commonly called the armature-rail interface, or simply, the interface. Figure 2.1 shows the two principle types of contacts used in the lab and the geometry of the interface each produces. The ability to manage effects that occur at this interface affects not only the launch in progress, but also

the following shots, and ultimately the life of the barrel. The surfaces of the armature and rails typically wear as a result of high current passing through the interface, which cause the surfaces to heat up, melt, and then degrade further as a result of motion induced wear, and arcing.

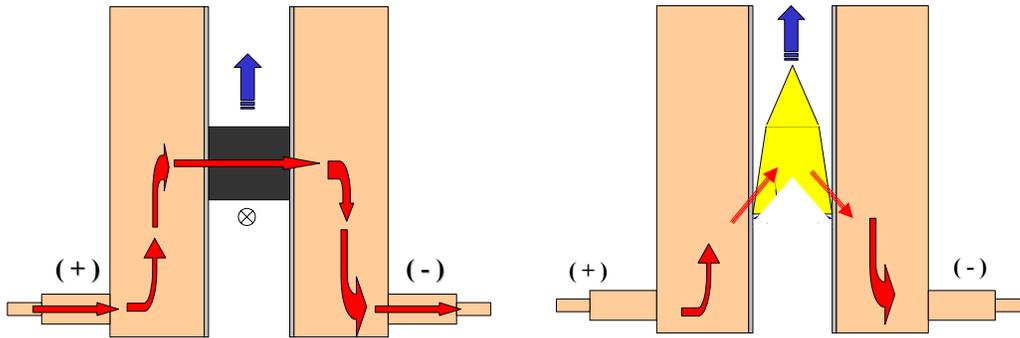


Figure 2.1 Examples of the interfaces made between the rails and square and angular armatures.

The melting that occurs as a result of the ohmic heating from large current densities through the interface is literally and figuratively, a hot topic. The effects on rail life and gun performance as a result of having a liquid metal interface are not completely understood. The benefits achieved as a result of the liquid metal interface are usually countered with serious and devastating consequences.

Liquid metal interfaces reduce the normal force on the sides of the armature from the rails. This reduction of the normal force produces a lower friction between the armature and rail. Since the Lorentz force has less opposition, a higher armature velocity is expected. Liquid metal flows into the peaks and valleys of the irregularities that exist on the interface surfaces. This conductive liquid-metal filler creates a larger contact area and lowers the current density. The liquid layer also comes under the influence of the Lorentz force, which accelerates it along with, or even pushes it ahead of the armature. It is estimated the viscous drag force of this liquid metal layer on the projectile is low. Simple viscous drag force is given by,

$$F = \eta A \Delta v / \Delta y \quad (3)$$

where η is the viscosity of the liquid, A is the contact area, Δv is the difference between the rail and the armature velocities, and Δy is the interface thickness.

One effect is that the interface material can accelerate faster than the armature and reduce the contact area of the beneficial liquid-layer. This movement of the interface material, independent of the motion of the armature, can ultimately lead to the presence of a high voltage contact. The high potential that develops across the interface then leads to an arc, which is known as *transition* [13].

Transition is one of the primary technological challenges facing barrel rail designers. It appears that if transition could be eliminated then rail life would be significantly extended.

E. MOTIVATION FOR THIS THESIS

Decades of research have gone into the development of three pseudo solid-armature rail gun rules of thumb aimed at improving rail gun performance and increasing barrel life. The first is the need to start the launch sequence with a *solid metal-to-metal contact*, i.e. a good electrical contact, between the armature and the rail. The use of a liquid metal interface at the outset is discouraged even though one develops as the projectile is accelerated.

The next rule is aimed at maintaining a *sufficient contact force* to ensure adequate electrical contact between the rail and armature. Since the interface region is metal-to-metal as per the first rule, the sufficient contact force requirement would preclude attempts to pre-accelerate the armature before current is turned on in the system. Put another way, if an armature can be *pre-accelerated*, the contact force must be too low to maintain the conditions of the first rule, which was to establish metal-to-metal contact.

The last rule is that *armature melting is necessary* to facilitate the production of a low-voltage liquid film interface. The longevity requirement of the barrel rails themselves precludes them from being used as the source of this liquid layer, and rule number two precludes addition of a liquid interface to begin this process. The desired presence of a liquid metal interface, as stated above, coupled with the first and second

rules dictates that the armature must be the source of the liquid metal interface material and thus must be the one to melt. The armature then becomes the sacrificial agent in the development of a liquid metal interface.

These rules have created a paradigm in the development of rail guns, which may need to be challenged to find a solution to the problem of rail wear. Rigid adherence to these three rules may overly restrict possible approaches and may preclude solutions to the rail degradation problem. All three of the rules are aimed at maintaining a suitable interface between armature and rail to facilitate the current flow in a rail gun and to manage the thermo-mechanical effects. An example of the inherent problems faced by trying to adhere to all three is as follows:

Armatures are designed to increase contact pressure between the sides of the armature and the rails to sustain metal-to-metal current flow. This increase in contact pressure causes more static friction at the interface. More static pressure requires a larger Lorentz force to initiate armature motion. A larger Lorentz force requires either a higher L' or higher current.

As stated previously, L' is a fixed value of the gun design. Therefore, a higher current is necessary to initiate armature motion. Development of a larger Lorentz force requires a longer *dwelt time*, which increases the heat buildup at the placement location of the armature in the breech. Eventually the armature surface melts and the contact pressure at the interface is reduced.

The contact region becomes smaller as the liquid interface layer is moved forward by the Lorentz force. This leads to more heating and eventually the interface becomes plasma. The plasma, also a conductor, continues to move under the Lorentz force and as it accelerates out ahead of the armature, the contact region is reduced yet again. More heating results and this cycle continues until the contact region can no longer be maintained. Once the contact is degraded enough to halt current flow, a voltage potential increases. As this potential increases, arcs may ensue, which are very damaging to metals. Thus erosion occurs at the point of arcing, more irregularities ensue and this effect continues until something breaks the cycle. A method of breaking this cycle may be possible, but the three-rule paradigm above must be altered in order to investigate it.

The applications of sacrificial material, a *coating*, to the armature and rails, needs to be examined to determine the proper interface thickness and protection it offers.

II. EXPERIMENTAL METHOD

Gillich [8] conducted experiments on the effects of current densities on armature damage. He found that liquid interfaces reduce damage and raised allowable current densities. An improved set up has been designed and fabricated to continue with rail gun research and, more specifically, to examine the effects of liquid interfaces on rail and armature damage.

A. EQUIPMENT FOR STATIC TEST

The goal of the static tests was to assess the effects of interface thickness on the rail. Therefore, it was imperative that tight tolerances were maintained. The first modification made to the four-inch, 83 kJ, test rail gun designed by Gillich [8], was the replacement of the compressible phenolic spacer that separates the two rails in the barrel by an incompressible ceramic spacer. Rail spacing is critical to assess the effects of interface thickness as to the onset of blow-by, protection of armature, and protection of rail. After testing with torque wrenches to see if we could alter the rail separation by applying more force to the cover plates it was clear that the phenolic spacers were compressing. Furthermore, even if we repeated the tightening of the cover plate with the same torque pattern and force, the rail separations could differ by as much as 0.005 inches.

The ceramic spacer, which replaced the phenolic spacer has a surface irregularity of 0.0025 inches. Shims were used to even out these irregularities.



Figure 2.2 Ceramic spacer permits access from the top.

The rail spacer was cut to permit access between the rails, see Figure 2.2. Caliper gages could now be placed directly in front of and behind the armature to measure the rail spacing for each shot, which subsequently determined the interface thickness. An important finding in the static tests was the need to provide more stability to the armature between the rails. The next phase of tests would require a more stable interface to ensure accurate data collection.

B. EQUIPMENT FOR DYNAMIC TEST

To investigate effects of liquid metal interfaces on sliding electrical contacts, further modifications were made to Gillich's gun. To develop a sliding electrical contact at controlled currents, a pre-accelerator assembly has been fabricated. The dynamic test experiment was designed to operate with a novel grooved rail design. The fabrication of the new rails and components of the accelerator assembly are discussed below. The modified rail gun has not been tested fully, but drives a projectile through the rails with substantial velocities that have yet to be measured.

The mechanical part of the assembly consists of an *accelerator*, a *transfer block*, and a *pusher assembly*; see Figure 2.3. Additionally, an optical trigger was added to facilitate precise triggering of the high voltage circuit.

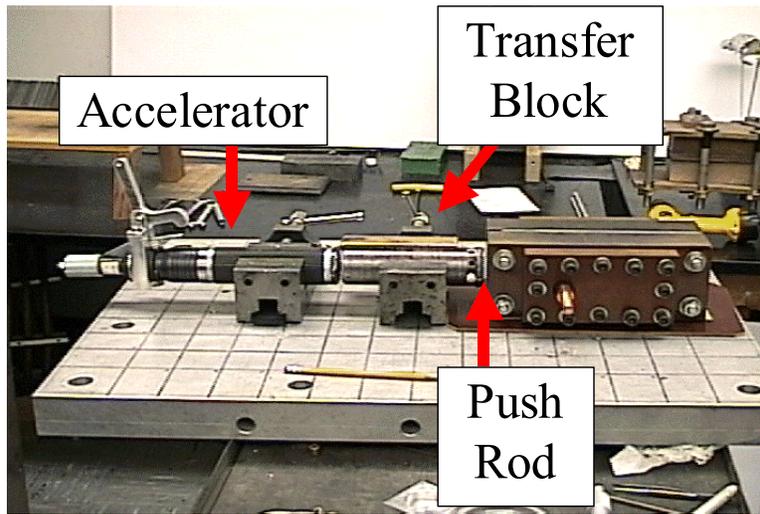


Figure 2.3 The accelerator assembly fitted to the rail gun.

1. Accelerator Assembly

a. Accelerator

The accelerator is a cattle stunner, model ME Schermer Stunner. The stunner accelerates a 175-gram captive bolt to a max distance of approximately 8 cm before hitting three, internal, rubber compression rings and stopping. Four cartridge loads can be used in the stunner and it has been estimated that the black load #21 and is capable of firing the captive bolt approximately 100 m/s.

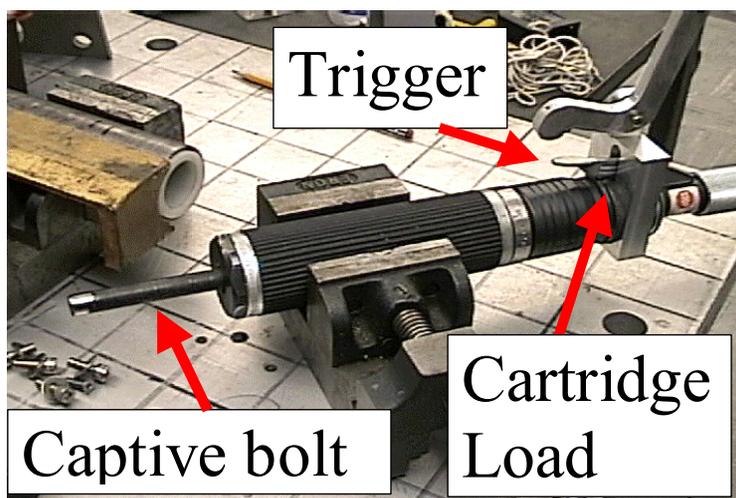
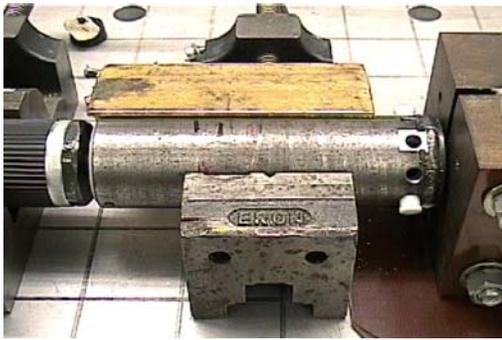


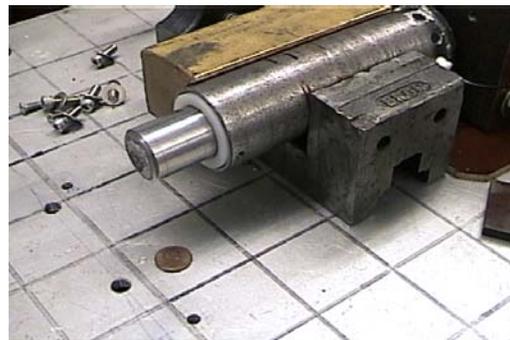
Figure 2.4 The accelerator

b. Transfer Block

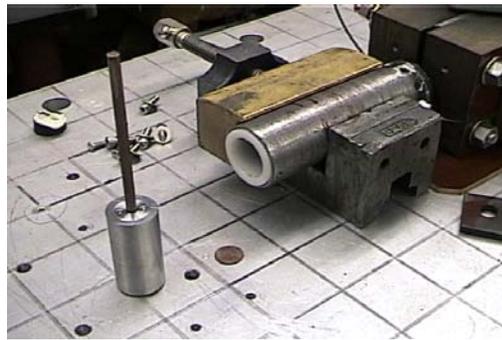
The captive bolt on the accelerator is metallic, which precludes using the stunner to directly accelerate the armature. A transfer block, see Figure 2.5, was developed to transfer the kinetic energy of the bolt to a pusher rod, which is non-metallic and non-conductive. The transfer block houses the pusher assembly, which contains the striker block and the pusher rod.



(a)



(b)



(c)

Figure 2.5 The transfer block inline with the accelerator and the rail gun (a), showing the striker base protruding from transfer block (b), and pusher assembly removed (c).

c. Pusher Assembly



Figure 2.6 Break-down of pusher assembly with rod replacement tool.

The pusher assembly consists of a striker base and a phenolic push rod. The non-conductive push rod makes contact with the base of the armature and accelerates the armatures in the bore of the rail gun. The rod can be removed quite easily with the tool shown in Figure 2.6, and replaced or inspected.

d. Triggering Circuit

There are two interfaces between the pre-accelerator assembly and the rail gun. The pusher rod was mentioned above. The other interface is an optical triggering circuit (OTC); see Figure 2.7.

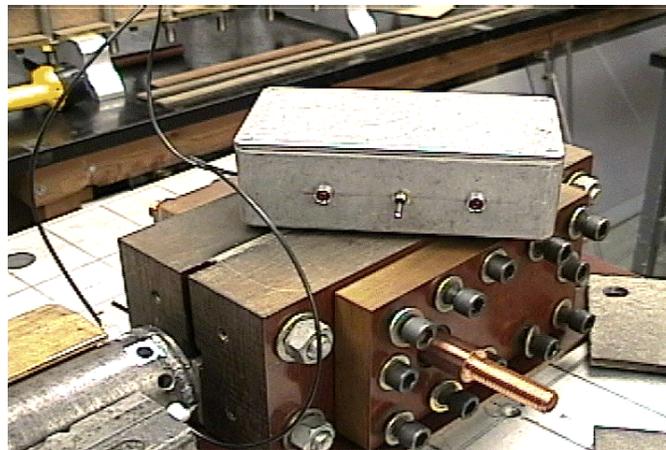


Figure 2.7 Optical Triggering Circuit (OTC)

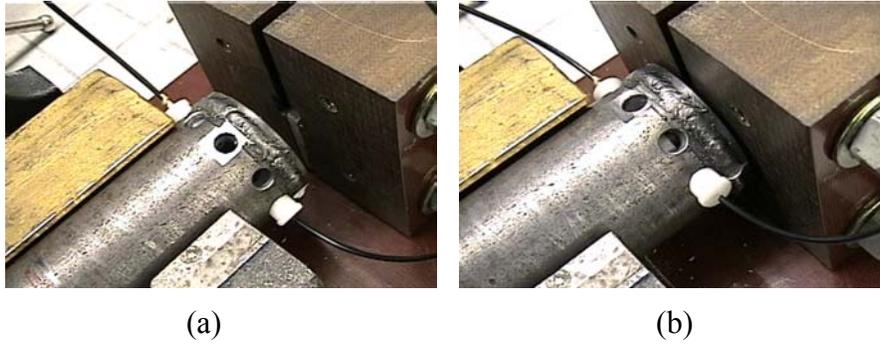


Figure 2.8 Light-path through transfer block. Not triggered (a), triggered (b).

The OTC generates the light beam that transmits through the transfer block; see Figure 2.8.a. When the pusher assembly travels to the end of the transfer block, it breaks the light beam, Figure 2.8.b, which triggers the OTC to send an *armature motion* signal to a delay generator, as shown in Figure 2.9. The delay generator produces a trigger signal for the high voltage switch.



Figure 2.9 Delay generator receives input from OTC and sends firing command signal to rail gun.

2. Pole Pieces and Rail Modifications

Flat rails were used in the static experiments as in Gillich's experiments. Grooved rails, however, were fabricated to investigate the interface under dynamic testing. The basic template for the rails was modified and so were the pole pieces that the rails are attached to in the gun. Drawings are shown in Appendix B. A sine wave crosscut pattern was chosen for the first trial grooves. The grooves were 0.005-inches deep and separated by 0.018-inches peak-to-peak. These rails were fabricated by Electrical Discharge Machining (EDM), which can cut complicated patterns in metal and

maintain high tolerances (within 0.0001”). Figure 2.10 shows the EDM set up for the grooved rails.

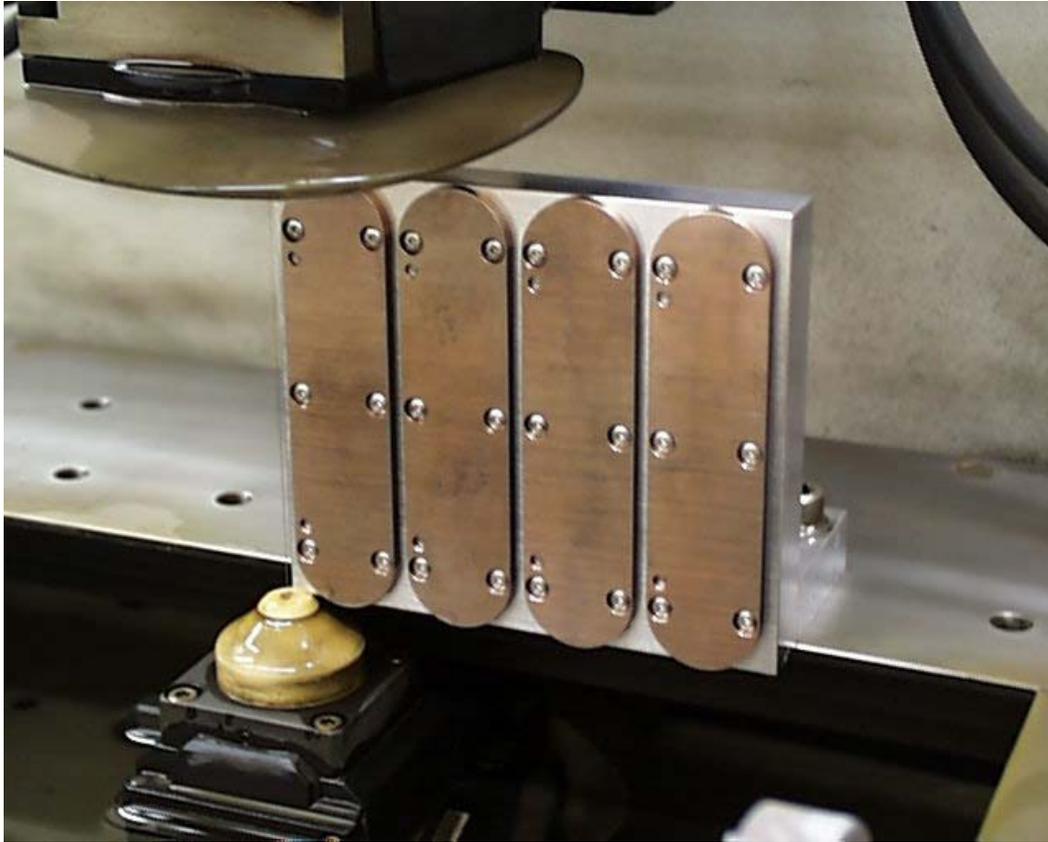


Figure 2.10 EDM set up for groove rail fabrication.

The two vertically spaced insulators next to the first rail on the left side of Figure 4.1 have a wire 0.005” diameter passing between them. The grooves are cut by passing current through the wires, and the table containing the grooves moves in two dimensions; laterally, as well as fore and aft. As the rails come into contact with the wire, the material is eroded away. Tolerances were held to 0.0005”.

For reproducibility and accuracy, two pins were placed in the pole pieces to assist in aligning the rails on the poles and to hold the rails while tightening the screws. The pole pieces are now of one solid material; see Appendix B.

C. COMPLETE ASSEMBLY

The experiments for the static tests used the same basic set up as Gillich, except that only square armatures were used. The new ceramic spacer did not alter the basic set up, it just permitted the viewing and measuring of the armatures in between the rails. Additionally, if the armatures were to move, they would not exit the barrel with the viewing spacer in place. The same power supply, trigger circuit, etc., were used.

The dynamic test set up is very different from the original version. All the modifications mentioned above were assembled and mounted to a single table and robustly built to handle the impact loading of the cattle stunner. According to the engineers who manufactured the stunner, the black, #21 loads deliver 10.5 kN through 80mm.

III. RESULTS

Using flat sided armatures with surface areas of 0.062 in² (0.4cm²), on flat rails, high currents ranging from 10 kA to 128 kA were passed through the rail and armature. In terms of current density, 161 kA per square centimeter if the current flowed uniformly across the interface for the 400V shot. The 5000V shot would produce 2 MA per square centimeter. A series of eleven static test shot were made to investigate the effects these high current densities had on the integrity of the materials, and on the performance of the interface material.

The rails were typically spaced 0.250” apart and a 60/40 indium-gallium alloy was used as an interface material applied to the armature. The effects on the interface and rail are noted in Table 3.1 as voltage and interface thickness were changed. It was inferred that flat rails would not facilitate coating the projectile. As the voltage was raised to 5kV, the armature moved, and damage occurred to the positive rail. The negative rail was undamaged during the shot.

Shot	Supply Voltage	Peak Current <i>Note 1</i>	Interface Thickness (inches) (+) Side only (-) Neg side only (+/-) Combined	Motion	Damage
1	400V	10kA	(+) 0.006	No	No
2	400V	10kA	(-) 0.002	No	No
3	1000V	25kA	(+/-) 0.010 note 2	No	Note 3
4	1500V	38kA	(+/-) 0.010 note 2	No	Note 3
5	2000V	51kA	(+/-) 0.010 note 2	No	Note 3
6	2500V	64kA	(+/-) 0.010 note 2	No	Note 3
7	3000V	77kA	(+/-) 0.010 note 2	No	Note 3
8	3500V	90kA	(+/-) 0.010 note 2	No	Note 3
9	4000V	103kA	(+/-) 0.010 note 2	No	Yes
10	4000V	103kA	(+/-) 0.011	No	Note 3
11	5000V	128kA	(+/-) 0.011	Yes	Yes

Table (3.1) CW 75 Rails with SW 65 Armatures Coated with In/Ga 60/40. (Note 1: Peak current derived from $I=(C/L)^{1/2}V$. Note 2: The total interface thickness between both sides was 0.010” forward edge, and 0.008” trailing edge. Note 3: Observation through the open access on top of the rail gun revealed no interface motion, nor armature motion so the rails were not disassembled.

Coatings were applied to both the negative and positive sides to see if there was a preference for one side (+ or -) to lose its interface first. No correlations were found. Another reason for separating the coatings between the sides of the rail gun was to determine how much of an interface resided on one particular side. When both sides were coated, shots 3-10, it could not be determined how much interface material resided on either side. Not being able to correlate data to thickness limits the usefulness of testing.

While it was seen that thicker interfaces shot the interface material forward and out of the interface region, the inability to determine the interface thickness on a particular side of the armatures in shots 9 and 11, where damage was found, confused interpretation of the observations. New rails had to be developed to tackle this issue.

IV. DISCUSSIONS

A. STATIC TESTS

The dependence of interface thickness on blow-by of the interface material may have been shown in this experiment; however, the inability to maintain rail separation tolerances, and interfaces thickness on each side independently, precludes making anything more than an educated guess at the dependence.

If rails were constructed so that there were grooves on them, then only rail separation would be an issue. If the armature surface was flat, then it would ride on the peaks of each rail. The grooves would hold the interface material, and the tops of the grooves would support the armature with solid metallic contact.

B. PRE-ACCELERATOR

Initially, the idea of a pre-accelerator was to eliminate the static friction factor and reduce armature dwell time when the current is turned on. It was not until later in the research that it became evident that higher velocities would be required, and therefore a larger acceleration before current turn on. Testing of sliding electrical contact at current densities appropriate to a naval rail gun would also require a large pre-acceleration.

C. GROOVED RAILS

The design of the Adamy-Maier grooved rail incorporates the beneficial aspects of a liquid metal interface and a solid metal-to-metal interface with the desire to maintain lateral support of the armature during launch.

As the design phase progressed for manufacturing grooved rails, other potential benefits were noted. The peaks of the grooved rails would provide lateral stability to the armature as it traveled down the bore. The peaks would also provide for metal-to-metal contact. The grooves, on the other hand, would permit liquid metal to be held onto the rails. In addition, when the liquid expands in the grooves, the outward pressure would be applied to the armature, thereby creating a greater stabilizing force, without increasing

the friction. Also possible are: grooved rails *and* a grooved armature to enhance the lateral stability of the interface, and armatures coated with a soft material, such as indium or lead to guide the armature and maintain electrical contact.

D. LIQUID METAL GROOVED INTERFACE

The area grooved was limited to the region where the armature would travel plus an eighth inch over to permit uniform coating of the surface of the rail; see Figure 4.1.

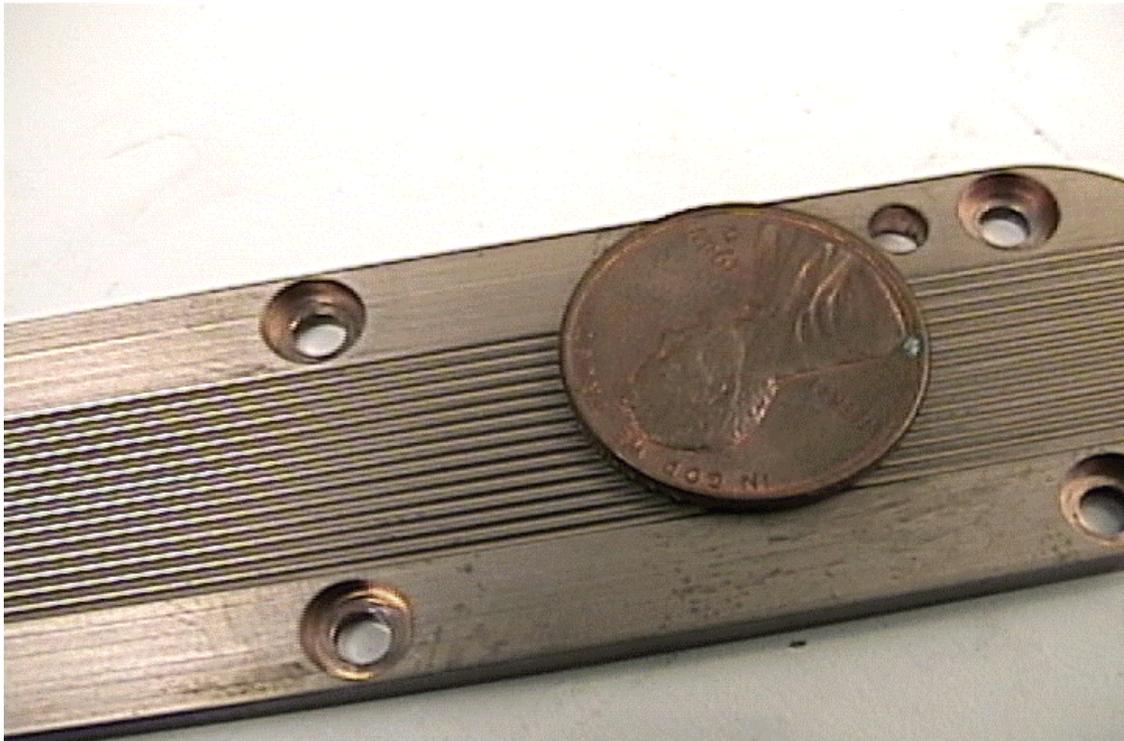


Figure 4.1 A $4 \times \frac{1}{2}$ " region was grooved. These grooves are 0.036×0.036 ".

The rails that were initially designed were made from the CW75 rails, where 75% by weight is tungsten. Several attempts were made to coat these rails. The surface tension of the indium-gallium did not permit the liquid to flow into the trial grooves, which were 0.005" deep and 0.018" peak to peak. The grooves in Figure 4.1 offered only a slight improvement.



Figure 4.2 Attempts at wetting CW75 rails with grooves 0.005" x 0.018".

Several indium fluxes were tried without success. Steel rails may perform better; because steel has a higher resistivity than CW75 and it may wet better than other the CW alloys. Once the effects of liquid metal interfaces are better understood, it may be more appealing to use a soft metal interface, such as indium, to fill the grooves. It would become a liquid metal interface soon after current turn on. Furthermore, one of the lowest recorded values of coefficients for kinetic friction is the combination of a thin indium interface on steel [14].

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V. SUMMARY AND FINAL REMARKS

An improved apparatus was designed and built to investigate the effects of liquid metal contacts in static electrical contact. From that investigation it was inferred that flat rails would not permit accurate testing nor would flat rails support the application of a liquid metal at the rail armature interface. It was shown that the application of a liquid interface layer protected the armatures and rails up to a current density of 1 MA per square centimeter.

Those results motivated the designed of an apparatus for controlled study of effects of sliding electrical contacts. It can further be used to investigate armature and rail materials. Additionally, the new apparatus permits the controlled study of sliding electrical contact utilizing a novel grooved rail design.

The modified 4-inch rail gun has been tested and research is now focuses on liquid interfaces with novel rail designs. Detailed results are expected by June 2002. Preliminary results have shown a significant reduction of the normal force required to stabilize the armature while still conducting current on the order of 40 kA/mm. The lower normal force directly relates to lower static and kinetic friction, which ultimately benefits armature velocity.

Rail guns may soon be a Navy weapons system. Students at the NPS would have the unique opportunity to conduct research on the ground floor of a weapon system that will soon revolutionize naval warfare. Novel ideas and concepts can be experimented with at the school to help the Department of the Navy determine if funding for further research is warranted in particular areas. Furthermore, students at NPS would have the benefit of working and struggling with issues associated with a ground floor program. Engineering duty officers, surface warfare officers, intelligence, IW, policy and plans, strategic studies, will play a vital role in effective utilization of this new weapon. The Navy's corporate university should be anticipating the impact of this new weapon and leveraging the talented and diverse pool of fleet experienced office it has to lead the way.

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LIST OF REFERENCES

1. Luke, I.T. and Stumborg, M.F., *The Operational Value of Long Range Land Attack EM Guns to Future Naval Forces*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 58-61, 2001.
2. McNab, I.R., Fish, S., and Stefani, F., *Parameters for an Electromagnetic Naval Railgun*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 223-228, 2001.
3. Beach, F.C., *Design and Construction of a One Meter Electromagnetic Railgun*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1996.
4. Johnson, S.E., *DBK: Opportunity and Challenges*, Dominant Battlespace Knowledge, The Winning Edge, National Defense University Press, 1995.
5. Stumborg, M.F., *The Impact of Gun Dimensions on the Operational Effectiveness of a Naval Surface Fleet Equipped with Long Range Electromagnetic Guns*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 498-501, 2001.
6. Fair, H.D., *The Science and Technology of Electric Launch*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 25-32, 2001.
7. *Chief of Naval Operations' Strategic Studies Group XVIII Final Report*, U.S. Navy, Newport, RI, 1999.
8. Gillich, D.J., *Design, Construction, and Operation of an Electromagnetic Railgun Test Bench*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 2000.

9. Lockwood, M.R., *Design and Construction of an Expandable Series Augmented Electromagnetic Railgun*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1999.
10. Juanche, F.M., *A Projectile for a Rectangular Barreled Rail Gun*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1999.
11. Feliciano, A.S., *The Design and Optimization of a Power Supply for a One-Meter Electromagnetic Railgun*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 2001.
12. Gurhan, Ozkan, *A methodology to Measure Metal Erosion on Recovered Armatures*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 2001.
13. Stefani, F., Levinson, S., Satapathy, S., and Parker, J., *Electrodynamic Transition in Solid Armature Railguns*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 101-105, 2001.
14. Minshall, H., *Coefficient of Friction*, Handbook of Chemistry and Physics, 53rd Edition, The Chemical Rubber Co., pp. F15 – F18, 1973.
15. Karl Schermer GmbH & Co., *Stunners by Schermer: Instruction on Handling and Maintenance*, 2001.

BIBLIOGRAPHY

Galanin, M.P., Lebedev, A.D., and Milyaev, K.K., *An Investigation of the Effects of Some Properties of Materials on the Characteristics of Armature Acceleration in a Railgun*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 411-415, 2001.

James, T.E., and James, D.C., *Resistive Contact Region Solid Armatures: Electro-Thermal Design Optimisation*, IEEE Transactions on Magnetics, Vol. 31, No. 1, pp. 162-167, 1995.

Schoolderman, A.J., de Zeeuw, W.A., and Koops, M., *Electrothermal Design Aspects of Transitioning Solid Armatures*, IEEE Transactions on Magnetics, Vol. 29, No. 1, pp. 865-870, 1993.

Bedford, A.J., *Rail Damage and Armature Parameters for Different Railgun Rail Materials*, IEEE Transactions on Magnetics, Vol. MAG-20, No. 2, pp. 352-355, 1984.

Persad, C., Lund, C.J., and Eliezer, Z., *Wear of Conductors in Railguns: Metallurgical Aspects*, IEEE Transactions on Magnetics, Vol. 25, No. 1, pp. 433-437, 1989.

Cowan, M., *Solid-Armature Railguns without the Velocity-Skin Effect*, IEEE Transactions on Magnetics, Vol. 29, No. 1, pp. 385-390, 1993.

Marshall, R.A., and Persad, C., *Observation of Solid Armature Behavior*, IEEE Transactions on Magnetics, Vol. 31, No. 1, pp. 214-218, 1995.

Persad, C., *Solid Armature Performance: a Progress Review 1980-1990*, IEEE Transactions on Magnetics, Vol. 33, No. 1, pp. 134-139, 1997.

Challita, A., and Barber, J.P., *Railgun Armature Arcing Voltage Drop*, IEEE Transactions on Magnetics, Vol. 31, No. 1, pp. 118-122, 1995.

Drobyshevski, E.M., Rozov, S.I., Zhukov, B.G., Kurakin, R.O., Beloborodyy, M.V., and Latypov, V.G., *Physics of Solid Armature Launch Transition into Arc Mode*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 62-66, 2001.

James, T.E., *A Transitioning Hybrid Armature Concept*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 77-80, 2001.

James, T.E., and James, D.C., *Contact Pressure Distribution and Transition in Solid Armatures*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 81-85, 2001.

Kothmann, R.E., and Stefani, F., *A Thermal Hydraulic Model of Melt-Lubrication in Railgun Armatures*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 86-91, 2001.

McNab, I.R., and Thomas, C.A., *Thermal Control of Railgun Armatures*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 92-96, 2001.

Liu, G., and King, T.L., *Design of a Material Ablation Test Stand*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 252-256, 2001.

Monfredo Gee, R., and Persad, C., *Multishot Performance of an Insulator in a Laboratory Electromagnetic Launcher*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 257-262, 2001.

Monfredo Gee, R., and Persad, C., *The Response of Different Copper Alloys as Rail Contacts at the Breach of an Electromagnetic Launcher*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 263-268, 2001.

Hsieh, K.T., Stefani, F., and Levinson, S.J., *Numerical Modeling of the Velocity Skin Effects: An Investigation of Issues Affecting Accuracy*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 416-420, 2001.

Marshall, R.A., *Railgunnery: Where Have We Been? Where Are We Going?*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 440-444, 2001.

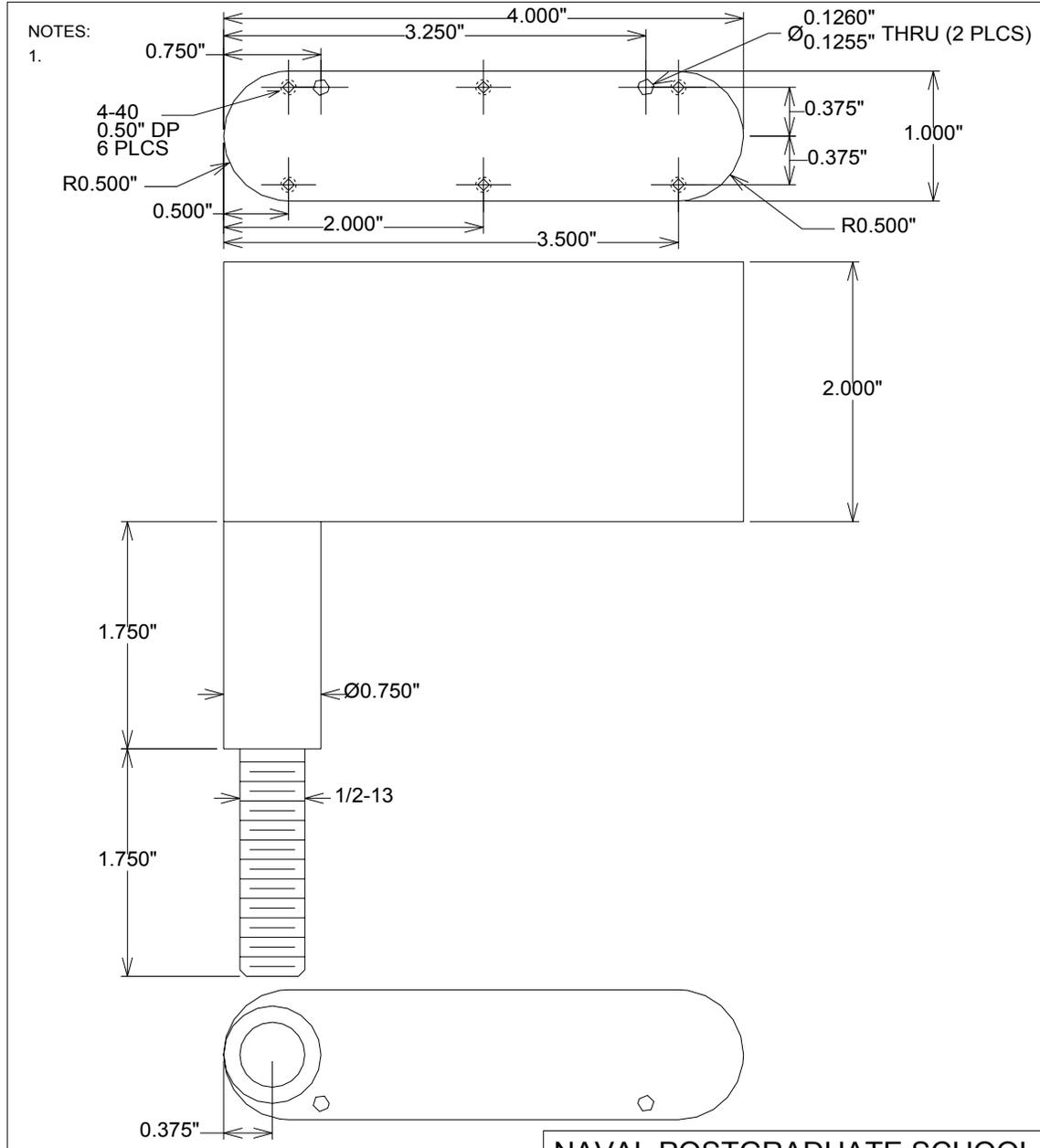
Vanicek, H., Fish, S., *Long-Range Ballistics with EM Guns*, IEEE Transactions on Magnetics, Vol. 37, No. 1, pp. 502-505, 2001.

Persad, C., Yeoh, A., Prabhu, G., White, G., and Eliezer, Z., *On the Nature of the Armature-Rail Interface: Liquid Metal Effects*, IEEE Transactions on Magnetics, Vol. 33, No. 1, pp. 140-145, 1997.

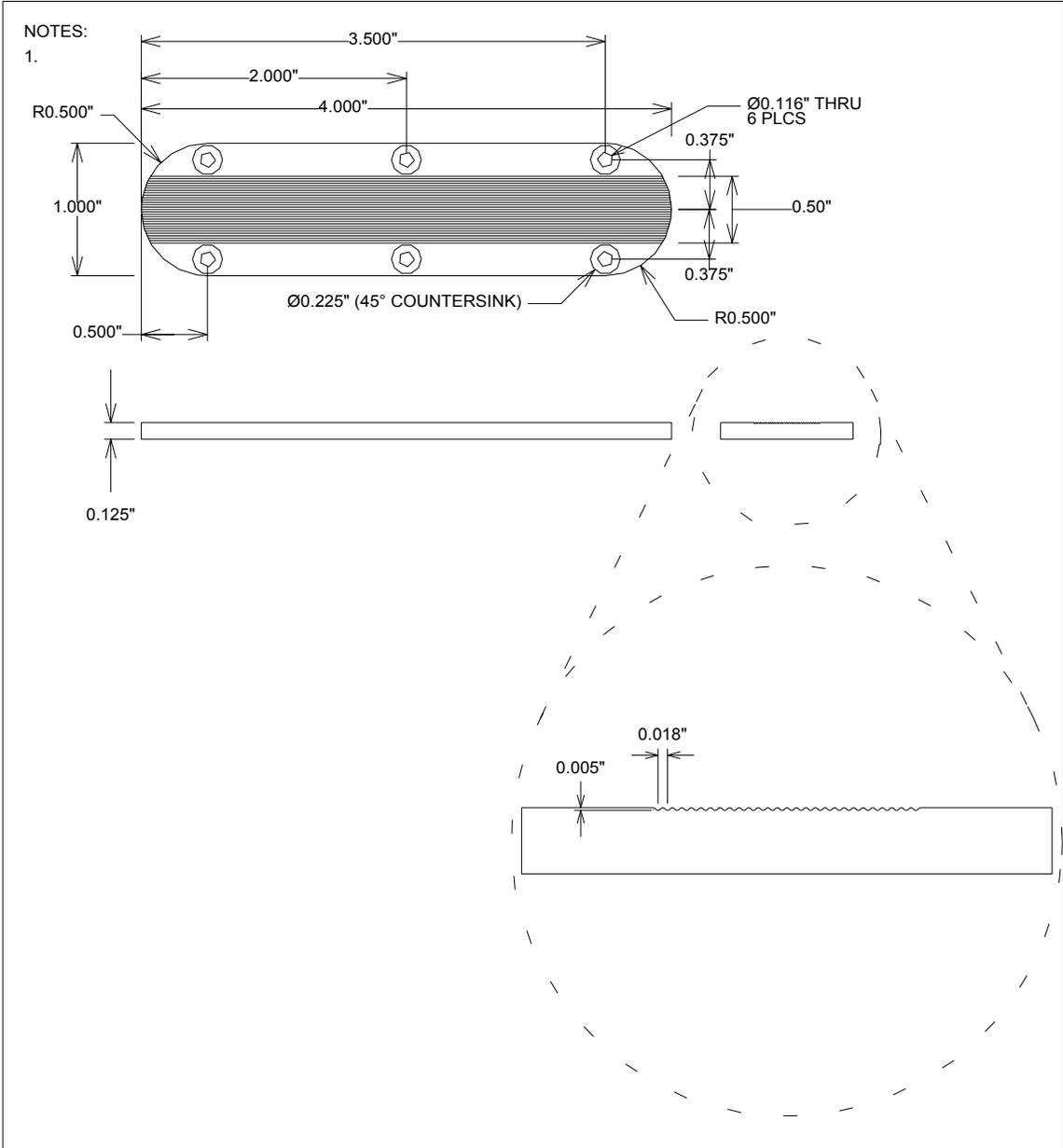
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APPENDIX A

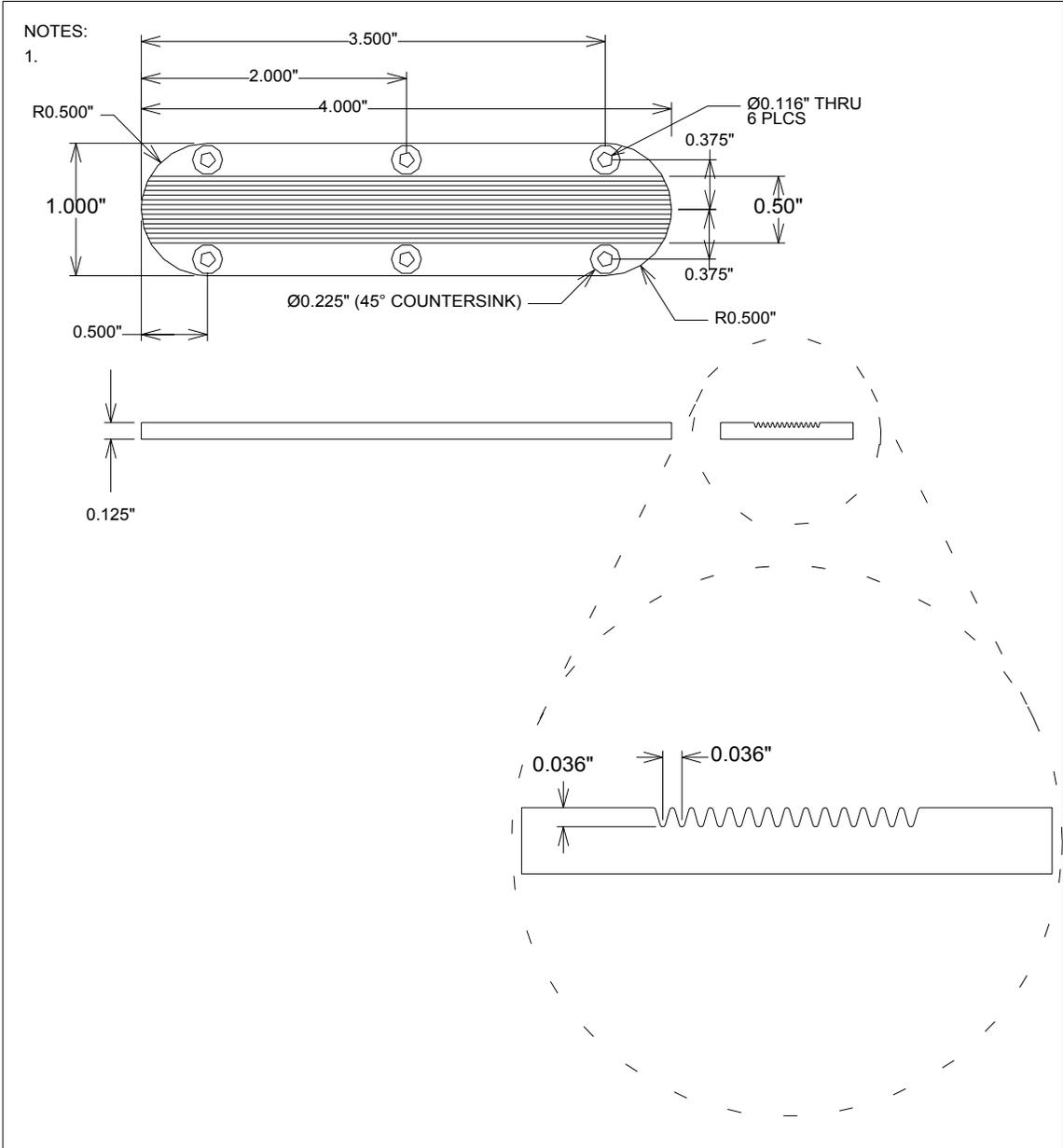
ADAMY-MAIER GROOVED RAIL DRAWINGS AND POLE PIECE



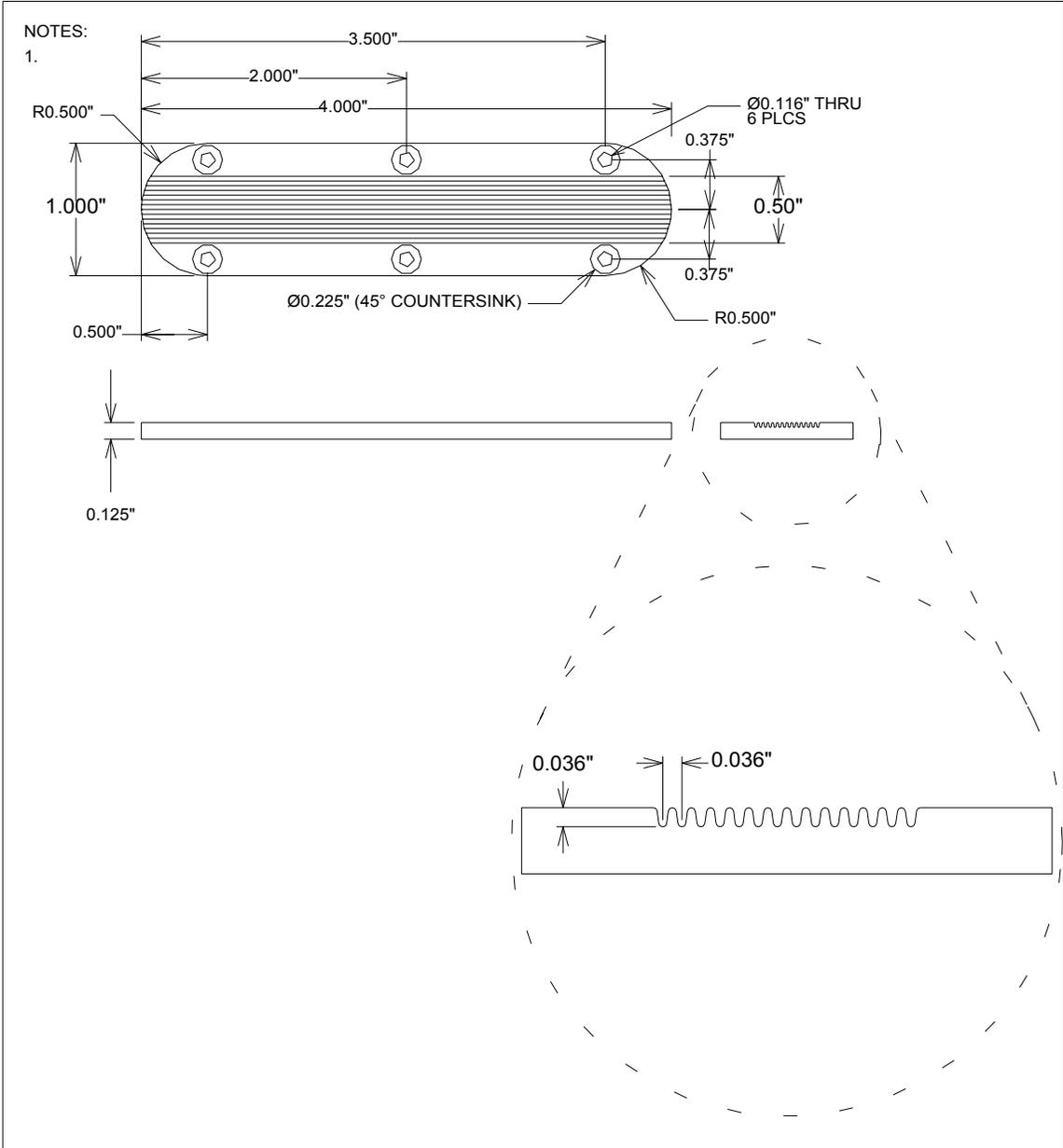
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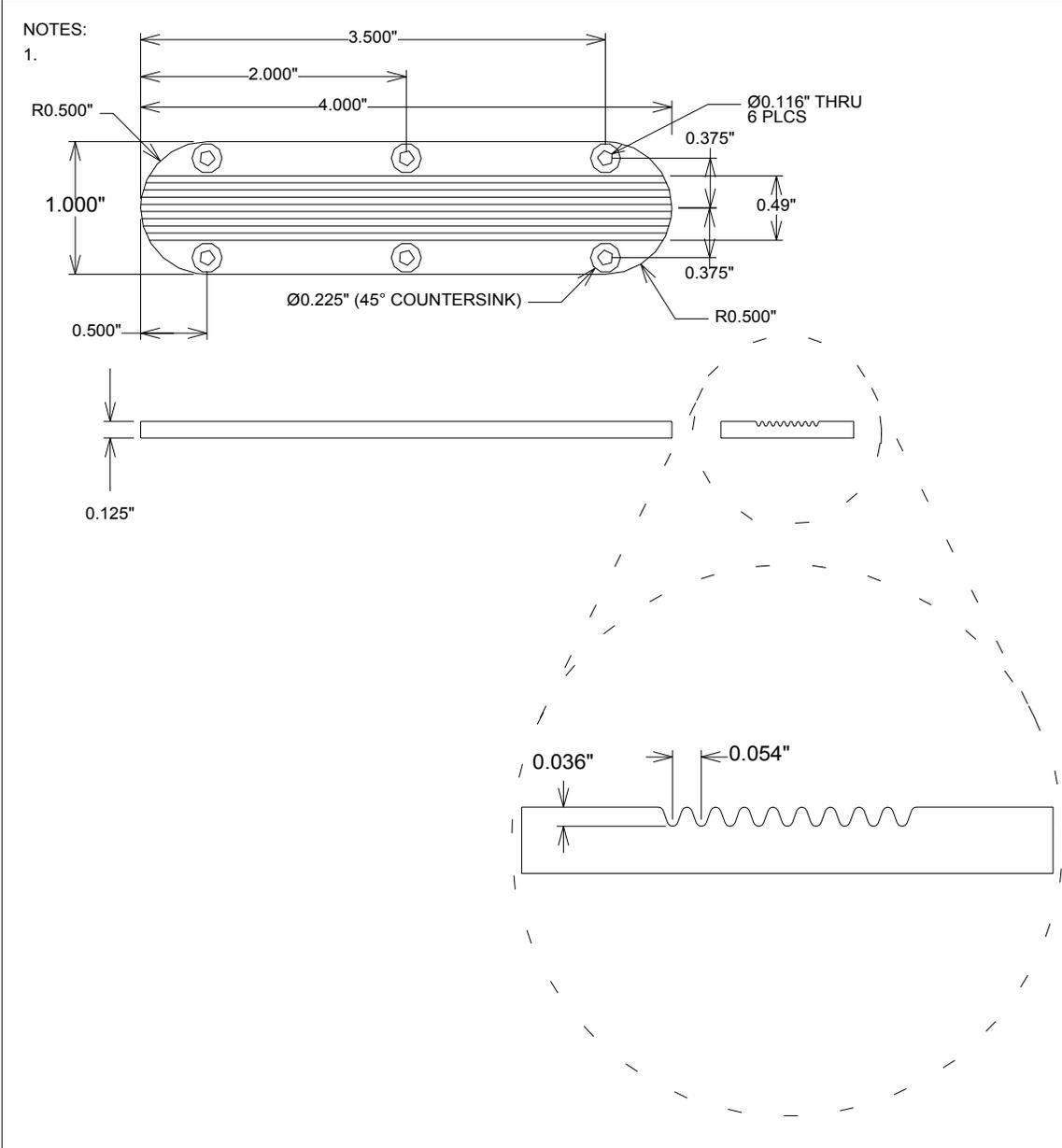
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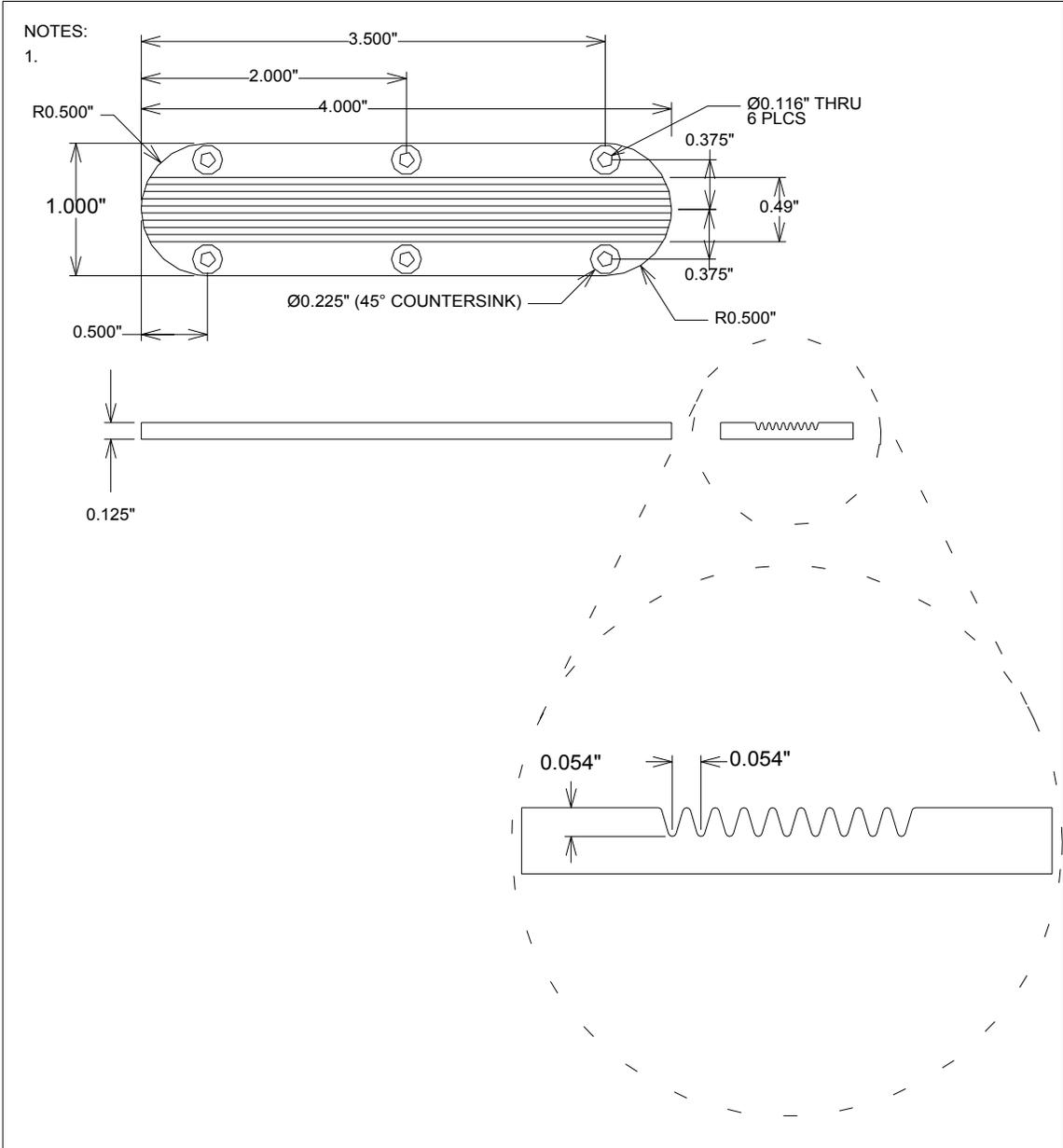
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0.125"

3.500"

2.000"

4.000"

Ø0.116" THRU
6 PLCS

0.375"

0.49"

0.375"

Ø0.225" (45° COUNTERSINK)

R0.500"

0.054"

0.054"

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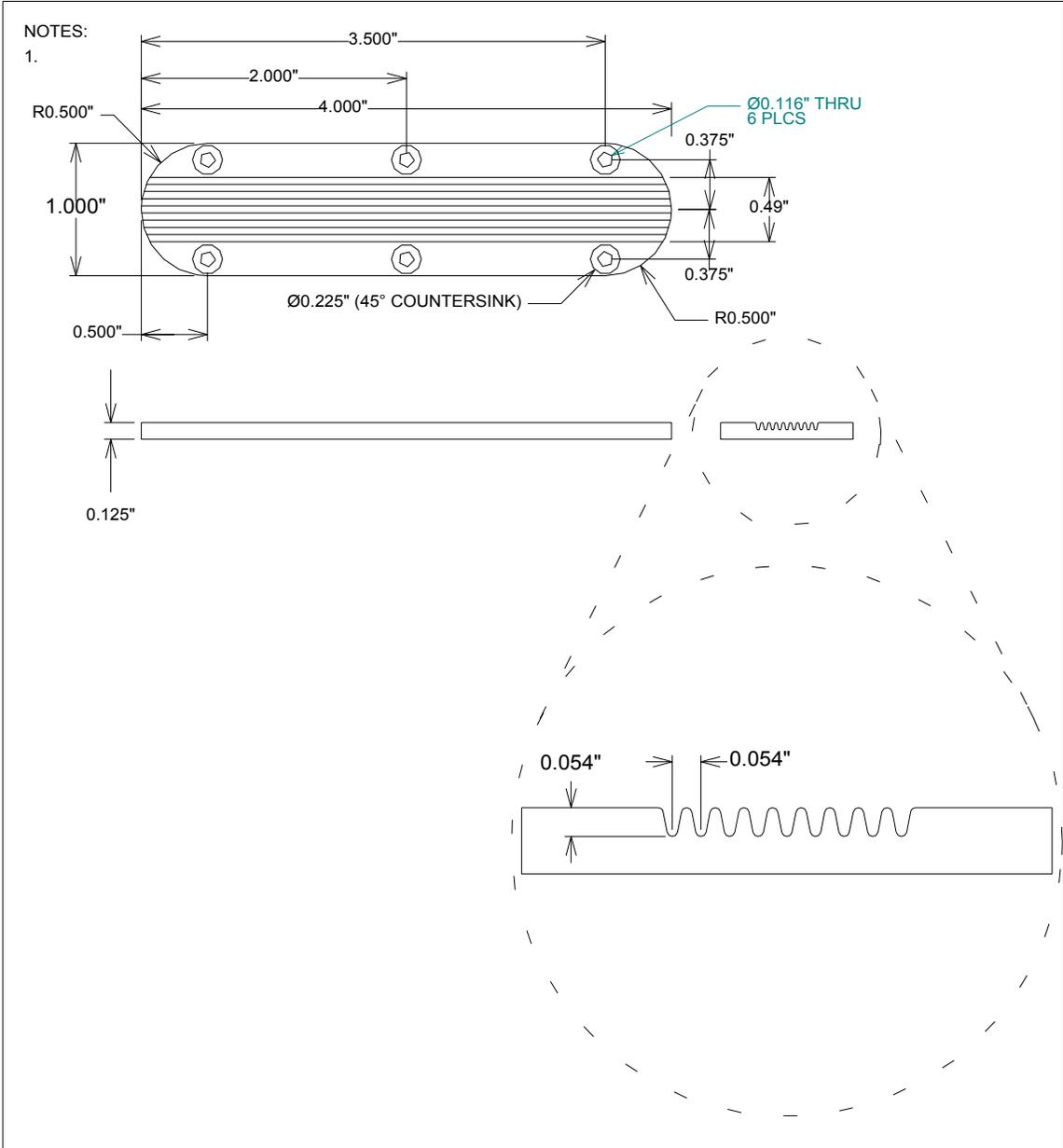
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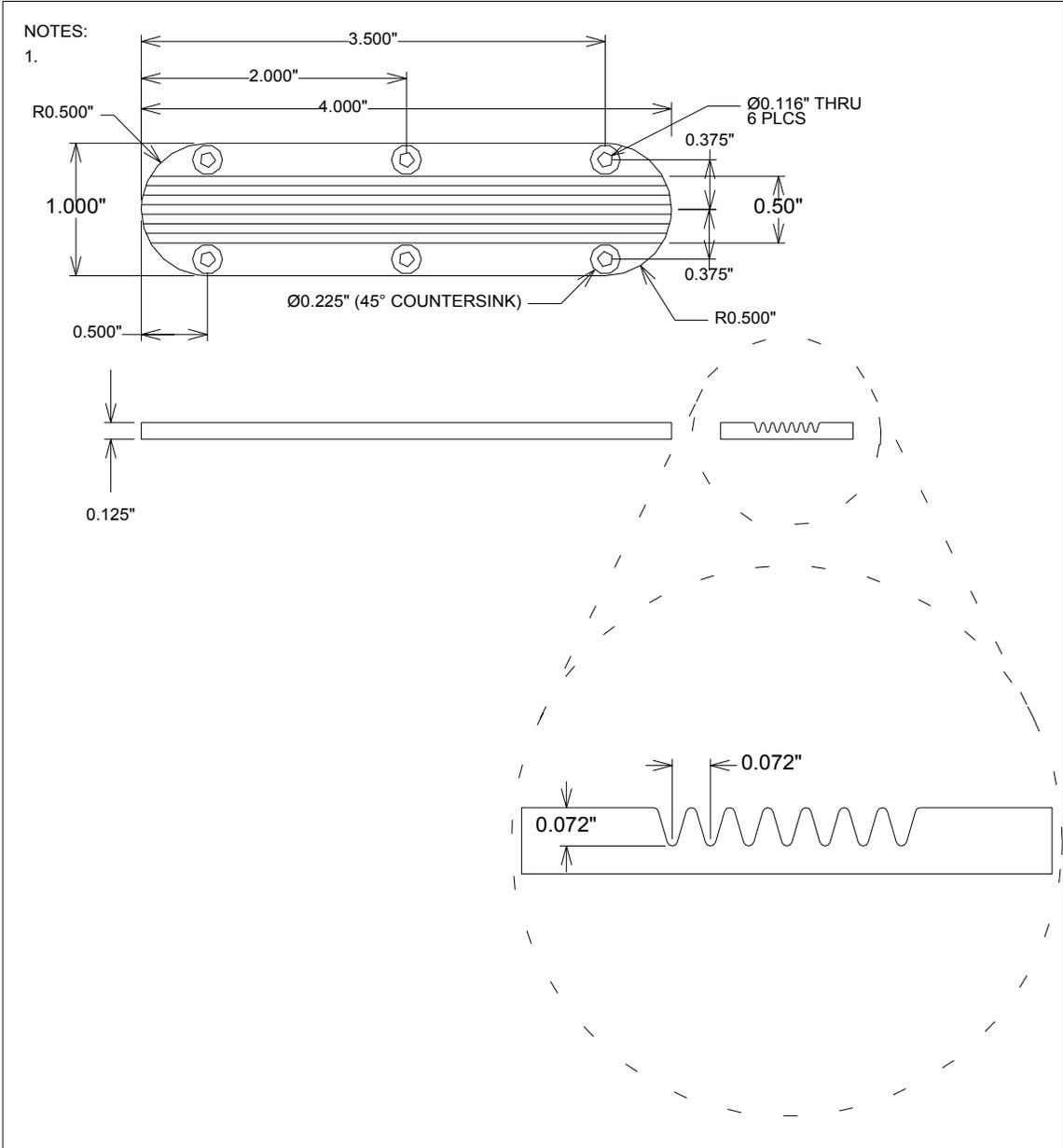
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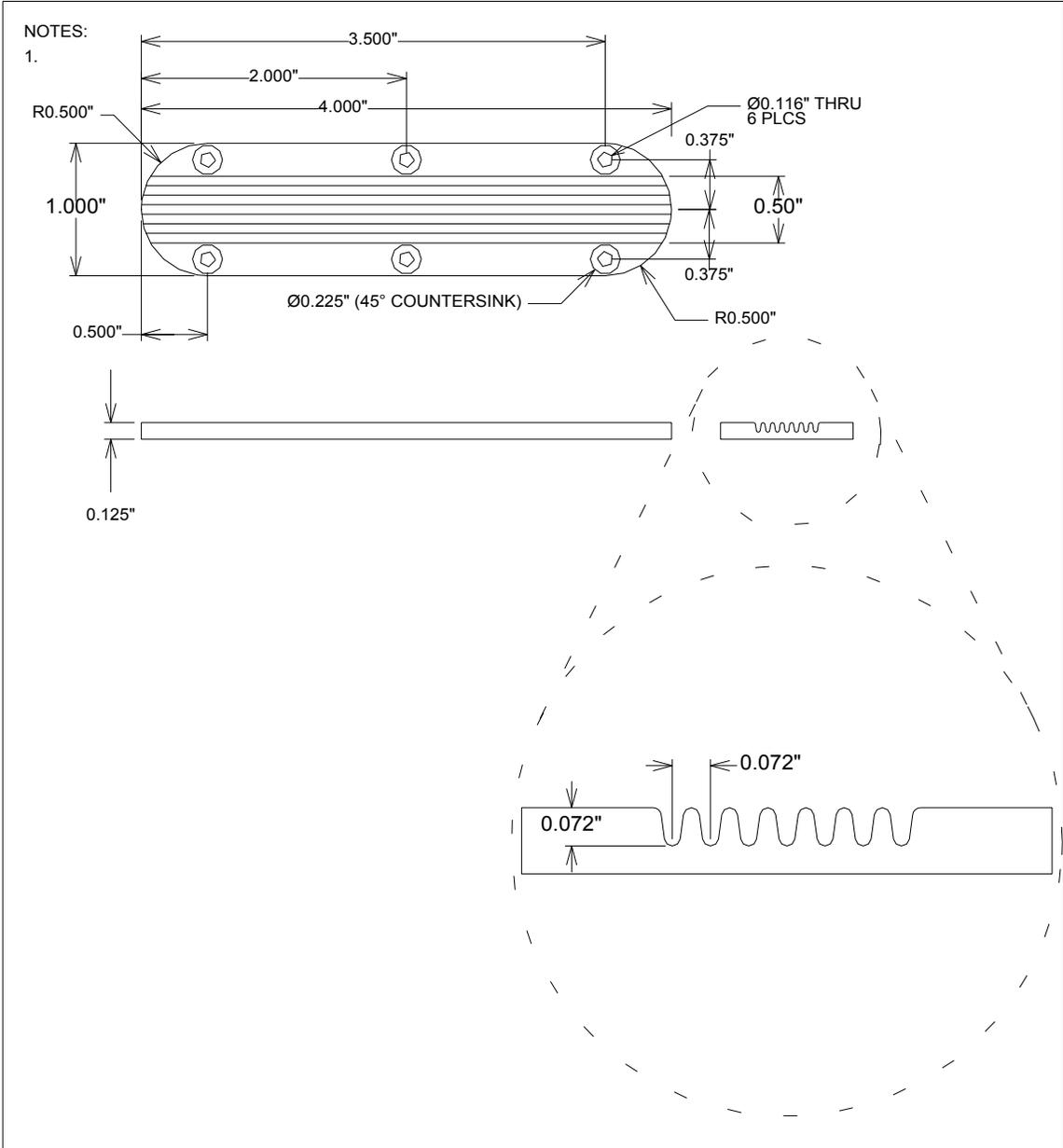
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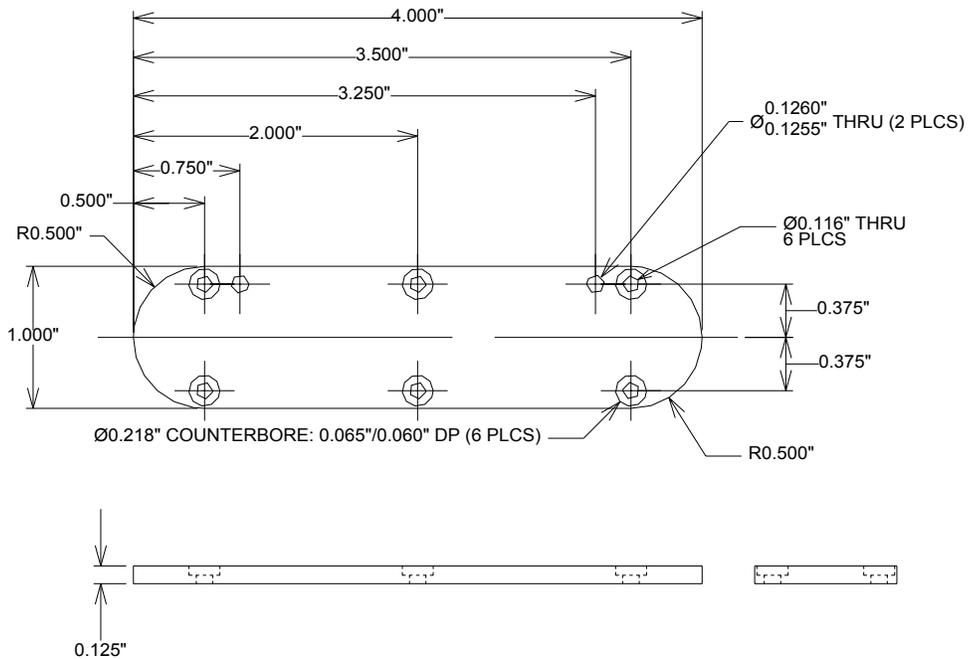
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