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SUPERCONDUCTING AUGMENTED RAIL GUN (SARG)

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Superconducting augmentation consists of a superconducting coil operating in the persistent mode closely coupled magnetically with a normally conducting rail gun. A theoretical investigation of the effect of this system on a rail gun has shown that two benefits occur. Projectile velocities increase by more than 50 percent and launch efficiencies increase by more than a factor of two depending on the magnetic coupling between the rail and augmentation circuits.

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20. ABSTRACT (Cont'd)

The previous work evaluated an idealized system by neglecting energy dissipation effects. In this report, we extend the analysis to include the neglected terms and show improved actual launch efficiencies for the SARG configuration.

To evaluate this concept, a one meter, 0.95 cm square bore rail gun powered by a 5 KV, 1440 μf capacitor discharging into a pulse shaping inductance of about 5 μh was constructed. This system will accelerate a 4 g armature type projectile to the 0.8 km/sec range.

Superconducting augmentation will be accomplished using a 4 Tesla dipole magnet recently acquired from DOE's Lawrence Berkeley Laboratory. This magnet system, originally designed as an ESCAR bending magnet, has been modified to a warm bore configuration operating in either the persistent or constant current mode powered by 1600 amp DC supplies. These modifications will allow the above rail gun to be inserted and tested in the SARG configuration.

Several factors, including magnetic quench protection, reproducibility of results, relatively low magnetic coupling coefficients, minimization of rail wear, etc., indicated that this experimental evaluation be conducted with an armature device. An advanced armature design is incorporated in our projectiles.

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We would like to express our appreciation to the Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory, DOE, and especially to Jeb Rechen and Bill Gilbert for providing not only the ESCAR magnets, but also their test results. Neal Sondergaard's (NSRDC) help in the design and fabrication of the projectiles is gratefully acknowledged.

INTRODUCTION

Previous theoretical analysis of a superconducting augmented rail gun (SARG) indicated that both muzzle velocities of the projectile and/or launch efficiencies may be significantly increased over the unaugmented rail gun (SRG) performance. SARG magnetically couples the superconducting augmentation coils with the normally conducting rails to achieve these results (ref 1).

To evaluate this concept, a joint Army-DOE study recently began to design, construct, and test a small rail gun which will be incorporated with a modified dipole magnet from DOE's ESCAR program to form the demonstrator SARG. Projectile launches in the unaugmented and augmented conditions will provide the statistical evaluation of the concept.

This report presents an extension to the theory developed in Reference 1 to include dissipative effects, details of the rail gun, projectile and magnet design, and the results of the analytical comparison of the unaugmented and SARG configurations using the extended theory.

THEORETICAL ANALYSIS

The SARG concept uses the flux trapping property of a closed superconducting coil to increase both the efficiency and launching force of a normally conducting rail gun. The efficiency increase is primarily accomplished by SARG's ability to reduce the magnetic field energy of the rail gun normally dissipated at the end of launch. The enhanced force is due to the augmented magnetic field produced by the supercurrent flow in the augmentation system.

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[1] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," <u>IEEE Trans. on Magnetics</u>, Vol. Mag-20, March 1984, pp. 366-369.

The flux trapping property is derived from the application of Faraday's law to a closed superconducting coil of length, ℓ, i.e.,

$$\int E \cdot d\ell = -\frac{d\phi}{dt} = 0 \text{ (Superconducting Coil)} \qquad (1)$$

where E is the induced electric field and ϕ is the magnetic flux threading the area enclosed by the coil.

Using Eq. (1), the SARG system, shown schematically in Figure 1, was analyzed for the constant current mode of operation (ref 1). In that analysis we found that at the end of launch, the mechanical energy W_M was

$$W_M = \tfrac{1}{2} LI^2(1-k^2) + kII_{so}\sqrt{LL_s} \qquad (2)$$

The magnetic field energy W_m was

$$W_m = \tfrac{1}{2} LI^2(1-k^2) \qquad (3)$$

and the work supplied to the SARG from the energy source W_s was

$$W_s = LI^2(1-k^2) + kII_{so}\sqrt{LL_s} \qquad (4)$$

In these expressions, L is the self-inductance of the rail circuit, I is the rail current, L_s is the self-inductance of the augmentation coil, and I_{so} is the initial supercurrent in the augmentation coil. The coupling coefficient k is defined by the mutual inductance in the usual manner, i.e.,

$$M = k\sqrt{LL_s} \qquad (5)$$

By comparison, the same energies for the unaugmented rail gun for constant current operation are:

$$W_M = \tfrac{1}{2} LI^2 \qquad (6)$$

$$W_m = \tfrac{1}{2} LI^2 \qquad (7)$$

$$W_s = LI^2 \qquad (8)$$

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[1] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," IEEE Trans. on Magnetics, Vol. Mag-20, March 1984, pp. 366-369.

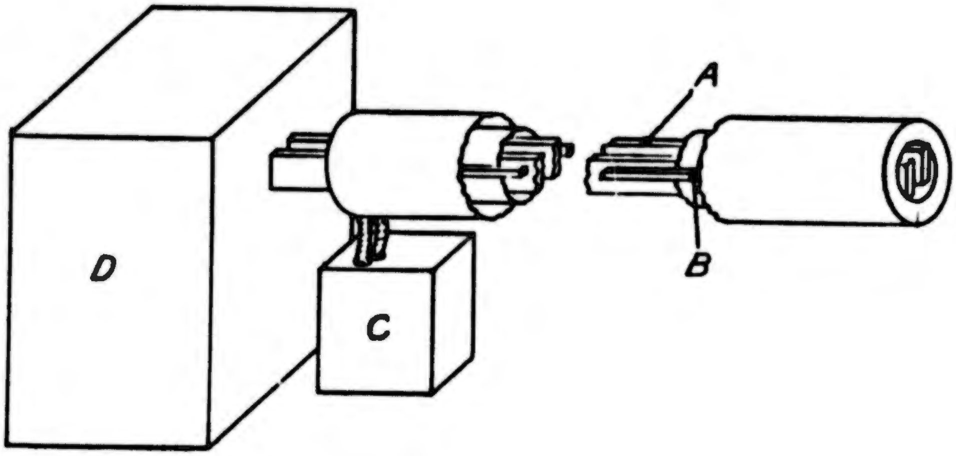

Figure 1. Schematic of SARG. A - rails, B - superconducting augmentation system, C - cryogenic refrigeration and superconducting coil power system, D - pulse power supply.

Previously (ref 1) we neglected dissipative terms in the analysis. The dissipative terms can now be introduced using the procedure outlined by Hammond (ref 2).

Since the magnetic field energy is only a function of the constant currents and the inductances of the circuit, W_m is a function of system geometries only. Thus, for a nonideal rail gun, the dissipative terms must be included as a portion of the mechanical energy, W_M. Writing these dissipative terms in the form of energies, we find that

$$W_M = \frac{1}{2} m_p v_p^2 + \frac{I^2 R \Delta t}{2} + f \tag{9}$$

where m_p and v_p are the projectile's mass and muzzle velocity, respectively; R/2 is the mean room temperature total resistance; and Δt is the projectile's

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[1] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," IEEE Trans. on Magnetics, Vol. Mag-20, March 1984, pp. 366-369.

[2] P. Hammond, Energy Methods in Electromagnetism, Oxford: Clarendon Press, 1981, Chapter 6.

barrel transit time. Thus, the right-hand side of Eq. (9) represents the sum of the projectile's exit kinetic energy, the Joule heating loss due to the room temperature rail resistance, and all other dissipative losses, f. Intuitively, we feel that energy losses due to rail heating will dominate f and thus expect f to vary as I^2 to a good approximation.

For the SRG, the actual launch efficiency α is defined as

$$\alpha = \frac{\frac{1}{2}m_p v_p^2}{W_s} \tag{10}$$

which may be determined experimentally. Thus, using Eqs. (6), (8), and (10) we can show that

$$f = \tfrac{1}{2} LI^2(1-2\alpha) - \frac{I^2R\Delta t}{2} \quad \text{(SRG)} \tag{11}$$

To extend this analysis to SARG, we note that the adjunct superconducting augmentation system is coupled magnetically to the rail surface and is non-dissipative. Thus, if we limit our analysis to the case where the kinetic energy of SARG's projectiles is the same as the SRG, then the dissipative terms due to friction, etc., will be equivalent in both cases. In this case, it seems reasonable to assume that

$$f_{SARG} = f_{SRG} \frac{(I_{SARG})^2}{(I_{SRG})^2} \tag{12}$$

The assumption must be used with some caution, since using Eq. (12) with Eqs. (2) and (11), we obtain

$$\tfrac{1}{2} LI^2(2\alpha-k^2) + kII_{so}\sqrt{LL_s} = \tfrac{1}{2} m_p v_p^2 \tag{13}$$

for SARG. Clearly, a nonphysical singularity would occur if the first term in Eq. (13) were dominant and negative. However, there are engineering relationships between k, L_s, and I_{so} which prevent this singularity in a properly designed system. In general, I_{so} should be chosen as large as is practicable for the superconducting wire chosen.

The choice of a large I_{so} will also reduce the possibility of projectile retardation by the augmentation coil. This effect, which is distinct from the singularity of Eq. (13) is apparent in the expression for the variation of the supercurrent at the end of launch, i.e.,

$$I_s = I_{so} - Ik\sqrt{L/L_s} \qquad (14)$$

Obviously, a negative value of I_s would produce a diminishing magnetic field leading to deacceleration of the projectile.

The analysis of the two systems presented in this report appears to be proper, since the coupling constant is between $0.05 \leq k \leq 0.15$ so that the leading term in Eq. (13) is positive. However, future experimental results will determine the efficacy of the assumptions leading to Eq. (12).

RAIL GUN AND PROJECTILE DESIGN

Since the magnetic coupling coefficient was relatively low in this SARG demonstrator, we decided to perform repetitive launch tests at different power levels in both configurations, in order to statistically evaluate the SARG concept.

To further reduce experimental uncertainties due to rail wear, we designed the rail gun to allow rail replacement. Figure 2 is the layout and cross-section drawings of the rail gun which illustrate the essential design features.

The rail gun is assembled in the following manner. The rails which were fabricated from high conductivity copper bar stock (Cu ETP alloy 110) are bolted to the notch in the round high conductivity leads. The rail spacer and

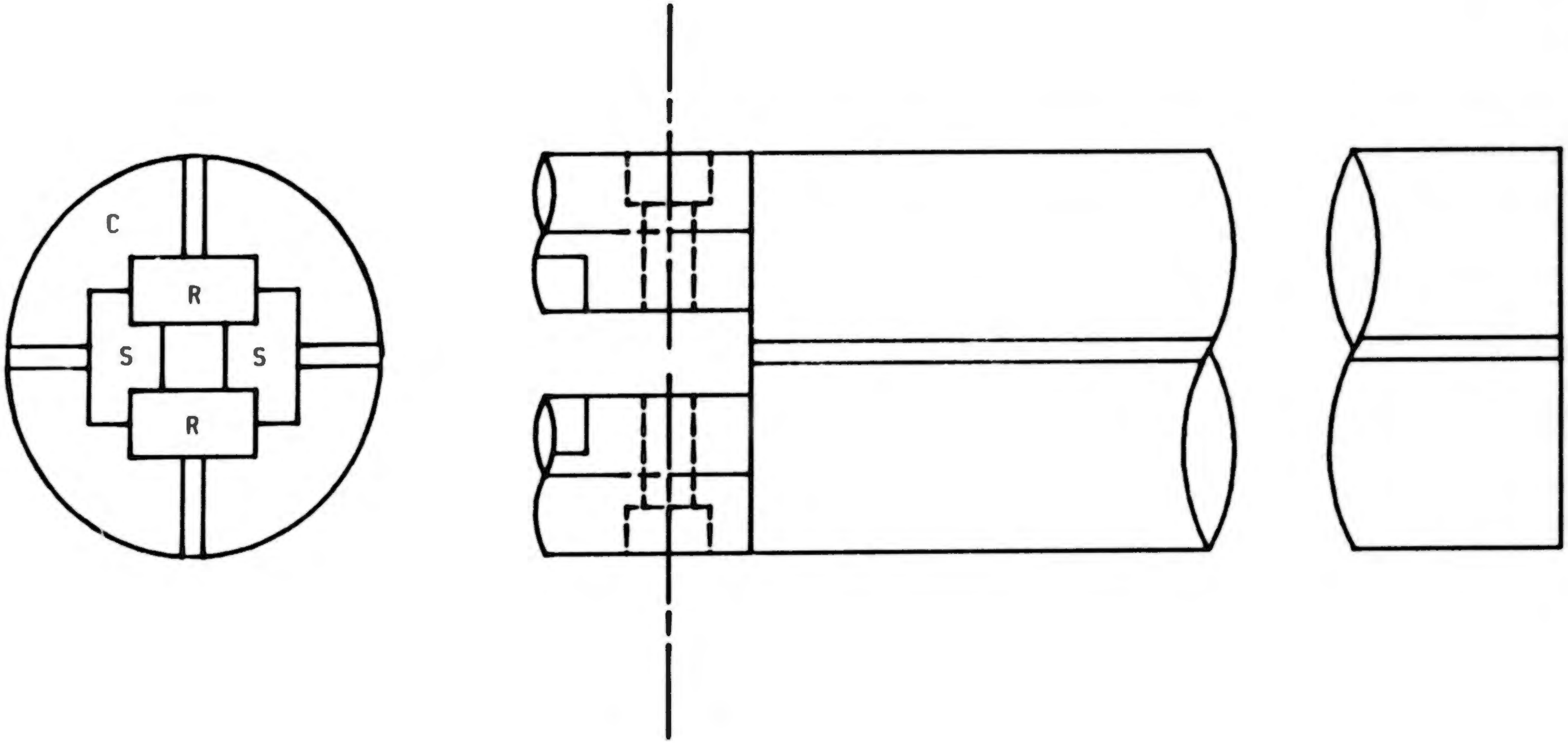

Figure 2. Layout and cross-section of SARG's rail gun.
C - core assembly, R - rails, and S - rail spacer assembly.

core assembly, which were fabricated from Nema grade G-10 fiberglass standard stock are assembled as shown in Figure 1. The G-10 housing assembly is positioned over the rail section and tensioned appropriately. The G-10 lead spacers are slipped over the protruding leads completing the assembly. The only critical machining occurs in the rail spacer which controls the bore size of the assembled gun.

The length of the bore tube of the magnet system Dewar is approximately two meters long, whereas the central active length of the uniform field region is only one meter long (see next section). As such, the length of the gun assembly is designed so that the gun can be supported outside the magnet Dewar.

The rails extend to the outside of the Dewar to facilitate this clamping. To improve the analysis, we coated both surfaces of the rails with nonconducting Al_2O_3 so that the effective rail length of one meter coincided with uniform field region of the magnet. Coating both sides of the rails allows them to be conveniently reversed when damaged or worn.

To power the rail gun, a six capacitor bank was constructed to provide a potential 4800 V, 1440 μf storage of 18 kJ for the energy source. This source will discharge into a 6 μH pulse shaping coil, which can be immersed in liquid nitrogen to control coil resistance from shot to shot. During actual launches, the power supply will be charged to a maximum of 15 KJ. An explosively fired crowbar switch to prevent source ringing completes the power module.

Projectiles are fabricated from 0.375 inch square Lexan bar stock. Each 1.0 inch long projectile has a 0.2 inch long slot machined to accept the metal armature. Metal armatures are machined from a composite of niobium fibers imbedded in a copper matrix. The fibers are approximately 0.001 inch in diameter and represent more than 20 percent of the volume fraction of the composite. The armatures whose length is slightly larger than the bore dimension are then etched to expose the niobium fibers for approximately 0.06 inch on each end.

Launch tests of the unaugmented rail began in the spring of 1986. At a later date, test data will be compared with analytical results for the SRG presented below.

SUPERCONDUCTING AUGMENTATION SYSTEM

The magnet system used for SARG was originally designed for DOE's superconducting synchrotron (ESCAR) system. Two magnets and a Dewar test station were provided by Lawrence Berkeley Laboratory (LBL) for modification to an augmentation system.

The coils of these dipole magnets were constructed from 17-strand Rutherford type cable of 6:1 aspect ratio. Each 0.020 inch diameter strand contains 2100 NbTi filament, 6 microns in diameter in a copper matrix with a thin coating of silver-tin solder on each strand. The coil, when wound and baked, is insulated, permeable to liquid helium, and moderately rigid.

All active coil turns are connected in series in the low field region. The beginning and end of the entire coil emerge at opposite ends, with a straight through conductor for return currents at the midplane for accessible coil connections.

The cylindrical coil assembly is supported on a stainless steel lined epoxy fiberglass bore tube. Radial and longitudinal restraint of the coil is provided by a system of external aluminum alloy rings and longitudinal tie rods. The surrounding helium vessel is eccentric to the boil assembly to provide maximum helium flow. The vacuum enclosure surrounding the helium vessel contains a liquid nitrogen heat shield and support through several epoxy fiberglass structures to the room temperature outer shell of the cryostat. The cryostat assembly is rigidly attached to an iron return yoke, which supports and locates the entire assembly.

LBL personnel assembled, tested, and fabricated this magnet system. The results for a single magnet are summarized in Table I.

TABLE I. TEST RESULTS OF AN ESCAR DIPOLE MAGNET

Central Dipole Field (Max)	4.3 Tesla single pulse 3.6 Tesla continuous
Length of Uniform Field	~ 1 meter
Magnetic Field Error	~ 0.1%
Cryogenic Heat Load During Powering	12.5 watts at 4.5°K
Cool Down	~ 5 hours
Warm Up	~ 6 hours

In these tests, LBL used a 360 ℓ/hr liquifier capable of 1450 watts at 4.5°K refrigeration designed to cool a complete accelerator ring composed of 56 magnets.

In the accelerator configuration, the interior stainless steel tube is at 4.5°K and provides cryopumping for the high vacuums required for beam line use. In order to modify this system for SARG use, it was necessary to convert the system to a warm, room temperature bore configuration. This was accomplished by using a fiberglass tube, together with its own liquid nitrogen shield and vacuum insulated from the original ESCAR bore. The entire modification is shown in Figure 3.

These modifications provide a warm (room temperature) bore at room pressure into which the rail gun described earlier may be inserted. The

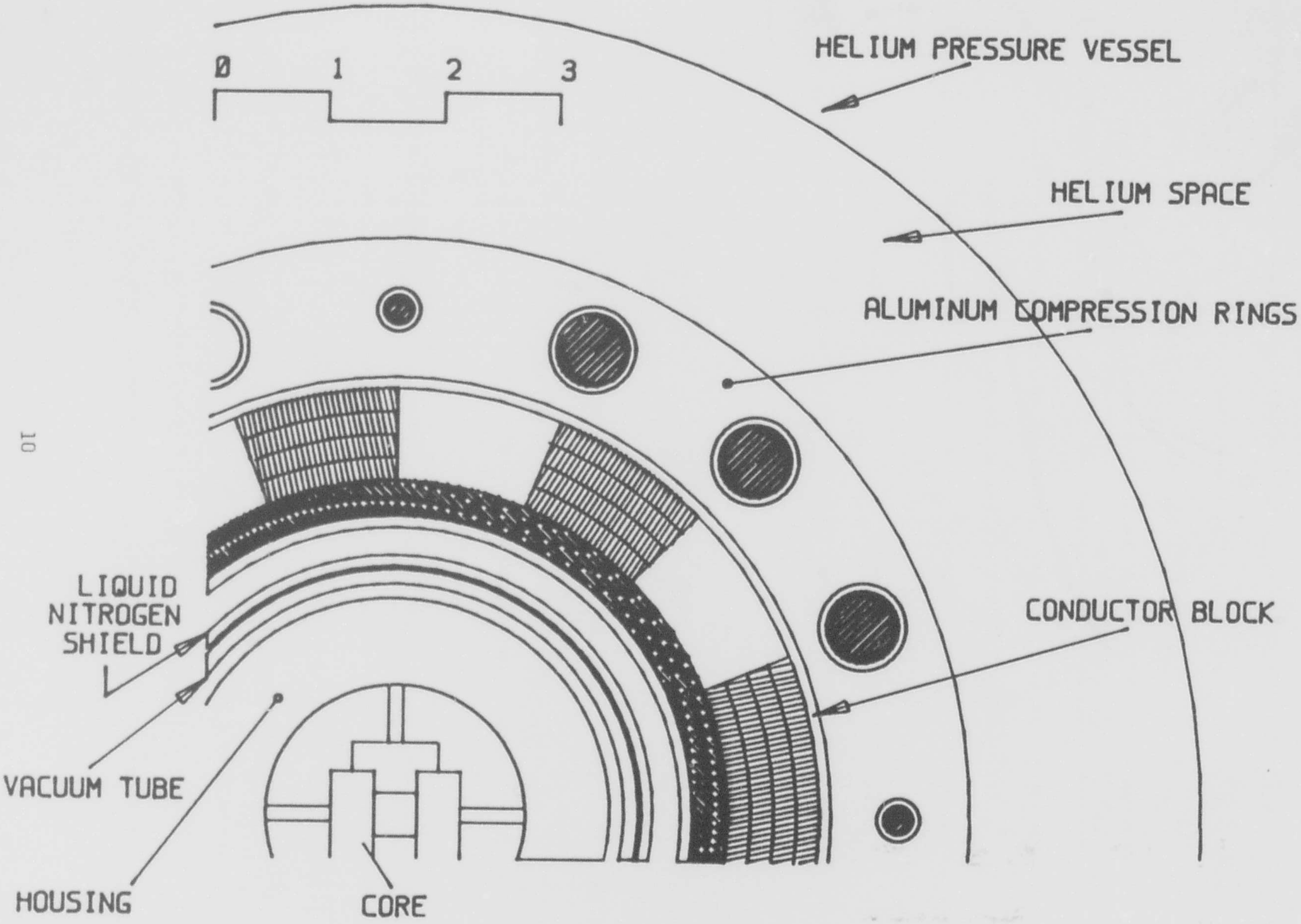

Figure 3. Cross-section of demonstrator SARG.

combined system is a SARG system having a fairly low coupling constant ($k \sim 0.1$).

The augmentation system will be operated at half-field to provide quench protection for the magnet system. The two-Tesla field will be initially established using a 1000 A power supply and maintained in the persistent mode by an appropriate switch.

Tests of the augmented launches recently began. Meanwhile, calculations of SARG performance using the above theory are presented below for comparative purposes.

COMPARISON OF THE SRG AND SARG CONFIGURATIONS

In this analysis, we assume a constant current source for the rail gun in either configuration from a source having a maximum deliverable energy of 15 kJ. We then calculate the several energies using the procedure described above holding the projectile muzzle energy constant. For our comparison we used the system parameters listed in Table II.

TABLE II. PARAMETERS USED IN COMPARATIVE ANALYSIS OF RAIL GUNS

$\alpha_{SRG} = 0.1^{**}$
$m_p = 4\times10^{-3}$ kg
W_s (Max) $= 1.5\times10^{4}$ J
$L = 1\times10^{-6}$ H*
$L' = 1\times10^{-6}$ H/m*

$L_s = 0.188$ H
$I_{so} = I/100$
$\ell = 1$ m
$k = 0.05 - 0.15$
$R = 400\times10^{-6}\ \Omega$*

*Calculated
**Assumed

Using Eq. (8), we find that the rail current will be 1.22×10^{5} amps for the SRG for 15 kJ supplied to the gun from the power source. Since we assumed the launch efficiency of the SRG is ten percent (i.e., $\alpha_{SRG} = 0.1$), we compute the projectile muzzle energy to be 1.5 kJ. This energy yields a muzzle velocity of 866 m/sec for the 4 g projectile.

A rail gun operating a constant current will have a constant applied acceleration force. For negligible frictional retarding forces, we calculate that the barrel transit time Δt is approximately 1 msec using

$$\Delta t = \sqrt{\frac{2\ell m_p}{L'I^2}} \qquad (15)$$

From these results, we estimate that both f and $I^2R\Delta t/2$ will be 3.0 kJ each using Eq. (11), and that the magnetic field energy W_m which must be dissipated at the end of launch will be 7.5 kJ.

Since the degree of coupling, k, is difficult to estimate theoretically in this rather complex SARG demonstrator configuration, we calculated the SARG performance for the conservative range $0.05 \leq k \leq 0.2$. This rather poor coupling coefficient is offset by the extremely large inductance provided by the superconducting magnet system used in this SARG demonstrator. A short discussion of augmentation magnet engineering tradeoffs will be discussed below.

Using Eqs. (2), (9), and (12) we calculated the constant rail current I required to achieve a projectile energy of 1.5 kJ in the SARG configuration as a function of k. Using these currents, we calculated the magnetic field energy at the end of launch, W_m, from Eq. (3), the work required from the energy source, W_s, from Eq. (4), and the dissipative term $f' = I^2R\Delta t/2 + f$ from energy conservation.

The results of these calculations are shown in Figure 4 and indicate the potential improvement in performance that can be achieved by superconducting augmentation.

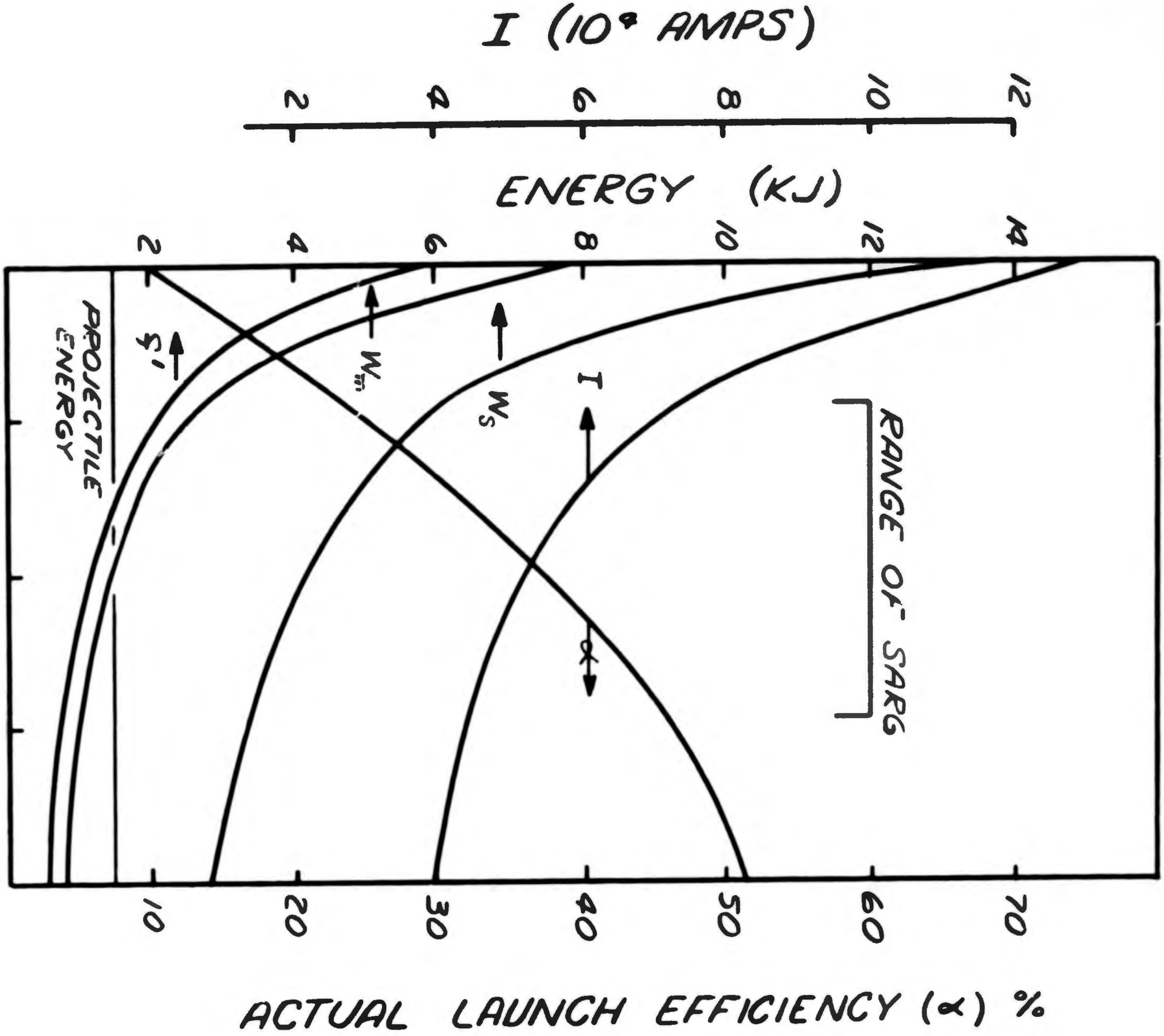

Figure 4. Plot of projectile energy. I - rail current, W_s - energy supplied to rail gun, W_m - magnetic field energy, f' - dissipative losses, and α - actual launch efficiency as a function of the magnetic coupling constant, k, for the demonstrator SARG.

It is important to note that this SARG demonstrator was designed around an existing magnet system, therefore no consideration was given to such important design parameters as system weight, size, or coupling parameters. Thus, the massive augmentation system used led to unacceptable projectile energy to barrel weight (or barrel volume) ratios for a useful system.

In a properly designed SARG system, the augmentation coils are designed to be as closely coupled as possible to the rail gun. Engineering tradeoffs include the physical size of the superconductor used, its maximum current capacity, and cryogenic considerations. These conditions will control the maximum values of k and L_S for a particular rail gun system. For example, if an adjunct augmentation system were designed for a rail gun having the parameters of an EMACK system (ref 3), we estimate that superconducting wire carrying 1.5×10^4 amps could be wound in a 30-turn coil having an inductance L_S of 1.4×10^{-3} h/m and $k \approx 0.5$. The actual launch efficiency of such a system is estimated to be more than doubled the reported EMACK efficiencies.

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[3] D. W. Deis and D. W. Scherbarth, "EMACK Electromagnetic Launcher Commissioning," IEEE Trans. on Magnetics, Vol. Mag-20, March 1984, pp. 245-248.

REFERENCES

1. C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," IEEE Trans. on Magnetics, Vol. Mag-20, March 1984, pp. 366-369.
2. P. Hammond, Energy Methods in Electromagnetism, Oxford: Clarendon Press, 1981, Chapter 6.
3. D. W. Deis and D. W. Scherbarth, "EMACK Electromagnetic Launcher Commissioning," IEEE Trans. on Magnetics, Vol. Mag-20, March 1984, pp. 245-248.

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