

# A COAXIAL RADIAL OPENING SWITCH FOR A DISTRIBUTED-ENERGY-STORE RAIL LAUNCHER

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# A COAXIAL RADIAL OPENING SWITCH FOR A DISTRIBUTED-ENERGY-STORE RAIL LAUNCHER

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## Summary

The current electromagnetic launch technology base suggests that a distributed-energy-store railgun may be an attractive alternative to chemical rockets for Earth-to-space launch. If homopolar generator-charged inductors are to serve as the basic energy stores, a difficult switching problem must be overcome. Several switching schemes (arc, liquid metal, and electromagnetic) have been investigated. Studies indicate that arc opening switches would prove to be too destructive when used with continuous rail launcher systems. The most attractive alternative is an electromagnetically actuated switching scheme. The operation, calculated performance, fabrication, and initial testing of a switch based upon this scheme is presented in this paper.

## Introduction

NASA-Lewis Research Center has been studying various methods for ballistically launching payloads from Earth's surface into space. These studies, conducted over the past several years, have resulted in a ballistic launch technological base which suggests that a distributed-energy-store (DES) railgun is the most viable launcher system.

The DES rail launcher under discussion in this paper is one in which the basic energy stores are homopolar generators (HPGs). HPGs transfer energy to inductors which in turn transfer the energy to the rail launcher. This energy transfer from inductor to rail launcher presents a difficult switching problem. Several methods of accomplishing this switching were examined by the Center for Electromechanics at The University of Texas at Austin (CEM-UT) under a NASA-Lewis grant.<sup>1</sup>

An examination of several recent arc switching transfer schemes as reviewed by Zowarka,<sup>1</sup> a paper dealing with energy considerations in switching energy from an inductor into a rail launcher,<sup>2</sup> and experience gained at CEM-UT in testing an arcing opening switch at high currents (300 kA), led CEM-UT to reject arc switching schemes as too destructive in the gigawatt power ranges necessary for Earth-to-space launchers. The destructive aspects result from the fact that arcs are inherently poor methods of building the resistance (i.e., dissipating energy) necessary to develop a voltage high enough to transfer current out of the switch into the rail launcher. With an arc, most of the power dissipated occurs at the contacts and this is where the destructive effects (contact melting or pitting) occur. Attempts to cool the arc effectively have failed or do not lend themselves to a high repetition rate.

These and many other problems associated with arc switching led CEM-UT to devise a method of switching in a non-arcing manner. In this non-arcing switch, the voltage required to transfer current to the rail launcher is generated in a fixed resistor sized to absorb the energy required to accomplish the switching.

This paper presents the design, fabrication, and initial testing results of this new switching scheme.

## Design Considerations

In designing the new switch, CEM-UT worked on the

premise that a practical launcher design requires the use of continuous solid flat rails. A continuous rail launcher design requires switches capable of dissipating the heat generated without being destroyed and capable of repetitive operation with little or no maintenance between shots.

The CEM-UT design effort drew heavily on existing opening switch testing as reported in the literature by Rioux and Rioux-Damidaou,<sup>3</sup> Vitkovitsky and co-workers,<sup>4</sup> Marshall,<sup>5</sup> and Inall.<sup>6</sup> The design also drew on first-hand experience in opening switch development acquired from joint testing performed by CEM-UT and the General Dynamics Corporation.

The design effort addressed the need for synchronous switching, isolation of depleted energy stores, tight coupling, and multiple gaps for prevention of arc formation within the switch. It was decided that the switching actuation scheme should be electromagnetic to decrease the switching time. Because the electromagnetic forces are proportional to  $I^2$ , a mechanical aid was devised to assist actuation during initial testing at low current levels. It was also decided to keep the means of actuation separate from the contact area so that damage in the contact area would not ruin the actuation scheme. To assist in minimizing the switching time, the mass of the switching element must be as small as possible, which necessitated using a proven lightweight sliding contact. The minimum switching element mass size was determined from tests conducted at CEM-UT on the nondestructive current carrying capabilities of copper test samples. In the tests 6.45 cm<sup>2</sup> (1.0 in.<sup>2</sup>) copper squares were placed in series contact under approximately 6.9 MPa (1,000 psi). Testing over a charging cycle of 300 ms showed that approximately 31 kA/cm<sup>2</sup> (100 kA/in.<sup>2</sup>) could be applied before the specimens welded. These data, along with a design goal of a 200-kA switch, presented a means by which the contact surface area required could be determined. Mechanical integrity of this contact surface ultimately determined the size and mass of the moving switch parts.

Multilam contact band, a commercially available material, as shown in Fig. 1, was selected to provide the lightweight sliding contact surface. The tolerances required for proper installation of the Multilam<sup>7</sup> required that the switch parts be shapes that can be easily produced to close tolerances. A coaxial geometry consisting of concentric rings allowed flexibility in defining the conductive and resistive portions of the switch. This geometry also provided tight coupling by minimizing the inductance of the current path between the charging path and the load path to minimize the fundamental energy absorption requirements.<sup>2</sup>

The resistive portion of the switch was composed of numerous circular steel ring laminations stacked in series. The rings were chemically milled and Mylar laminated to increase the current path greatly, thereby increasing the resistance while minimizing overall size. These rings produce a fixed resistance that was designed to survive a failure to transfer the current to the load. Experimentation on the commutation phenomena could be performed knowing the switch would absorb the inductive energy in the event of projectile failure.

At lower current levels, the fixed resistance scheme suffers. This is due to the primarily mechanical and relatively slow actuation of the sliding contacts onto the steel resistor. As current levels



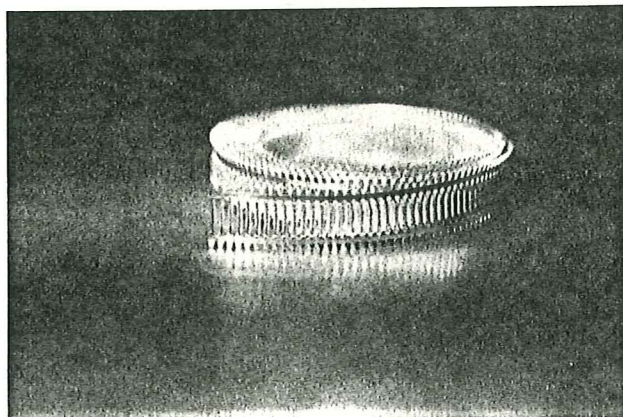


Fig. 1. Multilam band

increase, the electromagnetic forces associated with the higher currents will decrease the time necessary for actuation and thereby improve the efficiency of the voltage development across the resistor. This improvement will also be seen in current transfer from the switch into the rail launcher.

#### Switch Design Action and Predicted Performance

A switch design that addresses the above design considerations and can be modified to disconnect the energy stores from the rails is shown in the front cutaway drawing in Fig. 2 and the cross-sectional drawings in Fig. 3. In the cross-sections, the different current paths at various stages of the switching are shown.

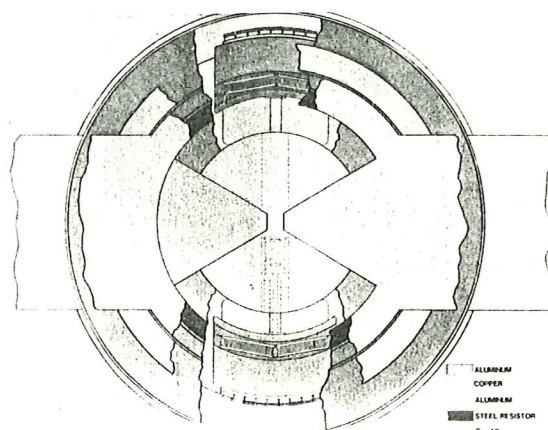


Fig. 2. Coaxial radial opening switch front cutaway

The launcher switch design utilizes radial actuation in which the switching is completed in three intervals. A simplified two-dimensional representation of the switch operating in the DES circuit is shown in Fig. 4. The switch position during the first interval is shown in Fig. 4a. During this time the HPG is charging the energy storage inductor through the short circuit path provided by the opening switch. Because of the coaxial geometry, a magnetic force is applied to the shuttles that form the inner conductor. The magnitude of this force in the switch as constructed is given by

$$F = \frac{1}{4} \frac{\mu_0 I^2 z}{4\pi r}$$

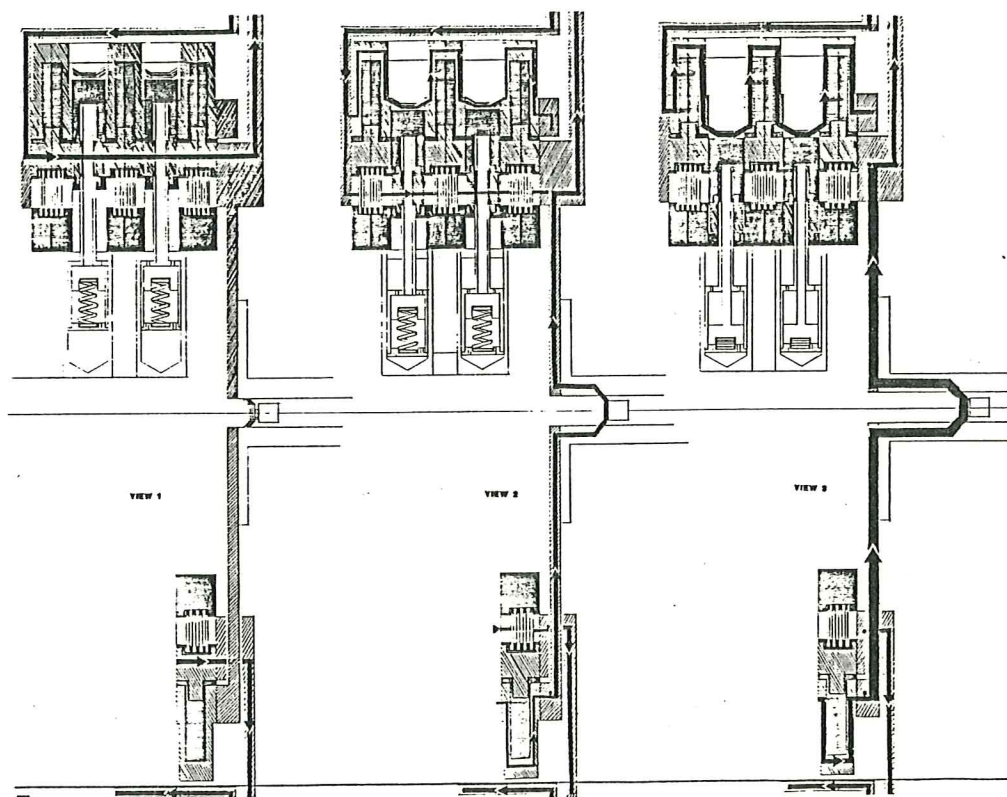


Fig. 3. Coaxial Radial Opening Switch  
Three cross-sectional views of possible current paths

$\mu_0$  = permeability of air,  $4\pi \times 10^{-7}$  Wb/A·m  
 $I$  = peak current, 47 kA  
 $\ell$  = length, 2.54 cm (1 in.)  
 $r$  = radius of shuttle conductor 17.2 cm (6.75 in.)

The factor of 1/4 appears because only one shuttle is under test in the four-quadrant design. The 47-kA peak current is the manufacturer's pulsed current rating for the LAI/.15 Multilam band shown in Fig. 1. The peak magnetic force during charging, 130 N (29.4 lbf) is counteracted by a telescoping air cylinder. At peak current the pressure on the back side of this cylinder is exhausted, and the pressure is redirected to the front of the cylinder. The magnetic force of 130 N (29.4 lbf) and the pneumatic force of 700 N (157 lbf) overcome the frictional force of the current-carrying Multilam louvers, 94 N (21.1 lbf), and the static friction of the air cylinder actuator, 9 N (2 lbf). The total applied force of 726 N (163.3 lbf) moves the 1.44-kg (3.173-lbm) shuttle mass to the position shown in Fig. 4b in 6.9 ms. As the trailing edge of the Multilam louvers moves onto the resistive path, an IR voltage is developed that commutates current into the electromagnetic launcher through the concurrently-formed conductive path B. The included inductance of the resistive path is 1.92 nH. The energy that must be absorbed as the 47-kA current transfers from the 10- $\mu$ H coil to the resistive path is

$$\begin{aligned}
 E &= \frac{L_A}{L_{\text{coil}}} \left( \frac{1}{2} L_{\text{coil}} I^2 \right) \\
 E &= \frac{1.92 \times 10^{-9} \mu\text{H}}{10 \times 10^{-6} \mu\text{H}} \times 0.05 \times 10 \times 10^{-6} \mu\text{H} (47,000 \text{ A})^2 \\
 &= 0.212 \text{ joules}
 \end{aligned}$$

The current,  $I_B$ , commutating into the railgun then applies a further magnetic force to the shuttle and drives this member into the position shown in Fig. 4c. In this position, current is cut off in the resistive path A, thus establishing full current in the railgun. In DES operation, the end of this final switch path could be resistive to essentially disconnect the energy store from the launcher. Such complication was not warranted in this design because the test facility available has only one energy store.

#### Fabrication

The various parts of the rail launcher switch were machined from ETP 110 electrical tough pitch copper plate, 2000 series aluminum plate, and close-tolerance sanded G-10 glass fiber-reinforced epoxy. The switch design, which was based around the operating limits and dimensional requirements of LAI/.15 Multilam contact bands, called for a number of concentric circular parts assembled together in an interlocking manner to form insulated and discrete-resistance current pathways. The rings making up the current pathways are shown in Fig. 2.

The Multilam bands or louvers are contained in copper pieces that make up an inner and outer shuttle mechanism. This shuttle mechanism (made of copper, G-10, and Multilam) is attached to a telescoping air cylinder made of stainless steel and brass. The cylinder is contained in an insulated aluminum plate attached to a steel shaft with an interference fit. The shaft provides air passages from external air supplied to the cylinder. The shaft also serves to position the shuttle switch mechanism between the

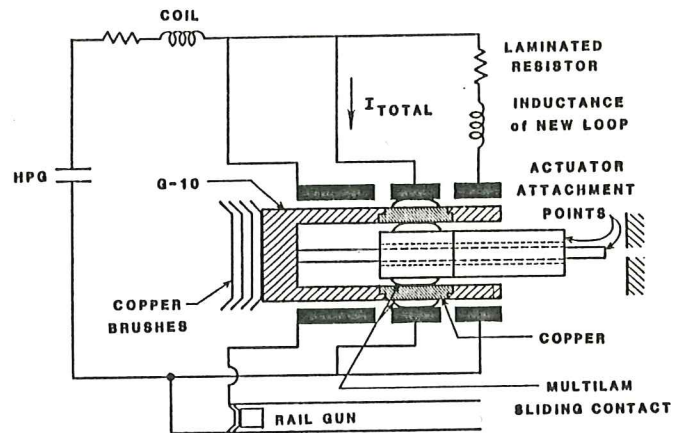


Fig. 4a. Switch in the inductor-charging position

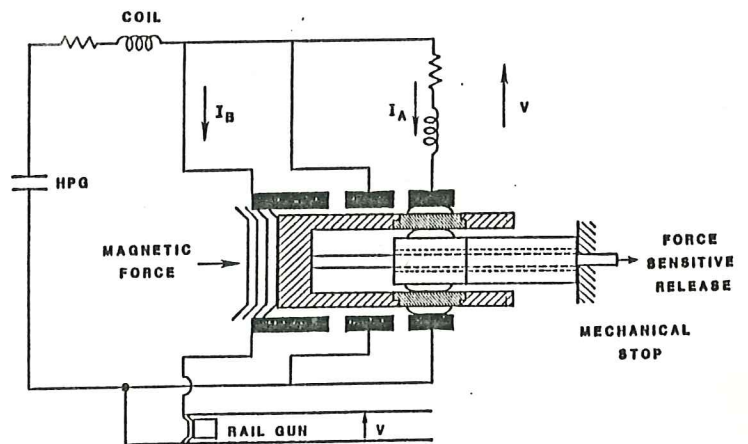


Fig. 4b. Switch building commutation voltage

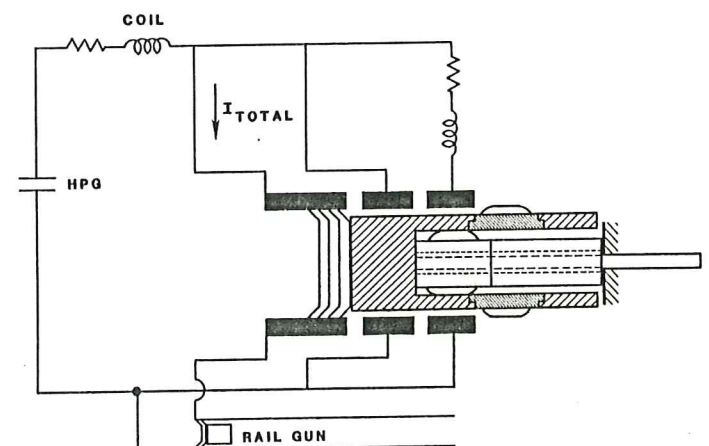


Fig. 4c. Switching complete -- total current established in railgun

Fig. 4. Action of DES circuit switch

interlocking current pathway plates that are held apart by a close-tolerance spacer ring. This spacer ring was



made of mild steel flame sprayed with aluminum oxide insulation and ground to the proper dimension required for the Multilam to make good electrical contact.

The shuttle mechanism, current pathway plates, shaft, etc., are contained in a copper housing and are secured by means of front and back plates of aluminum and G-10. The housing and back plates serve to bus current from the homopolar inductor energy store to the switch. Current that then passes through the switch is carried away by an aluminum busbar arrangement that connects the switch to the rail launcher.

#### Testing Procedure and Results

In the initial testing of the coaxial radial opening switch, it was important to separate the charging duty of the switch from the opening function. This separation was required to prevent charging damage associated with the contact dissipative losses from being confused with possible damage incurred due to excessive energy absorbed during commutation.

Two sets of tests were designed. One test would involve testing the switch up to design current without actuation. The second test would attempt to actuate the switch at design current to determine the effectiveness of the switching concept.

During the first set of tests, in which the switch was not actuated, it passed currents of 10 and 31 kA. Voltage traces at the 31-kA level showed some form of contact instability, from which it was inferred that some form of contact damage had occurred. Another test was conducted at the 30-kA level, and activation of the switch was attempted. A displacement probe indicated that no actuation had occurred. The switch was disassembled, and inspection showed a small welded spot between one of the four series contacts and one of the copper current rings. From the inspection it was felt that the damage occurred due to a possible misalignment and incorrect tolerance between the damaged parts. This conclusion was reached because the three other contacts in series, which saw the same  $\int I^2 dt$ , were undamaged. The misalignment was corrected, the damaged parts were repaired, and the switch was reassembled.

In the second series of tests, the switch was actuated at current levels of 16 and 24 kA. A calibrated displacement probe showed that actuation occurred. Data collected from these tests are shown below:

Peak Charging Current (kA)	Charging Current Rise Time (ms)	Interrupted Current (kA)	Voltage Developed (V)	Current Rise Time in Load (ms)
16	300	10.5	10.3	?
24	300	15.4	15.2	1

Switch actuation at 30 kA was attempted, but did not occur. Voltage traces showed some form of contact instability similar to that seen during the first series of tests when switch actuation was not attempted. Disassembly and inspection of the switch showed that again one of the four series contacts had failed. The 61.25 kA, 200 ms charging cycle as predicted by the Multilam Design Guide (already derated to 47 kA under the current design) now came into question. Further research into the Multilam contact performance as presented by independent researchers<sup>8</sup> predicted slight contact instability at 34 kA and pitting and slight silver transfer at 50 kA. Because these numbers approach the current at which contact failure occurred,

further design effort to increase the current-carrying capacity of the switch will focus on the sliding contact design.

#### Conclusions and Future Action

Test results at this point are inconclusive, but it has been shown that the coaxial radial switching scheme will transfer current at levels less than 20 kA. Two of the four contact series are being refurbished with double their initial Multilam contact area and future tests are planned to see whether this arrangement will allow the switching scheme to operate at higher current levels. If this change is unsuccessful, a new sliding contact system will be devised and tested.

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