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RAIL-GAP SWITCH MODIFICATIONS AND TEST DATA FOR THE ATLAS CAPACITOR BANK*

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Abstract: Atlas is a facility being designed at the Los Alamos National Laboratory (LANL) to perform high energy-density experiments in support of weapons-physics and basic-research programs. The capacitor bank design consists of a 36-MJ array of 240-kV Marx modules. The system is designed to deliver a peak current of 45- to 50-MA with a 4- to 5-us risetime. Evaluation, testing and qualification of key components of the Marx module are being conducted. One key element of the Marx module is the low inductance, high-voltage, high-current, high-coulomb transfer spark-gap switch needed for this application, 304 of which will be used in the Atlas capacitor bank. Because of the Marx module configuration, overall system inductance requirements and the need for a triggered switch, the design team initially selected the Maxwell Technologies rail-gap switch. The switch has been used in other high-voltage, high-current, high-coulomb transfer applications and would meet the Atlas facility requirements with some modifications. Testing of the Maxwell rail-gap switch under expected Atlas conditions is in progress. For the Atlas application, the rail-gap switch required some mechanical design modifications, which are discussed. Maxwell provided two modified switches for testing and evaluation. Results of this testing, before and after modifications, and inherent maintenance improvements to meet overall system reliability will be discussed.

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Atlas Marx Description

Atlas is a facility being designed at Los Alamos National Laboratory (LANL) to perform high energy-density experiments in support of weapon-physics and basic-research programs. Atlas is designed to be an international user facility, providing experimental opportunities to researchers from national laboratories and academic institutions. For hydrodynamic experiments, Atlas will be capable of achieving a pressure exceeding 30-Mbar in a several cm^3 volume. With the development of a suitable opening switch, it will be capable of producing more than 3-MJ of soft x-rays.

The capacitor bank design consists of a 36-MJ array of 240-kV Marx modules. The system is designed to deliver a peak current of 45- to 50-MA with a 4- to 5-us risetime. The Marx modules are designed to be reconfigured to a 480-kV configuration for opening switch development. The capacitor bank is resistively damped to limit fault currents and capacitor voltage reversal.

The capacitor bank design contains 304 closing switches. The primary candidate is a modified version of a Maxwell rail-gap switch originally designed for the DNA-ACE machines. Considering the large number of switches in the system, individual switch prefire rates must be less than 10^{-4} to protect the high-value loads and targets.

Switch description

Los Alamos advertised for a switch which would meet the following specifications:

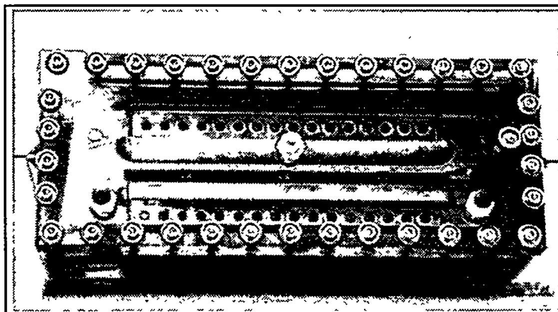
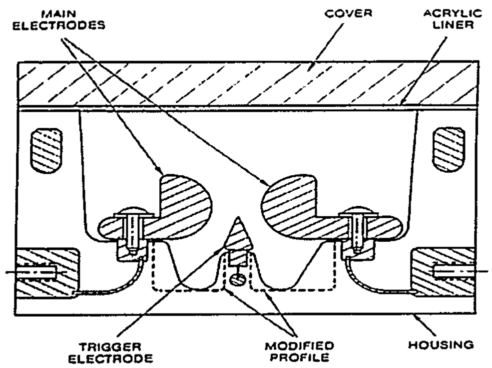


Figure 1 Model 40200 Rail-Gap Switch

Electrical Parameters:	
Operating Voltage	25-kV to 120-kV
Peak Current	1-MA
Max. Charge Transfer	10-C
Inductance, Planar Geometry	<20-nH
Lifetime Parameters:	
Shotlife, Design	5000
Shotlife, Maintenance	100
Jitter:	
Measured from trigger input to high-voltage output	<2 sigma, with a 100-kV pulse with a 10-nsec rise time
Mechanical Parameters:	
Max. Dimensions	39.0-in x 7.6-in. x 5.5-in.
Internal Dielectric Gas	SF6 Argon, Air
Operating Environment, External	Oil Air, SF$_6$
Mechanical Connection	11.75-in. long, brass electrode for 16-ea. ¼-20 screws

The utility industry, Maxwell Technologies and other high voltage switch manufacturers responded to the advertisement. The only switch meeting the Atlas specifications was the Maxwell rail-gap switch, Model 40200 (see Figure 1). The Maxwell switch has been used in several other applications such as the SHIVA and the subsequent SHIVA STAR facility at Phillips Laboratory, the Pegasus facility at Los Alamos, the DNA ACE II facility, and the Magneform 8000 machine. The switch outside dimensions are: 19.6-in. long x 7.62-in. wide x 4.62-in. deep. The unique feature of the Maxwell switch, which narrowed the competition, is the



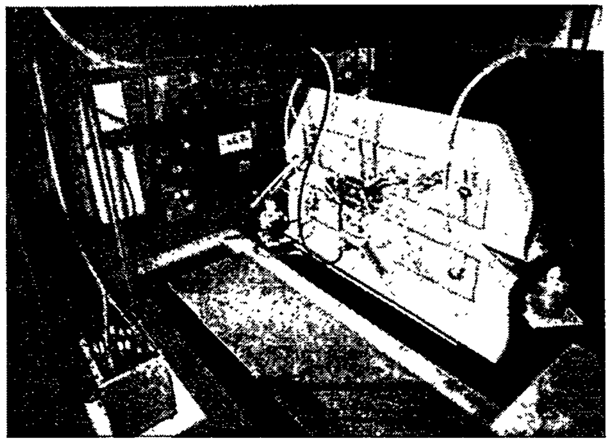


Figure 2 Rail-Gap Switch Cross-Section **Figure 3 Test Setup #1**

planar configuration of the rail-electrodes (see Figure 2). This feature lends itself ideally to the Atlas requirements and minimizes the associated inductance. More traditional spark-gap switches could be used but the associated inductance would be higher. With a fixed design for the physical location of capacitor pairs and the connecting switch, it would be difficult to improve on this planar inductance and still meet the Atlas requirements.

After choosing the rail-gap switch as a major component in the Atlas Marx configuration, research and development testing was initiated to verify the switch selection and accumulate data at proposed Atlas conditions. Two different testing setups were used. The original setup consisted of 6-ea. 6-µF capacitors arranged as a stacked module (see Figure 3). This arrangement allowed the switch to be placed between the top and bottom half modules. Electrical circuit (resistor and inductor) component values were chosen such that the current and voltage waveforms were equivalent to Atlas circuit parameters.

Switch Performance, Original Configuration

Early testing was intended to test switches to prefire and to define other failure modes. Three switches, A, B, and C, were tested until each prefired, which ended each shot series (see Table 1). Only then, were switches refurbished using the published standard maintenance procedure. Switches A and C survived only 3 prefires, switch B survived 5 prefires using the original trigger terminal design. For these 3 switches, the average Maintenance Shotlife was 79 shots and total average Design Shotlife was 291 shots. Performance was reasonable under the Atlas electrical conditions and mechanical constraints but did not meet either the Shotlife Design or Maintenance requirements of 5000 or 100 shots, respectively. Changes in the mechanical design were made to improve the Design Shotlife and a series of changes in operating mode and maintenance were made to improve the Maintenance Shotlife.

Table 1 Switch Test to Prefire

Switch	A	B	C
	109	113	109
	94	147	50
	66	22	130
		14	
		19	
Shot Life	269	315	289

As experiments were performed and prefires on the switch accumulated, it became clear that the switch needed to be mechanically toughened to resist damage from prefires. There were four mechanical failure modes observed: 1) bent trigger rails, 2) broken trigger rails, 3) stripped trigger terminal threads, and 4) trigger screw failure. Progressive trigger terminal deformation between shot series made it more and more difficult to position and secure the trigger rail after each prefire refurbishment. Figure 4 shows a plot of the measured trigger rail and trigger terminal deformations after prefires on switches B & C when the trigger rail did not break. Of the four mechanical failure modes, only the stripped out screw hole in the trigger terminal caused the switch body to be abandoned as unusable.

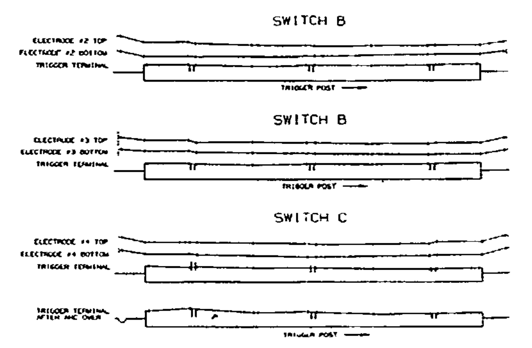


Figure 4 Trigger Rail Deformation

Switch Mechanical Modifications

Because of the nature of a switch prefire, it is difficult to consistently predict the magnitude and direction of forces causing mechanical damage. Instead, we used the original switch design to calculate geometric and strength properties from which any performance improvements could be measured and compared. The trigger terminal molded into the polyurethane base was changed from three separate free machining brass pieces that required soldering to a single machined profile of 17-4PH stainless steel. Changing the shape of the trigger terminal also improved its resistance to pullout from the base. Table 2 presents the data for the original and modified design for the switch base, the trigger terminal, and hold down screws. Note that the equivalent base height, area or CG did not change appreciably - because the inside polyurethane profile remained the same. Only the equivalent base stiffness, I, changed - increasing by a factor of 3.6x.

Table 2 Switch Mechanical Properties

Base	**Original**	**Modified**
height, in	0.874	0.874
cross sectional area, in^2	0.180	0.312
polyurethane CG y, in	0.447	0.430
polyurethane I, in^4	0.0263	0.0239
equiv. poly I, in^4	2.74	9.79
Trigger Terminal	**Original**	**Modified**
material	360 brass	SS 17-4 PH
treatment	½ hard	H1150
yield strength, psi	52,000	125,000
tensile strength, psi	68,000	150,000
elongation, %	18.0	19.0
Young's Modulus, psi	14.0E+06	28.5E+06
metal I, in^4	0.0145	0.0189
Trigger Screw	**Original**	**Modified**
material	SS Nyloc	SS302 Hq
yield stress, psi	150,000	35,000
tensile stress, psi	180,000	90,000

The change from brass to stainless steel improved the yield strength and the toughness by a factor of 2.4x and altered the order of component failures in the modified design. This allowed the trigger terminal to be the strongest, toughest component, thereby reducing the number of switch bodies that become unusable because of stripped trigger terminal screw threads. The trigger rail screws were changed from relatively short, high strength, Nyloc screws to longer, softer stainless steel screws. This change allowed the screws to act as tensile springs that hold the trigger electrode in place during a normal shot and allow it to displace during a prefire. The screws are also designed to be the weakest link, and are cheap components that are easy to replace if they break during a prefire.

The trigger electrode was modified slightly to improve it's resistance to prefire forces. Trigger electrodes experienced bowing in the plane of the main rails and bending in the plane of the base after a prefire. The addition of 6 shear pins reduced bowing and kept separation tolerances acceptable between the large rails and the trigger electrode. During refurbishment, triggers were successfully straightened using a gapping tool and pressure from a mill head. Broken trigger electrodes had to be replaced. The change in screw head design from socket head to low profile heads eliminated the need to hide the screw head and increased the electrode cross sectional area and moment of inertia by factors of 3x and 32x, respectively. The location of the outer hold down screws was moved closer to the end of the electrode. This reduced the length of the cantilevered end by 1-in. and increased its stiffness by a factor of 874x.

Switch Maintenance & Refurbishment, Original and Modified

During early testing, the standard published refurbishment procedure provided with 260-kJ SHIVA style module was used and is as follows:

ATLAS Testbay Rail-Gap Refurbishing Procedure

Step 1: Remove Lexan cover, Brass electrodes and Trigger electrode from rail-gap base.

Step 2: Bead blast brass electrodes. Clean residue with ethanol and wipe dry with Kimwipes. **Do not touch with bare hands after electrodes are clean.**

Step 3: Clean the trigger electrode using scotchbrite and ethanol. **do not touch with bare hands after it is clean.**

Step 4: Using isopropyl alcohol and scotchbrite, clean the polyurethane base thoroughly. Wipe off any residue using Kimwipes and isopropyl alcohol.

Step 5: Wearing latex gloves, install trigger electrode on the trigger terminal.

Step 6: Loosely install brass electrodes with three bolts each. Place gapping tool between brass electrodes and on the trigger electrode, squeeze the brass electrodes tight against the gapping tool and tighten the bolts. Install the remaining bolts and torque to 60 - 70 in-lb.

Step 7: Place o-ring in groove on polyurethane base and install the Lexan cover. Use the proper torque sequence and torque the lid bolts to 60 in-lb.

Steps 2, 3, and 4 of the refurbishing procedure were modified. The electrodes were sanded with medium, then with fine grit sandpaper using a drill mounted rotary flapper disc. The polyurethane base was sanded and then polished using very fine grit SiC emery type paper. The acrylic cover was polished to remove contaminant buildup. All surfaces, including the inside of each screw hole, were swabbed and cleaned with 2-propanol, then the residue was removed with ethanol and Kimwipes. With this procedure, a refurbished switch operates similar to a new switch being used for the first time. Data indicates (see Table 1) that a new switch, in its pristine state, will operate for more shots before prefire than a switch having many series of shots. The data also suggests that subsequent shot series become shorter. Data suggests a buildup of foreign material that accumulate on the switch base surface or just below the base surface. The labor intensive cleaning, and polishing removes this surface contamination.

A second significant change was made to the operating mode during later testing for all switches tested after switch D. The gas plumbing system was modified to allow the insulating gas to be flushed immediately after each shot. This was done in an effort to remove as much of the contaminants before they burned into or settled out on the polyurethane switch base surface.

Switch Performance, Modified Configuration, Maintenance and Operation

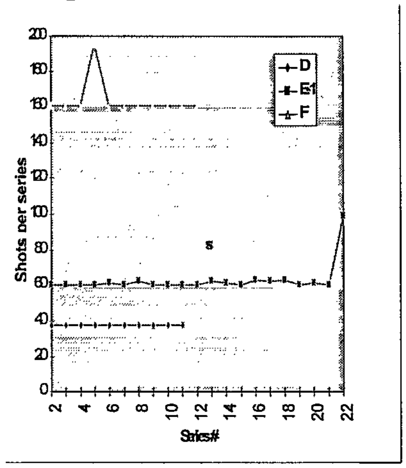


Figure 5 Shots to Prefire

Changes in the switch maintenance and operating mode were made with switch D. The testing criteria changed from testing to prefire - to testing for a set number of shots, then refurbishing, then repeat testing - to determine how many shots a switch could accumulate without a prefire. Switch D was operated for 38 consecutive shots, then refurbished using the original procedure. After 10 shot series, and 380 total shots, it had not experienced a prefire (see Figure 5). Maxwell, using the mechanical design changes, fabricated two switch bodies, E-1 and F-1. Switch E-1 was operated in several test modes, with the data plotted in Figure 5, illustrating the test mode to accumulate shots between prefires. Switch E-1 accumulated a total of 1215 shots without a prefire in 20 shot series using the modified refurbishment method and gas flushing after each shot. The switch was then tested to prefire - which occurred in the next shot series at 99 shots. The E-1 trigger terminal was still intact at retirement. Switch F, original configuration, was tested to 160 shots per series to attempt to improve the maintenance life beyond 60 shots per series. It ran 4 series at 160 shot without a prefire, then was tested to prefire which occurred at 195 shots. Switch F was retired after 1795 shots with only a single prefire and the trigger terminal still intact.

Changes in the maintenance and refurbishing procedure reduced the prefire rate from and average of a prefire every 79 shots to no prefires for each of 380 shots, 1215 shots and 1760 shots. The mechanical changes to switch E-1, improved Design Shotlife from an average 291 shots to over 2785 shots.

Summary

Results of the Atlas R&D rail-gap switch testing to date have been presented. Mechanical modification to the trigger terminal and electrode were required to stiffen and strengthen the switch. Such design modifications have been incorporated into the switch to be delivered to Atlas for the 240-kV Marx module. The modified maintenance procedure appears to be single most important factor in extending the Maintenance Shotlife of the rail-gap switch during testing. The increased strength and toughness of the trigger terminal and the change in failure mode have proved to extend switch Lifetime Shotlife.

Acknowledgments

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