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Title: Series Fault Limiting Resistors For Atlas Marx Modules

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## SERIES FAULT LIMITING RESISTORS FOR ATLAS MARX MODULES

by

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### ATLAS BASE DESIGN


The proposed Atlas design provides a current pulse to the experiment chamber from a set of 20, 3-Marx-unit-wide modules radially positioned around a rectangular disk transmission-line system (total of 60 Marxes in parallel)<sup>1</sup>. The Atlas circuit is designed to be a near-critically-damped network with a total erected capacitance of 200  $\mu\text{F}$  at 600 KV. The justification for the necessary circuit resistance in this approach is based on reliability, fault tolerance and operational maintenance<sup>1</sup>. Also the use of high energy-density capacitors that have lower tolerance to voltage reversal is a primary reason for the damping provided by significant series resistance.

To obtain the damping there are two system resistors in the Atlas design. One resistor is a shunt element designed to damp the resonance caused by the relatively high-Q disk transmission-line capacitance and the Marx bank inductance. The second, more significant resistor is a series, fault-current limiting element that also performs the necessary damping for voltage reversal at the bank capacitors. The Series resistor is the subject of this paper.

### THE SERIES RESISTOR

The series resistor is distributed in the Marx module structure as an integral part of the Marx output transmission-line feed system to the disk. We intend to use Reticulated Vitreous Carbon (RVC)<sup>2</sup> foam blocks for the series resistor element. The blocks will serve as a resistive transmission line on the back side of the Marx modules. RVC is the product of a carbonized polyurethane foam with pore densities that typically range from 10 to 100 pores per inch (up to 500 when process-compressed). The resulting density of this form of Carbon is 5-15% by volume. The effective bulk resistivity range is 0.4-0.08 Ohm-cm fitting our requirements well. The process of producing RVC results in a reproducibly refined form of continuous-fiber, vitreous Carbon in a controllable density, lacking the grain boundary character of common carbon-ceramic-mix resistors. The RVC material provides a low inductance resistor in the Marx transmission line system due to its available form and shape. The RVC foam can be cast and/or machined to shapes of myriad form. Our design will use a relatively thin rectangular sheet that is about one inch thick, 22 inches wide (2 pieces, 11 inches wide each) and 18 inches long (56X46X2.5cm) in twelve locations in each module transmission line scheme.

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We have applied electrodes to small samples of the RVC material and pulse tested for current and energy density with results better than required performance for Atlas. In our first test series, the samples repeatedly managed over 17KA/cm<sup>2</sup> at the electrodes and 130 J/cc of 15% density foam material. Electrode application was accomplished by metal-arc spray methods with good results both mechanically and electrically. The metal-arc spray penetrated approximately 2-3 mm into the foam assuring both good adhesion and good interconnection to the filamentary carbon matrix.

The series resistor in the Atlas system circuit is distributed in each Marx bank as four (4) individual, series elements that interconnect stages of the Marx and provide a flat transmission line section between the stages (see Figure 1). This configuration lends itself to flat, robust, rectangular materials of which there are few on the market with the necessary resistivity. Consider also that there are 240 resistors in the Atlas configuration where each resistor must be about 0.12  $\Omega$  and manage the near 500 KA per Marx Atlas current (~ 700 KA per Marx fault). The mechanical constraints placed on the resistor design by this transmission line application allows about 140 cm<sup>2</sup> for the resistor contact face. This will cause a current density in normal operation of about 3200 A/cm<sup>2</sup> in the contact face. The resistor material has been tested (above) to considerably higher values of current density to the degree that current density (in this mechanical configuration) is not a problem. Likewise the energy density in the resistors is on the order of 20-30 J/cc even in the fault mode where the series resistors absorb all the Atlas stored energy.

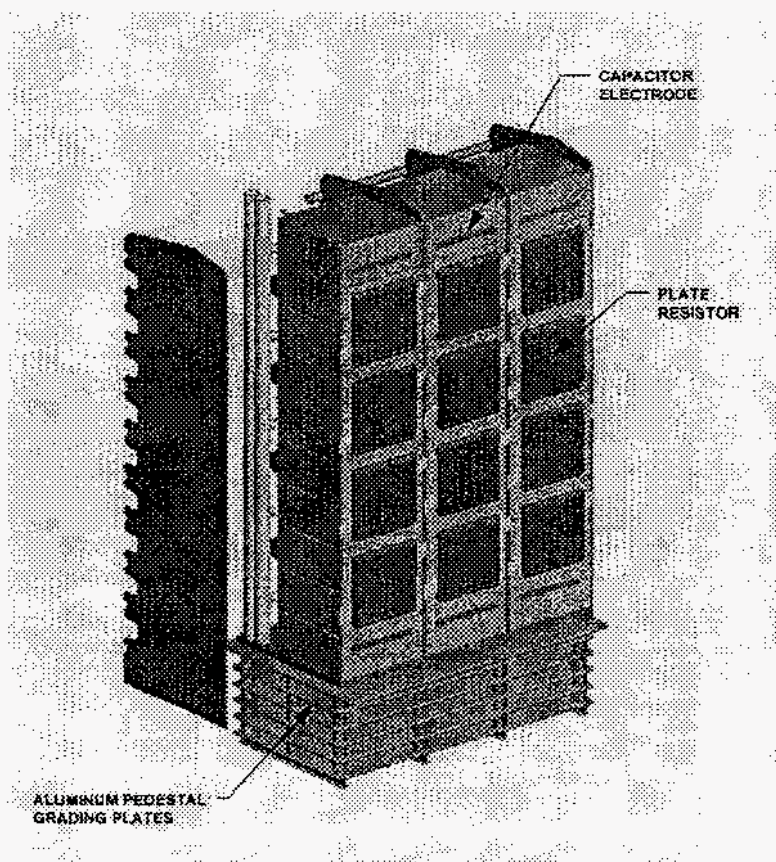


FIGURE 1

## THE ATLAS TEST FACILITY

The test facility that we have constructed to study these components is located in a building next to the eventual Atlas site. This large, high bay (10 m ceiling) building has a 15 ton overhead crane and over one megawatt of building power available. We have constructed a high energy test area, walled with multi-ton concrete blocks and steel sheet walls. This area will be the experimental area for the prototype Marx modules when the module structural and electrical components are available. This is expected to happen in the Spring of 1996. At present we have assembled a single stage Marx unit capable of up to 130 KJ stored energy at 120 KV. The Marx inductance is about 90 nH allowing good peak current delivery and test facility for both the series resistors and the Rail Gap switches that are part of the component validation program now in process.

### PERFORMANCE OF THE FULL-SIZED RVC RESISTORS

The RVC resistor blocks have been in the high energy test bank for about 2 weeks at the time of writing (July '95). The test program has been a combined series of tests on the resistor and the Rail Gap switch, one requiring the performance of the other. The electrode ends of the RVC resistors have been metal-sprayed with about 0.75-1mm of Aluminum directly on the Carbon foam. No in-depth study of the wetting or contact character between the Aluminum and the Carbon filaments has been done. The pulse electrical tests to-date have not required such. The resistors are clamped between flat headers (under less than 10 lbs pressure) with finger-stock like material insuring contact between the headers. There has been no indication of Carbon filament failure in the RVC, change in resistance (permanent) or etching around the interface area between the metalized region and the Carbon at these current densities. After a series of 10-20 pulses spaced about 1-2 minutes apart the resistor is just warm to the touch and no indications of resistance change, which is remeasured after each set of 10 shots. The interconnect quality has been monitored during the tests with very limited damage occurring only when the planar flatness of the electrode surface was rough enough to not make good contact with the header fingers. The damage was confined to the contact fingers and did not effect the metal sprayed surfaces.

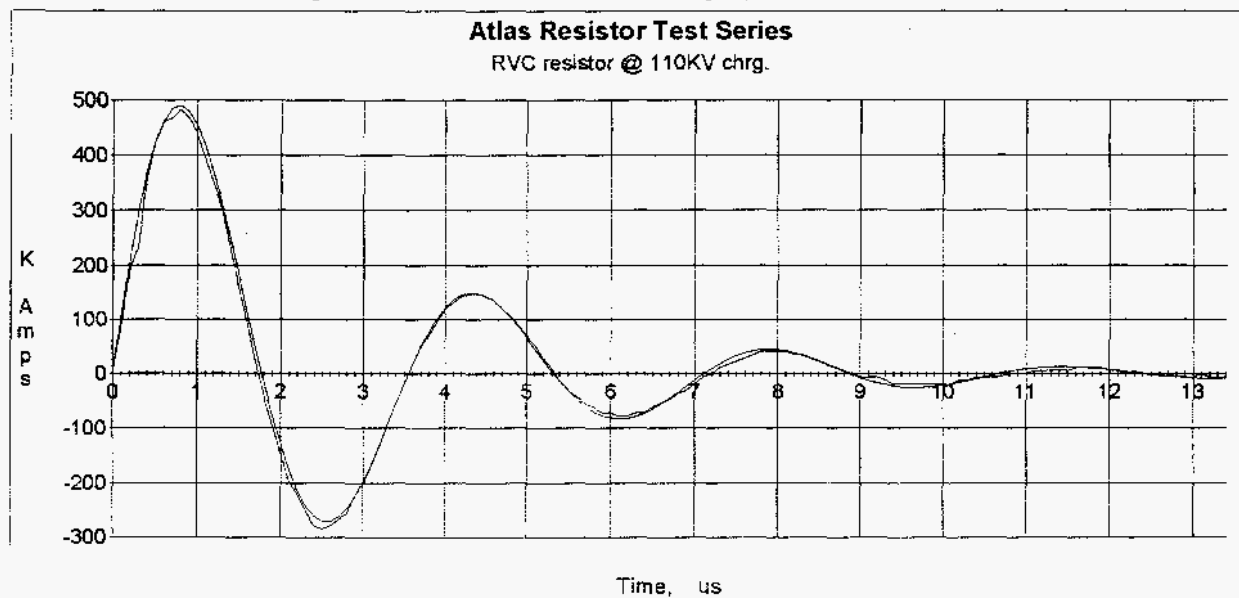


Figure 2

Data thus far obtained is shown in Figure 2, where the current monitor data is overlaid with the lumped circuit equivalent response. The current wave form follows that of a good linear circuit, showing that the resistor, is a good, linear device over this range of E-Field and thermal shock. The peak E-Field across the resistor element is on the order of 50 KV/meter, a field low enough that no significant E-Field induced non-linearity was expected. Thermal shock excited resistance change was of concern. The peak thermal loading of the bulk of the Carbon, which is a small mass, could be imagined to create some non-linear character during the pulse, but none has been noted as shown above.

## CONCLUSION

The resistivity of pure Carbon and its linearity under expected Atlas thermal and electric field conditions is as close as we can expect to get with practical materials. However not only is solid Carbon an impractical material but even then the resistivity is far too low to fit our mechanical and electrical needs. However in this foamed, low density form, vitreous Carbon has just the right qualifications to fit our requirements. It has proven mechanically sound and strong enough to withstand normal handling. It is of course a fit to our resistance requirements and in this form is proving to manage the power and energy density very well. The electroding was a major concern prior to our use of RVC as a true power resistor but again has proven to be easily electroded or "connected" to a circuit. The shape and form that RVC can be manufactured in is very broad and could reasonably fit any requirement. Probably the most rewarding facet so far is the electrical performance of these quickly assembled resistors. They have lived up to our best expectations in all of our tests so far and have shown no sign of failure of being fully qualified as an Atlas component.

## ACKNOWLEDGEMENTS

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