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REPETITIVE PULSE TESTING AND MODELING OF A HIGH POWER CERAMIC RESISTOR

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Introduction

HVR's U-Series resistors are designed to be used for circuitry which is prone to undergo surges, high peak power or high energy pulses. In pulsed applications, these resistors are designed to distribute the energy uniformly throughout the structure resulting in low thermal stress. It also contains an epoxy coating which protects the resistor from the environment. Experiments were performed to test its limitations under extreme conditions by pushing the resistor pasts its rated average power and rated energy. A thermal model was constructed in MATLAB to simulate the temperature the resistor would reach during the pulsed power experiments. The temperature and energy were analyzed for every experiment and a series of experiments were performed to determine the maximum power allowed by the resistor.

Experimental Methods

The U-Series resistors were placed under a series of experiments to gain information regarding its thermal and physical limitations shown in Figures 1 – 4. These experiments were designed to test the resistor in a variety of ways from quick power pulses to constant applied power. They demonstrated several ways the resistor can fail and safe operating regions which was related to the energy absorbed by the resistor displayed in Figure 5.

Table I. Manufacturer's specifications for U1320 [1].

Maximum Impulse Voltage	1500 V
Power	2.5 W
Peak Energy	400 J
Resistance	25 Ω ±10%

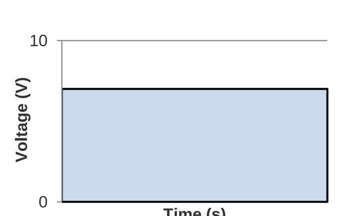

Figure 1. Constant Voltage Waveform.

Constant Voltage experiment
- 7.0 V (rated average power) (Table I)
- Also tested: 3.5 V, 5.0 V, 100.0 V

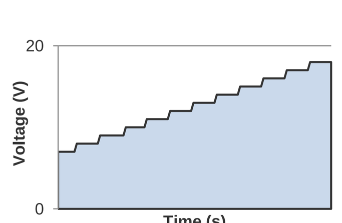

Figure 2. Gradual Voltage Increase Waveform.

Gradual Voltage increase experiment
- Gradually increased power to the resistor by incrementing the voltage from 7.0 V – 18.0 V.

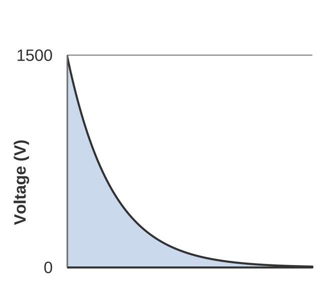

Figure 3. Exponential Decay Waveform.

Exponential Decay experiment
- Designed to ensure high power absorption by the resistor from a capacitive discharge.
- 1500 V (Rated impulse Voltage) (Table I)

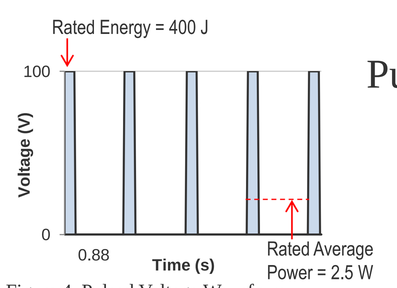

Figure 4. Pulsed Voltage Waveform.

Pulsed Power experiment
- Pulse period - 160 seconds
- Pulse duration - 0.88 seconds
- Perform at its rated average power and rated energy. (Table I)

Thermal Failure Modes

Transient Thermal Expansion
- The temperature difference between the resistor and epoxy coating, and different thermal expansion rates may have caused a breach in the resistor's epoxy coating, resulting in extruded solder. (Figure 6) In some cases, the surface of the resistor reached a temperature high enough to release smoke from the crack. (Figure 7) An extreme case of thermal expansion resulted in the resistor exploding. (Figure 9)

Ignition of the Epoxy Coating
- The surface temperature of the resistor reached a point of ignition for the epoxy coating material causing it to ignite. (Figure 8) Prior to the ignition point, the resistor's epoxy coating released smoke. (Figure 7)

Chemical Change in the Epoxy Coating
- The epoxy coating underwent a chemical reaction caused by heat and discolored from the original blue appearance which occurred in the gradual voltage increase experiment. (Figure 2) Similar to when the resistor ignited, the epoxy coating released smoke. (Figure 7)

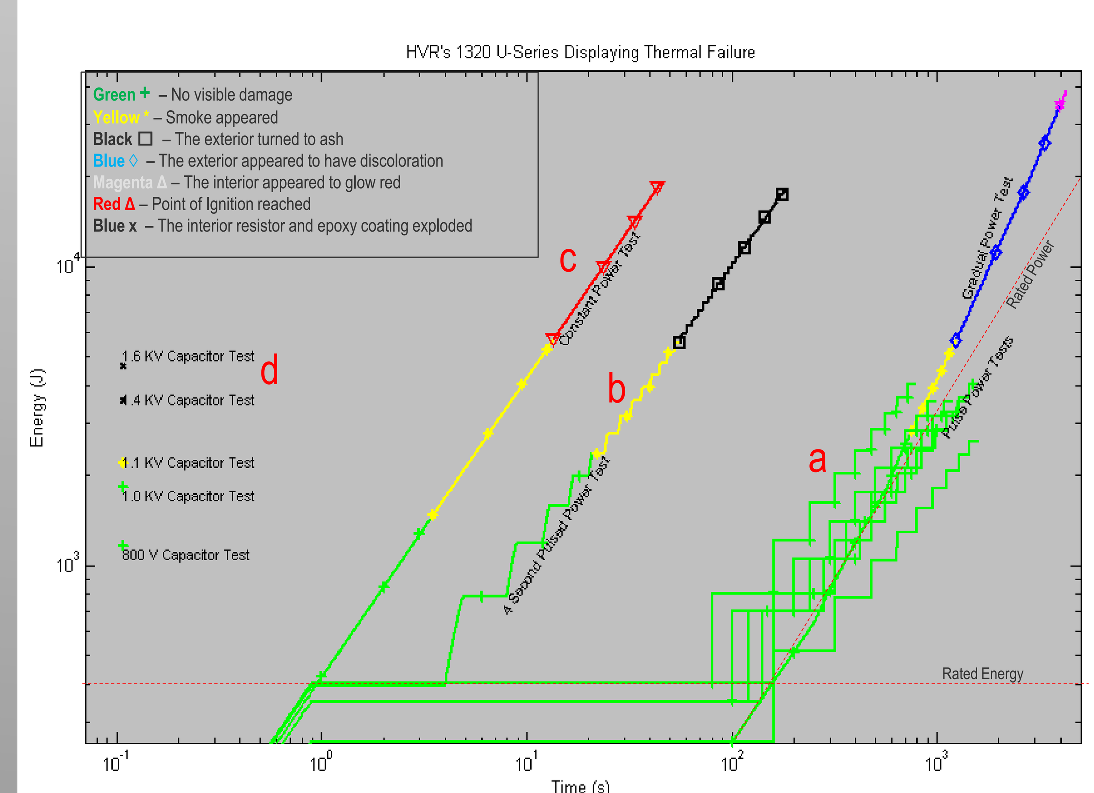

Figure 5. Graph displaying the thermal failure and energy relationship. The letters of Figures 6–9 correspond with their location on Figure 5.

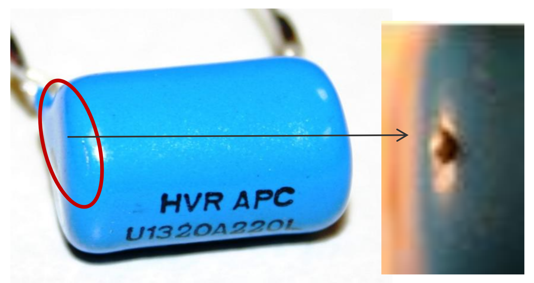

Figure 6. A crack in the resistor (a).


Figure 7. Smoke released (b).


Figure 8. Point of ignition for the resistor (c).


Figure 9. The epoxy coating and resistor exploded (d).

Linearizing the Radiation Equation

A lumped element numerical model in MATLAB was created in [2] to be able to understand the temperature rise in the resistor, and be able to predict the temperature of the epoxy on the resistor.

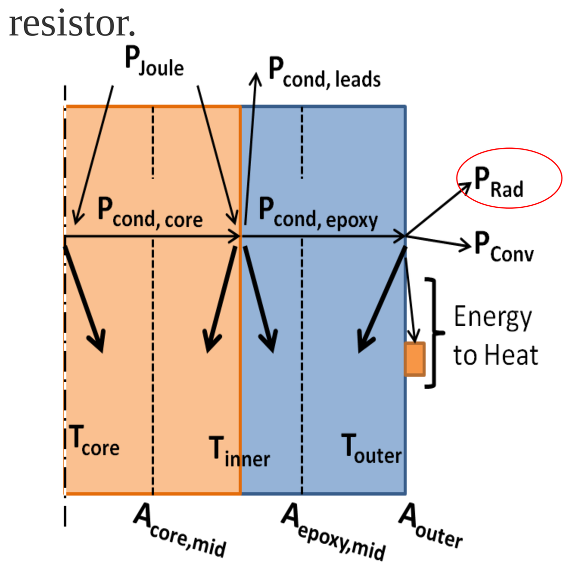

Figure 10. A diagram of the resistor to show the system of seven equations used to predict the temperature of the epoxy [2].

The radiation equation is non-linear. This equation can be linearized by using a temperature dependent radiation heat transfer coefficient, h_r.

Non-Linear: $P_{rad} = \sigma_{SB} \cdot \epsilon \cdot A \cdot \left(T^4 - T_{amb}^4\right)$ [3]

Linear: $P_{rad} = h_r \cdot A \cdot (T - T_{amb})$ [3]

Coefficient: $h_r = \sigma_{SB} \cdot \epsilon \cdot (T + T_{amb})(T^2 + T_{amb}^2)$ [3]

Variables:

- σ_{SB} Stefan-Boltzman constant
- A Area of the outer resistor A
- T Temperature of the surface
- T_{amb} Temperature of the surrounding environment
- ϵ Emissivity of the epoxy coating (0.9)

In order to calculate the heat transfer coefficient, the surface temperature from the previous time step must be used. To verify that the non-linear equation could be used, the difference between the non-linear equation and linear equation had to be compared. The difference was found to be minimal as the time step was increased.

Table II. Energy Comparison of Radiation Linear and Non-Linear Equations.

Time Step (ms)	Peak Difference In Power (mW)
1000	650
100	30
10	2.5
1	0.25

Maximum Allowable Pulse Power

A series of experiments were designed to test the manufactures maximum rated value for the power of the resistor, seen in Table I.

A periodic waveform is programmed into an open source programmable interface board called Arduino. The pulse period is then reduced following each experiment, which increased the pulse power. Each experiment is performed until the peak pulse temperature has four sequential pulses all within a tolerance of ±one degree. Figure 11 is an example of what the temperature pulses look like when they reach equilibrium. The equilibrium temperatures are circled in red.

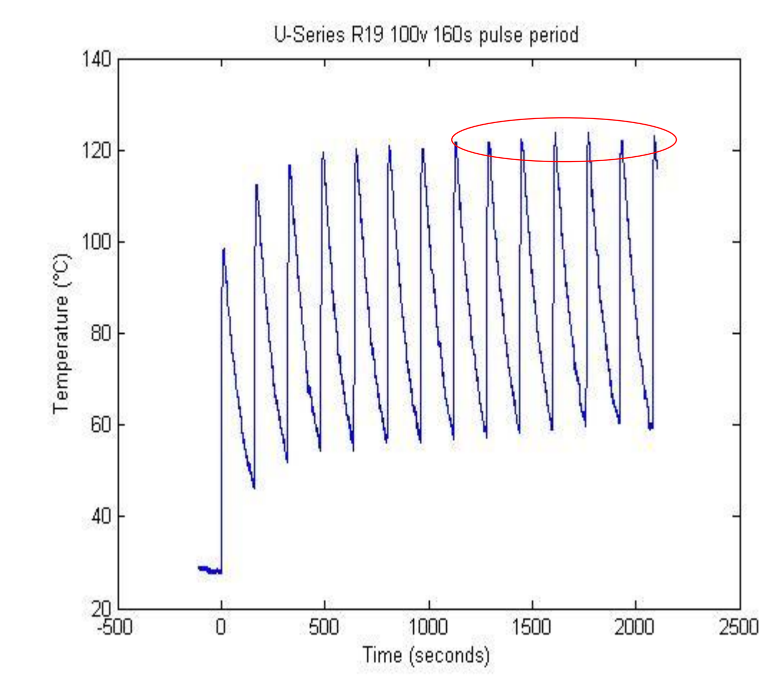

Figure 11. Peak pulse temperatures reaching an equilibrium temperature.

- Three resistors were used for all of the power tests.
- Pulse temperatures for each experiment are shown in Figure 12.
- The pulse power before thermal failure is 6.1 W.
- A crack formed (Figure 6) during the 6.66 W experiment.

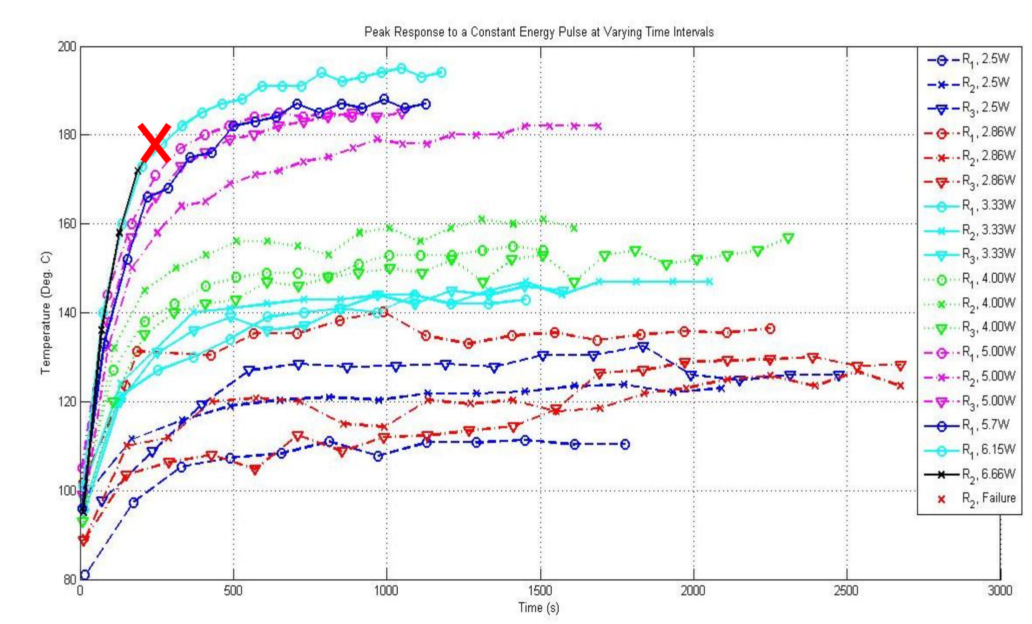

Figure 12. Rate of temperature response to a step input.

Conclusion

Through experiments, the safe operating regions of the resistor beyond the rated parameters from the manufacturer were found and shown in Figure 1. These tests were designed to find the maximum amount of power that the resistor can handle before failure. While doing this, temperature was found to be a factor to help determine if the resistor will fail. Using this information, the numerical model can be used to help predict the temperature of the resistor.

Acknowledgements

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References

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[2] D.P. Muffoletto et al., "Thermodynamic Modeling with Experimental Validation of the Pulsed and Periodic Operation of a High Power Resistor," in [18th IEEE International Pulsed Power Conference], [2011] © [IEEE].

[3] F. Incropera, D. Dewitt, T. Bergman, and A. Lavine, *Fundamentals of Heat and Mass Transfer,* 6th ed. Hoboken, NJ : John Wiley & Sons, 2007.