# Some Aspects of a Self-Limiting Resistive Electric Heating Element

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*Abstract*—**Power output of a resistive electrical heater is a function of resistance value. The authors describe a radiation cross-linked heater which undergoes dramatic resistance changes with temperature. Self-limiting features and some applications are discussed with special emphasis given to the self-limiting feature as applied to electrical pipe line heating.**

AN ELECTRICAL HEATER which provides varying amounts of energy only as needed, without external controls, is a new concept. To facilitate a demonstration of what this concept is and why it is new, let us review some basics.

James Prescott Joule stated that an electric current heats the conductor through which it passes. This simple statement is the basis for all electrical heating including our self-limiting resistive element. The Ohm's law and power relationships hold true for electrical resistive heating circuits

$$V = IR \tag{1}$$

$$W = IV. \tag{2}$$

Therefore,

$$W = \frac{V^2}{R}. \tag{3}$$

In conventional resistance heating elements, the voltage $-V$ and resistances $-R$ are the independent variables. The power $-W$ is dependent through the dependent variable current $-I$. Fixed resistive elements can be combined in either parallel or series. In series elements, the same current flows through all parts of the element. In a parallel network, a portion of the current flows through each part of the circuit. Fig. 1 shows schematics of a conventional parallel element, a parallel self-limiting element, and a conventional series element.

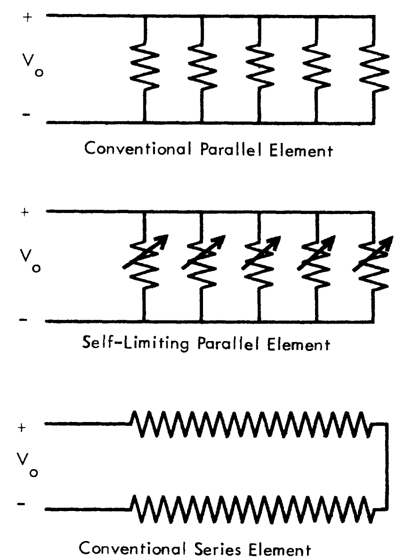


Fig. 1.

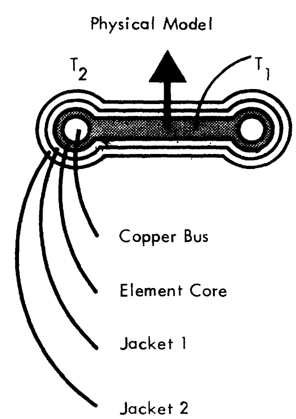


Fig. 2.

Inherent in series elements is that an interruption in any part of the circuit must interrupt the entire circuit. On the other hand, should an interruption occur in some leg of a parallel circuitry heater, other legs of that heater may not be affected. We see that the various resistive portions of a parallel circuit heater act independently with respect to other portions of the heater. When considering temperature control, it seems that the parallel heating system might contain the mechanism for a more precise control system. We have the possibility of putting independent controls on all legs of a parallel circuit, while a series circuit will be slaved to a single switch somewhere in the circuit. With a parallel circuit, we can obtain a maximum of control with an infinite number of controls and heating elements. This is the exact configuration of the self-limiting resistive heating element to be described. Its self-regulating features are on a microscopic level, making each molecular combination its own heater-thermostat. The heating element is composed of a selectively conductive core in parallel circuit configuration. A cross section of a typical element is shown in Fig. 2.

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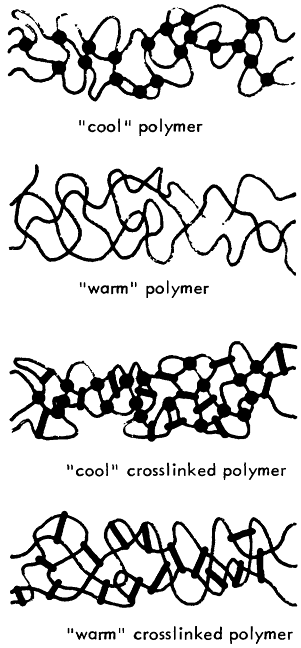

Fig. 3.

In this configuration, which is called 4ATV, parallel 20-gauge copper bus wires carry the full 115 V the entire length of the heater. The length may be any length up to 200 ft because of the parallel construction. The bus bars are electrically joined only through the conductive core. This core surrounds both bus bars and accounts for the self-limiting feature. The core is a blend of cross-linked polymers, graphite, and stabilizers. The process of cross-linking is utilized to fix the graphite molecules in position, making it impossible for them to migrate. The cross-linking of the polymer is a key to the successful operation of the heating element. The thermoplastic materials used in the core are normally long-chain molecules arranged in random order. The structural form of a thermoplastic is provided by a loose crystaline network of "nearby neighbors." When a thermoplastic is heated, these loose bonds are reduced and the material loses structural integrity. The thermoplastic may be altered in form by movement between molecules, and upon cooling, the loose bonding will again occur and another solid structure will appear.

If a thermoplastic material is given high-energy atomic radiation exposure, permanent cross-linking will occur by intermolecular joining of adjacent molecules. The cross-links are in addition to the loose bonds discussed previously and are temperature independent. Thus, these cross-links will have the effect of trapping the graphite molecules in the matrix and holding them there even at elevated temperatures. Fig. 3 shows a conceptual schematic of cross-linked polymers. When the material is heated, the weak bonds disappear, but the material can no longer flow and the graphite cannot migrate. The process of cross-linking is sometimes called "beaming," since the polymer is drawn past an atomic beam much like a directed beam of a dentist's X-ray but much higher.

When the graphite–polymer combination is heated, the thermal expansion of the polymer occurs in an extremely nonlinear

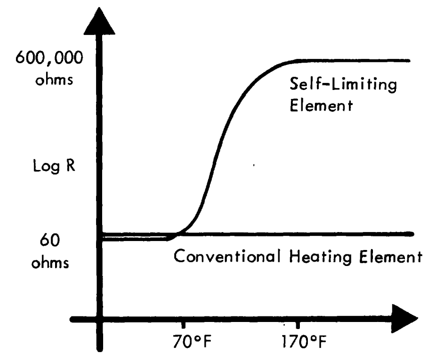

Fig. 4.

fashion, and this expansion has a direct relationship to the increase in electrical resistance of the element. Thus the mechanism of self-control is that the thermoplastic cross-linked polymer stresses the graphite molecule boundaries and they separate. This increases the resistance of that molecular region by orders of magnitude. Since the polymer is cross-linked it will, upon cooling, return to its original configuration, and electrical continuity between the graphite molecules will be restored. This process can be repeated indefinitely. Thus we do indeed have infinite individual thermostat-resistive element groupings on the molecular level.

Fig. 4 will help to explain some of the attributes of the self-limiting heater. This curve of temperature versus resistance shows the 4ATV element and a conventional heater. The slight positive temperature coefficient of the conventional heater is enough to cause a maximum increase in resistance of about 7 percent (nichrome) in 100°F, thus reducing power proportionately. This is not nearly enough to prevent overheating and resultant burnout of the element.

The R–T relationship of the 4ATV element is another story. In that same 100°F swing, the resistance of 4ATV increases more than three orders of magnitude, not 7 percent but more than 100 000 percent, reducing current from amperes to milliamperes. The drastically reduced current will stabilize at a point only high enough to produce sufficient wattage to make up for heat losses and to maintain the temperature arrived at. Should external conditions cause a shift in thermal balance such as a decrease in the ambient temperature, the resistance of the heater will respond to that change permitting more current to flow, thus zeroing directly in on a temperature.

An electrical and thermal model presents some interesting relationships. The following analogy helps to better explain the function of the self-limiting heater.

| Parameter | Electrical | Thermal |
|---|---|---|
| Driving Force | Potential Difference volts ($V$) | Temperature Differential °F ($T$) |
| Quantity of Flow | Current amperes ($I$) | Heat Energy Btu ($Q$) |
| Quality of Material | Conductance | Conductivity |
| | $\frac{\text{amperes}}{\text{volt}}$ ($c$) | $\frac{\text{Btu}}{\text{h} \cdot \text{ft} \cdot {}^\circ\text{F}}$ ($k$) |

In each case the quantity of flow is proportional to the product of the driving force and the flow quality of the material:

$$di = c\,dv \tag{4}$$

$$dq = \frac{A}{t}\,k\,dt. \tag{5}$$

In a typical heating situation, a constant voltage is applied across a relatively constant resistor to produce an almost constant wattage. That Joule energy must be dissipated by the heater, thus performing the heating function. Heat energy raises the temperature of the heating element to the point where all further energy becomes heat dissipated to surroundings. The relationship is

$$T_{\text{element}} - T_{\text{ambient}} = \frac{Q}{C_1} \tag{6}$$

and, at equilibrium,

$$\frac{V^2}{R} = Q\left(3.41\ \frac{\text{Btu/h}}{\text{W}}\right)^{-1} \tag{7}$$

where $C_1$ is some heat transfer constant associated with the ability of the system to lose heat to the ambient atmosphere. Since $Q$ at equilibrium must be equal to the electrical energy input and is a constant along with $C_1$, then the quantity $(T_{\text{element}} - T_{\text{ambient}})$ must also be a constant, and $T_{\text{element}}$ will rise and fall with the ambient temperature. A control thermostat is normally used in series with the heating element. In the conventional resistive heating element the thermal model is a constant *energy source.*

In the self-limiting element a different relationship exists. There is no fixed energy input to the system since resistance is a function of core temperature. The independent variables in this case are the core temperature ($T_{\text{element}}$) and the thermal conductances associated with the specific configuration. Equation (6) still applies, but now the temperature of the element becomes a constant and will no longer follow the fluctuations of the ambient temperature. The thermal model for the self-limiting element is a *temperature source.* Figs. 5-7 show the physical system, the thermal model and an electrical model for a typical configuration, 4ATV. Modeling the system by holding the core temperature at $T_1$ and the surrounding temperature $T_2$ gives the system the temperature difference driving force just as voltage gives the electrical system a potential difference driving force. Summation of the three film coefficients and two jacket thermal conductivities gives the parameters necessary for calculation of a heat output $Q$. To increase the heat output of the 4ATV, a decrease in $T_2$ is necessary. This makes the configuration of the element important in relation to its thermal output. By increasing or decreasing the thermal resistances, a lower or higher power output can be obtained with the same $T_2$. Increasing the supply voltage will not increase heat output as it does in conventional electric elements.

The self-limiting heater is, in fact, rather independent of line voltage fluctuations, while the output of a conventional heater varies as the square of the line voltage. Thus, while a ten-percent increase in line voltage will cause conventional heaters to generate 21-percent more energy, thus becoming

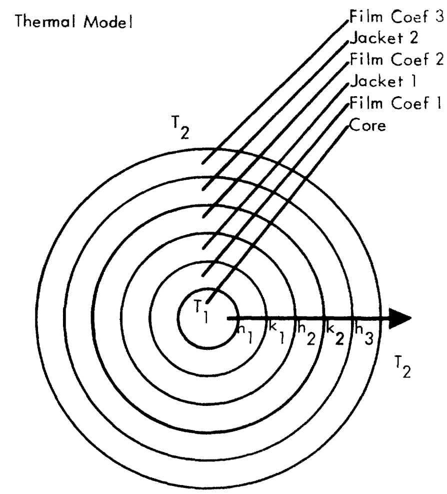


Fig. 5.

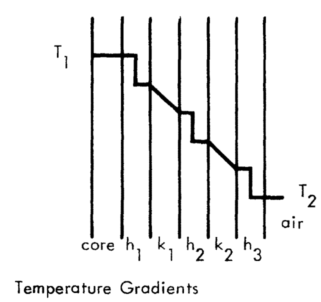


Fig. 6.

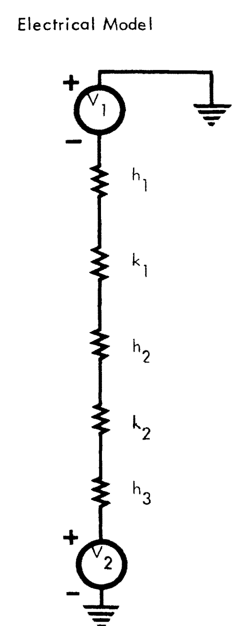


Fig. 7.

hotter, the effect on the self-limiting heater of a ten-percent increase in voltage is relatively negligible on both power output and temperature. This is because of the very large resistance increase which takes place.

In a conventional electrical heating element, one can measure the passive resistance and be very close to the operating resis-

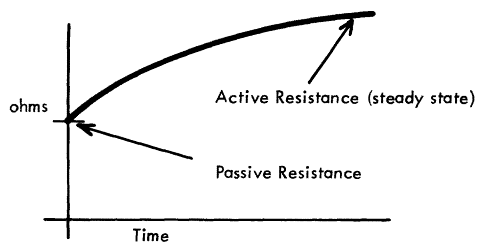


Fig. 8.

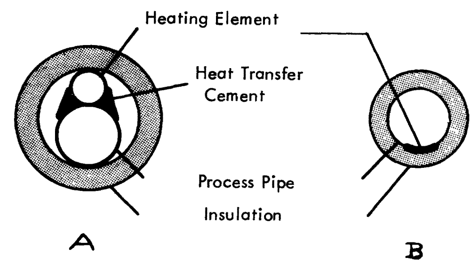


Fig. 9.

tance, but for the self-limiting element this is not true. The resistance of the element is a function of temperature. Thus we have two significant resistances for a self-limiting element:

passive resistance — no significant energy dissipation—an ohmmeter or a Wheatstone Bridge measurement with no current flow in the element;

active resistance — at thermal equilibrium with a constant voltage applied, the active resistance is defined as the applied voltage across the element ($V$) divided by the current through the element (1).

When voltage is applied, the passive resistance will prevail for an instant at the beginning of the power cycle. As the core heats and thermal equilibrium is approached, the resistance approaches the active resistance. A typical curve is shown in Fig. 8. The ratio of the active resistance to the passive resistance is a function of thermal constraints as well as chemical proportions, molecular structure, and degree of cross-linking.

The totally new concept of a temperature source is a bit difficult to appreciate at first encounter, but the benefits are very much appreciated when safety, reliability, and efficiency are considered. In a temperature source element, no overtemperature can occur any place, no "hot spots," and most important of all, no burnouts. The basic heating element is also a control system, bringing heat where needed and denying it where not needed. The parallel circuit allows various sections to demand and receive additional power in the amount needed to restore the local core temperature in that physical area to its operational value. There are many possible uses for this type of element, from cookery to snow melting. Briefly discussed is one application: the electrical heat tracing of industrial piping systems.

The purpose of pipe tracing is to prevent failure of a fluid system due to excessive heat losses. Under normal operation fluids flowing through a pipe system have no need for added heat unless flow is interrupted. An example is oil flowing at 600 gal/min through 100 ft of $2\frac{1}{2}$ in steel pipe with 1 in of thermal insulation. Entering oil temperature is 120°F in 50°F ambient. With no heat tracing the temperature of the oil at the outlet is $119\frac{1}{2}$°F, only a $\frac{1}{2}$°F less. Even without insulation, the oil temperature would drop only to 115°F, a five degree loss. If flow stopped, the insulated system would cool to ambient in 6 h and the uninsulated would cool in only 2 h. Viscosity would rise, and in some cases pumping would be impossible. The initial cost of pipe tracing is small compared to the costs involved in a failure. Most tracing systems work on a heat loss balance system. Approximately 85 percent of bare pipe heat loss is eliminated by proper thermal insulation and the other 15 percent is made up by heat added through tracing. In order to understand the attributes of the self-limiting element, a brief look at alternative tracing systems is in order.

Historically, steam tracing has been around longest. Despite numerous problems, not the least of which is thermal inefficiency, it is still extensively used, sometimes with good reason. Most other tracers are some form of a resistance wire, sometimes mineral insulated tubing, sometimes involving heat transfer foils or cements. Almost invariably they are series circuits slaved to a thermostat switch which is frequently remote from the heater. A sensor, in fact, can sense only one point, the often erroneous design assumption being that the thermostatic control element is an accurate monitor of the entire system. Of the various systems, the most economical seem to be the parallel strip elements and the 4ATV. The problems associated with pipe tracing are varied and the complexity of a system can be staggering.

A major cause of concern with respect to pipe tracing is the burnout or hot spot problem. In conventional elements there is a constant energy output independent of ambient temperature. If an element is in poor thermal contact with a pipe or some fitting, heat energy will raise the local element temperature to a point much higher than the rest of the system. This can cause a complete element failure in series elements and a localized failure in parallel elements. The more intimate the thermal contact with the pipe, the less chance of a burnout. A round tubular element should have a thermal heat transfer agent to insure efficient heat transfer. A flat and consequently lower watt density element would not require this heat transfer agent for proper operation. Fig. 9 illustrates the configuration of both systems. Note that system B uses a smaller diameter insulation.

Piping systems requiring tracing are usually not simple straight runs of pipe or tubing. There are pipe hangers, valves, tees, and elbows along with the more complicated pumps and other components. The complex thermal characteristics of these mechanical elements make the standard energy per unit length concept impractical. Fin effects from any of these mechanical elements can draw off enough energy to freeze the entire system. The physical shapes of valves and pipe hangers make them extremely difficult to trace with conventional heating elements. Using a flat, parallel, self-limiting element such as 4ATV, the job becomes much easier.

Fig. 10 shows a fairly complex system traced with 4ATV. Note that, even where the strip is doubled over itself, there is no danger of burnout. If this were attempted with a conventional heating wire, burnout could be safely predicted. The

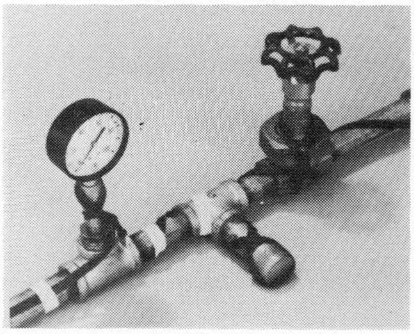

Fig. 10.

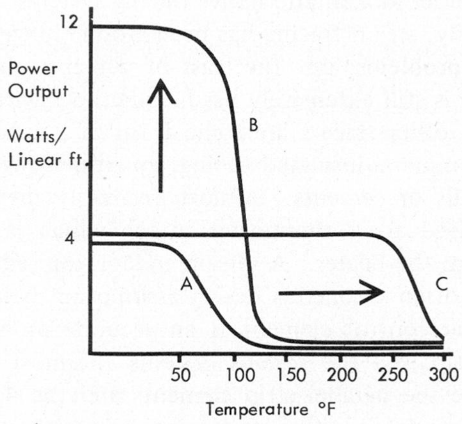


Fig. 11.

ability of 4ATV to decrease wattage when temperatures increase makes overlapping possible.

In designing 4ATV, the design objectives were as follows:

1) to keep water from freezing;
2) at the same time, it could not get the water too hot for comfortable safety shower use;
3) to be easy to install, almost idiot-proof;
4) to be parallel circuitry, able to be field cut to length;
5) to be flat, for better heat transfer.

All design objectives were achieved.

Having identified an application area, and having defined and solved the problem, the question is, "Where do we go from here?" The concept of a self-limiting heater is not limited to 4ATV, a pipe freeze protection system. By varying polymers, geometries, and radiation processing, we can vary the vertical magnitude of the resistance-temperature curve as well as the horizontal position of the knee or change in slope. Thus, as in Fig. 11, both peak power output and the temperature at which resistance soars upward can be varied within limits.

The future looks very bright for new configurations, new wattage ranges, new temperature ranges, and new areas of application.

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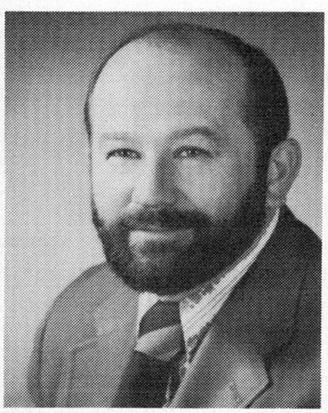

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