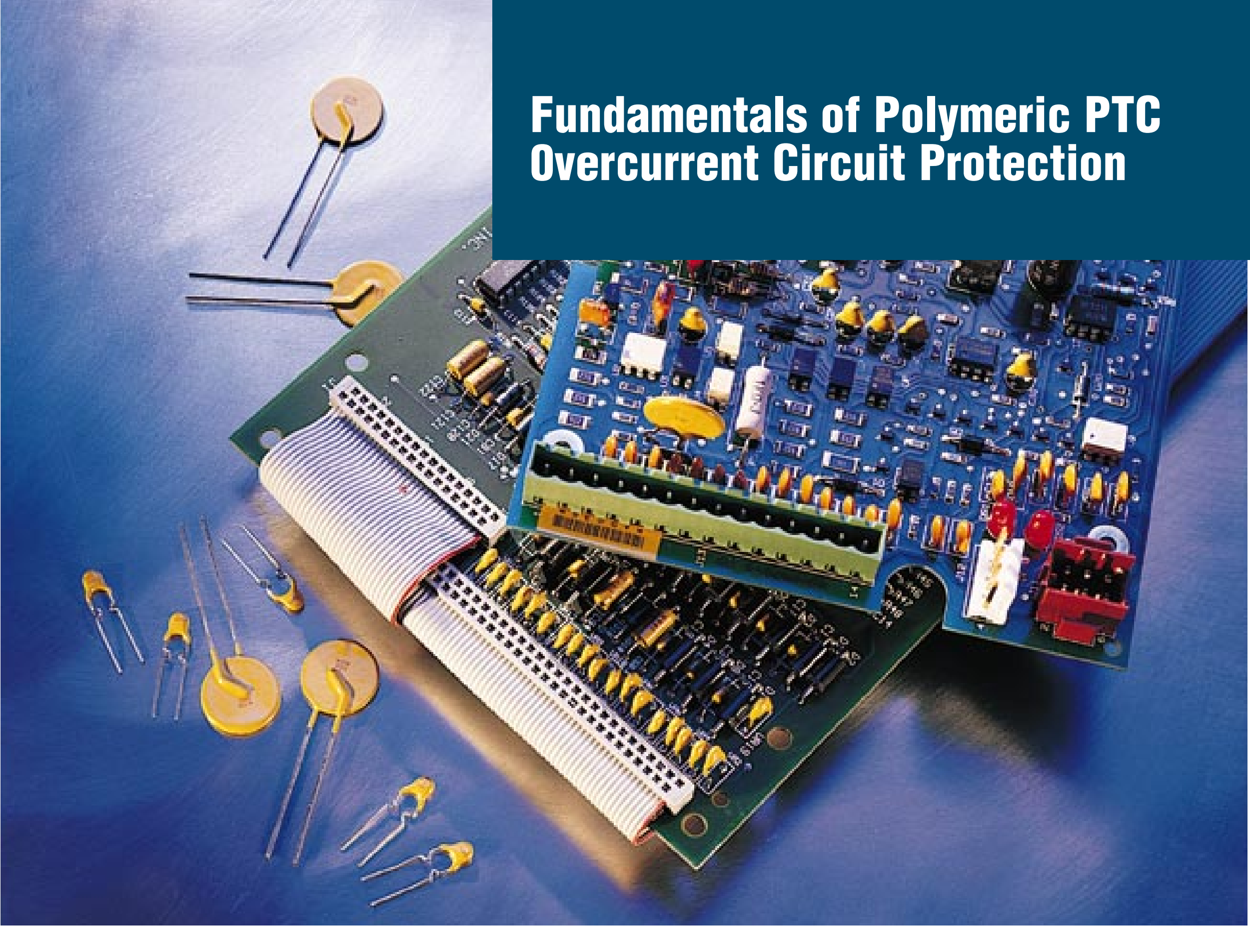
Fundamentals of Polymeric PTC Overcurrent Circuit Protection



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Polymeric PTC Technology

The Problem of Overcurrents

An overcurrent is an abnormally high current that has the potential to cause failure in an electrical circuit. An out-of-range condition in the power source or a decrease in load impedance can cause an overcurrent.

Source-generated overcurrents usually arise from overvoltages caused by the abnormal operation of a power supply, or as a consequence of overvoltages on a power line. Source-generated overcurrents may also arise from voltage sags.

Power line overvoltages may arise from power crosses, surges, transients, or swells.[1]

A *power cross* occurs when a high-voltage circuit is inadvertently connected to a low-voltage circuit, for example, when a power line falls onto a telephone line during a storm.

Surges are short-duration increases in system voltage due to external events, such as lightning.

Transients are short-duration increases in system voltage due to the emptying of a circuit energy-storage element, such as an inductor or capacitor.

Swells are relatively long-duration increases in system voltage, generally caused by a failure in the system, for example, loss of the neutral connection at the transformer supplying a house.

Higher than normal voltages result in higher than normal currents in linear circuits. In nonlinear circuits, lower than normal voltages may lead to higher than normal currents, which is why voltage sags can cause an overcurrent problem. A common light bulb is an example of a nonlinear device that draws more current as the voltage is lowered.

[1] An excellent discussion of these effects can be found in IEEE C62 publications (C62: Complete [current year] Edition, IEEE, Piscataway, N.J.).

A partial or total failure of a circuit load can cause load-generated overcurrents. The failure lowers the total resistance in the circuit, allowing more current to flow. An example is a stalled motor, which gets hot because of excessive power draw, resulting in the insulation on the motor windings being destroyed, thus allowing adjacent windings to touch (short circuit).

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Overcurrent Protection Using a Polymeric PTC Device

A polymeric PTC (positive temperature coefficient) overcurrent protection device is a series element in a circuit. The PTC device protects the circuit by going from a low-resistance to a high-resistance state in response to an overcurrent. This is called "tripping" the device. Figure 1 shows a typical application.

Figure 1: Typical PTC Application

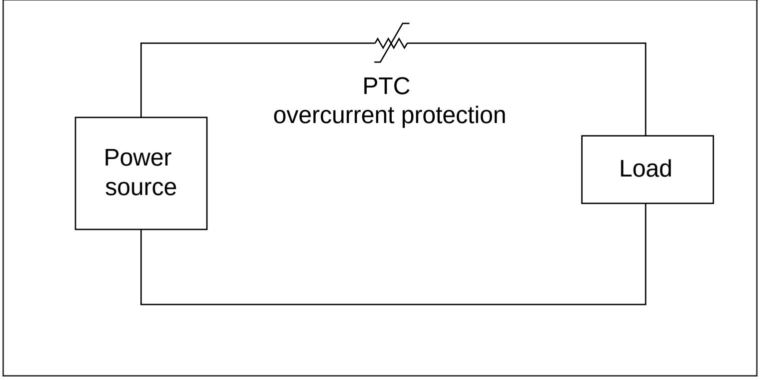
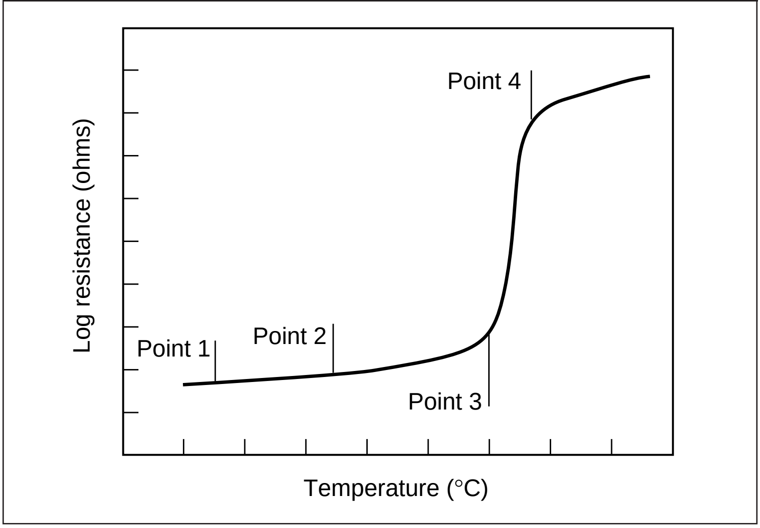


Figure 2: Example of Operating Curve for Polymeric PTC Device



Generally the device has a resistance that is much less than the remainder of the circuit, and has little or no influence on the normal performance of the circuit. But in response to an overcurrent condition, the device increases in resistance (trips), reducing the current in the circuit to a value that can be safely carried by any of the circuit elements. This change is the result of a rapid increase in the temperature of the device, caused by the generation of heat within the device by I^2R heating.

The PTC effect

Describing a material as having a PTC effect simply means that the resistance of the material increases as temperature increases. All materials having metal-like conduction[2] have a positive temperature coefficient of resistance. In these materials the PTC effect is characterized by a gradual increase in resistance that is linearly proportional to temperature. This is the usual, or linear, PTC effect.

The nonlinear PTC effect

Materials undergoing a phase change may exhibit a resistance that increases very sharply over a narrow temperature range as shown in Figure 2. Certain types of conductive polymers exhibit this effect. These conductive polymers are useful for making overcurrent protection devices, generally called polymeric PTC overcurrent limiters, circuit protection devices, or resettable fuses.

[2] Materials that conduct like metals have the lowest resistivity of all non-superconducting materials. (The resistivity of metals generally falls in the range of 1–100 microhm-cm.)

Principles of operation

The operation of polymeric PTC devices is based on an overall energy balance described by the following equation:

$$mC_p(\Delta T/\Delta t) = I^2R - U(T - T_a) \quad \textbf{[1]}$$

- I = Current flowing through the device.
- R = Resistance of the device.
- Δt = Change in time.
- m = Mass of the device.
- C_p = Heat capacity of the device.
- ΔT = Change in device temperature.
- T = Temperature of the device.
- T_a = Ambient temperature.
- U = Overall heat-transfer coefficient.

In this equation, the current flowing through the device generates heat at a rate equal to I^2R. All or some of this heat is lost to the environment, at a rate described by the term $U(T - T_a)$. Any heat not lost to the environment goes to raising the temperature of the device at a rate described by the term:

$$mC_p(\Delta T/\Delta t)$$

In order to keep equation **[1]** as simple as possible, a uniform temperature within the device has been assumed.

If the heat generated by the device and the heat lost to its environment balance, $(\Delta T/\Delta t)$ goes to zero and equation **[1]** can be rewritten as

$$I^2R = U(T - T_a) \quad \textbf{[2]}$$

Under normal operating conditions, the heat generated by the device and the heat lost by the device to the environment are in balance at a relatively low temperature, for example, Point 1 in Figure 2.

If the current through the device is increased while the ambient temperature is kept constant, the heat generated by the device increases and the temperature of the device also increases. However, if the increase in current is not too large, all the generated heat can be lost to the environment and the device will stabilize according to equation **[2]** at a higher temperature, such as Point 2 in Figure 2.

If, instead of the current being increased, the ambient temperature is raised, the device will stabilize according to equation **[2]** at a higher temperature, possibly again at Point 2 in Figure 2. Point 2 in Figure 2 could also be reached by a combination or a current increase *and* an ambient temperature increase.

Further increases in either current, ambient temperature, or both will cause the device to reach a temperature where the resistance rapidly increases, such as Point 3 in Figure 2.

Any further increase in current or ambient temperature will cause the device to generate heat at a rate greater than the rate at which heat can be lost to the environment, thus causing the device to heat up rapidly. At this stage, a very large increase in resistance occurs for a very small change in temperature (see “The Physics of Polymeric PTC,” which follows). In Figure 2, this region of large change in resistance for a small change in temperature occurs between points 3 and 4, and is the normal operating region for a device in the tripped state.

This large change in resistance causes a corresponding decrease in the current flowing in the circuit. The reduced current protects the circuit from damage.

Since the temperature change between Points 3 and 4 is small, the term $(T - T_a)$ in equation **[2]** can be replaced by the constant $(T_o - T_a)$, where T_o is the operating temperature of the device. Then equation **[1]** can be rewritten as

$$I^2R = V^2/R = U(T_o - T_a) \quad \textbf{[3]}$$

Since U and $(T_o - T_a)$ are now both constants, equation **[3]** reduces to I^2R = constant, that is, the device now operates in a constant power state. Expressing this constant power as V^2/R emphasizes that, in the tripped state, the device resistance is proportional to the square of the applied voltage. This relation holds until the device resistance reaches the upper knee of the curve (Point 4 in Figure 2).

For a device that has tripped, as long as the applied voltage is high enough for the resulting V^2/R power to supply the $U(T_o - T_a)$ loss, the device will remain in the tripped state (that is, the device will remain latched in its protective state). When the voltage is decreased to the point where the $U(T_o - T_a)$ loss can no longer be supplied, the device will reset.

The physics of polymeric PTC

A polymeric PTC material is a matrix of a crystalline organic polymer containing dispersed conductive particles, usually carbon black. The sharp increase in resistance, as shown in Figure 2, is due to a phase change in

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the material. In its cool state the material is mostly crystalline, with the conductive particles being forced into the amorphous regions between the crystallites.

If the percentage of conductive particles in the polymer is low, the resulting material will not conduct current. If the percentage of conductive particles is increased to (or beyond) a level called the percolation threshold, the conductive particles touch, or nearly touch, forming a three-dimensional conductive network[3].

When the device is heated to the melting point of the polymer, the crystallites melt and become amorphous. This increases the volume of the amorphous phase, disrupting the network of conductive paths. As the network is disrupted, the resistance of the device increases. Since melting occurs over a relatively narrow temperature range, the change in resistance also occurs over a relatively narrow temperature range. When the temperature of the device has reached Point 4 in Figure 2, the connection of the conductive network is essentially complete.

Design Considerations

Besides hold and trip current, the factors to consider when designing PolySwitch devices into a circuit include the effect of ambient conditions on performance, reflow and trip jump, device reset time, the resistance temperature behavior prior to tripping, the application of devices in parallel combinations, and the effect of inductive spikes.

Figure 3: Example of Hold and Trip Current as a Function of Temperature

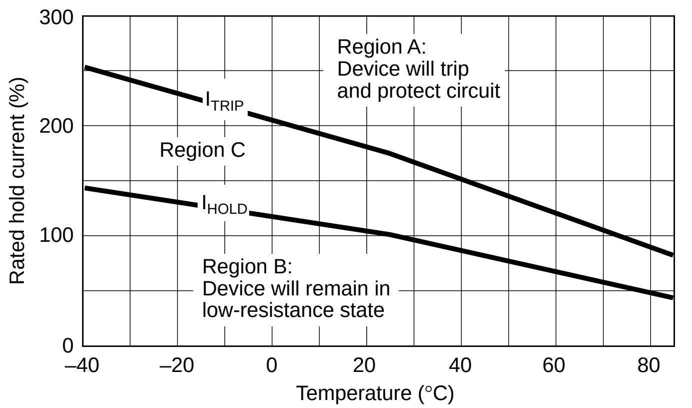

Table 1. I_{HOLD} vs. temperature (RXE devices)

Part Number	Maximum ambient operating temperatures (°C) 0°	20°	40°	50°	60°
RXE050	0.60	0.50	0.41	0.36	0.32
RXE065	0.77	0.65	0.53	0.47	0.41
RXE075	0.89	0.75	0.61	0.54	0.47

Device Selection: Hold and Trip Current

Figure 3 illustrates the hold and trip current behavior of PolySwitch devices as a function of temperature. One such curve can be defined for each available device. Region A describes the combinations of current and temperature at which the PolySwitch device will trip (go into the high resistance state) and protect the circuit. Region B describes the combinations of current and temperature at which the PolySwitch device will allow for normal operation of the circuit. In Region C, it is possible for the device to either trip or remain in the low-resistance state (this will depend on the individual device resistance).

Since PolySwitch devices are thermally activated, any change in the temperature around the device will impact the performance of the device. As the temperature around the device increases, less energy is required to trip the device and thus the hold current decreases. This is why the I_{TRIP} curve and I_{HOLD} curve have negative slopes in Figure 3. Thermal derating curves and I_{HOLD} versus temperature tables are provided with each product family to help design the parts into applications over a wide range of temperatures. Table 1 is an excerpt of the derating table for RXE devices.

To use Table 1, the maximum operating temperature needed and hold current of the intended application must be known. If, for example, the application requires an operating current of 500 mA at 60°C, an RXE090 or an RXE075 would be the proper

[3]A chain of particles that nearly touch conducts via the tunneling effect. For more details, see "Electron Transport Processes in Conductor-Filled Polymers," by R. D. Sherman, L. M. Middleman, and S. M. Jacobs, in *Polymer Engineering and Science*, Vol. 23, No. 1, 36–46.

choice (an RXE050 would only hold 320 mA at 60°C).

Effect of Ambient Conditions on Performance Parameters

As noted under “principles of operation,” the heat transfer environment of the device can greatly impact the performance of the device. In general, by increasing the heat transfer of the device the following will also increase:

- The device’s power dissipation. (This reflects the change in the heat transfer coefficient.)
- The device’s time-to-trip. The impact will be greater at long trip times where the effect of heat transfer is more significant.
- The device’s hold current.

The opposite will occur if the heat transfer from the device is decreased. Furthermore, the time-to-trip can be modified by changing the thermal mass around the device. Again, changing the thermal mass around a device has a greater impact on slow trip events.

Power Dissipation

Power dissipation (P_d) is (to a first order), a good way to measure the change in the heat transfer environment of a device. In other words, if a change is made that might impact the heat transfer, power dissipation measurements taken before and after the change will provide information on the significance of the change. Power dissipation is relatively easy to determine since it can be computed from a measured leakage current and a measured voltage drop across the device ($P_d = VI$). From equation **[3]**, $P_d = I^2R = U(T_o - T_a)$, we note that P_d is equal to an overall heat transfer coefficient, U, multiplied by a temperature differential (the difference between the PolySwitch device temperature and ambient temperature). In the tripped state, the temperature of most PolySwitch devices is approximately 125°C[4]. If we assume that U does not vary substantially with temperature, then by measuring the power dissipation in the tripped state, we can compute the overall heat transfer coefficient for any ambient temperature.

Time-to-trip

As noted in the Performance Testing section, the time-to-trip of a device is defined as the time it takes for the voltage drop across the device to rise to greater than 80 percent of the voltage of the power source, or when the resistance of the device increases substantially relative to the load resistance. Furthermore, a trip event is caused when the rate of heat
lost to the environment is less than the rate of heat generated. If the heat generated is greater than the heat lost, the device will increase in temperature. The rate of temperature rise and the total energy required to make the device trip depend upon the fault current and the heat transfer environment.

For low fault currents—for example two to three times the hold current—most devices will trip slowly since there is significant loss of heat to the environment. This is due to the fact that a substantial proportion of the I^2R energy generated in the device is not retained in the device and does not increase the device temperature. A trip event of this kind can be viewed as a non-
adiabatic trip event. Under these conditions, the heat transfer to the environment will play a significant role in determining the time-to-trip of the device. The greater the heat transfer, the slower the time-to-trip.

At high fault currents—for example, 10 times the hold current—the time-to-trip of a device is much less because most of the I^2R energy generated in the device is retained in the device and thus increases the device temperature. A trip event of this kind can be regarded as an adiabatic trip event[5]. Under these conditions, the heat transfer to the environment is less important since the heat loss to the environment is less significant in determining the time-to-trip of the device.

As tripping is a dynamic event, it is difficult to precisely anticipate the change in the time-to-trip since a change in the heat transfer coefficient is often accompanied by a change in the thermal mass around the device. If for example, a large block of metal is placed in contact with the device, not only will the heat transfer increase, but the device will also need to heat some fraction of the metal (due to the intimate contact) before the device will trip. Therefore, not only is the thermal conductivity of the metal important, but the heat capacity of the metal plays a role in determining the time-to-trip.

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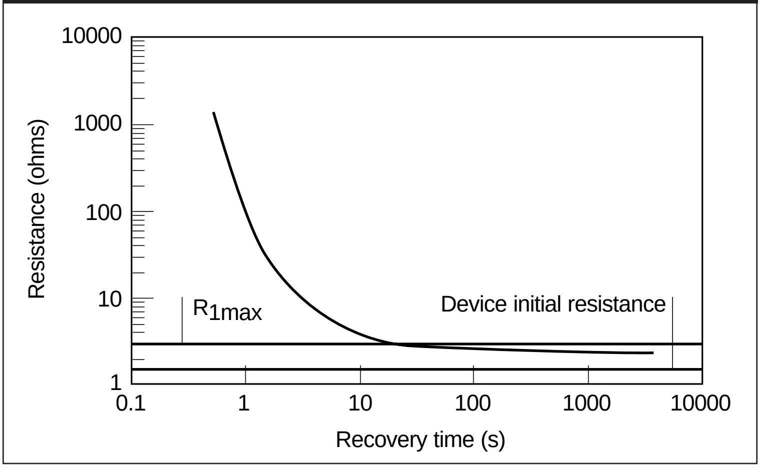
[4] Most PolySwitch devices transition from a low to high impedance state at 125°C, although devices are available with both lower and higher transition temperatures.

[5] Typical time-to-trip curves for Raychem circuit protection devices can be found in the following data sections for individual devices. For most devices there is a break in the time-to-trip vs. resistance curve, which denotes the transition from an adiabatic to a non-adiabatic trip event.

Figure 4: Typical RXE025 Resistance Recovery after a Trip Event



Hold current

The hold current (I_H) is the highest steady-state current that a device will hold for an indefinite period of time without transitioning from the low- to the high-resistance state. Unlike time-to-trip, the hold current of a device is a steady state condition that can be fairly accurately defined by the heat transfer environment. Under a steady state condition, equation **[3]** holds true and the heat-generated I^2R equals the heat lost to the environment. Therefore, if U increases, the hold current will increase, with the approximate relationship:

$$I_H \propto \sqrt{U} \qquad \textbf{[4]}$$

The heat transfer for the devices can be impacted by a multitude of design choices. Some examples include the following:

- The ambient temperature around the device increases, resulting in a reduction in the heat transfer. This can be caused by an overall increase in the ambient temperature, or by placing the device in proximity to a heat-generating source such as a power FET, resistor, or transformer. As a consequence, the hold current, power dissipation and time-to-trip of the device are all reduced.
- The designer changes the size of the traces or the leads which are in electrical contact with the device. For example, a surface mount device originally placed on a 0.030-inch-wide, 1 ounce copper trace is instead connected to a 0.060-inch, 1 ounce copper trace, resulting in an increase in the heat transfer. This results in larger hold current, slower time-to-trips and higher power dissipations.
- An RUE device is attached to a long pair of 24 gauge wires before being connected to the circuit board. This effectively increases the lead length of the device and results in a reduction of the heat transfer. As a consequence, the device's hold current, power dissipation, and time-to-trip are all reduced.
- The air flow around the device is increased. For example, a surface mount device is mounted beneath a fan, which creates air flow around the device; the fan suddenly speeds up. This results in an increase in the heat transfer.

Reflow and Trip Jump (R_1max)

PolySwitch devices exhibit some resistance hysteresis when tripped, either through an electrical trip event or through a thermal event such as reflow. This hysteresis is observed as a resistance increase over the as-delivered resistance of the PolySwitch device.

Figure 4 shows typical behavior for a PolySwitch device that is tripped and then allowed to cool. In this figure, we can clearly see that even after a number of hours the device resistance is still greater than the initial resistance. Over an extended period of time, the resistance will continue to fall and will eventually approach the initial resistance[6].

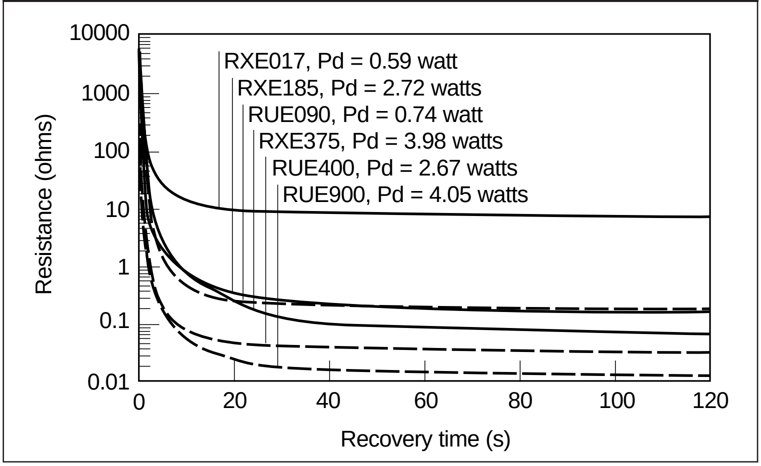
However, since this time can be days, months, or years, it is not practical to expect that the device resistance will reach the original value for operational purposes. Therefore, when PolySwitch devices are being developed, this "trip jump" or "reflow jump" is taken into consideration when determining the hold current. This increase in resistance is defined as R_1max and is measured one hour after the thermal event. It should be noted that these trip jumps are non-cumulative over sequential trip events.

Device Reset Time

Returning to Figure 4, we note that after a trip event, the resistance recovery to a quasi-stable value is very rapid, with most of the recovery occurring within the first one to two minutes. Figure 5 shows the

[6] Please see Engineer Note SMD1.01, page 187, for a description of the effects of the reflow process and the resistance recovery of SMD devices.

Figure 5: Typical Resistance Recovery after a Trip Event



resistance recovery curve for a number of other leaded PolySwitch devices. The power dissipation values were also measured to provide the user with a sense of the thermal environment the device was placed in for the measurement.

As with other electrical properties, the resistance recovery time will depend upon both the design of the device and the thermal environment. Since resistance recovery is related to the cooling of the device, the greater the heat transfer, the more rapid the recovery (see Figure 6 for miniSMD075 devices on boards with traces of 0.010-inch and 0.060-inch).

Devices in Parallel

When two identical PolySwitch devices are placed in parallel, the hold current of the devices will increase and the combined resistance should be half the resistance of one of the devices. The magnitude of the hold current increase is dependent on the configuration of the devices and the consequent impact on the power dissipation. If the power dissipation doubles, the hold current will roughly double as well. If the power dissipation increases by less than a factor of two, then the hold current for the two devices will be less than twice that of a single component. Two examples illustrate this:

1. Two devices are placed in parallel and are soldered to individual traces that are thermally isolated from each other (this can be done by placing the traces far away from each other). By doing this, the power dissipation will be double that of a single part. The resistance will decrease by half and the hold current will double.
2. Two devices are placed in parallel and are soldered within close proximity, perhaps on a single trace. In this case, depending on the trace width, the power dissipation ranges from that of a single device to double that of a single device. If the power dissipation is the same as a single device, then the hold current will increase by roughly 40 percent. If the power dissipation is some where in between, then the hold current can be approximated using the following equation:

$$I_{Hp} = \sqrt{2}\, I_{Hs} \times \left(\frac{\sqrt{P_{dp}}}{\sqrt{P_{ds}}} \right) \quad [5]$$

I_{Hp} = Hold current for parallel devices.

I_{Hs} = Hold current for a single device.

P_{dp} = Power dissipation for a parallel device.

P_{ds} = Power dissipation for a single device.

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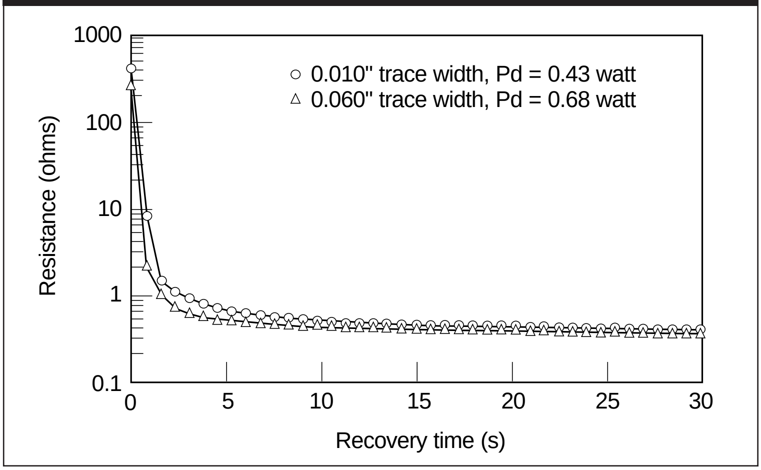
Figure 6: Typical miniSMD075 Resistance Recovery vs. Trace Width



Resistance Prior to Tripping

While a significant increase in the resistance of the device occurs when the device trips, a much smaller change in the resistance is also noted at temperatures below the transition temperature. For example, in Figure 7, we see that for an RUE device, over a temperature range of 20°C to 75°C, the resistance increases by approximately 40 percent[7].

Inductive Spikes

The normal time-to-trip for a PolySwitch device can range from milliseconds to many seconds. However, the actual transition from low-impedance state to high-impedance can be much faster, potentially less than one millisecond, depending on the trip current and the size of the device. This is important since the change in current over time (di/dt) can be quite large. This di/dt, in combination with a significant circuit inductance (L), can result in a large inductive voltage spike.

$$V = -L\frac{di}{dt} \qquad [6]$$

If this spike is large enough, it can potentially damage the PolySwitch device.

Design Calculations

This section includes calculations for voltage drop, resistance in a tripped state, leakage current in the tripped state, and automatic reset conditions.

Maximum Voltage Drop

Use the circuit's operating current and the PolySwitch device's R_1max resistance (from the product data for that device in Section 4 of this databook) to calculate the maximum voltage drop across the device, expressed as:

Maximum voltage drop =
(Operating current) X (R_1max resistance).

R_1max resistance =
Maximum resistance that can be expected in an application when the device is not in a tripped state and is measured at least one hour after reset or reflow of the device.

Resistance in the tripped state

The device's large change in resistance can be calculated by using the following equation:

$$R = V_{ps}^2/P_d \qquad [7]$$

R = Resistance in ohms of the PolySwitch device in the tripped state.

V_{ps} = Voltage across the PolySwitch device.

P_d = Power dissipated by the PolySwitch device from the product data for that device in Section 4 of this databook).

Leakage Current in the Tripped State

When the PolySwitch device is latched in its high-resistance state, the amount of current allowed to pass through the device is just a fraction of the fault current. The current can be calculated by using the following equation:

$$I = P_d/V_{ps} \qquad [8]$$

I = Self-heating current of a PolySwitch device in the tripped state.

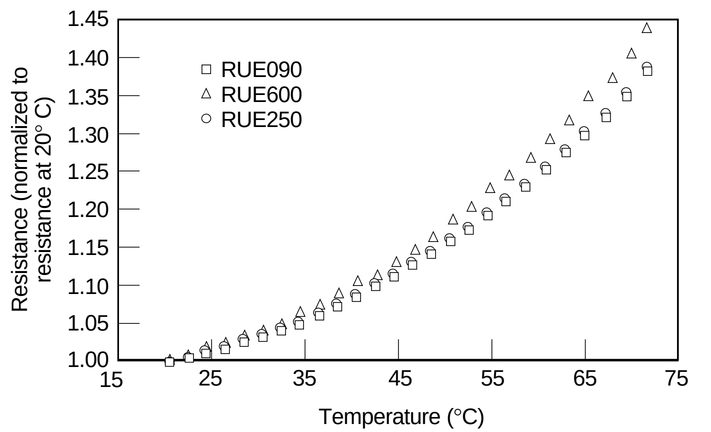
P_d = Power dissipated by the PolySwitch device (from the product data in Section 4).

V_{ps} = Voltage across the PolySwitch device.

Automatic reset conditions

Under certain conditions a PolySwitch device will automatically reset and return to normal operation. Automatic resetting can be very useful for applications where the voltage can be varied during operation.

Figure 7: Typical Resistance vs. Temperature Behavior for RUE Devices



[7]This increase is dependent upon the material used to construct the device and will vary from product family to product family.

When the following condition is met, the device will automatically reset:

$$\frac{V^2}{4R_L} < P_d \quad [9]$$

V = Operating voltage of the circuit.
R_L = Load resistance.
P_d = Power dissipated by the PolySwitch device.

Performance Testing

Performance Tests

The tests described in this section are commonly done to evaluate the performance of polymeric PTC devices. The descriptions are excerpted from a document that specifies how to test PolySwitch polymeric PTC devices[8].

Resistance

The DC resistance of a PolySwitch device is a relatively sensitive measure of the condition of the device under test, and is a key parameter for the use of a PTC device in an application. As such, it needs to be measured accurately.

Equipment

To obtain adequate accuracy for resistance less than 10 ohms, the 4-wire method must be used. The current for this measurement is subject to two conflicting requirements: it should be as large as possible to maximize the signal-to-noise ratio, but as small as possible to minimize device heating. Pulsing the current, using signal processing techniques to reduce noise, or both, are effective techniques for improving the signal-to-noise ratio, while minimizing device heating.

Procedure

The resistance of a PolySwitch device is sensitive to temperature, and to the time interval between stopping a given test or conditioning, and measuring the resistance. To obtain accurate resistance readings, the device temperature must be accurately known. In addition, the time interval between the end of a conditioning program, process, or power removal in a test cycle, and the measurement of the device resistance, must be controlled. This period should be a minimum of one hour. Note that if the test calls for repeated resistance readings, they should all be made at the same time interval after stopping the test or conditioning.

Resistance vs. temperature

This test is used to generate a profile of the resistance of a device as it changes with ambient temperature. A typical result is shown in Figure 2, page 18.

Equipment

This measurement requires an environmental chamber capable of maintaining any temperature up to at least 20°C above the nominal melting temperature of the material used to make the device. The general considerations for measuring resistance discussed at the beginning of this section apply here also.

Procedure

The sample temperature is controlled with the environmental chamber. Temperature increments can be of any suitable size, but must be of sufficient duration to ensure that the device temperature has equilibrated to that of the chamber. Generally the resistance of the device will be measured using the 4-wire method. However, if the resistance of the device exceeds 10 ohms, a 2-wire resistance-measuring method may be substituted for the 4-wire method.

Operating Characteristics of Polymeric PTC

Figure 8, on page 26, shows a typical pair of operating curves for a polymeric PTC device in still air at 0°C and 75°C. The 0°C and the 75°C curves are different because the heat required to trip the device comes both from electrical I^2R heating and from the device environment. At 75°C the heat input from the environment is substantially greater than it is at 0°C, so the additional I^2R needed to trip the device is correspondingly less, resulting in a lower trip current at a given trip time (or a faster trip at given trip current).

Hold current

A hold current test is done by powering the test device at constant current. The maximum output voltage of the power supply should be set to the maximum rated voltage for the device. A device fails the hold current test if the voltage across the device rises to less than 20 percent of the voltage set on the power source.

Equipment

The test requires a power source that allows both a voltage and a current limit to be set. Generally this type of source is direct current (DC), but an alternating current (AC) source could be used. A system is needed for measuring either the voltage across the test specimen, or the current through it

[8] "PS300 Specification: Test Methods and Requirements for PolySwitch Devices," latest revision (Raychem Corporation).

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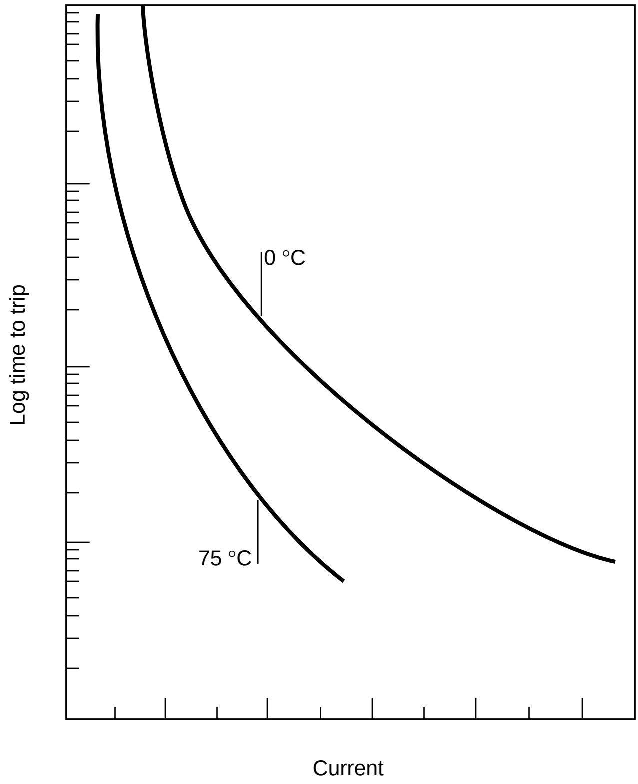
Figure 8: Example of Polymeric PTC Operating Characteristics



(or both), as a function of time. Suitable systems include (digital) oscilloscopes, A/D converters, and computer-controlled multimeters.

Procedure
The hold current of a PolySwitch device is very sensitive to device resistance, temperature, and heat transfer conditions.

Resistance
The resistance of a PolySwitch device at room temperature is increased by its first trip. Therefore, a PolySwitch device should be tripped and cooled before measuring its hold current.

Temperature
Because the hold current can be changed substantially by flowing air, no air circulation around the test specimen is allowed during the test, including air flow due to body motion. The test specimens should be allowed to equilibrate to the test temperature for at least 5 minutes. During the test, the temperature rise of the surrounding air should be monitored.

Heat transfer
In addition to controlling air flow, it is generally necessary to control the heat flow out through the leads of the device. Because of this effect, the method of mounting the device needs to be described when reporting test results.

Time-to-trip
A time-to-trip test is conducted by powering the test device from a constant-voltage power supply with a series current-limiting resistor. The maximum output voltage of the power supply should be set to the maximum rated voltage for the device. A device fails the time-to-trip test if the voltage across the device fails to rise to more than 80 percent of the voltage set on the power source, in the time allotted for the device to trip.

Equipment
The test requires a power source with a regulated output voltage, and a series resistor for adjusting the current to be applied to the test device. The source may be either DC or AC.

A system is needed for measuring either the voltage across the test specimen, or the current through it (or both), as a function of time. Suitable systems include (digital) oscilloscopes, A/D converters, and computer-controlled multimeters.

Procedure
The trip time of a PolySwitch device may be sensitive to temperature, heat transfer conditions, and device resistance. If the standard trip current of five times the hold current is used to establish trip time, the device may trip fast enough that heat transfer and reasonable excursions around the specified test temperature will not affect results.

Resistance
Trip time is inversely proportional to resistance. To make sure that a device will trip in the required time under worst-case conditions, the device is tested at its lowest

resistance. Generally a device that has been through the manufacturing process, but has not yet undergone testing or conditioning, is in its lowest resistance state.

Temperature
Because the trip time can be changed substantially by flowing air, no air circulation around the test specimen is allowed during the test, including air flow due to body motion. The test specimens should be allowed to equilibrate at the test temperature for at least 5 minutes.

Heat transfer
In addition to controlling air flow, it is generally necessary to control the heat flow out through the leads of the device. Because of this effect, the method of mounting the device needs to be described when reporting test results.

Trip cycle life
A trip cycle life test consists of repeated tripping of a PolySwitch device by electrical surges.

Equipment
The test requires a power source (either AC or DC) capable of supplying the maximum rms (root mean square) interrupt current specified for the device, at the maximum rms operating voltage specified for the test. The source voltage is controlled by the power supply; the source current is controlled by a load resistor.

The test also requires equipment for turning the power on for a specified period of time, and then off for a specified period of time. A cycle timer would work, as would various computer-programmable devices, including the power source itself (if it is programmable).

Procedure
The cycle life of a device may be sensitive to temperature and heat-transfer conditions. Generally cycle life testing is done at extreme electrical conditions, which greatly diminish the influence of heat-transfer conditions and temperature.

Test cycle
A test cycle consists of applying to a device the voltage and current specified for the device for the specified ON time, and then removing power from the device for the specified OFF period. After the required number of cycles are complete, the device is evaluated according to the test criteria previously selected.

Temperature
The air temperature next to the device under test should be controlled to 20°±10°C, unless otherwise specified.

Trip endurance
Trip endurance consists of tripping a PolySwitch device and holding it in the tripped state for a specified amount of time.

A single source may be used both to trip the device and to hold it in the tripped state. Alternatively, one source may be used to trip the device, and a second source to hold the device in the tripped state. In either case, the source may be AC or DC.

Power dissipation
This test is used to determine the amount of power dissipated by a device after it has stabilized in the tripped state. Generally it is done during a trip endurance test, by measuring the voltage across the test device, and the current through it, and then multiplying the two to get power.

Because the power dissipation can be changed substantially by flowing air, no air circulation around the test specimen is allowed during the test, including air flow due to body motion. In addition to controlling air flow, it may be necessary to control the heat flow out through the leads of the device. If so, the method of mounting the device must be described when reporting the data.

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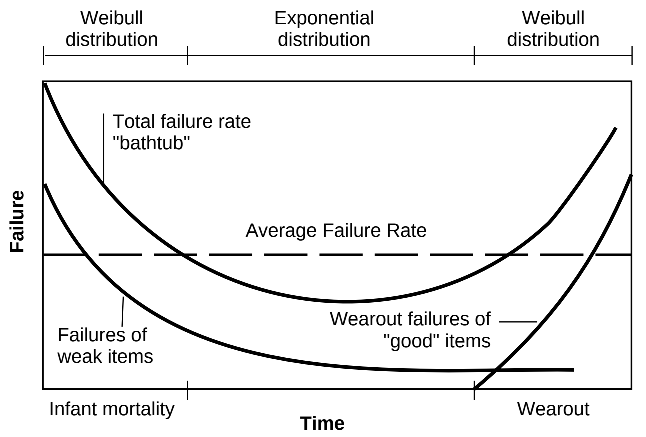
Surge withstand
In many applications, polymeric PTC devices must withstand surges specified by agencies or telecommunications organizations. The appropriate agencies or organizations should be contacted for details on how the surge tests are to be conducted.

Reliability
Reliability is defined as the probability of a part performing its purpose for a given period of time under stated operating conditions. A part that doesn't meet this performance criterion is considered a failure. A failure-rate model that is frequently used is the "bathtub curve" shown in Figure 9. In this model, early-life failures are usually due to manufacturing defects; end-of-life failures are caused more by design limitations.

A constant failure rate is often quoted for component reliability, and is computed as an average failure rate over the life of the product. Standard references for failure rates of electronic components are *MIL-HDBK-21 7*[9] and the *AT&T Reliability Manual*.[10] Failure rates in these specifica-

Figure 9: “Bathtub Curve” Failure-Rate Model



tions are usually based on pooled field data. Some examples are shown in Table 2.

Polymeric PTC devices are not included in *MIL-HDBK-217* because these devices have not been widely used in military applications. Using generally accepted methods, the average failure rate for PolySwitch devices, shown in Table 3, has been estimated as ≤ 10 FIT, using pooled field and test data for all PolySwitch devices.

Agency Approvals for PolySwitch Devices

PolySwitch devices, in many cases, have been tested and have gained the following safety agency approvals:

- UL Component Recognition in Category XGPU2, Thermistor-Type Devices.
- CSA Component Acceptance in Class 9073 32, Thermistors—PTC Type.
- TÜV Rheinland Certification, PTC Resistors.

Table 2. Baseline failure rates of typical electronic components

Component	Failures per billion device-hours (FIT)	Source
Disk thermistors	65	*MIL-HDBK-217F* and *AT&T Relia. Manual*
Thermal circuit breakers	38	*MIL-HDBK-217F* and *AT&T Relia. Manual*
Fuses	10	*MIL-HDBK-217F*
	25	*AT&T Relia. Manual*

Table 3. Baseline failure rate of PolySwitch polymeric PTC devices

Component	Failures per billion device-hours (FIT)	Source
PolySwitch polymeric PTC devices	≤ 10	Reliability reports are available with FIT calculations for the different product lines.

Conditions of UL approval

UL’s “Conditions of Acceptability” for PolySwitch devices include the following statements:

> “These devices provide over-current protection and have been evaluated for use in safety applications where a device is needed to limit current that may result in a risk of fire, electric shock, or injury to persons . . . These devices have undergone 6000-cycle endurance testing (appropriate for manual reset devices, since de-energizing is required to reset the PTC). However, they are not designed for applications where they are routinely caused to trip.”

Tests conducted for agency approvals

Typically, to qualify PolySwitch devices for safety agency approvals, a variety of tests are performed on samples to see what effect they have on properties, such as time-to-trip and resistance-versus-temperature characteristics. Examples of these are:

- Electrical cycles at 23°C, using maximum operating voltage and maximum interrupting current.
- Electrical cycles at 0°C, using maximum operating voltage and maximum interrupting current.
- Trip endurance at maximum operating voltage.
- Heat aging at 70°C and 135°C.
- Humidity conditioning at 40°C and 95% relative humidity.

[9] *MIL-HDBK-217, Reliability Prediction of Electronic Equipment.*

[10] Klinger, D. J., Y. Nakada, and M. Menendez, eds., *AT&T Reliability Manual* (Van Nostrand Reinhold), 1990.