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Composite PTCR thermistors utilizing conducting borides, silicides, and carbide powders

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Ceramic–polymer composite thermistors using conducting boride, silicide, and carbide powders that include TiB_2, ZrB_2, NbB_2, $NbSi_2$, WSi_2, $MoSi_2$, and TiC have been fabricated. Percolation and subsequent PTCR effects were observed for all the powders in both semicrystalline (polyethylene) and amorphous (epoxy) polymer matrix materials, however, as found for carbon black and metal fillers, both niobate powders did not exhibit a PTCR effect in the amorphous polymer. Results indicate that percolation and PTCR behaviour are related to the powder characteristics (size/distribution), composite microstructure and ceramic–polymer interface.

Composite thermistors with room temperature resistivities as low as 1 Ω cm and a nine-order of magnitude change ($\Delta\rho$) at 1 kHz (12 $\Delta\rho$ at d.c.) were achieved.

1. Introduction

Positive temperature coefficient of resistance (PTCR) thermistors are commonly employed in a wide range of applications including temperature sensors, protection circuits, flow meters, self-regulating heating elements, etc. Typically, donor-doped $BaTiO_3$ ceramics are used in thermistor applications, whereby a large change in electrical resistivity (~ four to six orders of magnitude) occurs near the Curie point, (T_c) as shown in Fig. 1a [1, 2], however, their relatively large room temperature resistivity (~100 Ω cm), inability to easily vary the PTCR transition temperature and high manufacturing costs have led to the development of composite thermistors [3–10].

Based on the concept of percolation (Fig. 1b), at a critical volume fraction (V_c) of conducting particles in an insulating polymer matrix, the particles form a continuous chain thereby drastically decreasing the composite resistivity. The associated PTCR effect occurs due to the elimination of this continuous chain by the expansion of the polymer. This expansion occurs near the melting point of semicrystalline polymers (T_m) and near the glass transition temperature (T_g) of amorphous polymers.

To date, most of the research and development of composite thermistors has been on carbon filled polyethylene (PE) though many others conducting fillers including Cu, Fe, Ag, TiO, V_2O_3, and various types of polymers have been investigated [11–21].

Composite thermistors comprised of highly conducting carbon black and polyethylene have reported room temperature resistivities of 1 to 100 Ω cm, a PTCR effect of six to eight orders of magnitude (at about 130 °C the T_m for PE), are easily fabricated and intrinsically low in cost. In addition it has been shown for composite thermistors that the transition temperature of the PTC effect can easily be adjusted through choice of polymer and subsequent variation in their associated T_m.

Despite the obvious advantages of carbon-filled polymer composite thermistors, some drawbacks exist including: (1) the presence of high resistance surface layer or "skin" effect on the carbon powder which limits the room temperature resistance, (2) the inability to easily modify the powder morphology, particle size and distribution in order to control the percolation behaviour, and (3) the fact that a PTCR effect is only demonstrated in semicrystalline polymer materials and not in amorphous polymers. Amorphous polymers have the advantage over semicrystalline polymers in that the latter must be crosslinked by irradiation [22–24] or by the addition of a third filler [25] to provide mechanical stability above T_m and overall reproducibility.

It was the objective of this work to demonstrate that PTC composite thermistors could be markedly improved by utilizing conducting fillers that possessed the following characteristics: (1) ultra low resistivities $< 10^{-4}$ Ω cm, (2) low susceptibility to surface oxidation and thus reduced "skin" effect, (3) exhibit percolation and subsequent PTCR behaviour in both semicrystalline and amorphous polymers, and (4) be readily available and low in cost.

Based on these requirements, the following conducting filler materials were proposed including TiB_2, ZrB_2, TiC, $NbSi_2$, WSi_2, NbB_2, and $MoSi_2$. Logically, metal filler materials would be ideally suited for composite thermistors due to their very low electrical

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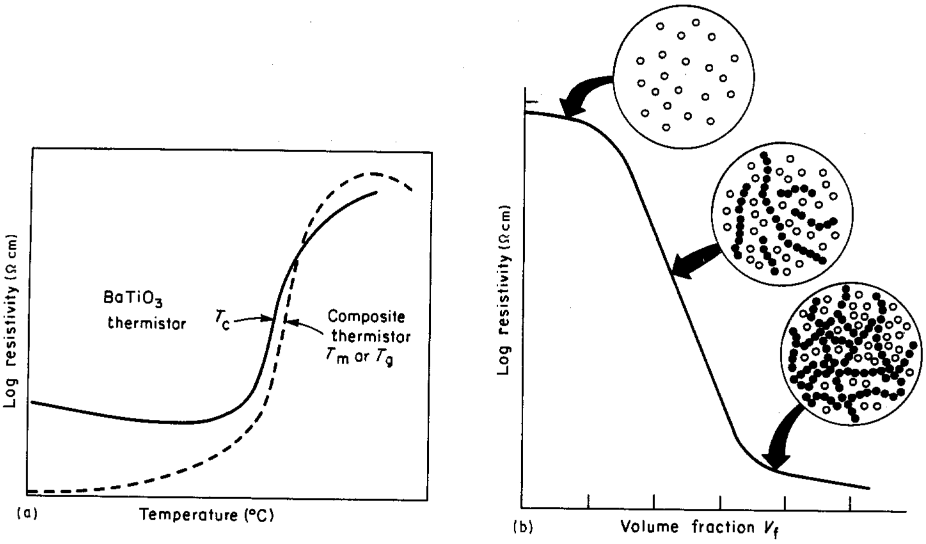

Figure 1 (a) Variation of electrical resistivity for $BaTiO_3$ and composite type PTCR thermistors. (b) Composite resistivity plotted against volume fraction (V_f) conducting filler illustrating percolation behaviour.

resistivities. However, composites comprised of metal fillers generally do not exhibit a strong PTC effect, though they do exhibit percolation.

The percolation behaviour and subsequent PTCR effect of composites comprised of the various borides, silicides, and carbide powders in both semicrystalline and amorphous type polymers were determined. The importance of filler particle size and ceramic polymer interface on percolation behaviour, and PTCR effect were addressed. The results are presented in the following.

2. Experimental procedure

2.1. Conducting filler

The conducting ceramic powders* utilized in this study were titanium carbide (TiC), titanium boride (TiB_2), niobium silicide ($NbSi_2$), tungsten silicide (WSi_2), niobium boride (NbB_2), zirconium boride (ZrB_2), and molybdenum silicide ($MoSi_2$). Basic material parameters including electrical resistivity (ρ) and resistance to oxidation [26, 27] are contained in Table I. For comparison, values for carbon are also reported. As shown, the electrical resistivities are quite comparable, if not superior, to that of carbon and for most cases the ceramic powders have a greater resistance to oxidation, which should decrease the overall composite thermistor resistivity in the low temperature state.

It should be realized, however, that the resistivities reported in Table I are for dense ceramics and may not be representative for powders with defined surface chemistry; i.e., the presence of a resistive oxide "skin". The presence of such a layer would increase the low temperature resistivity of the composite.

TABLE I Conducting materials characteristics [26, 27]

Material	Electrical resistivity at room temperature (Ω cm)	Resistance to oxidation[a]
TiB_2	28×10^{-6}	2–3
TiC	180×10^{-6}	3
NbB_2	$6–30 \times 10^{-6}$	—
ZrB_2	$60–80 \times 10^{-6}$	2–3
$NbSi_2$	6×10^{-6}	4
WSi_2	33×10^{-6}	1–2
$MoSi_2$	21×10^{-6}	1
Carbon	$\approx 10^{-3}–10^{-5}$	4

[a] Classed according to the temperature range in which the attack by air would cause erosion or failure of the coated specimen within a few hours. 1: above 1700 °C, 2: 1400–1700 °C, 3: 1100–1400 °C, 4: 800–1000 °C.

It is well known that the microstructural features of the conducting filler play an important role on the percolation threshold (level and "steepness") and subsequently, the PTCR effect, thus various sizes of TiB_2 and TiC were obtained. Table II summarizes the data collected on the conducting fillers. Powders were characterized for their particle size and distribution using a Micrometric Sedigraph (Model 5000) particle size analyser. Specific surface areas were determined using the BET nitrogen absorption method. The degree of powder agglomeration, designated AAN(50), was determined from the ratio of the median equivalent spherical volume (from the particle size technique) to the average volume calculated from the specific surface area. Results of the powder characterization are reported in Table II.

Fig. 2a to 2i contain scanning electron microscope (SEM) photomicrographs of the various powders. From these photos and as reported in Table II, the TiB_2 (A), TiC (A), NbB_2, and $MoSi_2$ had broad particle size distributions. Along with a broad size distribution, the above powders were highly agglomerated. Though the particle size distribution of the WSi_2 powder was found to be narrow, the SEM micrograph (Fig. 2h) indicated a broad distribution.

In terms of shape morphology, most of the powders had quite irregular shapes (probably due to a grinding step in their production), whereas the TiB_2 (B) powder was somewhat spherical with smooth surfaces (see Fig. 2b). The role of powder morphology on the overall thermistor behaviour has yet to be investigated.

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* All powders were obtained from Aremco Products, Inc., Ossining, New York, USA, except for WSi_2 which was obtained from Johnson Matthey, Inc., Seabrook, Ohio, USA.

TABLE II Ceramic powder characteristics

Material	Density (g cm^{-3})	Surface area (m^2 g^{-1})	Equivalent particle size (μm)	Median particle size (Sedigraph) (μm)	AAN (50) [28]
TiB_2					
(A) 1–5μ	4.52	0.85	1.6	10	224
(B) −325 mesh		0.21	6.3	7.2	1.5
TiC (A)	4.93	1.11	1.1	7.4	304
TiC (B) (100–200 mesh)		0.18	6.8		
NbB_2	6.97	0.90	1.0	2.9	24
ZrB_2	6.09	0.76	1.3	8.7	300
$NbSi_2$	5.29	0.78	1.5	5.1	39
WSi_2	9.4	0.25	2.6	2.9	1.4
$MoSi_2$ (−325 mesh)	6.4	0.723	1.3	9	20

2.2. Matrix phase—polymers

Properties of the matrix phase which play an important role in composite PTC phenomena include: (1) electrical resistivity, (2) thermal expansion behaviour, (3) maximum use temperature without "failure" (slumping), (4) processability, and (5) surface chemistry, i.e., does it "wet" the conducting filler. Two types of polymers for the insulating matrix were investigated: a semicrystalline polymer,* polyethylene, and an amorphous epoxy,† referred to as Spurrs. Polyethylene and Spurrs epoxy polymers are good insulators with reported resistivities of $> 10^{15}$ Ω cm and $> 10^{12}$ Ω cm, respectively.

3. Composite fabrication and characterization

To determine the percolation behaviour and subsequent PTCR effect a wide range of filler–polymer composites were fabricated. Composites with a polyethylene matrix were prepared in a Brabender Inc. high temperature shear mixer at 150 °C for 20 to 30 minutes. Resulting mixtures were then pressed into discs at 200 °C in a stainless steel die. Composites with a Spurrs epoxy matrix were mixed at room temperature, cast, and cured for 24 h at 80 °C. In general, composites with high filler content (> 50 vol%) were difficult to prepare as a result of poor wettability between the polymer and ceramic powder. All pellets were polished and then electroded with an air-dry silver paint.

Characterization of the composites included geometric density, and microstructural analyses the percolation behaviour and PTCR effect. The geometric density was determined and compared to the expected theoretical value in order to evaluate the amount of porosity or perhaps preferential segregation of dense particles due to settling. Microstructurally, the composites were fractured (after cooling in liquid nitrogen) and evaluated using SEM for the level of powder–polymer and particle size segregation, powder agglomeration, porosity, and polymer–ceramic bonding, or lack thereof.

As previously shown in Fig. 1b, the resistivity of a composite as a function of volume fraction conducting phase (V_f) constitutes its "percolation behaviour". Parameters used to describe the behaviour for a given ceramic–polymer system were the percolation threshold (V_c) and its "abruptness".

The PTC effect, as shown in Fig. 1a is characterized by measuring ρ against T. Parameters used to describe the effect include the order of magnitude change in resistivity (Δ_ρ) from the room temperature state to the high temperature state, the temperature at which the transition occurs, T_c and "sharpness" of the transition.

Experimentally, the percolation behaviour and PTCR effect were determined by measuring the low field resistivity from room temperature to 150 °C in a Delta Design Box furnace using an HP 4274A multi-frequency LCR meter at a frequency of 1 kHz. To examine dispersion behaviour additional frequencies were used in the range of 100 Hz to 10 MHz. The current voltage (I–V) characteristics were determined for selected samples at temperatures above and below the PTCR transition using a picoammeter (HP Model 4140B). Based on the above results, polyethylene composite samples with the low room temperature resistivities and large PTC effect were selected and irradiated (exposure to gamma radiation ~ 20 Mrad) to provide the necessary cross-linking and subsequent high-temperature ($> T_m$) mechanical integrity.

4. Experimental results and discussion

4.1. Composite homogeneity

The entire concept of percolation and PTCR behaviour in composite thermistors is strongly dependent on microstructure. Selected SEM photomicrographs of several composites are shown in Fig. 3a to 3c. The homogeneity of the composites, as determined by geometric densities and SEM analysis, revealed that most composites contained anywhere from 5 to 10% porosity (see Fig. 3a). Low fraction volume filler composites tended to have less porosity, but clearly indicated inhomogeneity in terms of overall uniformity of the polymer and ceramic regions as can be seen in Fig. 3b and 3c. This problem was most severe in highly (> 50 vol%) filled composites where large regions of polymer with no filler content were observed.

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* Phillips Petroleum (Marlex EHM 6001)

† Polysciences, Inc.

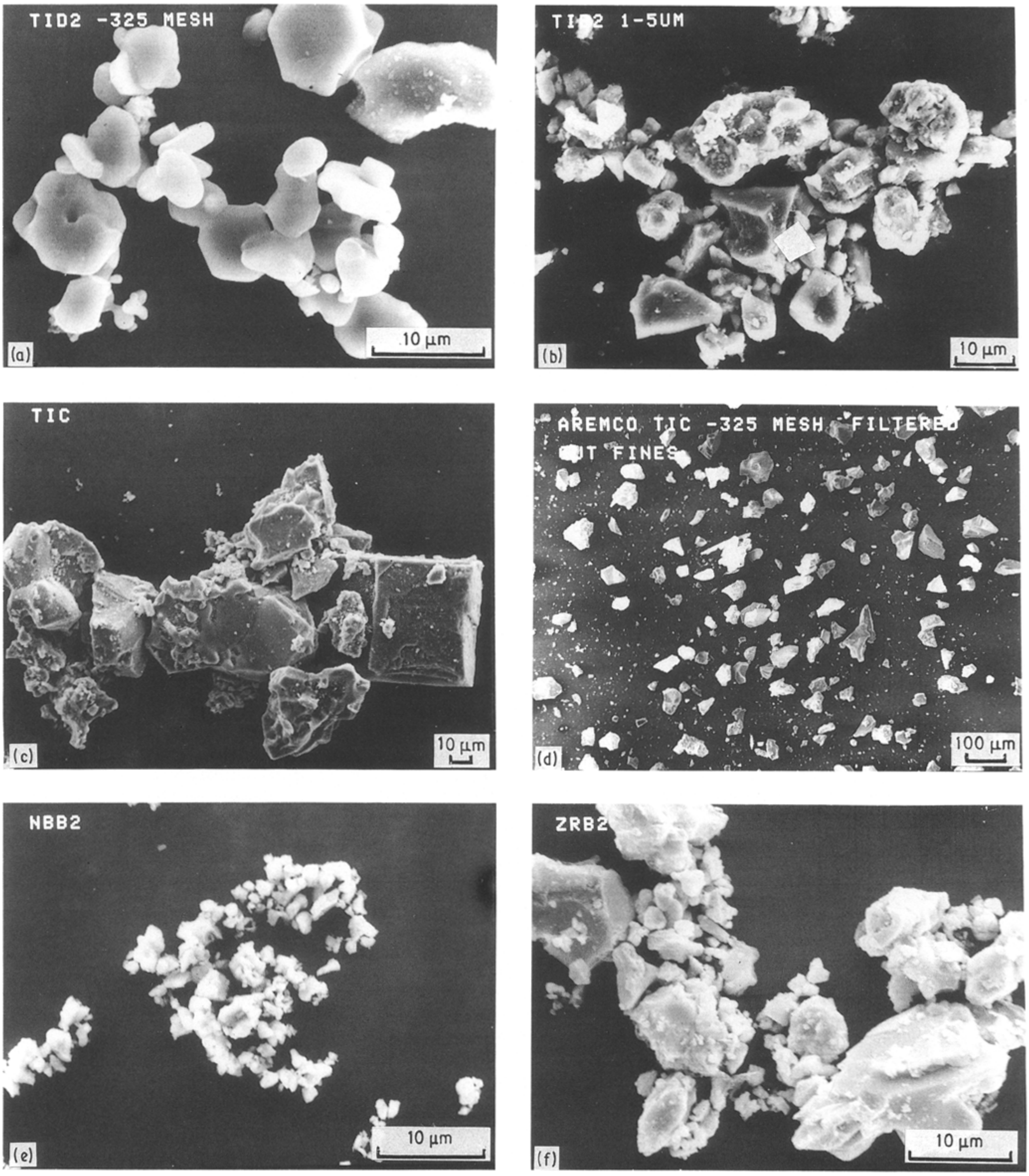
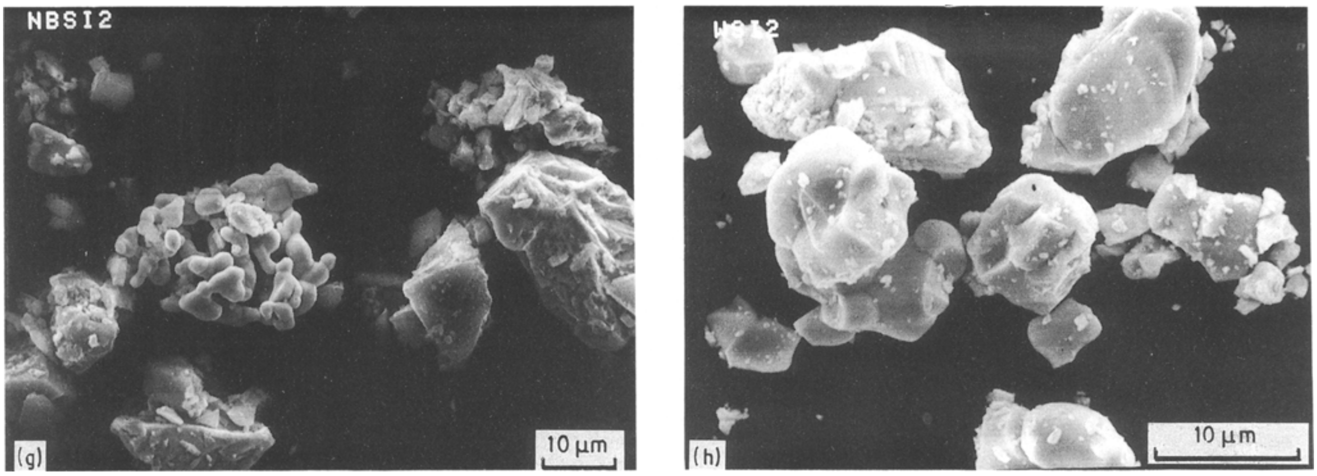


Figure 2 a–f

It has been found, only recently that using a slight vacuum during warm pressing of the polyethylene composites helped eliminate much of the porosity.

Composite inhomogeneity was most likely attributed to the fabrication technique. For instance, density gradients could have resulted due to poor mixing, porosity (trapped gases), or powder segregation due to settling. The latter is a major problem for composites with the Spurrs epoxy matrix; the low density and viscosity of the epoxy matrix allows the dense ceramic particles to partially settle during the curing stage. Non-uniform settling may also result in a distribution of particle sizes across the composite thickness.

Another important feature brought out in the SEM microstructures is that the polymer, whether polyethylene or Spurrs epoxy, does not appear to significantly wet the ceramic filler as indicated by the clean fracture surfaces, however, in the case of the NbB_2 and $NbSi_2$ samples, the fracture was transmatrix indicating á strong bond between the polymer and ceramic particle as shown in Fig. 4 for the NbB_2–polyethylene composite.



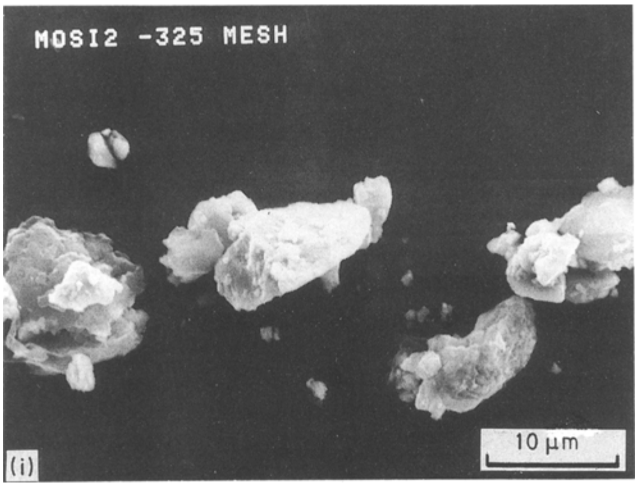


Figure 2 SEM photomicrographs of the various conducting filler powders. (a) TiB_2 (A), (b) TiB_2 (B), (c) TiC (A), (d) TiC (B), (e) NbB_2, (f) ZrB_2, (g) $NbSi_2$, (h) WSi_2, and (i) $MoSi_2$.

4.2. Percolation and PTCR behaviour

Percolation behaviour, or a large drop in resistivity with filler content, was observed for all the ceramic polymer systems investigated in this study. Representative of the various powders used, percolation curves for TiB_2, (A and B) and $NbSi_2$ powders dispersed in polyethylene are presented in Fig. 5a and 5b, respectively.

Typically, the percolation threshold level (V_c) was found to be in the range of 15 to 35 vol%, being similar for both polyethylene and Spurrs composites. In composite samples with lower fractions of filler, the resistivity was relatively high and there was no evidence of a significant PTC effect as shown in Fig. 6a to 6d. As the filler concentration was increased, a PTC effect was observed. For composites comprised of polyethylene the PTC effect was observed near 130 °C, the MP of the polymer, whereas the PTC transition in the composites comprised Spurrs epoxy typically occurred near 80 °C, the T_g temperature, as shown in Figs 7 and 8, however, a slight dependence of volume fraction filler content on the PTCR transition was apparent. With increasing filler content, the transition temperature shifted higher. This behaviour indicates that more volume expansion of the polymer, allowed for by the increased temperature, was required to pull the conducting particles apart. Increasing the filler concentration, well past the percolation threshold, tended to further decrease the room temperature resistivity and the magnitude in the PTC effect.

Composites with sharp percolation transitions or thresholds, such as shown in Fig. 5a for TiB_2 (A and B) and for TiC (now shown) powders consequently had sharp increases in resistivity with temperature or PTC ($\Delta\rho$) as evident in Figs 6b, 6c, 6d, 7, and 8. Exhibiting broad percolation behaviour, the niobate, $NbSi_2$ (Fig. 5b) had expectedly a poor PTC effect as shown in Fig. 6b. Similar percolation and PTCR behaviour was also found for the NbB_2–polyethylene composites.

For both polyethylene and Spurrs composites a PTC effect was observed over a wide range in filler concentration, however, for the $NbSi_2$ and NbB_2–Spurrs composites, little if any PTC effect was observed. As mentioned earlier, no PTC effect is observed for carbon–Spurrs composites as well. (Note: A small PTC effect may occur but only for a very narrow range in filler concentration.)

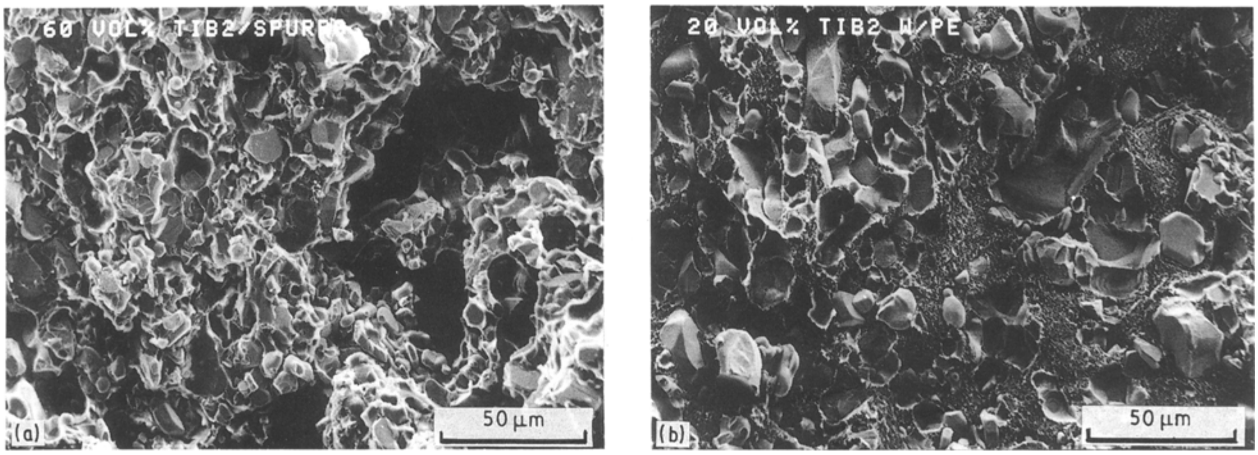
In contrast to the amorphous polymer composites (Spurrs) the semicrystalline polyethylene composites showed poor mechanical stability above the PTC transition, as indicated by an NTC (negative temperature coefficient) and overall erratic resistivity behaviour due to "slumping" of the polymer. Upon irradiation, however, a drastic improvement in mechanical stability was observed as shown in Fig. 9. It was found that low temperature resistivities did not significantly affect the irradiation.

Corresponding percolation threshold volume fractions, room temperature resistivities, and PTCR figure of merit ($\Delta\rho$) are contained in Table III. Only data for composite samples with low room temperature resistivities are reported. As presented, composite thermistors having room temperature resistivities as low as 1 Ω cm and $\Delta\rho$ during the transition of nine orders of magnitude were fabricated (see Figs 6d and 9). It is clearly shown that all the powders evaluated are capable of being utilized in PTC thermistors.

4.3. Microstructural effects

4.3.1. Particle size–distribution

If the particle size characteristics (Table II) and oxidation susceptibility (Table I) are correlated with the



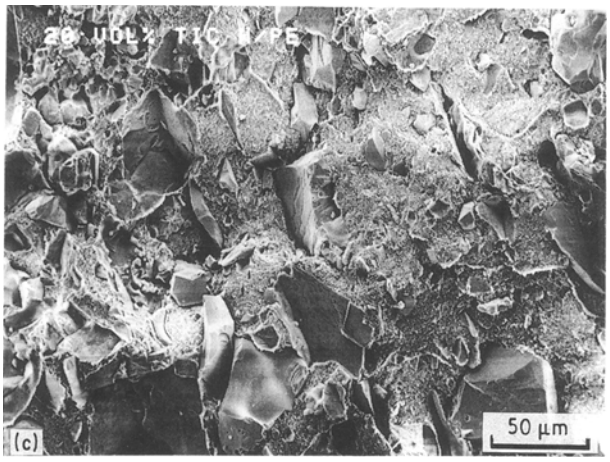


Figure 3 SEM photomicrographs of fractured surfaces for selected composites. (a) 60 vol% TiB_2 (A)–Spurrs, (b) 20 vol% TiB_2 (A)–PE, and (c) 20 vol% TiC (B)–PE.

data presented in Table III and corresponding figures, it is clearly evident that composites comprised of powders, such as $NbSi_2$ and NbB_2, which are more susceptible to surface oxidation and consist of many relatively small particles resulted in the highest resistivities due to surface "skin" effects. It follows that larger particle size fillers had the lowest resistivities, whereby the larger TiB_2 (B) powder resulted in lower resistivity composites than the finer TiB_2(A) powder as well as a lower percolation threshold V_c. Overall, composites containing large particles with narrow size distributions and a low level of agglomeration, not only had the lowest resistivities but the steepest percolation behaviour and subsequent PTC effect. It is important to point out that if one also obtained large particle size, and narrow distribution powders of WSi_2, ZrB_2, $MoSi_2$, etc., improved composite properties would result.

4.3.2. Polymer–ceramic interface

As mentioned, the percolation and PTCR behaviour may also be influenced by the overall composite inhomogeneity. This was clearly evident in high volume

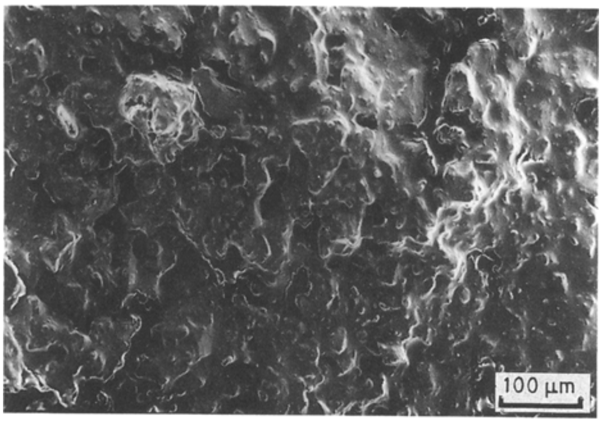


Figure 4 SEM photomicrograph of fractured surface for NbB_2–Spurrs composite.

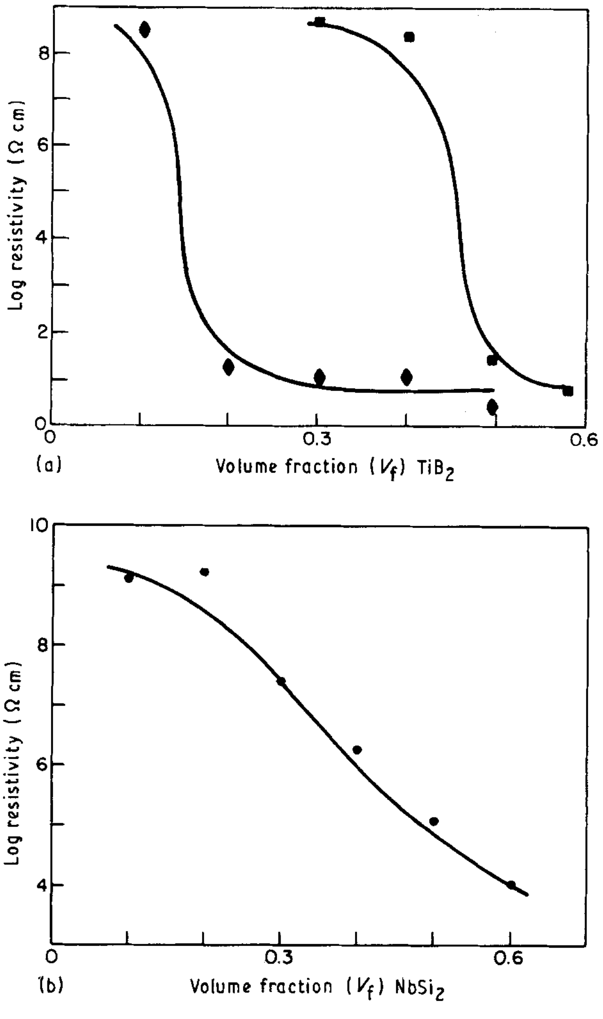


Figure 5 Percolation curves for (a) TiB_2 A (■) and B (◆) and (b) $NbSi_2$ (●) polyethylene composites.

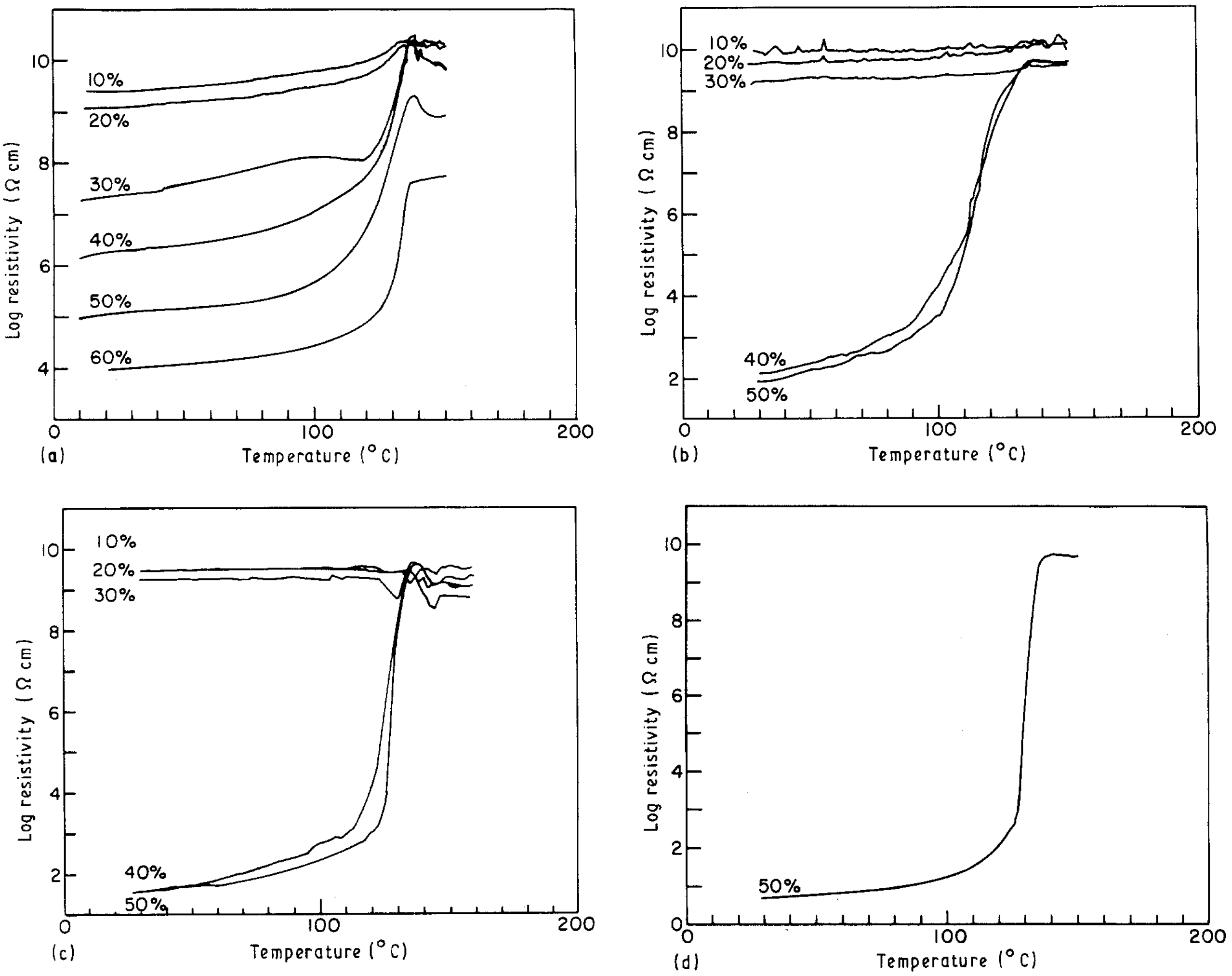


Figure 6 PTCR behaviour for various polyethylene composites. (a) $NbSi_2$, (b) ZrB_2, (c) TiC (A), and (d) TiB_2 (B).

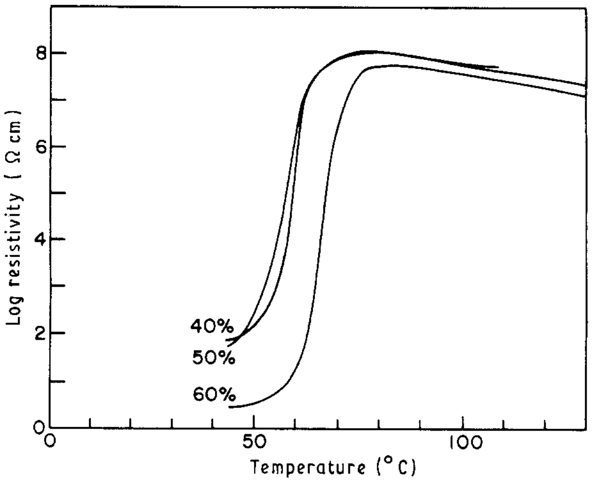


Figure 7 PTCR behaviour for TiC (A)–Spurrs composites.

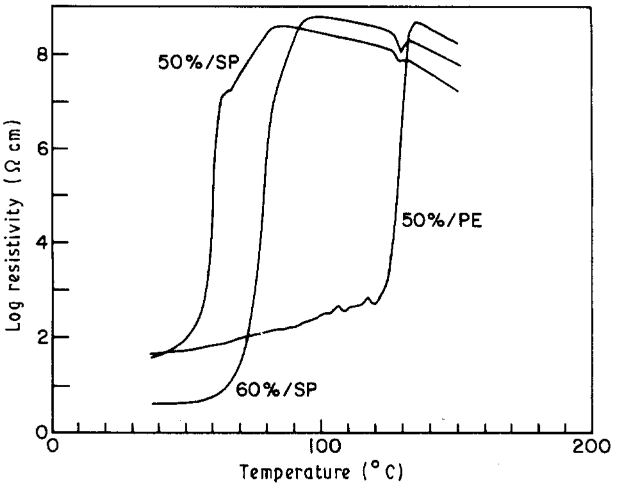


Figure 8 PTCR behaviour for both TiB_2 (A)–Spurrs and polyethylene composites.

% filler composites where poor homogeneity resulted in resistivities greater than that of lower vol% samples and subsequently poorer PTC behaviour. In general, using Spurrs epoxy, higher filler contents and lower room temperature resistivities could be achieved. The degree of dispersion, particle agglomeration, and wetting in short mixing capability, all depend upon surface chemistry aspects of the polymer matrix (polyethylene or Spurrs) and conducting filler (i.e., their respective surface energies). These parameters can influence thermistor properties in several ways. For example, if the polymer completely wets the surface of the powder, the high resistance "skin" will eliminate the percolative connectivity and result in a high resistivity. Conversely, non-wettability may cause microporosity or gaps between the polymer and powder interface, which could result in high resistivity, a poor PTCR effect, and a low electrical breakdown strength

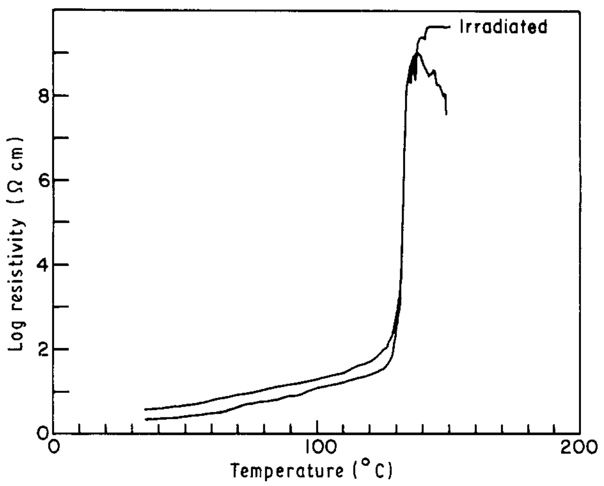


Figure 9 PTCR behaviour for irradiated and non-irradiated composites (−100 to 200 mesh powder). (60 vol% TiC–PE).

in the high temperature, "off" state. Modification of the polymer–ceramic interface with the use of various wetting agents (dispersants) did allow wettability and thus improved mixing, but such composites resulted in increased resistivities, perhaps due to a resistive surface layer (i.e., coating of polymer) or a variation in the particle–particle contact geometry. Also, as discussed earlier, the $NbSi_2$ and NbB_2 powders did not exhibit a PTC effect in the Spurrs epoxy, perhaps being a result indicative of wetting, see Fig. 4a and 4b.

4.4. Frequency characteristics

Equally important as the percolation and PTCR characteristics, the dispersive behaviour of the resistivity was determined on selective samples. The selective criteria of the samples studied, in general, was based on: (1) a very low room temperature resistivity ($< 10\ \Omega$cm) and (2) a very large PTC effect ($\Delta\rho \geq 7$ orders or magnitude), both having been determined at 1000 Hz.

At temperatures below the PTC transition ($T < T_{tr}$), the low resistivity state, the ρ was non-dispersive and a linear I–V response was obtained (slope ∝ resistivity). At temperatures above the PTC transition ($T > T_{tr}$), however, the ρ becomes very dispersive and the I–V behaviour non-linear. Regardless of filler type of polymer matrix, the resistivity (ρ)

TABLE III Percolation–PTC effects of composite thermistors

Material		Percolation threshold (V_p) shape	Resistivity (at RT) (Ωcm)	Figure of merit (Δ_p)
TiB_2	(A) polyethylene	~ 40%/broad	1×10^2	6
	Spurrs		5×10^1	
	(B) polyethylene	~ 15%/sharp	1–5 $\times 10^0$	9
	Spurrs		1×10^1	7
TiC	(A) polyethylene	~ 35%/sharp	5×10^1	7
	Spurrs		5×10^0	7
	(B) polyethylene	~ 25%/sharp	5–10 $\times 10^{-1}$	8, 9[a]
	Spurrs			
NbB_2	polyethylene	~ 30%/broad	5×10^2	7
	Spurrs		—	(no PTC effect)
ZrB_2	polyethylene	~ 35%/broad	1×10^2	7
	Spurrs		5×10^3	5
$NbSi_2$	polyethylene	~ 30%/broad	1×10^4	3
	Spurrs		—	(no PTC effect)
WSi_2	polyethylene	~ 25%/sharp	1×10^2	7
	Spurrs		1×10^1	7
$MoSi_2$	polyethylene	~ 35%/broad	5×10^2	7
	Spurrs		—	—

[a] Irradiated

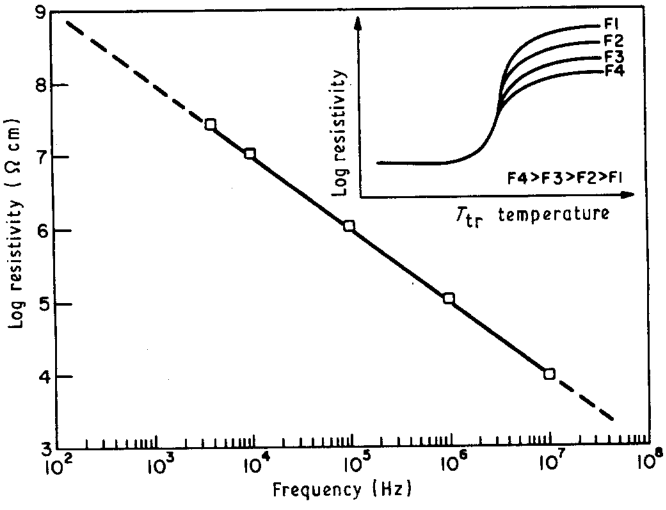


Figure 10 Characteristic dispersive behaviour of the resistivity above T_{tr} for a TiB_2 (B)–PE composite thermistor.

above the PTC transition was found to be very frequency dependent or dispersive (see Fig. 10). Dispersive behaviour has also been observed in other PTC composite (types) and can be understood by equivalent *RC* circuit analysis and resultant Maxwell interfacial polarization as discussed previously by numerous investigators [14, 29–31]. The importance from this dispersion values of the resistivity of all the various composites prepared in this study were measured at 1000 Hz and as such d.c. measurements show the resistivity at $T > T_{tr}$ to be $\sim$ three orders of magnitude greater thus giving a total $\Delta\rho$ of up to twelve orders of magnitude for particular composites, being significantly higher than that previously measured.

5. Summary

The following is a summarization of the results presented on the development of novel composite thermistors.

1. The feasibility of utilizing highly conducting ceramic powders including TiB_2, TiC, NbB_2, ZrB_2, $NbSi_2$, $WbSi_2$, and $MoSi_2$ to prepare PTCR thermistor composites was demonstrated.
2. Percolation behaviour and subsequent PTC effect was observed for all the materials for both semicrystalline (polyethylene) *and* amorphous polymers (Spurrs epoxy). As found for the filler material carbon, however, both NbB_2 and $NbSi_2$ did *not* exhibit a PTC effect in an amorphous polymer.
3. Though not fully understood, the entire concept of percolation and PTCR behaviour in the composite thermistors was found to be strongly dependent on microstructure, which was influenced by (a) particle characteristics, including size–distribution and level of agglomeration and (b) ceramic–polymer surface chemistry, including wettability and overall mixing capability resulting in composite inhomogeneity.
4. Composites comprised of relatively large particles and thus less resistive "skin" effects of TiB_2 and TiC in either polyethylene or Spurrs epoxy matrices, resulted in room temperature resistivities as low as $\sim 1\ \Omega$ cm and a nine-order magnitude ($\Delta\rho$) (measured at 1 kHz) resistance change at the $T_m \sim 130\,^\circ$C for polyethylene or $T_g \sim 90\,^\circ$C for Spurrs epoxy. The nine-order of magnitude change in resistivity observed is larger than that reported for carbon–polyethylene composite thermistors. Further, the electrical resistivity above the PTCR transition temperature, being dispersive reflects that the actual $\Delta\rho$ at d.c. measurement in actuality is twelve orders of magnitude.

6. Future work

Although an extensive amount of research has been presented on the use of highly conducting ceramic borides, carbides, and silicides for use in composite thermistors, many questions remain to be answered. A brief outline of our proposed objectives are as follows:

1. Optimize composite homogeneity and microstructure through (a) understanding the surface chemistry of the polymer and powder systems; (b) advanced fabrication techniques; and (c) development of procedures for powder classification techniques and agglomeration control.
2. Further study of the mechanism(s) responsible for the PTC effect observed in composites, in particular for amorphous polymers. This will also entail determining why carbon, $NbSi_2$, NbB_2, and metal powders in general, *do not* result in a PTC effect in various polymer composites.
3. Investigate other polymer systems for the matrix phase in order to provide flexibility with respect to operating temperature range, and percolation–PTCR behaviour.
4. Quantify the resistive "skin effect" of powders and explore possibilities of thermal and perhaps chemical treatments to eliminate or reduce the effect.
5. Fully characterize and model the electrical characteristics of the composite PTC thermistors, including: *I–V* behaviour, the dispersive behaviour of the resistivity (ρ), switching characteristics, power handling capabilities (current density), and high field breakdown mechanisms.

The aim of these objectives is to better understand the underlying basic science of composite PTC thermistor operation. Only through this approach will composite thermistors be developed to meet the needs of the wide variety of applications.

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