A NEW METHOD FOR TESTING THERMOELECTRIC MATERIALS AND DEVICES

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INTRODUCTION

A method was developed in the early 1960's by T.C. Harman(1) for testing the AC Resistance and Figure of Merit, Z, of a thermoelectric material sample. This method provided a direct measurement of Z but lacked precision and reproducibility primarily due to mechanical and electronic limitations of the instrumentation.

A new method has been developed which is roughly based on this same concept but has some fundamental differences which give rise to improvements in accuracy and reproducibility. The fundamental similarity is that both techniques are designed to resolve the voltage components of a TE device. The fundamental difference is that the Harman method does this by measuring the resistive component; whereas the new method measures the Seebeck component.

This new test method presented herein shall be referred to as the "TRANSIENT" test method. The TRANSIENT methodology applies to completed, modular devices as well as individual TE material samples. It provides for the direct measurement of all the parameters needed to thermoelectrically characterize the TE materials or device under test.

The key to the TRANSIENT method is a computer driven, high speed, high resolution, integrating voltage measurement system which is capable of accurately resolving the voltage components in an active TE device or sample. The subsequent computer analysis yields measured values for Seebeck coefficient, α, electrical resistivity, ρ, thermal conductivity, k, and Figure of merit, Z. These parameters are measured simultaneously on the same sample via an absolute method requiring no reference or standard material for comparison.

Data are presented illustrating application of this methodology over a wide temperature range with an extremely high level of reproducibility.

OPTIONAL TEST CONFIGURATIONS

The term, "thermoelectric device", shall be referred to herein as a "TED" and shall consist of either a TE sample pellet or a module composed of one or more pairs of N and P-type TE pellets. The versatility of the TRANSIENT test method allows for many different test configurations for both types of TEDs.

Figure 1 illustrates four different test configurations for a TE pellet sample. The first of these is a suspended sample employing a four-probe technique. This test method will be necessary whenever the contact resistance is unknown or significant compared to the resistance of the TE pellet. Copper/constantan thermocouples are attached directly to the TE pellet by resistance welding or some other suitable process. The copper halves of these thermocouples double as voltage probes. Difficulties with this configuration are that: (1) current flow through the TE pellet can be disturbed by the presence of the thermocouples; (2) voltage pick-up in the probes can result creating significant errors in the thermocouple readings; (3) precise measurements of the probe separation are usually very difficult to obtain; and (4) the voltage and temperature "planes" are affected by the probes and, therefore, not nearly as well defined at the probes than they are at the opposite ends where high conductivity end caps are applied.

The indicated two-probe configuration is recommended for most TE materials where good contacts are relatively easy to obtain. However, one should be careful to place the current and thermocouples at opposite edges of the end caps in order to avoid voltage pickup in the thermocouples. Essentially, the thermocouple should not be placed in a position on the end cap where current "lines" will intersect it. Tests were performed on the example TE pellet sample given in this paper to monitor the thermocouple reading with and without applied current and zero voltage pickup was confirmed.

The configuration indicated as "HEAT SUNK" is also applicable and, in fact, was used to obtain the temperature dependent data presented in this paper. There was some slight differences in the correction factors and in the TED time constant, but, due to the bi-polar test sequence employed, there was essentially no <u>significant</u> error difference between the suspended and HEAT SUNK configurations. The primary advantageous feature of the HEAT SUNK configuration is that the TED can be thermally attached to the top of a multi-stage TE cooler to easily control its temperature yet maintain a high degree of TED temperature stability.

The "NO THERMOCOUPLES" configuration is usable to obtain and ZT measurements. Very simple fixtures can be used to obtain "quick" data on these two key material parameters. These tests are very effective for screening samples for potential more rigorous testing. This mode is especially effective for rapid testing TE modules and will be discussed in more detail below.

Examples of some test configurations for a TE module are given in Figure 2. The SUSPENDED and HEAT SUNK configurations are essentially the same. The difference in the correction factors between these two configurations are even less than for the TE pellet samples. The method used to attach the thermocouples was simply to apply a tiny "dab" of thermal compound into which the thermocouple junction was imbedded. It was held in place under compression with scotch tape. This has proven to be very effective technique when properly applied.

Note that, unlike the TE pellet samples, the thermocouples will not be in contact with the active circuit and voltage pickup will not be a factor. However, care must be given to attach voltage probes directly onto the input tabs but not under the same junction as the current probes. This must be done in order to avoid the voltage created by contact resistance, especially if "alligator" clips are used. Dual contact "Kelvin clips" are excellent for this purpose and were used in the measurement of the module test data presented herein.

As mentioned above, the "NO THERMOCOUPLES" configuration provides the ultimate in simplicity in hook-up and test speed. As will be discussed below, the <u>measured</u> parameters obtainable via this configuration are and ZT. This is enough to assure the quality of production TE modules. Furthermore, since a +/- 3°C error in absolute temperature, T, produces only 1% error, the figure of merit, Z, is extractable even if the temperature of the TE module is only approximately known, such as in the ambient test of TE modules.

<u>DEVICE PERFORMANCE FORECASTS</u>

In order to translate the measured parameters into meaningful TE module parameters, algorithms have been developed which provide a quite dependable projection of Seebeck coefficient using ρ, Z and certain TE material factors derivable from prior tests using applied thermocouples on previous modules or TE materials. This algorithm process involves the determination of the parameter Qs which is related to the effective mass x mobility product. The shape of the Qs "response surface" as a function of the measured ρ and ZT yields a means to calculate the Seebeck coefficient with quite dependable results as will be shown below. Thermal conductivity, of course, is determinable from the other three parameters rounding out all that is needed to fully characterize the TE module at ambient temperature.

The Qs parameter plus another calculated parameter related to lattice thermal conductivity, Qk, provide the keys to a dependable method of forecasting the temperature dependence of each of the TE material parameters. These data are used in combination with a temperature dependent thermal model to forecast the performance of the tested TE module over the entire continuum of thermal and electrical parameters with remarkable accuracy. The key device performance characteristics of the TED are calculated such as, ΔTmax, Imax, Vmax, and Qmax. This information is projected for any selected hot side temperature enabling pass/fail forecasting under any conceivable ultimate use of the TED. Thus, this test, taking only about one minute to perform, can be used to determine whether or not the TED under test will perform properly in the final product.

The TRANSIENT test can be made on a completed assembly as long as the TE power leads can be accessed. Of course, the test time will be increased due to increased thermal masses in contact with the TE module, but this test will still take less time than a full performance test. Furthermore, the TRANSIENT test provides other key system information in addition to a full set of projected system performance curves. That is, comparison with prior TE module test data will yield the overall loss conductance of the system. This will provide a simple, fast and accurate means of evaluating the quality or effectiveness of a given TE assembly with no extra test time. Another important output from the TRANSIENT test is the overall time constant of the system. This information is very useful where system cool-down time is of interest.

These tests can also be used to define potential failure modes. If tests are made before and after and observed degradation or on a returned TE module or assembly, the material parameter data extracted via the TRANSIENT test can provide insight as to what caused the failure. For example, if ρ increased without a corresponding increase in α, the failure would most likely be due to failed contacts or mechanical fracture in the TE material. If

The overall correction factor, C, is equal to 1 plus a series of dimensionless correction factors derived from each remaining source of parasitic heat load. Each correction factor is a function of k itself, requiring an iterative calculation process. However, since these factors are typically quite small, convergence is usually achieved in just a few iterations.

Figures 11 and 12 are the calculated correction factors obtained from actual tests made on the TE module and sample described above. It is observed that the total correction factor is only 6%. Thus, if the total uncertainty in the model for the correction factors would be as high as 20%, the overall uncertainty of the final calculation of k or Z would only be 1.2%.

The correction factors for the TE pellet sample were much larger as illustrated in Figure 12 yielding a potential uncertainty of 6%. Half of that is due to convection heat loading which would disappear in a vacuum. Also, reducing the TE sample and end cap sizes dramatically lowered these factors as illustrated in Figure 13. These data were determined from actual tests on a smaller, 2mm square x 1.65mm long TE pellet sample mounted on top of a multi-stage TE cooler in a vacuum. As observed, the total correction factor varied between 2% and 4% over the indicated temperature range yielding an overall uncertainty of less than 1/2%.

Comparison testing in a vacuum versus air has provided a very accurate means of empirically establishing the overall convection and air conduction coefficients used in the corresponding correction terms. This further improved the accuracy of the correction coefficients and of the final test data.

The voltage equations for the TED under test are given by:

$$Vo = N*\alpha*(Th-Tc) + \alpha w*(Th-Tc) \quad (4)$$

$$Vo' = N*\alpha*(Th'-Tc') + \alpha w*(Th'-Tc') \quad (5)$$

$$Vi = N*\alpha*L*I + Vo \quad (6)$$

$$Vi' = N*\alpha*L*I' + Vo' \quad (7)$$

Note that the αw is the thermopower of the voltage wires and must be included for all TE pellet calculations. It is included throughout all formulas but simply set to zero for TE modules since both voltage probes will be at the same temperature.

The calculation of α and ρ are obtained from the set of voltage equations:

$$\alpha = \frac{Voa}{N*Da} - \alpha w \quad (8)$$

$$\rho = \frac{Via-Voa}{N*L*Ia} \quad (9)$$

Where: $Voa = (Vo+Vo')/2$
$Via = (Vi+Vi')/2$
$Ia = (I+I')/2$

The equation for k was formed by simply dividing equation (8) by equation (3) to yield the following equation:

$$k= \frac{L*ITa*Voa}{C*N*Da*Da} + \frac{L*ITa*\alpha w}{C*Da} \quad (10)$$

The equation for Z was formed by simply multiplying equation (8) by equations (3) and dividing by equation (9) to yield the following equation:

$$Z= \frac{C*Ia*Voa}{ITa*(Via-Voa)} - \frac{C*Ia*\alpha w/N/Da}{ITa*(Via-Voa)} \quad (11)$$

Note that each term on the right side of equations 8-10 are measurable parameters yielding a truly absolute test methodology for each TE material parameter. Also note that the second terms of equations 10 and 11 go to zero for a TE module or when αw can be ignored compared to α. If this is applied together with the realization that Ia/ITa is neartly equal to 1/T, Equation 11 reduces to the well-known Harman formula:

$$ZT= \frac{Voa}{(Via-Voa)} \quad (12)$$

This simplified formula accounts for the fact that the resultant Z test data (presented below) exhibits very low scatter, since it is primarily dependent on Vo and Vi which are accurately measurable via the TRANSIENT test method.

TE MODULE TEST RESULTS

To illustrate the output obtainable from the TRANSIENT test system, the TE module described in Figure 7 was tested via the SUSPENDED and NO THERMOCOUPLES configurations in ambient air. The results were plotted as a function of temperature in order to separate temperature dependent effects from data scatter.

Electrical resistivity and Z data are given in Figures 14 and 15. As expected, the scatter was less than 1% for both parameters. See the 1% reference bar at the far left border of the graph. Furthermore, there was no significant difference between the test results with and without thermocouples.

Seebeck coefficient data are given in Figure 16. The following observations were made: (1) The scatter in the data taken using thermocouples was significantly higher than that with no thermocouples. This was due to the resolution limitation of the measured small ΔT of the TED and the imperfect thermocouple attachment of a thermal grease dab and scotch tape. With this taken into consideration, the observed maximum deviation of less than 1% was very good. Incidentally, the Seebeck scatter of TE pellet tests is typically better because of the better thermal contact of the thermocouples. This will be validated in the temperature dependent data presented below. (2) There was approximately 1% separation between the algorithm-derived Seebeck coefficient and the measured it did track with α (yielding not much change in Qs), it would imply a change in the material properties probably resulting from contaminant diffusion perhaps due to overheating.

THERMOELECTRIC DEVICE VOLTAGE

In order to fully understand the nature and detail of the TRANSIENT test methodology, a review of some of the basic effects of a TED is appropriate. As an electrical current, I, is applied to a TED, it will develop a voltage, V. If Ohm's Law were the only phenomenon to occur, the resulting voltage would be in direct proportion to the applied current. The constant of proportionality would be the electrical resistance, R. However, a TED does not follow Ohm's Law. This is because a "good" TED will have a significant device Seebeck coefficient, S, and low enough thermal conductance, K, to support a temperature differential, ΔT. This will result in the creation of a significant additive Seebeck voltage, Vo. The resulting expression for the voltage across a TED is, therefore, given by the following equation:

$$Vi = Vo + Vr \qquad (1)$$

Where:

$$Vo = S * \Delta T$$
$$Vr = I * R$$

At first glance, one might also surmise that if the current is kept very low, perhaps a ΔT will not be created and the first term can be ignored. This is definitely not the case! In fact, the Vo term can be proportionally larger for small currents. After all, it can easily be non-zero even when the current, and therefore, Vr is zero.

Certainly, one can measure Vi, I, and even ΔT, but it is not easy to separate the two components of voltage, Vo and Vr. The Harman(1) method resolves these two voltage components by creating a bi-polar square-wave AC current using a mechanical chopper. Thus, Vr reverses polarity but Vo does not. The resulting voltage signal is sent back through the same chopper used to generate the AC current in order to convert the AC voltage to DC for measuring purposes. There are several problems with this experimental set-up including noise generated by the opening and closing of electrical contacts and a momentary dead band during each half-cycle. Some improvements have been made over the years using more sophisticated electronic switching, but fundamental problems still exist in obtaining precise measurements.

One of these fundamental problems is that the Peltier effect is still operable during the half-cycle of applied current and this voltage does, indeed, rise during each on-cycle. A typical TE pellet of 1.14 mm long has a time constant of less than one second. This means that, at the typical applied current frequency of 40 Hz, the voltage will rise as much as 5% during each half cycle. This introduces corresponding errors in the measurement of Vr. Higher frequencies will lower this error but will create other errors in the voltage measurement due to inductance in the circuit.

Commercial AC resistance meters are also not the answer. They typically employ sinusoidal applied currents and measure the RMS AC voltage. They, too, are not accurate for thermoelectrics because the resulting instantaneous sinusoidal Peltier effect will not be in phase with the slower Joule and thermal conduction effects. This very complicated thermal situation can seriously affect the accuracy of the readings. One can prove this to himself by simply monitoring the "AC-resistance" of a TED using a commercial AC resistance or voltage meter and quickly heat one surface with a lighted match. An anomalous transient AC resistance reading will be clearly evident, not explainable from the temperature dependence of TED resistance. This simple test will confirm the inability of AC meters to accurately resolve the Seebeck and resistive voltage components to the precision levels needed to accurately characterize TE materials or devices.

The solution to this problem is to not measure Vr at all, but measure Vo. If one removes the current and instantaneously measure the "residual" voltage, that measured voltage will essentially be Vo. The problem is that the time constant for the initial decay of Vo, immediately after the current is removed, is extremely fast. This will be the case even if large thermal masses were attached to the ends of the TED to slow it down. There will be a significant initial decay as a consequence of the time constant of the TE pellet which is usually very small in size and even a few milliseconds will result in significant voltage decay and uncertainty of the true Vo. Nevertheless, the TRANSIENT test and analysis technique described herein is capable of precisely determining Vo.

The situation is shown graphically in Figures 3 and 4. As current is applied in accordance with Figure 3, the voltage across the TED will be that shown in Figure 4. The voltage rises instantaneously to the value Vr and then asymptotically to a value of Vi = Vr + Vo at steady-state. As the current is shut off, the voltage drops instantaneously to Vo and decays exponentially to zero. An important aspect of the hardware was to ensure that the current waveform was extremely "clean", i.e. did not contain any "spikes" or anomalies. The method employed was checked with a high speed, high resolution oscilloscope to assure that this condition was indeed met.

The key to the TRANSIENT method is to accurately reconstruct the detail for the waveform of the actual voltage at the precise instant of the switch point. The key to this reconstruction is the utilization of a high speed, high resolution, programmable, integrating, analog-to-digital (A/D) computer board.

An A/D board was obtained which met all of these requirements. It also included a remote terminal board which contained especially designed isothermal terminals for thermocouples together with self-contained reference junction compensation. It had 16-bit resolution which produced sub-microvolt resolution of the millivolt voltage signals obtained from single TE pellet samples. By way of software selection, a "filter mode" provided for integration of the instantaneous voltage over a specified period of time (approximately 20 milliseconds). This filter mode was one of the keys to this methodology since it yielded the time averaged voltage over this period even for the unusual waveform produced during the "switch point".

The waveform analysis process is illustrated in Figures 5 and 6. Each square represents an actual measured voltage data point of a TE module. These data were obtained via repetitiously measuring the TE module voltage at a known frequency, referred to herein as the "burst" measurement. At a time of approximately 275 milliseconds from the start of the burst measurement, the applied current to the TE module was abruptly shut off. When this happened, an "intermediate voltage" reading was evident followed by the decaying "residual" voltage. The intermediate voltage reading represented the average voltage made up of the Vi(t) voltage prior to the switch point plus the rapidly decaying Vo(t) voltage after the switch point. This data point was used to determine the exact instant in time of the switch point, tsw. That is, several test points were curve-fitted with a linear regression process to define the equation of the Vi(t) curve. Actually, a simple averaging process would have probably sufficed, but the slope from this regression served the dual purpose of double-checking temperature stability. That is, whenever the slope was not very nearly equal to zero, the test was automatically recycled. This check was applied as an additional constraint to the stability check discussed below.

A similar process was applied to the first few initial points following the intermediate data point in order to define the equation of the Vo(t) curve. It is plotted against some of the initial test data points after the switch point as shown in Figure 6. Although the nature of the voltage decay is exponential, it is not a simple exponential since it is made up of several discrete masses connected together. In fact, a simple exponential did not fit very well for the initial set of data points. Further discussion on this subject is given below. In the final analysis, it was discovered that the linear regression of the first three points yielded the most dependable extrapolation of the time dependent Vo(t) voltage nearby the true switch point time, tsw. Incidentally, notice that a 1.26% error would have resulted from simply accepting the first measured voltage for the value of Vo. This error could be as much as 6% for small suspended TE pellet samples.

The time, tsw, was calculated by constructing the original waveform using the two curve-fit equations described above and the switch point, tsw, as a variable. An expression was subsequently set up for the area under this zig-zagged broken line from the time interval of the last test point before tsw and the "test data point during switch", shown in Figure 5. This expression was set equal to the area over that same time interval using the constant voltage defined by the measured "test data point during switch". With tsw determined therefrom, the true values of Vi = Vi(tsw) and Vo = Vo(tsw) were defined using the respective extrapolation formulas for Vi(t) and Vo(t). Notice that these values are for the same instant in time, tsw. The current, I and temperatures Th and Tc are measured prior to initiating the burst measurement, but many checks and double-checks were made to make sure the TED under test was extremely stable prior to initiating the burst test, as discussed in more detail below.

TEMPERATURE STABILITY

Actual test data of a "extended burst" test on the TE module example presented above is given in Figure 7. This graph is a line graph of over 2500 test points and illustrates, among other things, the excellent, low-scatter characteristics of the test system. However, the main point of these data and the similar TE pellet test given in Figure 8, is to serve as the basis for determining the time constant of the TED under test. This parameter for each case is shown in Figures 9 and 10, respectively. The time constant was calculated from the slope change between data points over the 2 second burst test. The relatively large amount of scatter is due to the fact that there was not much time between points (yielding a small denominator) and not much difference in measured voltage between points (yielding low resolution for the numerator). Nevertheless, the average calculated time constant was quite well defined and highly reproducible. This is essentially "free" data since it is a basic necessity of the TRANSIENT test technology. The resulting time constant was not only usable to characterize system cool-down, but was very useful in determining the time needed for TED temperature stabilization. That is, using 5 to 6 times the time constant for stabilization time, yields approximately 24 and 60 seconds for the TE module and TE pellet stabilization times, respectively. This agrees quite well with the corresponding test data given in Figures 7 and 8.

The significance of this result is that this tested stabilization time is compared with the actual "wait time" prior to initiating the burst sequence. If the wait time had been less, the test was automatically recycled forcing the tested stabilization time on this and all subsequent tests, at a minimum. This process is repeated for each test and the stabilization time is automatically updated as required. The effectiveness of this feature is that it not only allows complete and dependable automation while maintaining test precision but minimizes the wait time and, thus, maximizes overall test speed.

Note the increase in the calculated time constant for the TE module in Figure 9 immediately after the switch point. This is a result of the composite thermal structure of the TE module as discussed above. This effect is indicative of the impact of the lower time constant of the basic TE pellet(s) composing the TE module and the imperfect diffusivity of the composite structure of conducting tabs and ceramic plates. Within a few hundred milliseconds, the data more exactly correspond to a simple exponential decay with a time constant consistent with the overall thermal mass of the system. Thus, the average time constant as calculated was appropriate to determine the minimum test stabilization time. Notice in Figure 10 that an initial rise is not evident for a relatively large TE pellet. This is because the composite thermal structure is much less complicated and consists of a relatively small copper end cap.

BI-POLAR TESTING

All TRANSIENT tests were made via a two-step, bi-polar process. That is, the test was performed using one polarity of applied current and then the current was reversed and the test repeated. The primary purpose of this bi-polar process is that it reduces the magnitude of the correction factors and maximizes the overall accuracy of the results.

This reversal process corrects for any thermal emf's in the test circuit and for any imperfections in the thermocouples which might cause them to not be totally identical. Since the accuracy of the test results are mostly affected by temperature differences, this reversal process totally cancels any unbalance or zero offsets.

Bi-polar testing is actually the key to precision testing of all the parameters of the TED. That is, each parameter is calculated from voltage and/or temperature differences. The equations for each parameter derived below reveal this fact. For example, Seebeck coefficient is calculated from two basic quantities: Vo and ΔT. Vo, in turn, is actually the difference between two voltage measurements and ΔT is the difference between two temperature measurements. Application of the bi-polar method further corrects for any zero offset in voltage and any unbalance of thermocouples. Essentially, the accuracy of the results is mostly dependent on the linearity of the measurement system which is an inherently excellent feature of the A/D board used by the TRANSIENT test system.

THERMAL MODELING AND EQUATION DERIVATIONS

One of the key features of the TRANSIENT test method is the utilization of a very low test current. It is calculated from the input geometry of the TED under test to yield approximately $4^{\circ}C$ across the TED. This corresponds to approximately 1/50th of the current that would normally produce maximum ΔT. This magnitude of ΔT provides plenty of signal for accuracy but not so much that it will take the TED below dew point and introduce large condensation heat loads which are difficult to accurately quantify. Also, since the ΔT is so small, the assumption of constant parameters is very good making the closed form, simplified heat source equations quite rigorous. These low currents also allow testing of even extremely high current TE material wafers.

The first step in setting up the equations for determining the TE material parameters was to set up expressions for each component of heat flow for the chosen test configuration. These expressions are summarized in Table 1. They include all active and parasitic heat sources applied to a suspended or heat sunk TE module. Very similar expressions can be set up for TE pellet samples and each of the configurations described above.

Table 2 is a set of equations formed from the sum of each corresponding expression taken from Table 1. Note that the Wire conduction losses and Joule heat terms are zero as a result of using the same absolute value of applied current in each mode of the bi-polar process. Also note that the radiation terms reduce to Th^4-Tc^4 since the ambient temperature drops out. Since Th and Tc are set by the experiment to be a small ΔT, the first term in the Taylor expansion is an excellent approximation, as indicated in Table 2. The resultant is that each term below the Peltier term contains the same temperature expression.

The heat balance equation is given by:

$$-Qp = Qk + Qri + Qre + Qc + Qa \qquad (2)$$

Substitution of the expressions from Table 2 yields an equation for α/k (Seebeck coefficient / thermal conductivity) as a function measured parameters multiplied by an overall correction factor, C:

$$\alpha/k = \frac{C*Da}{L*ITa} \qquad (3)$$

Where:
$C = 1 + Radi + Rade + Conv + Cair$
$Radi = Kri*L/N/k$
$Rade = Kre*L/N/k/2$
$Conv = H*L/N/k/2$
$Cair = Ka*L/N/k$
$ITa = I*(Th+Tc)/2+I'*(Th'+Tc')/2$
$Da = (Th-Tc+Th'-Tc')$

Seebeck. This level of agreement validates the dependability and effectiveness of the algorithm. (3) The scatter in the "NO THERMOCOUPLES" data was very low as one might expect since it was calculated from the low scatter ρ and Z data.

Thermal conductivity data are given in Figure 17. Basically, the same observations made for the Seebeck data also applied to these data. However, the scatter was a little larger for the "thermocouple" case and the separation between test configurations was approximately 2%. This is still considered very good considering the complexity of the thermal algorithm used to forecast this parameter.

TEMPERATURE DEPENDENT TEST DATA

Temperature dependent TRANSIENT testing was performed on one "standard" and one "special" TE pellet sample. Both samples were 2mm square x 1.65mm long TE pellets mounted on top of a multi-stage TE cooler in a vacuum. The correction factors calculated from the "standard" test data were presented in Figure 13.

This configuration is particularly effective whenever extreme precision of all results is required. For "unusual" TE materials, it is also useful to test at least one TED from these materials to "calibrate" the algorithms used in the "NO THERMOCOUPLES" test mode and to project temperature dependence for thermal modeling TE module performance parameters.

The test data collected on both samples (tested 3 times each) are given in Figures 18-21. The following observations were made: (1) The resistivity scatter was <u>very</u> low since the data was not dependent on thermocouples, correction factors or vacuum level. (2) The Seebeck scatter was not quite as good because of the dependence on ΔT measurements. Nevertheless, the scatter was still quite low because of the special care given to precision thermometry. (3) The thermal conductivity scatter was largest as expected since these measurements were affected by correction factors, thermocouples and vacuum level. (4) The Z scatter was better than the thermal conductivity scatter because it was not affected by thermocouples as explained above. (5) Overall, the reproducibility was excellent to the point that it is difficult to identify the three separate measurements made for each parameter at each temperature point.

Finally, the importance of the precision and flexibility of the TRANSIENT test methodology presented herein is exemplified in Figure 21. The Z versus temperature for the standard sample is quite typical for "normal Bismuth-Telluride" TE materials. If only tested at room temperature, the "special" TE material produced at TE Technology, Inc. would not have indentified any significant Z enhancement. However, its low temperature Z data represents unusually high performance. It would greatly improve the cooling performance of a low temperature multi-stage cascade. This and other exciting applications of this special TE material will be presented in future publications.

DISCUSSION AND SUMMARY

A new TRANSIENT test methodology has been developed and has been described in detail. It provides the basis for a high speed, high precision measurement system for thermoelectric ingots, wafers, pellets, modules and systems. It offers significant improvements but maintains all of advantageous features of the Harman test method.

The TRANSIENT technique employs a detailed thermal model created for the TED under test automatically by the computer software. The software drives a PC computer with a special A/D board plugged into an expansion slot of the computer. The test sequence employs a transient technique and extracts the key TE material parameters via analysis of the digital waveform data. Rigorous formulas are used which separate the "zero order" TE material Z and thermal conductivity terms from several correction terms involving internal radiation, external radiation, air conduction, external convection and, in the case of single TE pellets, conduction through the test wires and thermocouples.

Data have been presented on TE modules and samples which validate the claims for this test methodology. It is simple, fast accurate and very easy and affordable to use. It is, therefore, presented to the thermoelectric community for consideration as the standard for the industry. Since it is particularly accurate in its measurement of ZT, this test technology is presented with the expectation that it will virtually eliminate conflicts in TE quality claims that might otherwise arise between the various TE organizations of the world.

REFERENCE:

(1) T. C. Harman and J. M. Honig, 1962, J. Appl. Phy., <u>13</u>, 440.

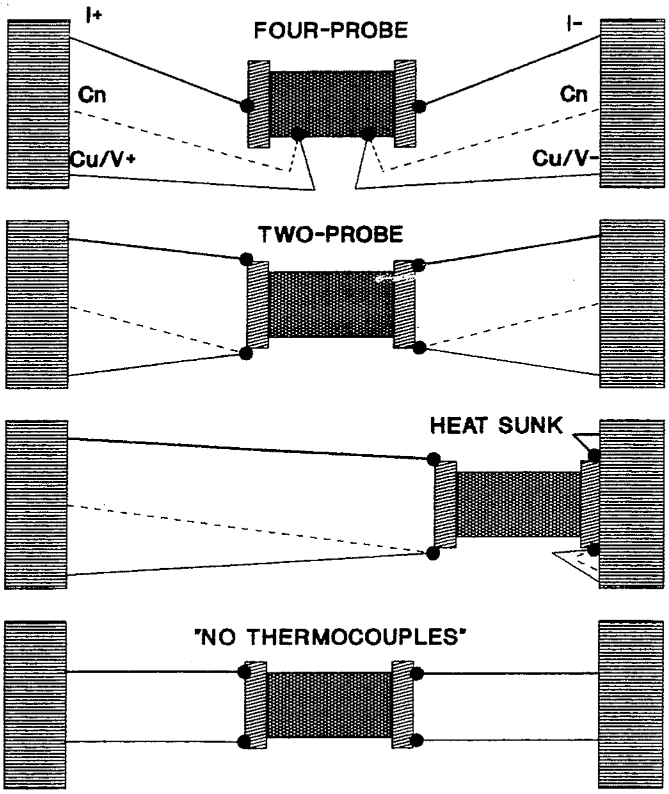


Figure 1: Optional test configurations for a TE pellet sample .

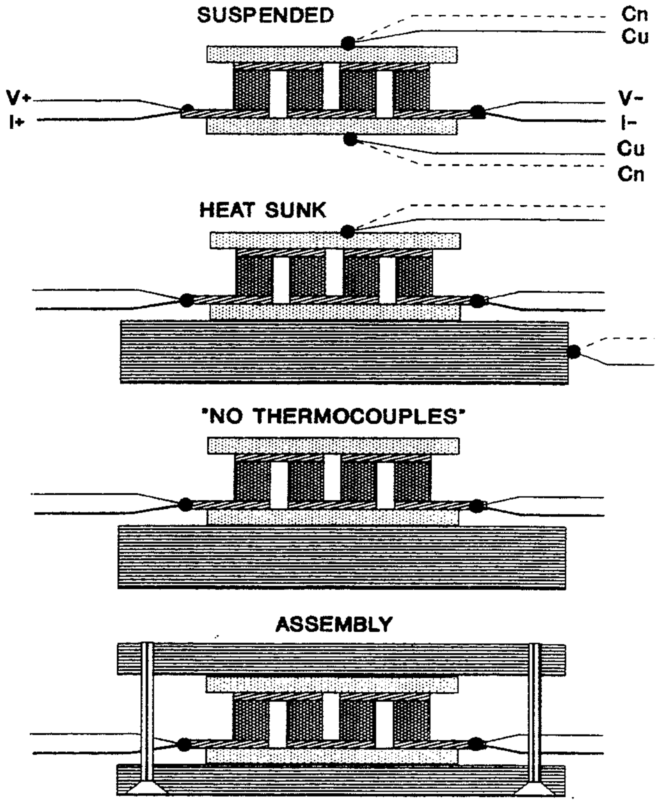


Figure 2: Optional test configurations for a TE module.

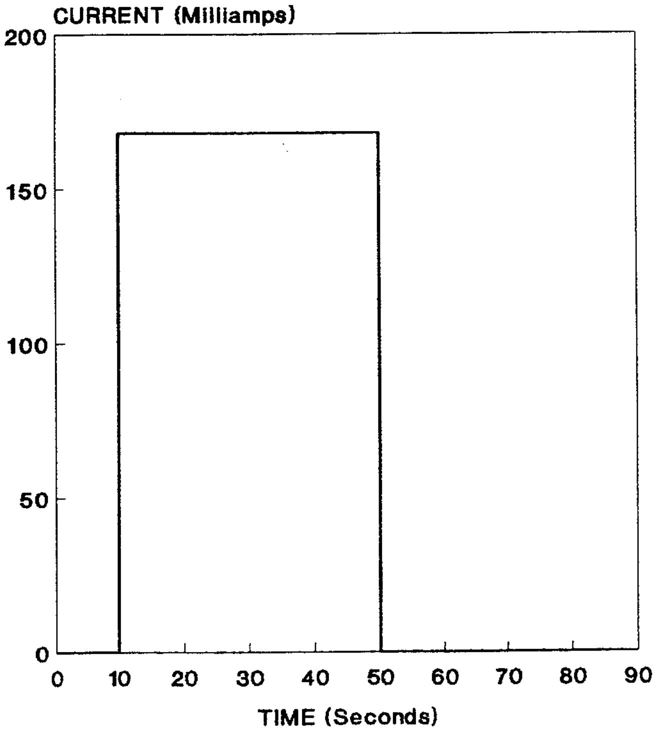


Figure 3: Current pulse applied to a TED.

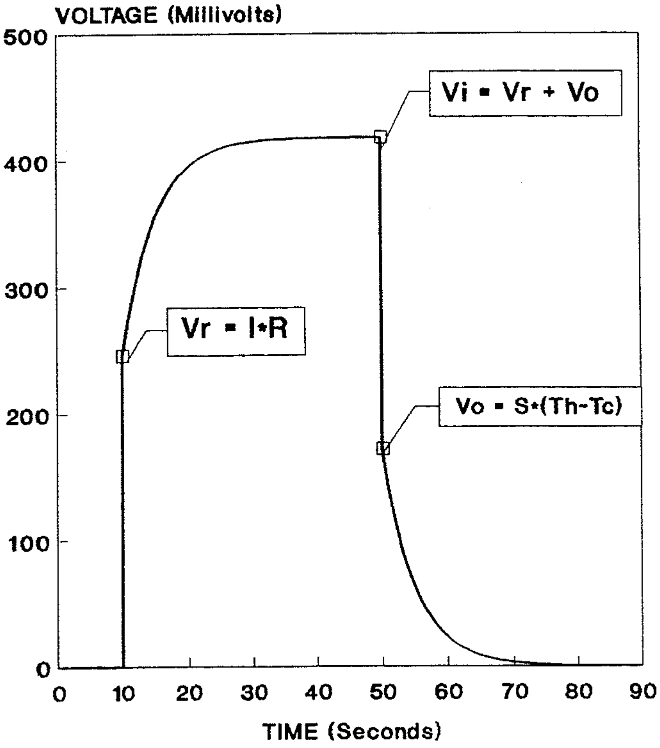


Figure 4: TED transient voltage due to the Figure 3 current pulse.

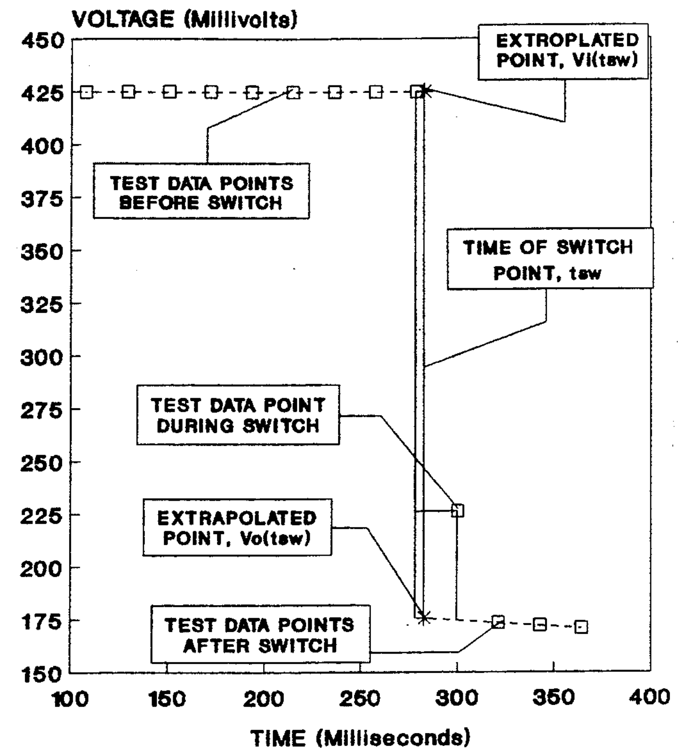


Figure 5: Determination of switch time, tsw, and corresponding voltages Vi(tsw) and Vo(tsw).

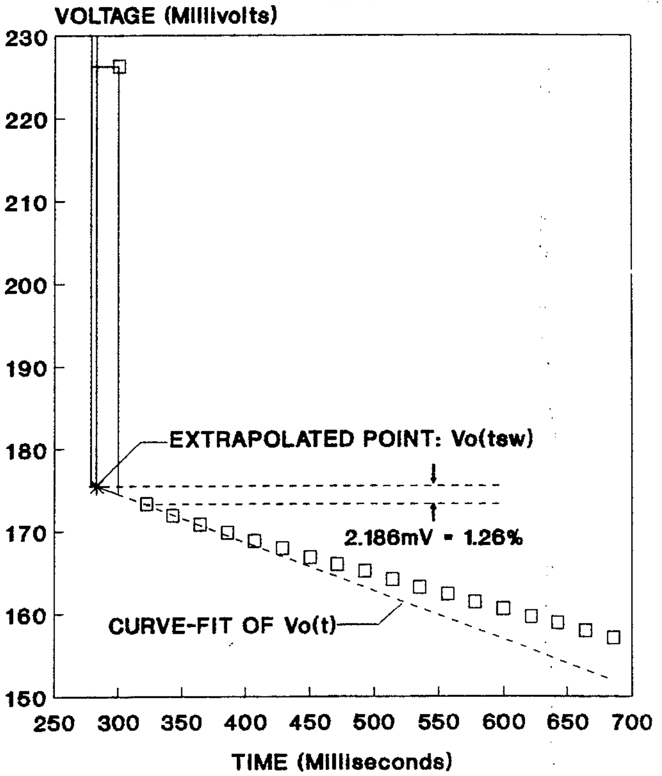


Figure 6: Analysis of data immediately following the switch point.

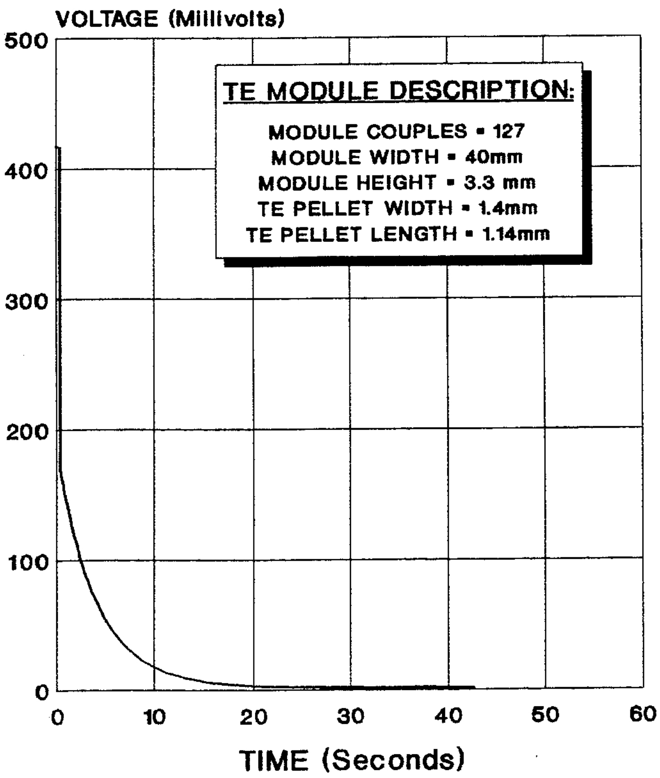


Figure 7: Transient test data from a TE module.

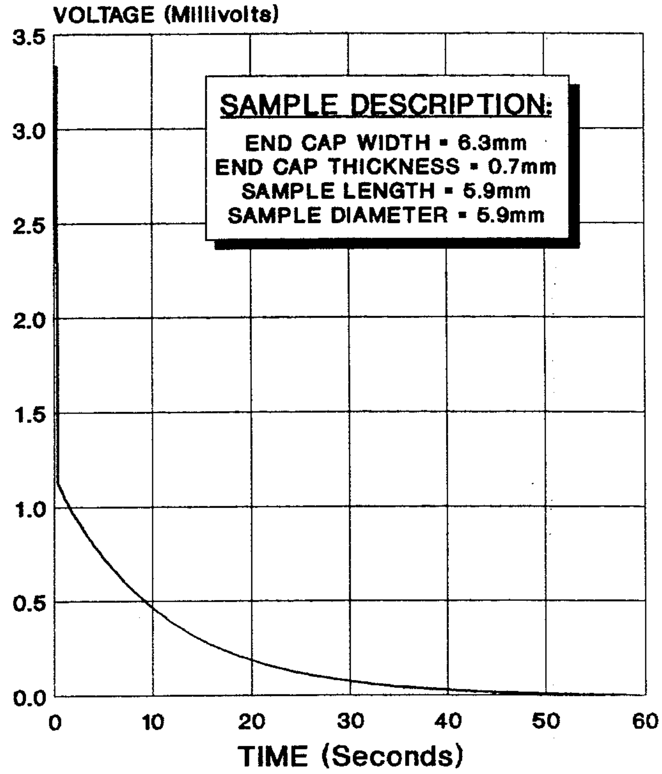
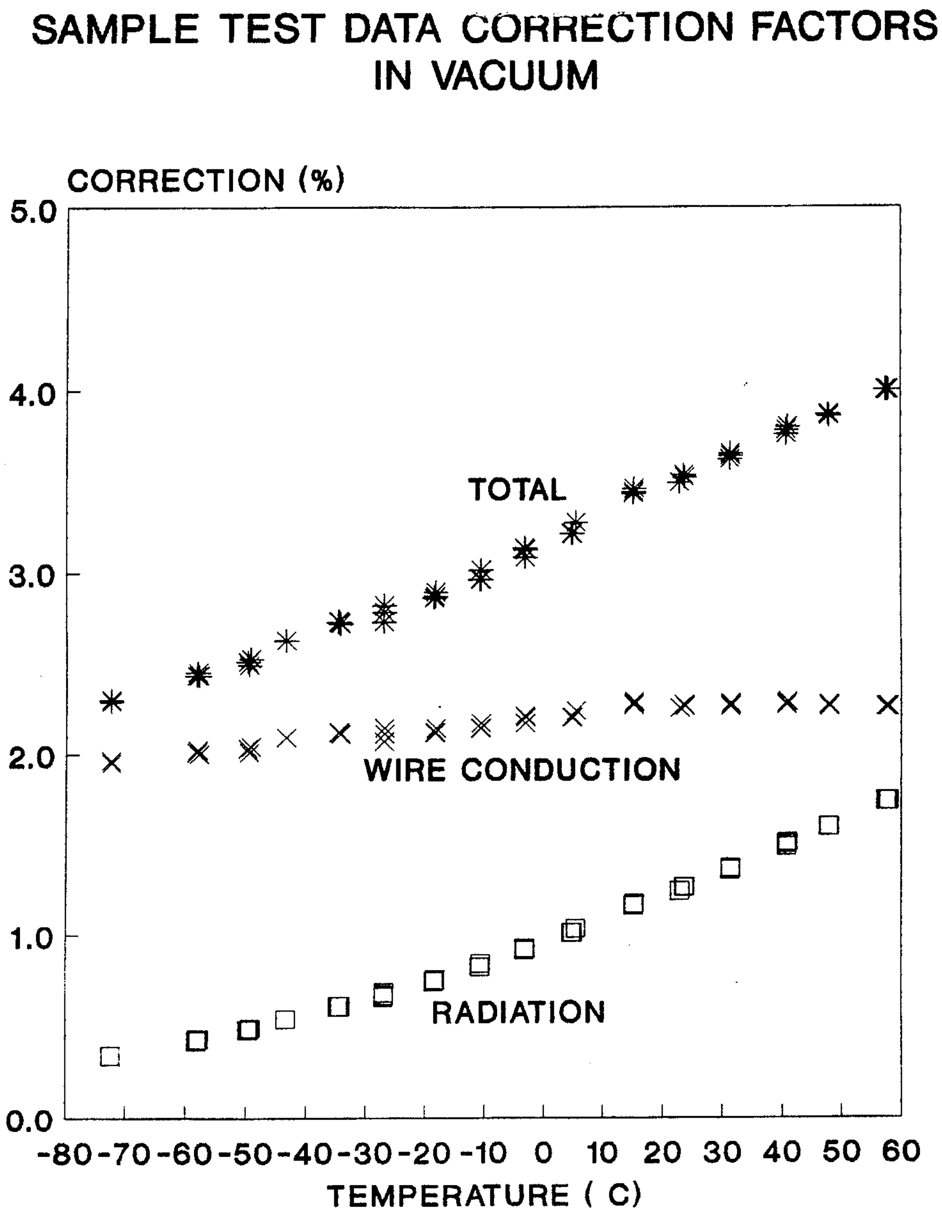


Figure 8: Transient test data from a TE pellet sample.



SAMPLE TEST DATA CORRECTION FACTORS IN VACUUM

Figure 13: Correction factors for a 2mm square x 1.6mm long TE pellet sample mounted onto the top stage of a multi-stage thermoelectric cooler in a vacuum of 10 milliTorr.

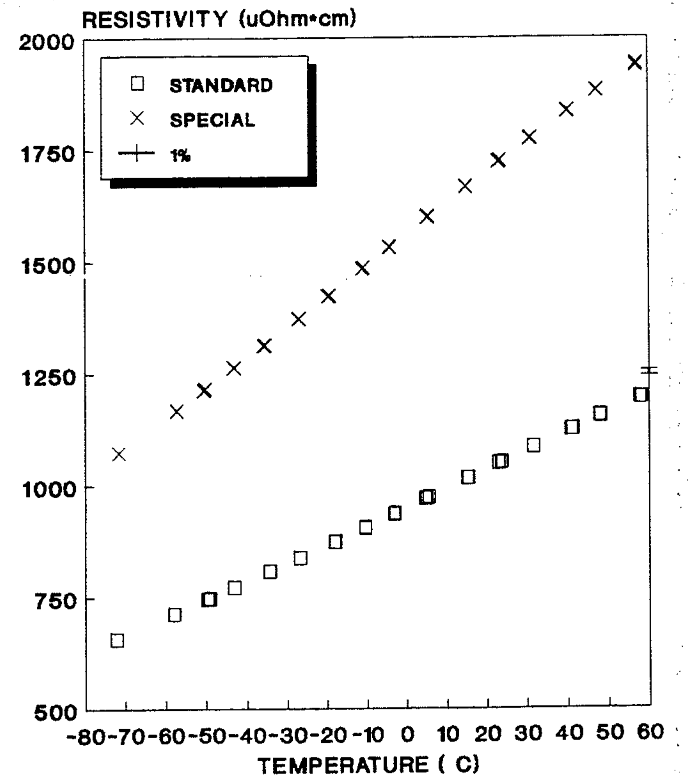


Figure 18: Electrical resistivity test data taken on standard and special N-type TE pellets as identified in Figure 13.

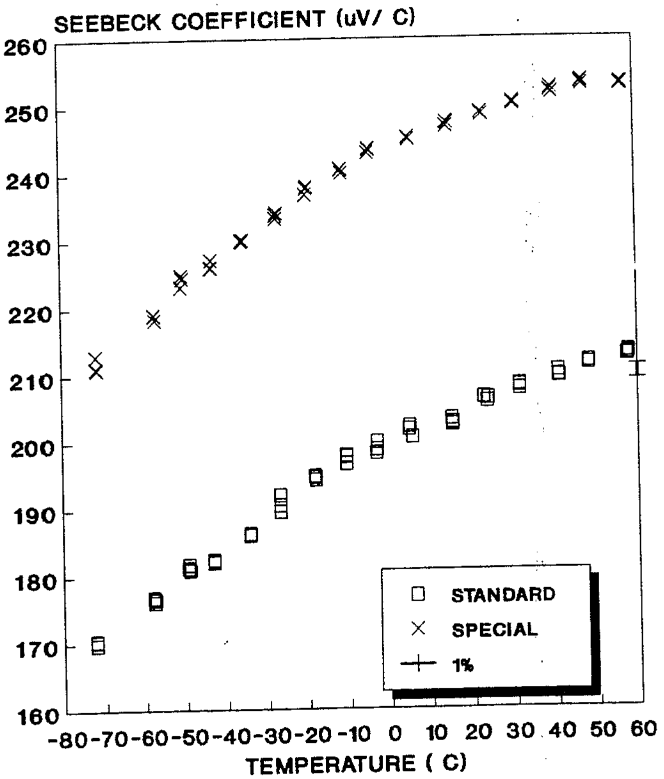


Figure 19: Seebeck coefficient test data taken on standard and special N-type TE pellets as identified in Figure 13.

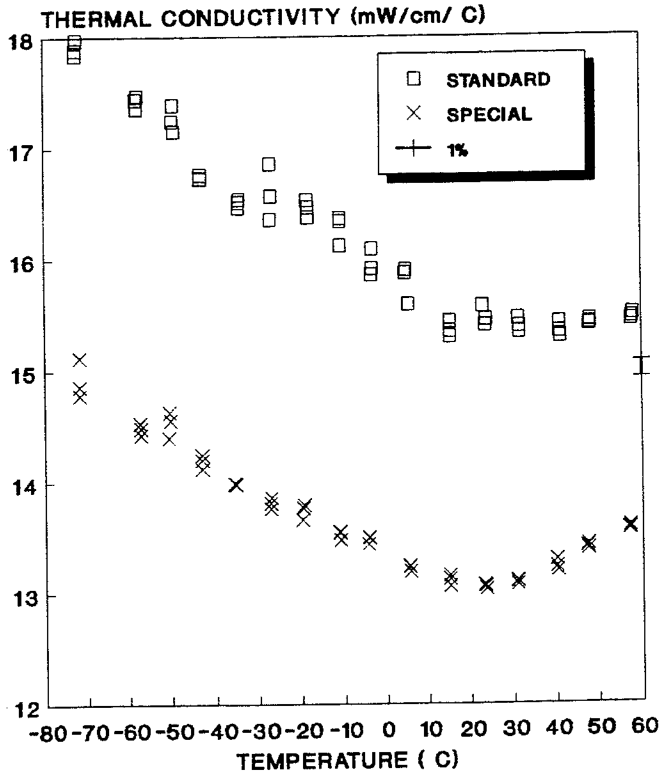


Figure 20: Thermal Conductivity test data taken on standard and special N-type TE pellets as identified in Figure 13.

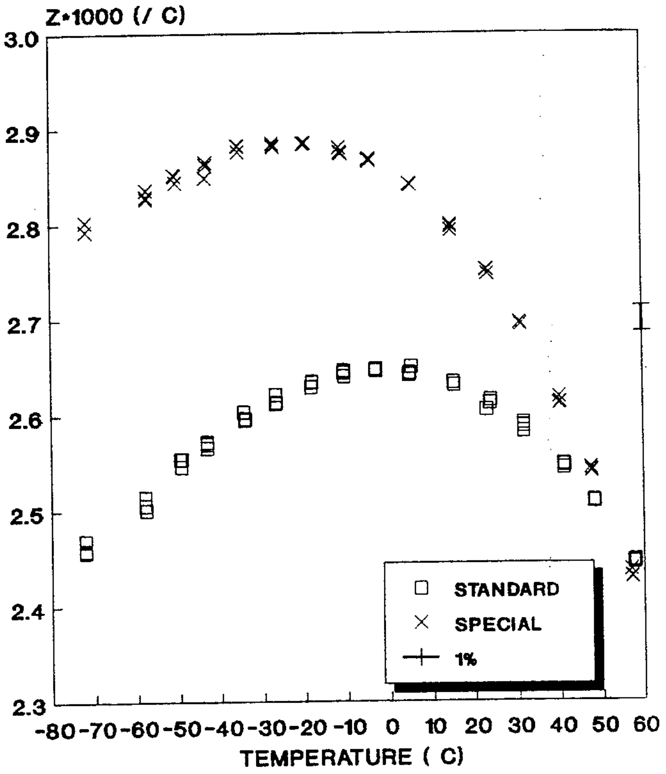


Figure 21: Figure of merit test data taken on standard and special N-type TE pellets as identified in Figure 13.

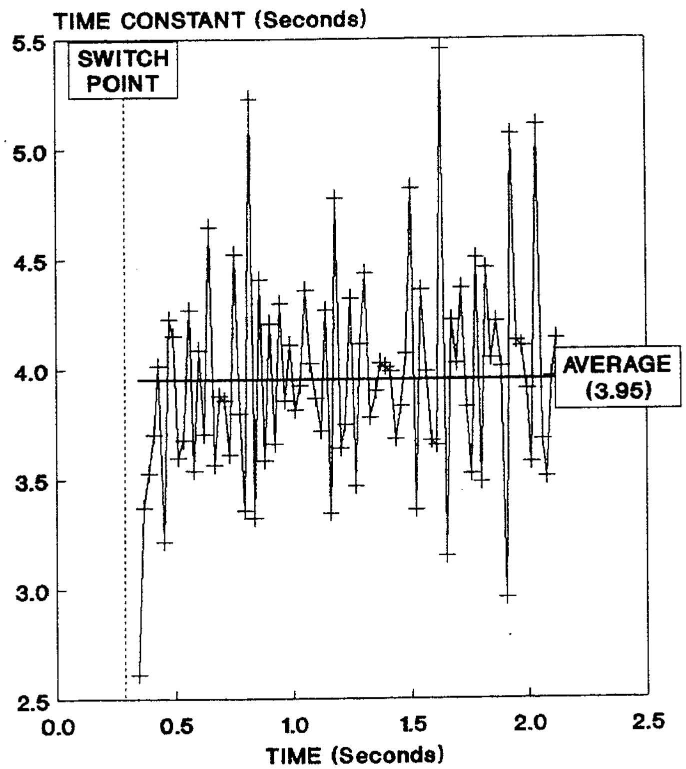


Figure 9: Time constant calculations from a point-to-point analysis of data taken from Figure 7.

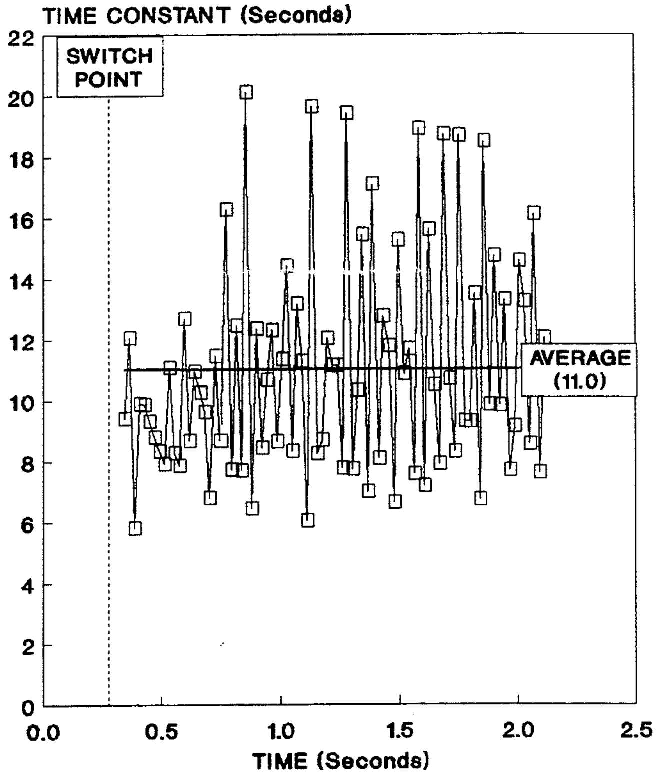


Figure 10: Time constant calculations from a point-to-point analysis of data taken from Figure 8.

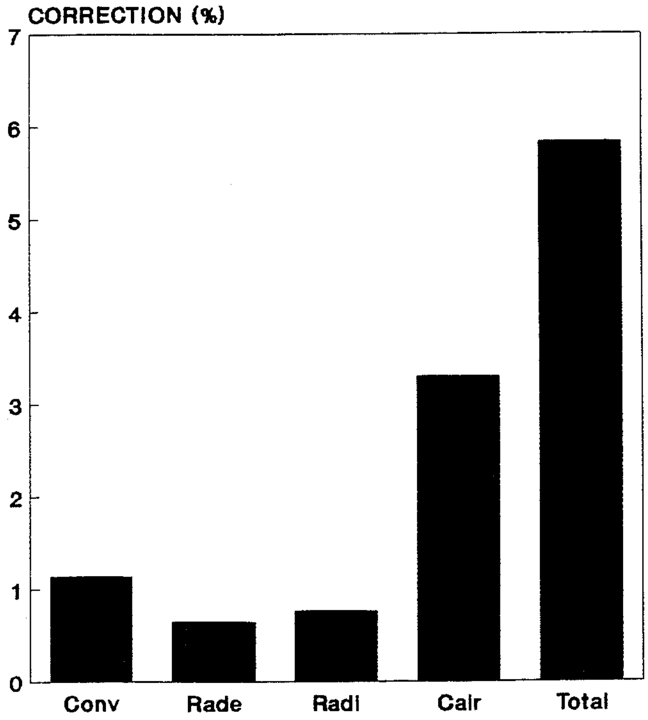


Figure 11: Correction factors for the TE module identified in Figure 7 tested in ambient air.

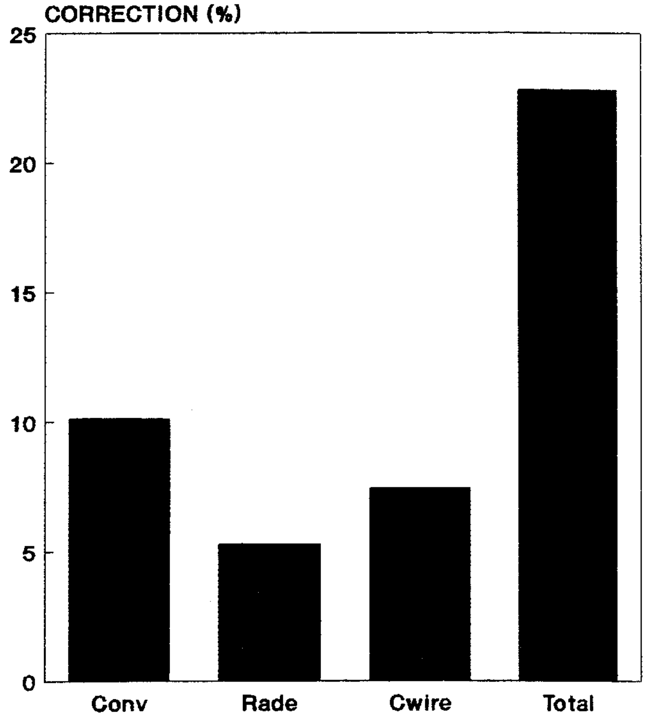


Figure 12: Correction factors for the TE pellet identified in Figure 8 tested in ambient air.

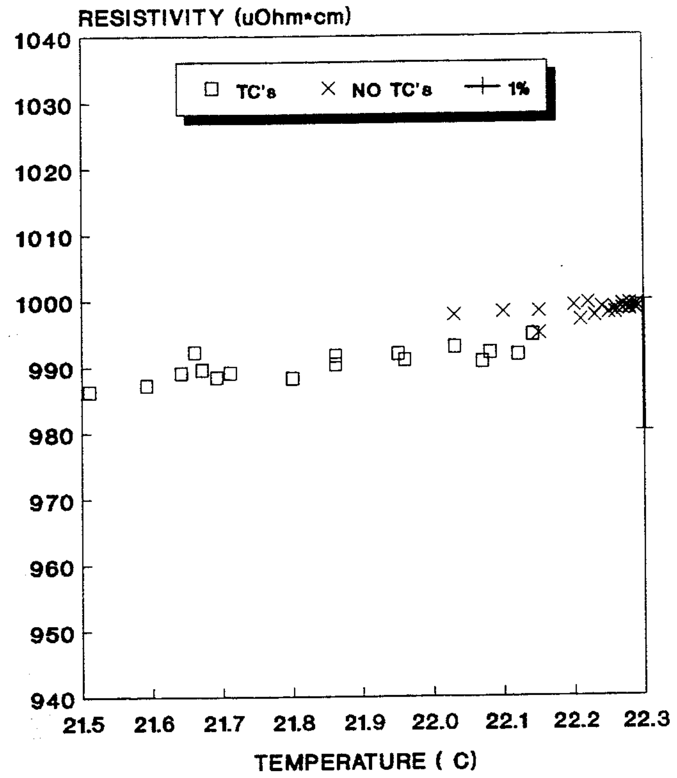


Figure 14: Electrical resistivity test data taken on the TE module tested via the SUSPENDED and NO THERMOCOUPLES configurations.

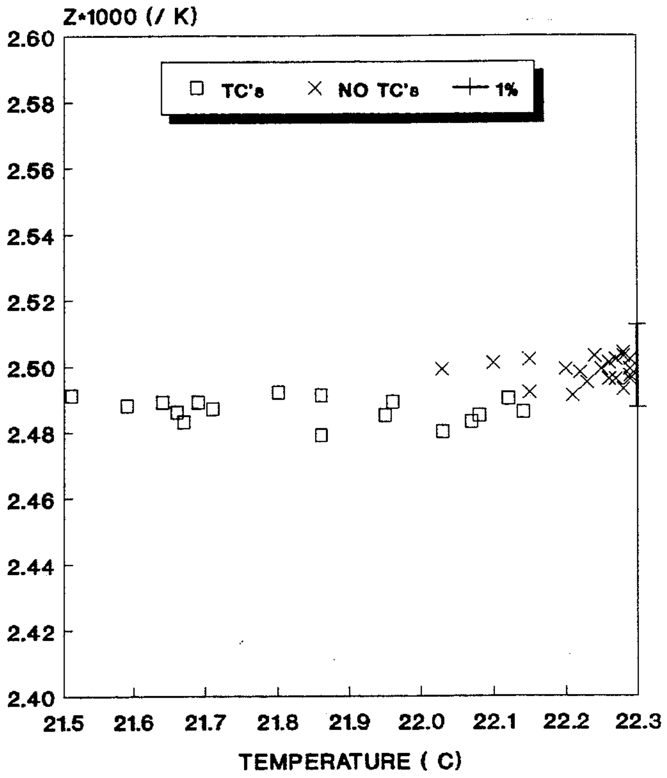


Figure 15: Figure of merit test data taken on the TE module tested via the SUSPENDED and NO THERMOCOUPLES configurations.

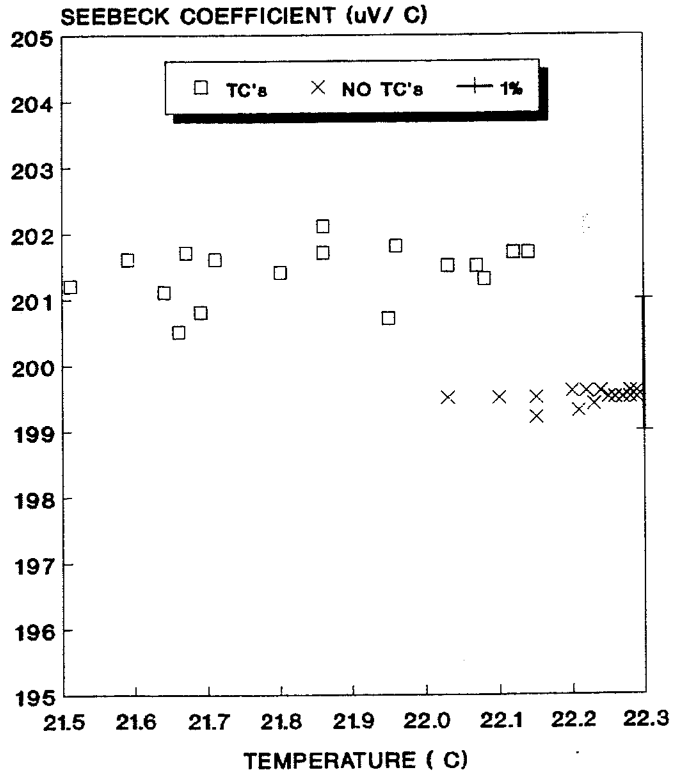


Figure 16: Seebeck coefficient test data taken on the TE module tested via the SUSPENDED and NO THERMOCOUPLES configurations.

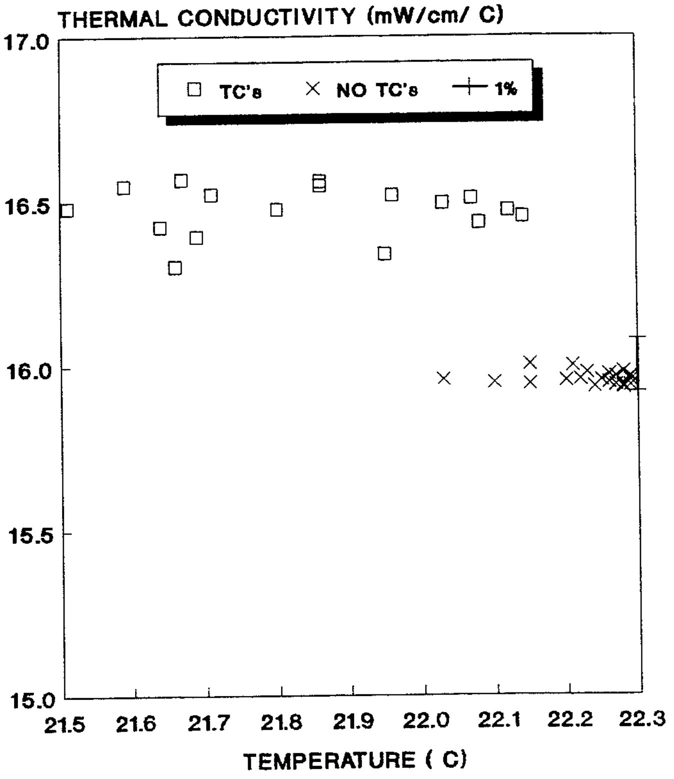


Figure 17: Thermal Conductivity test data taken on the TE module tested via the SUSPENDED and NO THERMOCOUPLES configurations.

TABLE 1
JUNCTION HEAT LOAD CALCULATIONS FOR A TE MODULE

	POSITIVE TEST MODE		NEGATIVE TEST MODE	
	HEAT ENTERING COLD JUNCTION	HEAT EXITING HOT JUNCTION	HEAT ENTERING COLD JUNCTION	HEAT EXITING HOT JUNCTION
1. Module Peltier	$-N*\alpha*I*Tc$	$-N*\alpha*I*Th$	$-N*\alpha*I'*Tc'$	$-N*\alpha*I'*Th'$
2. Module Conduction	$N*k*(Th-Tc)/L$	$N*k*(Th-Tc)/L$	$N*k*(Th'-Tc')/L$	$N*k*(Th'-Tc')/L$
3. Internal Radiation	$Ri(Th^{4}-Tc^{4})$	$Ri(Th^{4}-Tc^{4})$	$Ri(Th'^{4}-Tc'^{4})$	$Ri(Th'^{4}-Tc'^{4})$
4. External Radiation	$Re(Ta^{4}-Tc^{4})$	$Re(Th^{4}-Ta^{4})$	$Re(Ta'^{4}-Tc'^{4})$	$Re(Th'^{4}-Ta'^{4})$
5. Convection	$H*(Ta-Tc)$	$H*(Th-Ta)$	$H*(Ta'-Tc')$	$H*(Th'-Ta')$
6. Air Conduction	$Ka*(Th-Tc)$	$Ka*(Th-Tc)$	$Ka*(Th'-Tc')$	$Ka*(Th'-Tc')$
7. Wire Conduction	0	$W*(Th-Tw)$	$W*(Tw-Tc')$	0
8. Module Joule	$I^{2}*R/2$	$-I^{2}*R/2$	$I'^{2}*R/2$	$-I'^{2}*R/2$
9. Wire Joule	0	$-I^{2}*Rw$	$I'^{2}*Rw$	0

TABLE 2
SUM OF JUNCTION HEAT LOAD CALCULATIONS FOR A TE MODULE

1.	Module Peltier:	$Qp = -N*\alpha*(I*(Th+Tc) + I'*(Th'+Tc'))$
2.	Module Conduction:	$Qk = 2*N*k(Th-Tc+Th'-Tc')/L$
3.	Internal Radiation:	$Qri = 2*Kri*(Th-Tc+Th'-Tc')$
4.	External Radiation:	$Qre = Kre*(Th-Tc+Th'-Tc')$
5.	Convection:	$Qc = H*(Th-Tc+Th'-Tc')$
6.	Air Conduction:	$Qa = 2*Ka*(Th-Tc+Th'-Tc')$
7. *	Wire Conduction:	$Qw = 0$; Since $Tw = Th = Tc'$
8.	Module Joule:	$Qmj = 0$; Since I w I'
9.	Wire Joule:	$Qwj = 0$; Since I w I'

Where:
N = total number of TE pellets
α = TE material Seebeck coefficient
I, I' = Electrical current in POS & NEG modes
Th, Th' = Hot junction temperatures in POS & NEG modes
Tc, Tc' = Cold junction temperatures in POS & NEG modes
k = TE material Thermal conductivity
L = Length/area of TE pellet
$Ri = \sigma * \epsilon *$Internal surface area
$Re = \sigma * \epsilon *$External surface area
σ = Boltzman constant
ϵ = Effective emissivity (including shape factor)
H = Convection coefficient * External surface area
Ka = Air conductivity * Internal space area
W = Sum of wire thermal conductances
R = TE Module electrical resistance
Rw = Electrical current wire electrical resistance
$T = (Th+Tc)/2$
$Th^{4}-Tc^{4} = 4*T^{3}*(Th-Tc)$
$Kri = 4*T^{3}*Ri$
$Kre = 4*T^{3}*Re$