TRANSIENT ANALYSIS OF THERMAL JUNCTIONS WITHIN A THERMOELECTRIC COOLING ASSEMBLY

Authors:
Michael J. Nagy and Richard J. Buist

TE Technology, Inc.
1590 Keane Drive, Traverse City, Michigan 49686 USA

Abstract

The performance of a thermoelectric (TE) heat exchanger assembly is greatly affected by the quality of the thermal junctions connecting the modules and the mounting surfaces of the heat/cold sinks. The quality of this junction, in turn, is affected by many different variables. These include heat sink surface quality, quantity of thermal grease, contaminates in the thermal grease, assembly screw torque, tapped hole quality, surface finish of the modules and the variance in module heights.

Until now, junction quality could only be verified by disassembly of the heat exchanger or inferred from a full cooling performance test of the assembly. This paper details a new, transient test method which accurately and dependably characterizes the module-to-heat-sink thermal junctions. A small current is applied to the TE modules in a thermoelectric assembly. This induces a small temperature difference across the module and between the ceramics of the module and its neighboring heat/cold sink. Power is then removed and the module's ceramics return to the temperature of its neighboring heat sink. The rate of temperature decay is directly proportional to the junction quality. Thus, the residual Seebeck decay waveform directly correlates to thermal junction quality, providing the means for rapidly and accurately characterizing assembly quality.

Introduction

The performance of a thermoelectric assembly is largely affected by the quality of the thermal junctions between the module and the heat sink and cold sink (see Figure 1).

This is the most troublesome area in an assembly. Historically, it has also been one of the most difficult areas in an assembly to check for quality. Heat sinks, for example, can be visually inspected for quality. Modules can be tested prior to use. The AC resistance of an assembly can be checked to ensure the modules haven't been damaged during assembly. Thermal junctions, however, are buried in the assembly. Visual inspection of these junctions is difficult and not always accurate. For example, one may determine that a module is making contact with a heat sink, but it is impossible to know whether or not the correct compression force is being applied, even though the torque applied to each assembly screw is correct..

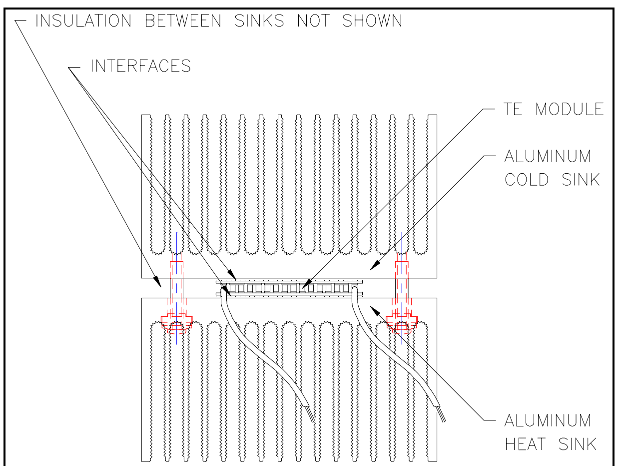

Fig. 1 TE heat exchanger configuration.

Typically, the only way to measure the quality of these junctions has been to actually test the completed assembly for thermal performance - either by measuring its steady-state cooling performance or by measuring its transient cool-down capabilities. Poor junctions lead to poor performing assemblies in both cases. However, these measurement techniques take a considerable amount of time and require the attachment of instrumentation to achieve proper results. Thus, a new measurement technique for determining the quality of a thermal junction is desirable. An ideal test would exhibit these criteria:

1. The test must be reproducible.
2. The test must work when the assembly is not isothermal.
3. Sensitivity must be greater than the measurement error.
4. With all other aspects of quality assured, passing the junction quality test should mean the assembly delivers acceptable performance.
5. No additional instrumentation of the assembly should be required.
6. The test should be much quicker than a full performance test.

This paper introduces a different method of testing which determines the quality of a thermal junction reproducibility and in a minimum amount of time without instrumentation.

Test Method

Figure 2 represents a simplified thermal model of an unpowered assembly. A temperature difference can be introduced between the module ceramics and their neighboring heat/cold sinks by applying a small current to the module. Removing current from the module allows the temperature difference within the module to decay. Varying thermal resistance between a module and the sinks will affect the rate at which this temperature difference decays. This phenomenon is the crux of this testing method. By analyzing the Seebeck decay waveform of an assembly, it is possible to differentiate between assemblies of identical construction yet varying thermal junction quality.

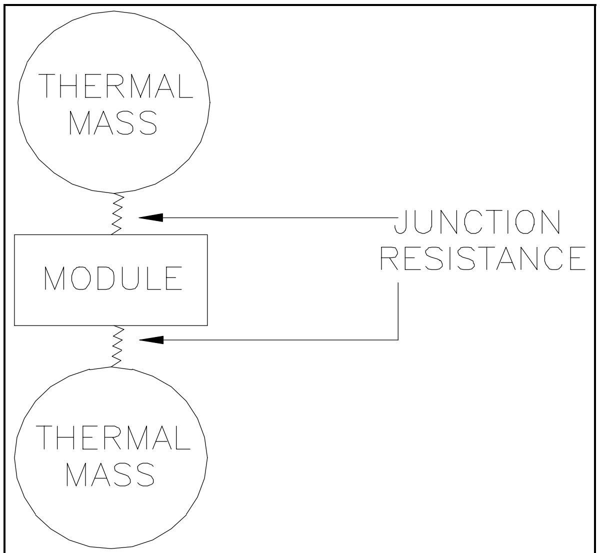

Fig. 2 Model of Heat Exchanger.

All test data gathered was taken on a TE Technology, Inc. model TS-205 test system [1]. This tester is capable of supplying a constant current to the TE assembly, switching power off, and the monitoring and storing the voltage decay.

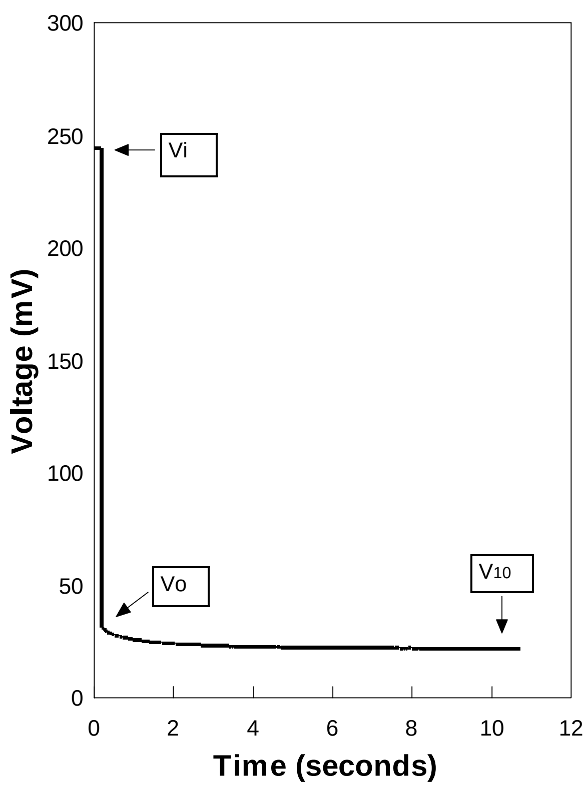

Fig. 3 Transient test waveform.

A typical test waveform is shown in figure 3.

Current was applied to the assembly for 120 seconds. The magnitude of the applied current was equal to 3% of Imax. This current and time combination was chosen because it created a sufficiently large Seebeck voltage (temperature difference) across the modules. Current was then switched off and the residual Seebeck voltage was recorded. The decay waveform was then analyzed to produce a junction quality factor which was proportional to the quality of the thermal junctions within the assembly.

Testing

The first series of tests shows the difference between junctions of varying quality. Two aluminum heat sinks of equal size and mass were combined with a 6 amp 127 couple module to make a test assembly. For the experiments, an assembly with infinitely poor junctions was represented by a module itself (no heat sinks used). An assembly with moderately poor junctions was represented by using no grease during the assembly process. Finally, an assembly with good thermal junctions was represented by using thermal grease during the assembly process. Figure 4 shows the transient decay waveforms for these three cases.

This same assembly was then tested when it was not in an isothermal state. This non-isothermal state was induced by

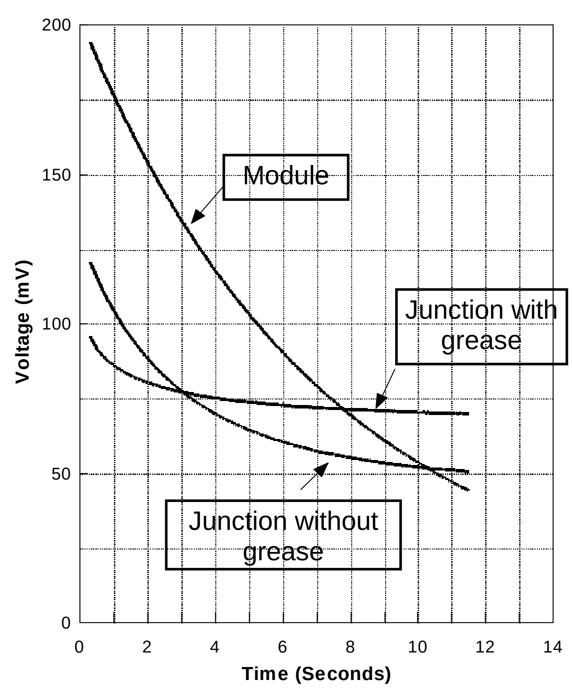

Fig. 4 Voltage decay waveforms for various configurations.

using positive and negative test currents to create a significant temperature difference between the heat and cold sinks of the assembly. The most extreme temperature difference between the sinks took approximately one hour to create at the extreme case. This data is shown in figure 5. In the case where the voltage actually appears to level off at a negative voltage, the assembly was “charged” to allow a negative temperature difference to build between the heat sink and cold sink. Then, the leads were reversed and a test cycle was completed.

Results

Figure 4 clearly shows the difference in transient waveforms between assemblies of varying junction quality. The general

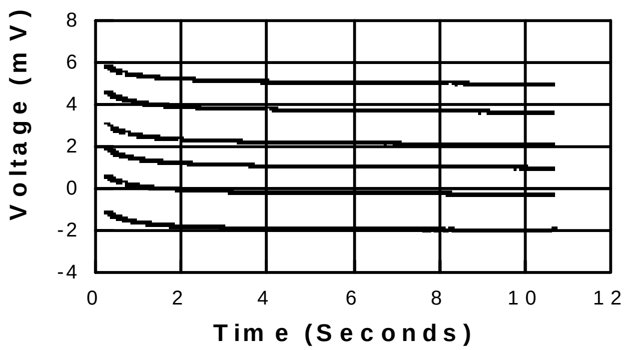

Fig. 5 Voltage decay waveforms for various starting conditions.

trends are as follows: for any given charge time and current,

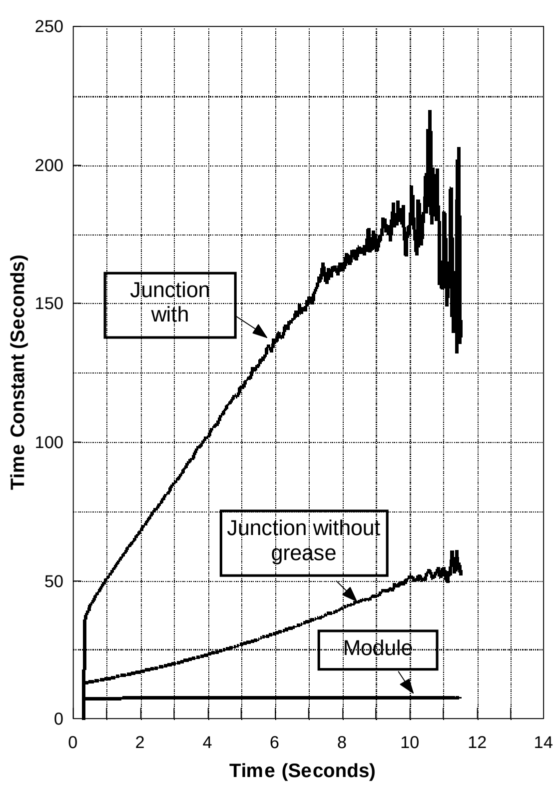

Fig. 6 Calculated time constants of various configurations.

the assembly with better thermal junctions will exhibit a lower initial Seebeck voltage. The decay waveform is much slower for an assembly with good thermal junctions.

Figure 6 shows the time constants for the three waveforms of figure 4. An assembly with better thermal junctions will, in general, have a larger time constant. However, only the module exhibited a steady time constant.

Figure 5 shows that, regardless of the temperature differences between the heat sink and cold sink, the shapes of the transient decay waveforms are nearly identical by visual inspection. This is further supported by figure 7. Here, the waveforms of

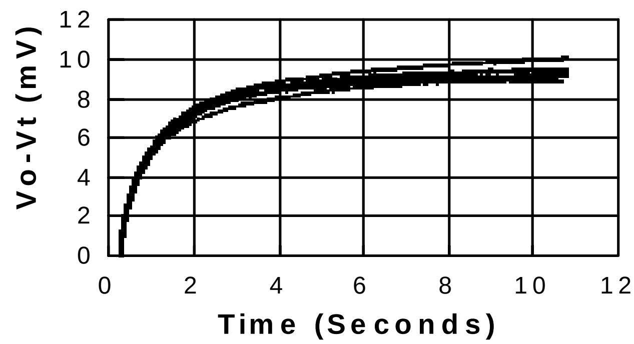

Fig. 7 Residual Seebeck decay for various starting conditions.

figure 5 have been adjusted to show the amount of change in Seebeck decay as a function of time. Once again, these waveforms are nearly identical.

Derivation of Junction Quality Factor

Figures 4, 5 and 7 clearly show that an assembly will have a characteristic decay waveform and that its shape is dependent on the quality of the thermal junctions in the assembly. A formula has been created to extract a factor from the decay waveform which corresponds to the quality of the thermal junctions. This factor, called the junction quality factor, is defined by the equation:

$$Qjctn = (V_i - V_o)/(V_o - V_{10}) \quad (1)$$

Where: V_i = Voltage just prior to current turn off,
V_o = Voltage immediately after current turn off,
V_{10} = Voltage 10 seconds after current turn off.

In order to understand how this formula was derived, it is necessary to understand some proposed analysis techniques which were not chosen.

A calculation of time constant was initially thought to be the choice method for characterizing junction quality. However, this proved to be impractical. Figure 5 shows that, if there is a temperature difference between the heat sink and cold sink, the transient voltage will decay to an apparent non-zero asymptote. This shall be called V_∞ for the sake of analysis. If we assume the decay can be characterized by a simple first order exponential equation (which it cannot), the equation would be written:

$$Vt=(Vo- V_\infty)e^{-t/\tau} + V_\infty \qquad (2)$$

The equation can be rewritten as:

$$\tau = \frac{-t}{\ln\left(\frac{Vt - V\infty}{Vo - V\infty}\right)} \qquad (3)$$

Clearly V_∞ must be known for τ to be calculated. Because V_∞ is really only an apparent asymptote, and because it occurs a considerable time after current switch off in a "good" assembly, this was deemed impractical.

The ratio of Vt/Vo was also considered. This too, was considered unacceptable because of the unknown value of V_∞.

One quickly calculable number which was representative of the quality of the junction was Vo-Vt where Vt represents the module voltage "t" seconds after current switch-off. This number proved to be very sensitive to junction quality. A poor junction allows a relatively high initial Seebeck voltage followed by a rapid decay. Thus, Vo-Vt is large for this case. Conversely, a good junction allows a lower initial Seebeck voltage followed by a slow decay. This causes Vo-Vt to be small for a good thermal junction. Furthermore, because Vo-Vt represents only the amount of decay in Seebeck voltage, it is insensitive to a waveform which decays to a non-zero asymptote.

Used alone, the above defined difference varies directly with both the number of couples and current in the module or series/parallel combination of modules. The resistive voltage drop measured immediately prior to current switch off was then used to normalize this difference. Thus, a series combination of n modules will increase both the resistance and Seebeck voltage by a factor of n. Conversely, paralleling n modules will reduce the reduce the resistance by a factor of 1/n. However, the current per couple (and thus Seebeck voltage) is also reduced by a factor of 1/n. Inclusion of this resistive voltage lead to the Qjctn formula as defined in equation 1. By dividing the resistive voltage with the decay in Seebeck voltage a dimensionless number is derived which is directly proportional to the quality of the thermal junction yet insensitive to varying series/parallel combinations of modules.

The sensitivity and reproducibility of Qjctn was measured by testing the three original assemblies. Figure 8 shows a threefold increase in Qjctn between a module and an assembly made without thermal grease. Qjctn then doubled when the assembly was made with grease. Reproducibility was excellent. All three repeat tests for each type of assembly yielded nearly identical results.

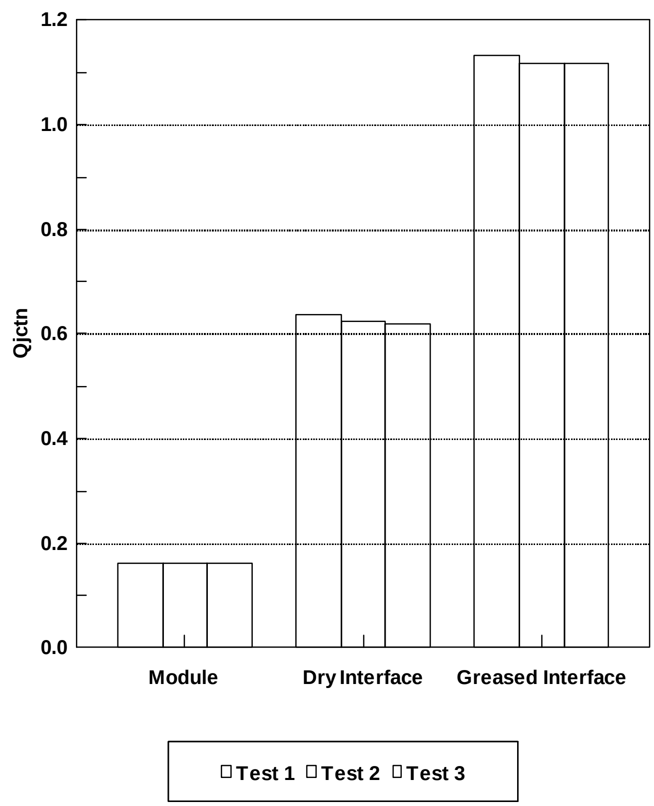

Fig. 8 Qjctn for various configurations.

Discussion

Figure 5 shows that the slope of the curves, and therefore Qjctn, is relatively insensitive to temperature differences that exist between the heat and cold sinks in an assembly. We can deduce from this data that the test has a strong dependence on the time constant of the module and relatively little dependence on the time constant of the assembly. As the time constant of module is orders of magnitude lower than that of an assembly, it should stand to reason that test times are orders of magnitude lower than assembly performance tests. However, this strong dependence on the module's time constant suggests that the thermal mass of a module's element length, ceramics, tabs and solder would affect the test and produce a unique Qjctn per type of module.

Currently, no method exists for the prediction of Qjctn. However, a transient model such as the one developed by Lau and Buist [2] could very well be adaptable for prediction of Qjctn. This work is currently underway.

Finally, it should be noted that this transient test only qualifies the thermal junctions in an assembly. Therefore, it must be used in conjunction with other tests to qualify an assembly. These tests include the testing of modules for figure of merit, testing the AC resistance of the modules before assembly and testing the AC resistance of the modules after assembly. However, since the latter is easily extractable from the same raw data base, Qjctn and AC resistance are essentially tested simultaneously.

Summary/Conclusions

A new method has been developed to test the quality of the module-to-heat/cold sink thermal junctions within a thermoelectric assembly. A small current is applied to the modules for 120 seconds. The current is then removed and the residual Seebeck voltage decay is monitored. Thermal junctions of differing qualities will exhibit different decay waveforms. These waveforms differ in the amount of residual Seebeck voltage as well as the rate at which it decays. Thus, a formula for junction quality, Qjctn, was defined which compares the power-on resistive voltage to the decay in Seebeck voltage 10 seconds after current is switched off. Qjctn becomes larger as the quality of the thermal junction increases. The inclusion of resistance voltage drop in the equation makes Qjctn insensitive to any series or parallel combination of modules.

The test has important applications as a quality control tool. It reproducibility exhibits a high sensitivity to thermal junction quality. Furthermore, testing can be completed in about two minutes, making the test much quicker than other methods used to distinguish junction quality. This method has been evaluated by Ritzer, Nagy and Buist [3] and established as a very effective quality control tool for production.

References

[1] R.J. Buist, "A New Method for Testing Thermoelectric Materials and Devices", *11th International Conference on Thermoelectrics*, Arlington, Texas, USA , (1992).

[2] P.G. Lau and R.J. Buist, "Temperature and Time Dependent Finite Difference Model of a Thermoelectric Pellet and Couple", in *Proceedings of the XV Conference on Thermoelectrics*, Pasadena, California, USA, 1996.

[3] T.M. Ritzer, M.J. Nagy and R.J. Buist, "Evaluation of Thermal Junction Quality in Thermoelectric Assemblies Using Transient Analysis Technology", in *Proceedings of the XV Conference on Thermoelectrics*, Pasadena, California, USA, 1996.