A Critical Evaluation of Today's Thermoelectric Modules

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Abstract

Today's thermoelectric module (TEM) users are experiencing a growing world marketplace filled with new or undiscovered sources for components. Selecting the right thermoelectric module supplier for a particular application is not as easy as it once was.

New applications in thermoelectrics are occurring faster now than ever before as more people learn the benefits of using the technology. As these applications become more diversified and the variety of the customer's needs expands, other criteria should be considered before selecting a TEM supplier based solely on price, performance and delivery.

This paper examines TEMs produced by manufacturers from all over the world. A module performance survey illustrates the range of products available today. Some of the TEM's were selected from this survey to undergo a variety of quality and reliability tests. These tests include electro-thermo cycling, high temperature ramp and soak, and thermal pulse. In addition, dimensional and visual inspections were performed and the results are included as a part of the overall "vendor qualification" process described in this paper.

Introduction

A series of tests and measurements should be performed in order to thoroughly evaluate a TEM. Most of these tests are designed to examine the performance and reliability of the module. Failures, as a result of these tests, usually occur in the areas of pellet joining.

After a TEM has passed the performance requirements of a particular application, the next step is to determine whether or not the device will be reliable. To do this, the TEM is subjected to three standard tests incorporating various conditions designed to stress pellet diffusion barriers and the module's mechanical joining quality.

TEM Performance Test

The first area of interest when selecting a TEM is typically the performance of the device based on the particular requirements of the application. The test method most widely used to measure the performance characteristics of a TEM is referred to as the modified Harman technique.

This test, originally developed by T. Harman and J. Honig[1] in the early 1960's, was modified by R. Buist[2] to incorporate a "transient" method that enabled one to quickly and accurately measure the Seebeck coefficient, α; electrical resistivity, ρ; thermal conductivity, κ; and ZT.

The data presented in Figure 1 illustrates the ZT values for a standard 127 couple, 6 amp module. The Y-axis represents the ZT value measured in the thermocouple mode[2] at room temperature. Each letter designation on the X-axis represents a different TEM manufacturer. The second set of points for letters E, A, and F represents the values of modules commonly found in products produced by these vendors. The high levels of ZT by these vendors illustrates what they're capable of producing upon "special selection". This is especially interesting to note in the "A" vendors' case, having the capability of producing the best performing TEM in the lab and nearly the lowest in large volume production.

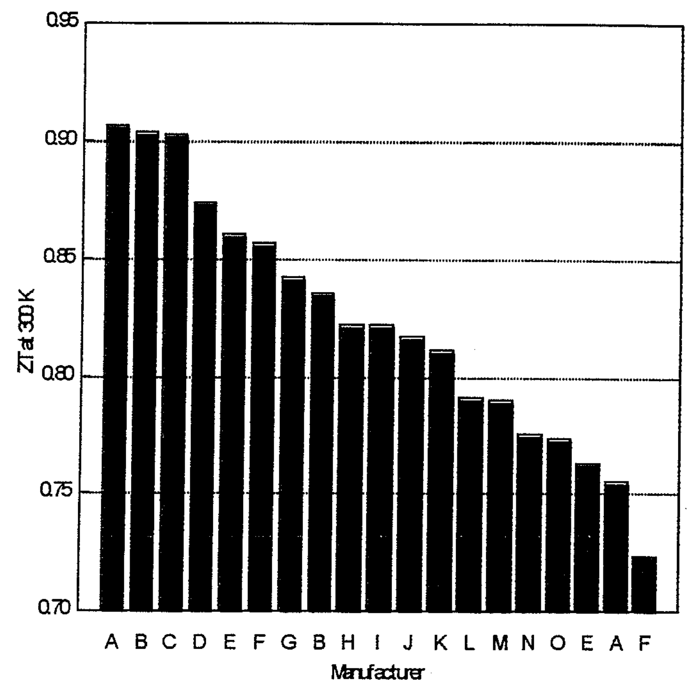

Figure 1 Thermoelectric Module Survey

Cycle Test

The next test, TEMs are commonly subject to undergo, is often referred to as the cycle test. Techniques of this type of test vary from manufacturer to manufacturer but the basic principle remains the same. The TEMs are usually temporarily assembled between two heat sinks. Power is then applied to the module for a short period of time, usually 5 to 10 minutes. An automatic timer switch then reverses (some only power off as in Bell 40/90 test) the power to the TEM for another short duration, thus completing a cycle.

The test method used for gathering this data applied approximately 12 VDC in the positive or "cooling direction" for 5 minutes. The power is then reversed to the negative direction for a 5 minute increment at approximately 5 VDC.

The temperatures that were produced during this particular test were approximately -15°C in the cooling mode and approximately 50°C when heating. A counter recorded the number of cycles completed throughout the test. The test apparatus incorporated the "bang-bang" or "full-power-on" process when power is applied to the module and was capable of testing up to 6 TEMs simultaneously. This particular method was more severe than the standard "Bell 90/40" test, therefore, reducing the time required to determine TEM reliability.

The data presented in Figure 2 illustrates the shift in AC resistance as a result of over three thousand temperature cycles. The test data shows rapid degradation in modules #4 and #5. This trend indicates likely catastrophic failure for these two modules. The continuing increase in AC resistance for the other three modules is further evidence this manufacturer has unreliable TEMs.

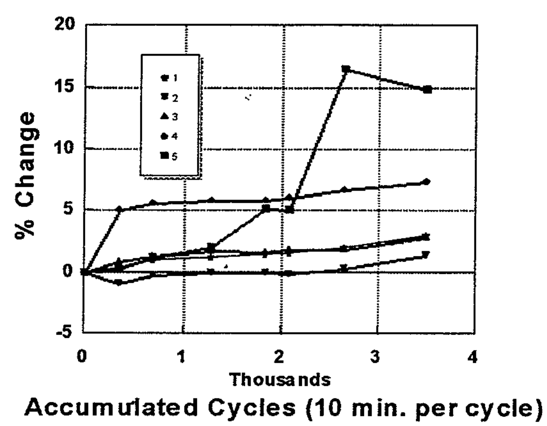

Figure 2 Percent Change in AC-Resistance Due to Temperature Cycling

Figure 3 is an example of a group of TEMs that have undergone the same test. These TEMs exhibit a slight shift in AC resistance initially, however, level-off at an acceptable value, <5% change.

High Temperature Ramp and Soak Test

This test, sometimes referred to as a bake test, is used to thermally stress a TEM. The TEM is subjected to elevated ambient temperatures near the maximum operating range for extended periods of time. The stresses incurred during this type of test affect both the effectiveness of the nickel diffusion barrier on the TE material and the mechanical integrity of the solder bonds at each junction.

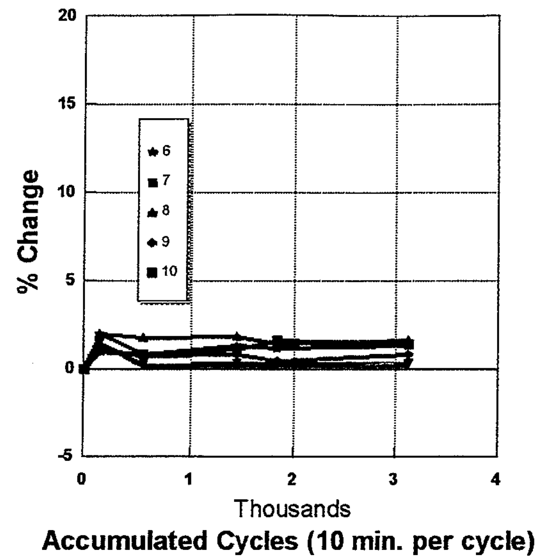

Figure 3 Percent Change in AC-Resistance Due to Temperature Cycling

The TEMs used for this test are standard high temperature devices that are rated for continual operation up to 200°C. Before exposure to the high temperature environment, the modules were tested to measure the AC resistance and ZT. Any increase in AC resistance and/or decrease in ZT observed in TEMs after this type of high temperature exposure would be an indication of an inferior TEM.

The TEMs were placed in a laboratory oven and heated to 160°C for a 24 hour period. The TEMs were then removed from the oven and allowed to cool to room temperature. The AC resistance and ZT values were measured again and TEMs were placed back into the oven for another heating interval at 160°C. After approximately 72 hours, the TEMs were removed from the oven, allowed to cool to room temperature, and the AC resistance and ZT measured again. A final sequence of baking at 160°C for 168 hours was completed and again, the values for AC resistance and ZT measured.

Figure 4 shows the effect on the AC resistance as a result of over 260 hours of exposure at 160°C. These 10 TEMs exhibit an alarming rise in AC resistance at a temperature 40°C lower than the specified operating range. Some TEMs changed over 40% and all of them continued to increase when the testing was stopped. It was clear from this dramatic increase that the TEMs would likely not survive an operating environment near 200°C. It was not certain whether the actual failure mechanism was due to a degradation in the diffusion barrier or a mechanical breakdown in the solder junctions. Further analysis is needed to make this determination.

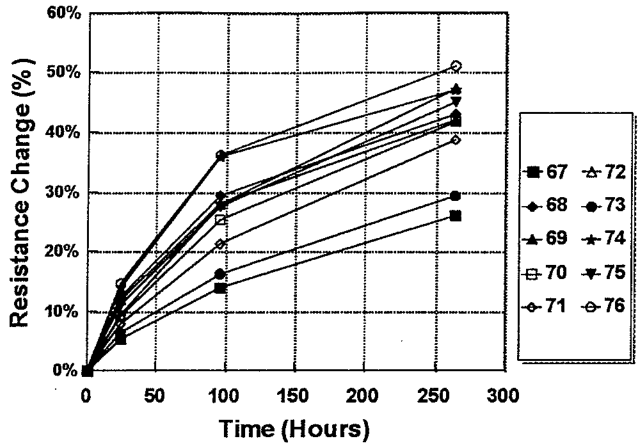

Figure 4 Effect of Exposure at 160°C on Resistance of TE Modules

Figure 5 illustrates the effect the high temperature exposure had on the ZT of the TEMs. It can be expected that a dramatic increase in AC resistance could result in a significant decrease in ZT. This phenomenon was observed in all 10 TEMs as a result of this test.

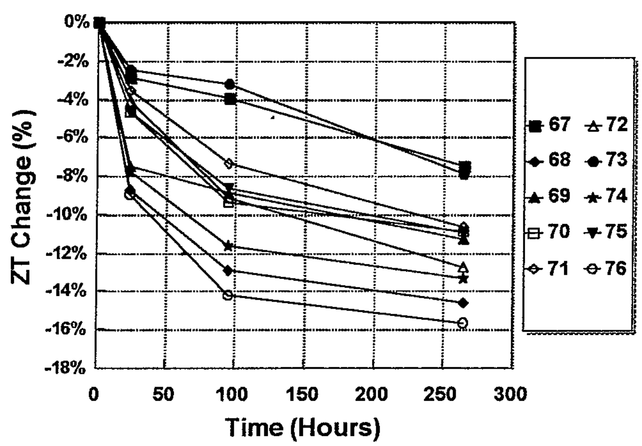

Figure 5 Effect of Exposure at 160°C on ZT of TE Modules

However, this degradation was not as extreme as in the case of the shift in AC resistance. In fact, the ZT failures made a significant shift initially, while beginning to level off after 100 hours. These observed changes could be as a result of diffusion of copper into the TE material. Since the magnitude of the AC resistance increase was so great and was continually rising, it can be surmised that the nature of the failure was more mechanical than chemical.

Thermal Pulse Test

There is another type of test that can be performed on TEMs to evaluate the integrity of solder junctions. This test applies a brief pulse of AC voltage to all the solder connections in a TEM. This instantaneous high voltage burst of energy will create substantial heat in solder connections that are inadequate. This heat energy, which is a function of contact resistance, can be observed by placing a piece of thermally activated paper, such as ordinary facsimile paper, against both surfaces of the TEM as the pulse is applied. Any extreme "hot-spots" in the TEM will expose the thermal paper somewhat like opening the shutter on a camera exposes film.

This test can be performed on any type of TEM and yield results in only a few seconds. Having the ability to quickly test a TEM for solder junction integrity has its advantages and disadvantages though. One shortcoming of this technique is that it is not very quantitative. It cannot always be determined whether or not the TEM is certain to fail during operation or not. It has been the author's experience, however, that these "hot-spots" are an indication of poor workmanship and/or inferior TEM components such as ceramic metalization, nickel plating on tabs or insufficient solder bonding.

The photograph in Figure 6 illustrates the results from a pulse test that was performed on two TEMs produced by different manufacturers. Both of the modules were similar in type and tested under the same conditions. The voltage was adjusted to 100 VAC and the pulse time to 1/10 of a second. It was determined through a few set-up runs that these parameters produced the best exposure for this particular type of TEM.

It can be observed that the thermal paper in the top of the photograph has a relatively uniform exposure of both sides of

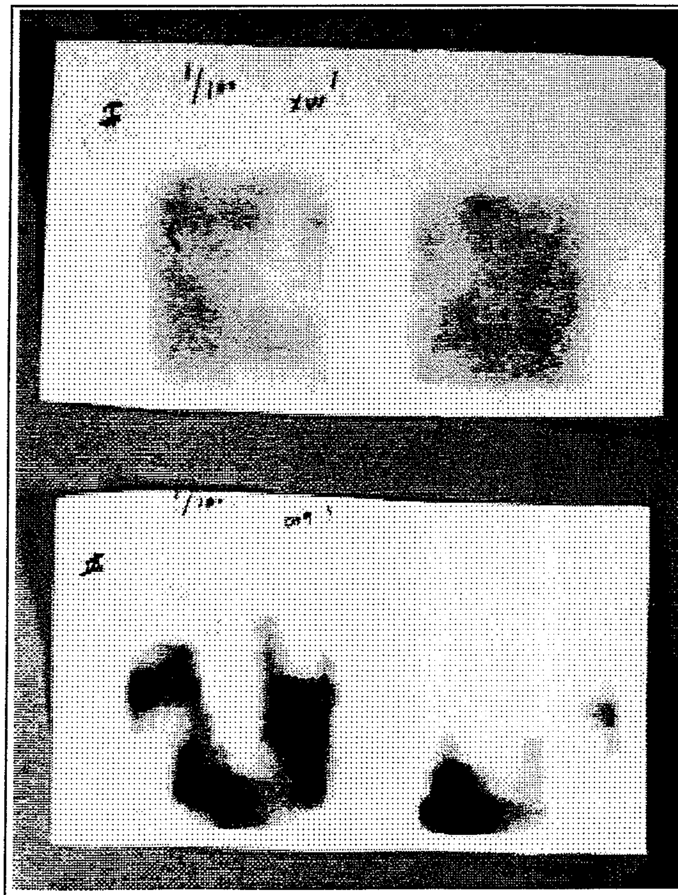

Figure 6 Exposed Thermal Paper due to Thermal Pulse Test

the TEM. From this type of even heat spreading throughout the module it can be surmised that this was a good module. However, the exposure pattern in the bottom sample shows evidence of extreme heating in several pellet junction areas on both sides of the TEM. This type of pattern is evidence of non-uniform contact resistance throughout the TEM.

Discussion

The data presented in the previous sections illustrated several cases where TEMs failed due to the rigors of vigorous testing. The actual cause for these failures is not always easily recognized from the results of the tests performed.

For example, the TEMs in Figure 4 exhibited extreme increases in AC resistance as a result of exposure to high temperatures. To determine the exact cause of the failure, further analysis is required.

The photo in Figure 7 was produced through use of a Scanning Electron Microscope (SEM). The TEM was sectioned through a row of TE pellet junctions to analyze the mechanical integrity of the solder joint and the effectiveness of the nickel diffusion barrier. It was determined from this analysis that there was no evidence present that would verify any copper had migrated into the TE material. This photo does, however, reveal a substantial crack along the entire solder connection between the flame sprayed nickel barrier and the TE material. This type of separation as result of poor nickel bonding verifies that these particular TEMs will not withstand the mechanical forces exerted by thermal stress and vibration.

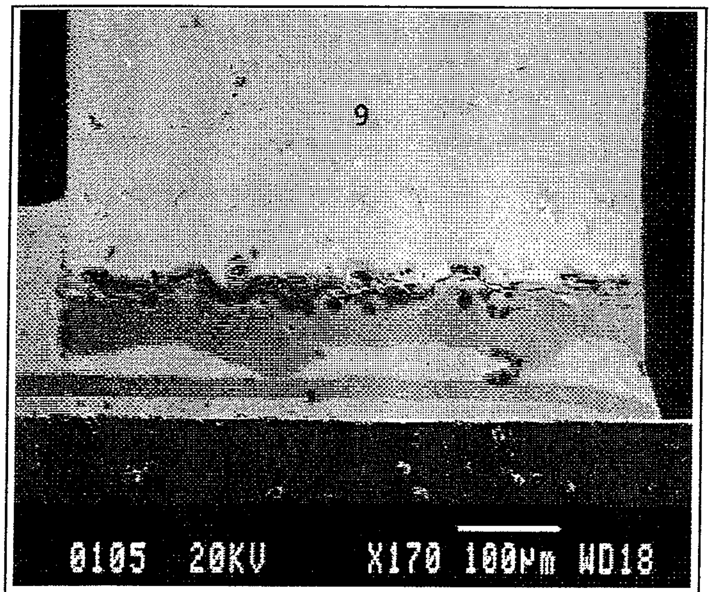

Figure 7 SEM Analysis of High Temperature TEM Solder Joint

Sometimes, mechanical failures in solder junctions are not caused by assembly process but by inferior raw materials such as ceramics and copper tabs. Figure 8 is a photograph illustrating an example of a standard alumina ceramic substrate (top) that was used in a TEM. The substrate had poor adhesion between the alumina and the metalization. The tab array patterns on the substrates in the bottom of the photo exhibits copper tabs that have insufficient nickel plating. When tabs of this nature are used in a TEM, the probability is quite high that the module will fail due to inadequate solder adhesion and/or copper diffusion.

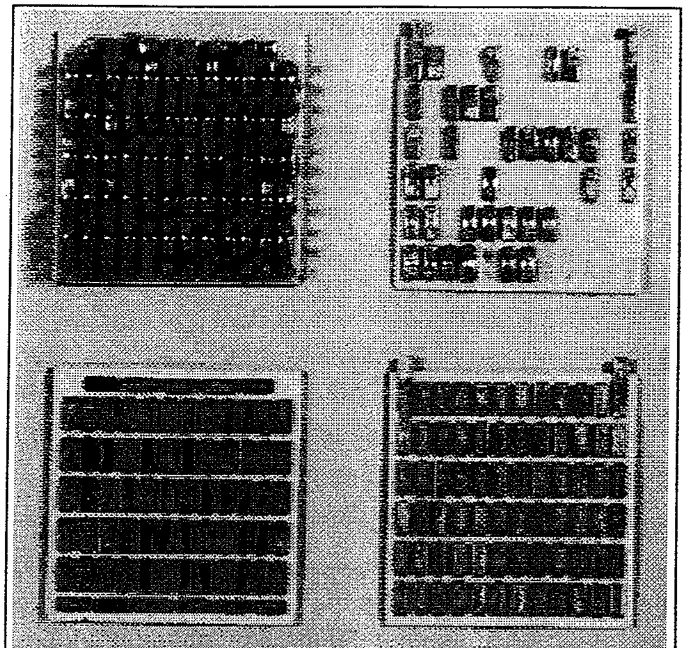

Figure 8 Sample of Inferior TEM Substrate Assemblies

Another condition that sometimes exists with the ceramic substrate is irregular surface finish or blemishes. A TEM should always be lapped or ground flat after assembly in order to achieve smooth, flat and parallel mounting surfaces. However, if the module has weak solder junctions, machining the ceramic surfaces can sometimes destroy the TEM. In one particular case, a TEM manufacture was unable to lap its modules due to weak solder connections. These modules had extremely wavy mounting surfaces. The measured "wave form" across the surface varied between 0.040mm to 0.072mm in height. Typically a TEM should have a surface finish that measures no more than 0.5µm and a flatness of ±0.025.

Excessive solder in a TEM can also be a problem for some manufactures. Electrical shorts between couples and excessive solder wicking can cause a TEM to perform lower than desired or may even become inoperable all together. Figure 9 is a photograph of a TEM magnified through a microscope, illustrating excessive solder wicking up the sides of the TE pellets. This type of condition can greatly reduce the overall performance of the module. Corrections in the assembly process should be made in order to minimize the amount of solder that is applied.

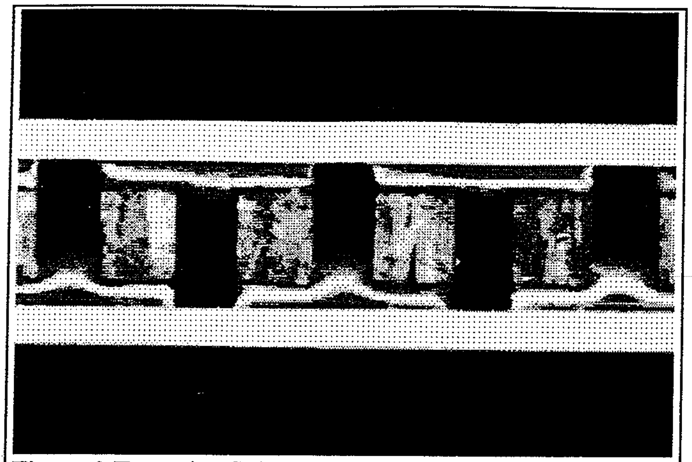

Figure 9 Excessive Solder Build Up in a TEM

Conclusion

The evaluation of TEMs is an on-going process at TE Technology, Inc. Verifying the performance and quality of the various suppliers from around the world is crucial to any manufacturer that needs to assure quality, performance and reliability.

It is apparent from this survey that not all TEMs produced today meet the specifications claimed. Differences in processes, raw materials and skill level all contribute to the variation in products that exist throughout the industry. Refining the techniques required to produce reliable TEMs is not as easy as it may appear. The delicate nature of the TE material, coupled with the difficulty in solder adhesion has made advancements in manufactureability a challenge for most, if not all, suppliers.

The future success of thermoelectrics is becoming increasingly more dependant on costs, performance and reliability. Experimentation in material science, material processing and assembly automation should be a priority for any supplier striving to improve its products. That is why we are continuing to explore new methods in TEM testing, manufacturing and design as part of our day to day operations.

References

[1] Harman, T. C. and Honig, J. M., "J. Appl. Phys.", 13, 440, 1962.

[2] Buist, R. J., "Methodology for Testing Thermoelectric Materials and Devices", *CRC Handbook of Thermoelectrics*, CRC Press, Inc., 1995