

Thermoelectric Device Packaging for High Reliability Aerospace Applications

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Abstract

Modern military aircraft increasingly use optical components and systems to process information. Thermoelectric coolers (TEC's) improve performance in similar terrestrial applications by providing active temperature control of the optical components. Thermoelectric coolers are generally not used in aerospace applications because of concerns with reliability. While, thermoelectric coolers have a long history of reliable use in land based optical communication systems, aircraft environmental requirements are much more severe. This highlights the need for a better understanding for the role of packaging and joining materials in thermoelectric/optical component reliability and the ability to model and predict internal stress.

To investigate, test specimens were prepared using different size thermoelectric coolers, packaging materials and solder types. TEC's of 10 and 16 mm size were soldered to metal plates with CTE values from 6 to 10 ppm/°C. Solder joints included Tin/Lead and Indium/Silver based solders. The specimens were thermal cycled with different temperature ranges to determine the point of failure, the most severe range being +125 to -55°C, a typical qualification requirement for aerospace components. Each specimen was modeled using multiphysics FEA software. The goal was to determine a life-stress model that could predict thermal cycle life for a specific stress level.

The results revealed TEC's can readily survive over 1000 thermal cycles for aerospace qualification. Indium mounting solders performed the best and allowed the greatest devices size and difference in thermoelectric to package CTE. Finally, the life-stress model was applied to a unique planar-multistage thermoelectric cooler to explore the range of its application.

Key Words: thermoelectric coolers, aerospace, thermal stress, reliability

Introduction

Thermoelectric coolers have a long history of use in land based telecommunication applications. In this application, they have with a well established track record of highly reliable service. The service requirements can be up to 25 years of operation in their environment. The qualification requirements have been established by industrial organizations such as Telecordia. These requirements include

power cycling, thermal cycling, high temperature storage and mechanical shock and vibration.

Modern aircraft, particularly military aircraft, have great demands to process and handle information. This information processing is increasingly being performed in the optical domain. Current and future aircraft optical systems and components would benefit from the cooling and temperature stabilization ability of TEC's that are routinely used in land based system.

There are numerous benefits from TEC use in aerospace applications. TEC's normally do not add much to the physical size of a device, and can fit within close physical proximity of the cooled device. The same TEC can cool or heat. They can be quickly optimized for the required temperature difference, and the amount of heat transfer. Lack of moving parts provide a reliability advantage. Since there is no vibration, they can be used for temperature control where mechanical stability is required.

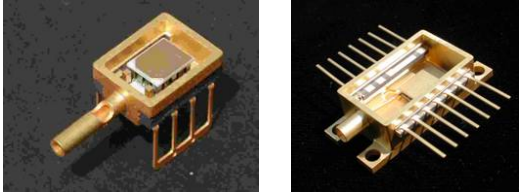


Fig. 1 Example TEC packages.

In general, aerospace communication applications fall in three groups for single stage TEC's:

- Control is required within a temperature range to avoid damage caused by an excursion, or to bring a device to operating temperature quickly. Cooler size varies.
- Control is required for temperature tuning, particularly for active optical sources. Typical devices are physically small ($< 2 \text{ cm}^2$), medium delta-T (nominal 50°C), medium heat transfer ($0.2 - 0.5 \text{ watts}$).
- Control is required for stability. Typical devices are large (up to a few square inches), but required for control of passive devices such as filters, low to mid delta-T ($20 - 50^\circ\text{C}$), low heat transfer (from ambient only).

Multistage varieties of coolers are used more in sensor applications where physical device size is small to medium ($< 1 \text{ cm}^2$), the delta-T is large and heat transfer small.

There are significant differences between qualification requirements of land based TEC's with those of typical aircraft components. One of the most significant is in thermal cycling requirements. Telecordia GR468 defines a thermal cycle qualification of -40 to $+85^\circ\text{C}$ for 500 cycles for TEC's. Many aircraft components must survive a qualification of -55 to $+125^\circ\text{C}$ for 1000 cycles. This is clearly much more severe and highlights the need to characterize TEC's under aircraft requirements.

Experiments

Thermoelectrically cooled telecom packages have been produced in many sizes and shapes. A

typical configuration is depicted in Fig. 2. A TEC is installed in a hermetic package with a base, sidewalls and lid. The TEC is soldered to the package base. A separate platform is soldered to the TEC top, which holds various active and passive components. The base and platform can be metal or ceramic and are selected to match the CTE of the TEC ceramics.

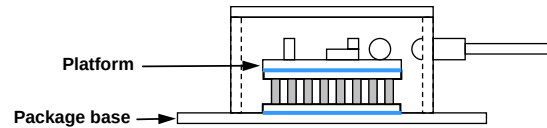


Fig. 2 Diagram of internal TEC/package layout.

For this program, a stress environment for the TEC similar to a hermetic package was created by attaching external metal plates to the top and base surfaces. A diagram of a test specimen is shown in Fig. 3. TEC's are made using ceramic substrates. These are typically alumina, but beryllia and aluminum nitride are also used. Alumina has a CTE of approximately $6.3 \text{ ppm}/^\circ\text{C}$. To vary internal stress levels, The experiments used different materials for the metal plates and different temperatures for thermal cycling to accelerate the internal stress in the TEC's.

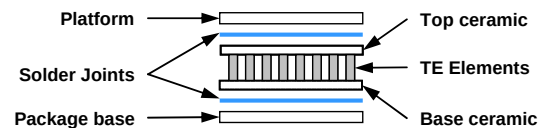


Fig. 3 Test specimen design to simulate TEC/package.

Three metals were used for the external plates. Kovar provided one material with a CTE similar to the TEC while Alloy48 and 430SS provided progressively greater CTE values. Specimens with different combinations of these

Table 1 Materials used for test specimens.

Material	CTE, ppm/ $^\circ\text{C}$
430 Stainless Steel, "SS"	10.4
Alloy 48 (48Ni/Fe), "A48"	8.3
Kovar, "Kov"	5.8

plates were then cycled over different temperature ranges and monitored to identify the point of failure.

Two TEC's of different sizes were chosen for testing, the SP5415 and SP5420. The SP5415 has 36 couples with a top ceramic diagonal size of 16 mm. The SP5470 has 24 couples with a 10 mm top diagonal.

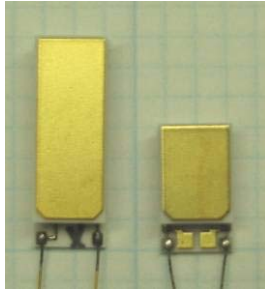


Fig. 4 TEC's used in tests.

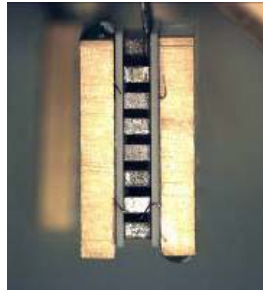


Fig. 5 Typical test specimen.

The exterior of the TEC's and the metal plates were nickel plated with a gold flash. The primary attachment solder for the external plates was 63Sn/37Pb (183°C melting point). A 0.1mm thick preform of solder was cut to size and reflowed to attach the plates to the TEC. All specimens were allowed to cure or anneal for 3 days minimum at room temperature.

The TEC specimen lead wires were attached to a fixture with a test connector. The TEC's then hung freely from their leads to eliminate unwanted sources of stress. This also allowed the specimens to closely follow the temperature in the thermal cycle chamber. The fixture allowed for connection to a data logger so the TEC resistance could be monitored continuously during cycling.

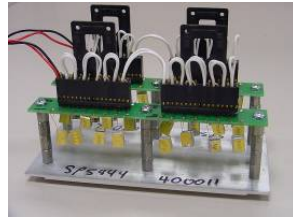


Fig. 6 Test fixture.

Results

A graph of typical results for an accelerated stress test is shown in Fig. 7. The graph shows the TEC resistance during cycling. This resistance can be

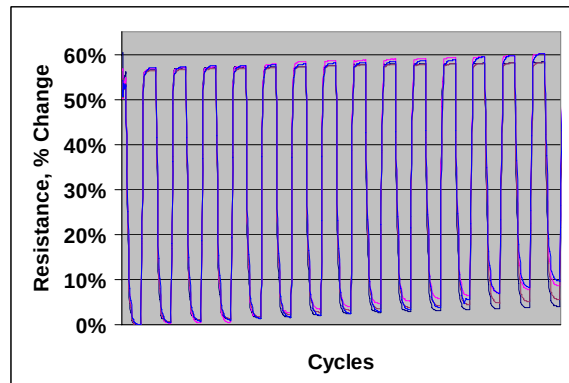


Fig. 7 Example of data collected during thermal cycling.

seen to increase and decrease with the chamber temperature. The specimens first show signs of change during the lower temperature phase of the cycle. The resistance at the first low temperature phase was used as an initial value to calculate a percent increase. For this analysis, an increase of 5% was used as an indicator of failure.

The overall results for the larger SP5415 and smaller SP5470 are listed in Table 4 and shown in Fig. 8 as a log-normal distribution. Table 3 lists the configurations of the test groups. The analysis used is a power-law/log-normal life model that follows the development given in Nelson [1]. This model is used to describe many life-stress relationships.

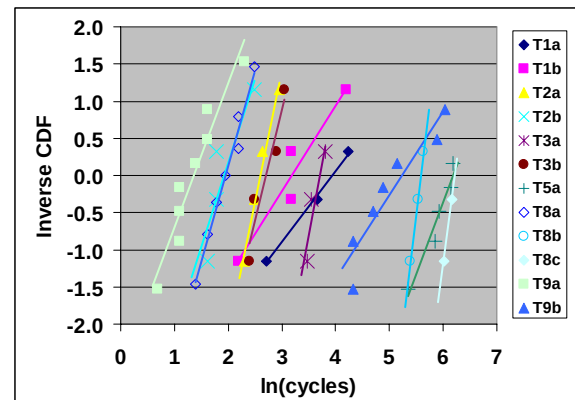


Fig. 8 Log-normal plot of test results.

For each test group, the cycles to failure are sorted and the midpoint plotting position, or F value, is calculated for each point. Table 2 gives these values for test group T9b. The inverse normal CDF (cumulative density function) value is then calculated for these points. This defines a linear scale for a normal density on the y-axis. The zero point is the median or point where 50% of the test group has reached a 5% increase in resistance.

Table 2 Example plotting position calculation for test T9b

X-axis		Y-axis		
Cycles to Failure	ln(cycles)	Rank	F	Inverse CDF
76	4.331	1	0.0625	-1.53
76	4.331	2	0.1875	-0.89
109	4.691	3	0.3125	-0.49
131	4.875	4	0.4375	-0.16
170	5.136	5	0.5625	0.16
358	5.881	6	0.6875	0.49
416	6.031	7	0.8125	0.89
430+		8		

The x-axis defines the log of number of cycles to 5% increase in resistance. Larger number of cycles and thus lower stress levels are to the right while higher stress levels are to the left.

The slope of the trend line for each test group defines the log standard deviation for that group. Some devices and materials show increasing variation with decreasing stress. Since no clear evidence of any trend can be seen in these data, the analyses were made using a constant standard deviation. The slopes or standard deviations are made equal for all groups. A simple average was taken and the trend lines replotted as shown in Fig. 9. This standard deviation will be used to estimate failure rates.

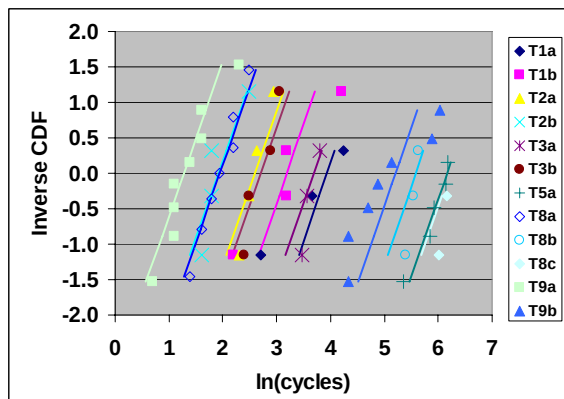


Fig. 9 Test results replotted with equal variance.

The actual failure point in the TEC always occurs at the ends of one or more of the corner elements. A fracture develops that can progress across the entire element and continue to adjacent elements at very high stress levels. In some severe cases these fractures are visible under inspection. Fig 10 shows one such case.

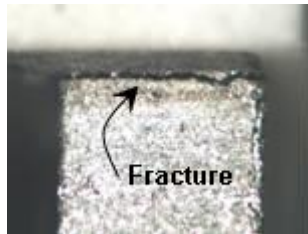


Fig. 10 Stress fracture at end of element.

Many times the fracture is not visible under inspection. Fig. 11 and 12 show sections of solder joints at the ends of elements. Fig. 11 is an element without any signs of damage. Fig. 12 shows a



Fig. 11 TEC element solder joint cross section.

fracture and its precise location. Stress fractures always occur at the end of the element, near the diffusion barrier, but in the TE material itself.

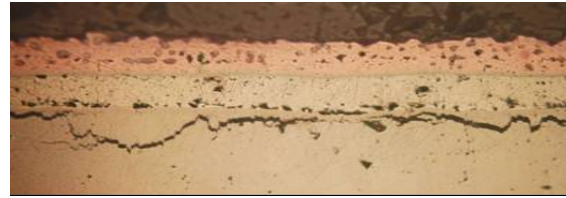


Fig. 12 Stress fracture at end of element.

A second campaign of tests was performed using an indium based solder rather than Sn/Pb. The specific alloy was 97In/3Ag with a 143°C melting point. The larger SP5415 was tested with Alloy48 base and top while the smaller SP5470 had a Stainless Steel base and top.

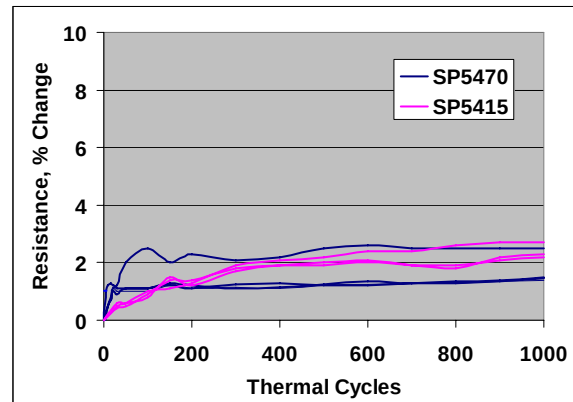


Fig. 13 Test results with In/Ag solder.

For this test the temperature range was set to +125 and -55°C. The results, shown in Fig. 13, reveal little change over the course of the 1000 cycles and show the remarkable ability of In/Ag solder to dissipate thermal stresses. Similar test configurations using Sn/Pb solder failed rapidly. Since there were no failures, no attempt was made to model the results. Future tests will require higher CTE plates such as copper and aluminum to attain sufficient stress levels for analysis.

FEA Model

To correlate with experimental results and to extend the stress model to other configurations required an FEA model. Some of the many factors that affect the internal TEC thermal stress include the TEC size and number of couples, the element dimensions, TEC substrate material and thickness, base and platform material and thickness, and internal and external solder. ANSYS Multiphysics software was used to capture these factors over the

range of geometry's and materials tested and provide a relative stress level.

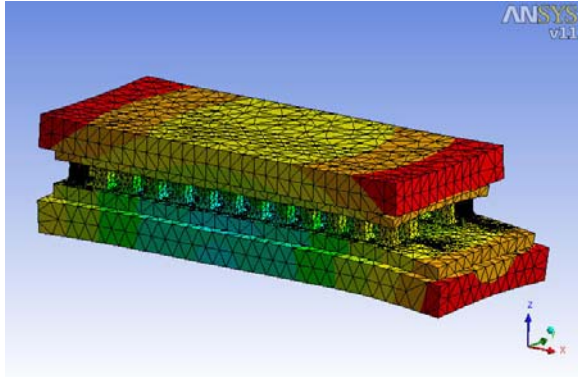


Fig. 14 Image of SP5415 TEC from FEA analysis.

The TEC was simulated as a single, multi-body part of all 3D tetrahedral elements. Although a stress value could be computed for every finite element in a model, we know historically that TEC's virtually never fail in the central elements. The failure location in virtually any stress environment is fracture of the ends of the corner elements. The inspection of the test failures supports this observation.

If we look at FEA model images that show the deformations, we can see the corner elements are the obvious high stress location in the TEC. The images in Fig. 15 show the exaggerated deformations at -55°C . We also know that TE materials, like other brittle materials, can take large compressive loads but relatively small tensile loads. Tensile conditions occur at the low temperature phase of the thermal cycle. For this analysis, we looked at the maximum stress value of a corner element at the lower cycle temperature.

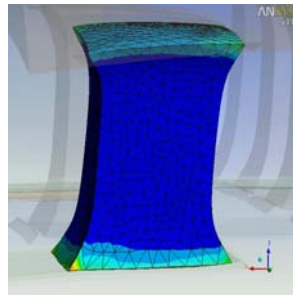


Fig. 15 Image of deformed element under stress.

The neutral temperature, where the internal stresses from CTE mismatches are zero, directly affects the critical stress value. It is also difficult to determine experimentally or otherwise. During assembly, the external solder solidifies and the dimensions of the TEC and external plates at that temperature are "locked" into position. The cool down to room temperature can be the most severe thermal cycle the TEC experiences. Fortunately, solder will deform and stress relieves itself if given the opportunity. The specimens were allowed to cool

gradually and 3 days minimum was allowed for the solder to "cure" before testing. We selected for the neutral temperature a value of 115°C ; approximately the mid point between room temperature and the external solder melting point of 183°C .

Several possible measures of stress include the maximum shear, tensile and 1st principle (1P) stress in the corner element location. Fig. 16 shows the relative changes in these as the CTE of the external plates is changed. We see that both tensile and 1P change significantly with CTE while the shear stress is much less sensitive.

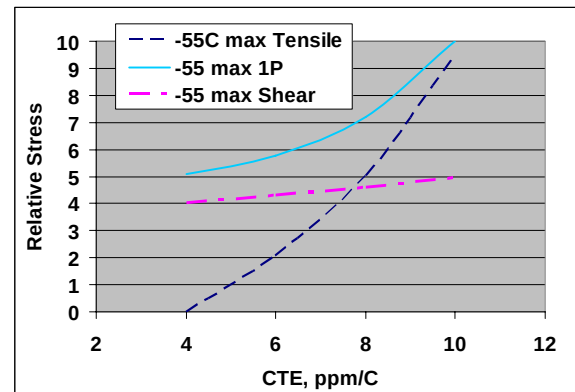


Fig. 16 Stress type variation with CTE.

1P was selected based on the maximum normal stress theory for brittle materials. This states that a brittle material will fail when the maximum 1P stress in the material reaches a limiting value equal to the ultimate normal stress. This provides a stress value that has a direct relation to failure. 1P also takes into account the fact that the maximum stress depends on the angle of inclination of the plane on which these stresses act. The deformed images in Fig. 15 show the corner elements experience a complex combination of stresses that are captured in the calculation of the 1P stress value.

Constant, near room temperature material property values were chosen from readily available sources such as handbooks and data sheets. Many properties, such as CTE, change substantially from room temperature to -55°C . Reliable values at these temperatures are difficult to obtain. Additionally, properties of the thin metallization and solder layers are poorly known. With these considerations, computed stress values have only relative merit. For this analysis, the predicted 1P stress values were normalized.

Life-Stress Model Analysis

The predicted relative stress levels for each of the test groups are listed in Table 3. An inverse power relation, Eq. (1) was used to model the test

data. The analysis follows the development given in Nelson [1].

$$\text{Stress} = b \cdot \text{Cycles}^{-m} \quad (1)$$

Here b and m are constants to be determined. This is converted to Eq. (2) to plot the log of cycles-to-failure versus the log of relative stress in Fig. 17.

$$\ln(\text{Cycles}) = -m \cdot \ln(\text{Stress}) + b \quad (2)$$

We see the median cycle life points reasonably form a straight line. This supports the assumption of an inverse power relationship.

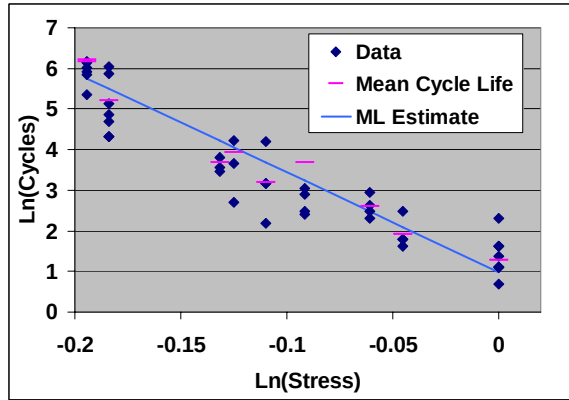


Fig. 17 Test results plotted with final model.

Tests T6 and T7 were stopped before any failures occurred and were not included in the analysis. Tests T8a and T8b were also removed since they showed longer cycle life than expected and did not fit the model. The reasons are under investigation.

We are usually interested when a small fraction of a population would fail when subject to a specific stress level. The mean cycle life is shifted to the fraction of interest by expanding the model in (3).

$$\ln(\text{Cycles}) = -m \cdot \ln(\text{Stress}) + b - \sigma \cdot Z_p \quad (3)$$

Here σ is the standard deviation and Z_p is the standard normal percentile for the fraction of interest. A least squares trend line through the median cycle life points could provide reasonable parameter values for Eq. (2). However, this does not provide an estimate for the standard deviation needed for (3) or include the influence of test groups with few or no failures. To overcome these issues, maximum likelihood (ML) estimates were calculated.

The likelihood function is the probability of the entire set of test data occurring. We use the log likelihood function, Eq. (4). Here, ϕ is the normal density and Φ the cumulative normal distribution.

The log values of the normal density results are summed over the 44 test units that failed. The log values of 1 minus the cumulative distribution results are summed over the 28 units that did not reach failure.

$$\begin{aligned} \ln \text{Likelihood} = & \sum_{i=1}^{44} \ln \left(\phi \left(\frac{\ln(\text{Cycles}_i - b + m \cdot \ln(\text{Stress}_i)}{\sigma} \right) \right) \\ & + \sum_{i=1}^{28} \ln \left(1 - \Phi \left(\frac{\ln(\text{Cycles}_i - b + m \cdot \ln(\text{Stress}_i)}{\sigma} \right) \right) \end{aligned} \quad (4)$$

The three derivatives of (4) with respect to b , m and σ , are set to zero and solved simultaneously to find the parameter values. These values of b , m and σ maximize the likelihood function or probability of the data set. The final model from the experimental data becomes Eq. (5).

$$\ln(\text{Cycles}) = -24.593 \cdot \ln(\text{Stress}) + 0.982 - 0.664 \cdot Z_p \quad (5)$$

With this model we can assess if a lognormal distribution adequately fits the data. Residuals are calculated by taking the log of cycles-to-failure for each data point and subtracting the median cycle life for that stress level, Eq. (6).

$$\text{residual}_i = \ln(\text{Cycles}_i) - (-m \cdot \ln(\text{Stress}_i) + b) \quad (6)$$

These residuals should follow a normal distribution. The plot of the residuals in Figure 18 gives graphical support for the life model.

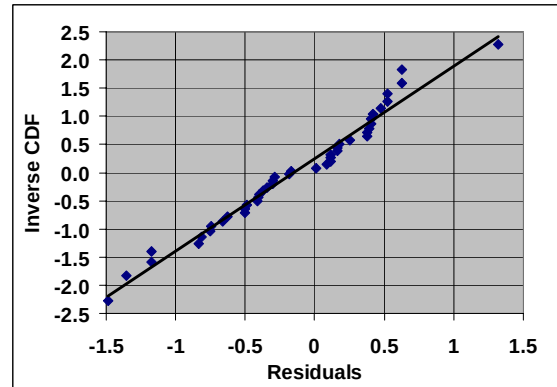


Fig. 18 Normal distribution plot of residuals

The estimate of log cycles from Eq. (5) also has variation. We need to estimate this overall variation to determine confidence limits. The technique employed is sometimes called the delta method and is calculated by Eq. (7).

$$\text{Variance}(\ln(\text{Cycles})) = \mathbf{H}^T \cdot \mathbf{V} \cdot \mathbf{H} \quad (7)$$

$\mathbf{H}$ is the matrix of derivatives of Eq. (5). $\mathbf{V}$ is the covariance matrix. $\mathbf{V}$ is estimated by taking the inverse of the matrix of negative second partial derivatives (the local Fisher information matrix). The square root of variance gives us the standard deviation. The cycle life with a particular one-sided confidence limit is Eq. (8).

$$\ln \text{Cycles}_{\text{CL}} = \ln \text{Cycles} - \sigma_{\text{CL}} \cdot Z_P \quad (8)$$

As an example, assume we have a TEC package design with a relative stress level of 0.706. We can calculate 13961 cycles for the population mean cycle life from Eq. (2). If we wanted the cycle life for an expected 0.1% of the population to fail, we first determine the corresponding Z factor of 3.09. From Eq. (6), the 0.1% cycle life is 1923 cycles. If we are now interested in the cycle life with a 95% confidence limit., we determine the corresponding Z factor of 1.645. From Eq. (8), we calculate the 0.1% cycle life with a 95% confidence limit of 1000 cycles.

Application Case Study

A recently developed configuration, called a planar multistage TEC, provided an opportunity to apply the life-stress model. This new configuration converts a traditional, pyramidal shaped multistage (Fig. 19) into a flat, planar shape. The height of a multistage TEC is reduced to a single stage one.

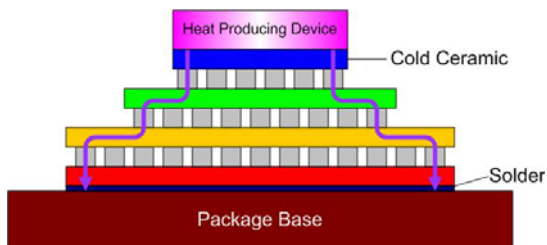


Fig. 19 Schematic of traditional multistage TEC.

This single stage configuration eliminates concerns with height and allows thicker ceramics and electrical conductors that can reduce power consumption. In addition, single stage fabrication methods will allow significant cost reductions over traditional multistage TEC's.

For a planar multistage, the top stage is arranged in a rectangular array of N and P type elements just like a traditional multistage. The next (lower) stage is placed in the same plane as the top stage. The elements are either divided along two sides of the top stage or along all four sides. Heat from the base of the top stage must conduct entirely sideways through the ceramic to get to the cold side of the next (lower) stage (Fig. 20). This next stage is

actually upside down relative to the direction of heat pumping of the top stage. Other stages are similarly arranged so that the whole TEC is in a single plane.

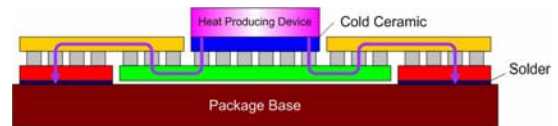


Fig. 20 Schematic of planar multistage TEC.

With such a radical configuration change, little could be anticipated about the thermal stresses from simply operating such a device. The configuration could be very fragile and unable to survive the large temperature differences produced when a multistage TEC is operated. To investigate, a large 5 stage design was developed and modeled. The cooler was "turned on" using the multiphysics Peltier capability in ANSYS.

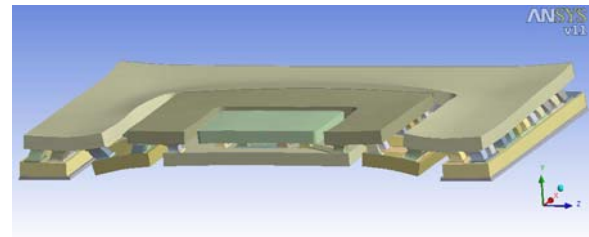


Fig. 21 FEA model of deformed planar multistage TEC.

The maximum stress could then be computed based on the temperature gradients during operation of the TEC. Fig. 21 shows an image of the deformed TEC. The predicted relative stress level of 0.273 suggested the TEC should readily survive operation.

To verify the modeling results, prototypes were fabricated.

Power cycling tests were performed as an accelerated reliability test. The repeated thermally induced stress should cause any over-stressed elements to fracture and fail.

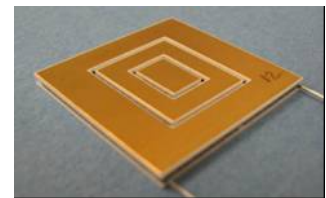


Fig. 22 Photo of prototype planar 5 stage TEC.

While under vacuum and held at 50°C, the TEC's were powered 2 minutes on and 3 minutes off for a total of 960 cycles at a current of 2 amps, a value near the maximum current for this device. This caused the top stages to cycle from 50°C to approximately -87°C, a temperature swing of 137°C. A performance test was done at intervals to monitor

the condition of the TEC's. The results, Fig. 23, show virtually no change over the course of this test. This provides at least a one-sided confirmation of the modeling results.

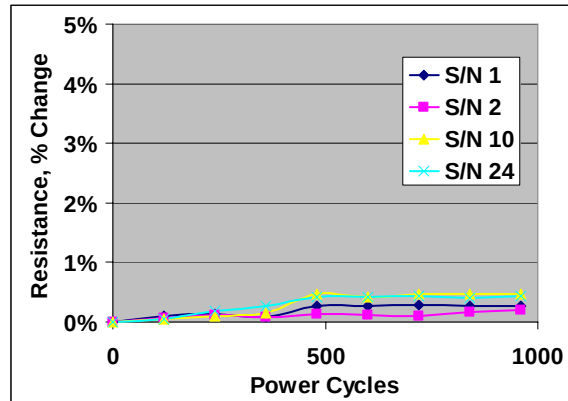


Fig. 23 Power cycling test results.

Summary

Experiments and analyses necessary to develop a model to mechanically design TEC's for the severe requirements of aerospace applications have been presented. A life-stress model was developed that allows prediction of cycle life for specific TEC stress levels. The data show TEC's follow an inverse power law; the log of median cycle life versus log stress is a linear relation with negative slope. The data also follows a log normal distribution with the standard deviation constant with stress.

The life-stress model was applied to a new planar multistage TEC concept. This radically different approach collapses a traditional multistage TEC to the height of a single stage one. Positive model results led to the successful fabrication and testing of prototypes.

Properly designed TEC packages can readily survive aerospace thermal cycling requirements of +125/-55°C for 1000 cycles. Marlow plans to continue testing to further validate the life-stress model and define improved model parameters and confidence limits.

Acknowledgements

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References

[1] Wayne B. Nelson, "Accelerated Testing", John Wiley & Sons, Hoboken, New Jersey, 2004.

Table 3 Test configurations and predicted stress levels.

Test #	Size, mm	Solder	Qty	Base/Top	Cycle Range, °C	Relative Stress
T10	10	Sn63	8	Kov/Kov	125/-55	0.677
T4a	16	Sn63	8	Kov/Kov	85/-55	0.713
T5b	16	Sn63	4	A48/Kov	85/-25	0.722
T5a	16	Sn63	8	A48/A48	85/-25	0.824
T8c	16	Sn63	4	A48/A48	85/-25	0.824
T9b	16	Sn63	8	Kov/A48	85/-55	0.832
T6b	10	Sn63	8	SS/A48	85/-5	0.871
T7b	10	Sn63	8	SS/Kov	85/-15	0.871
T3a	16	Sn63	4	A48/Kov	85/-55	0.877
T6a	16	Sn63	8	SS/A48	85/-5	0.878
T1a	16	Sn63	4	A48/A48	85/-35	0.882
T8b	16	Sn63	4	SS/Kov	85/-25	0.887
T7a	16	Sn63	8	SS/Kov	85/-15	0.891
T1b	10	Sn63	4	A48/SS	85/-35	0.896
T3b	10	Sn63	4	A48/A48	85/-55	0.913
T2a	16	Sn63	4	A48/A48	85/-45	0.941
T2b	10	Sn63	4	A48/SS	85/-45	0.956
T9a	16	Sn63	8	A48/A48	85/-55	1.000
T8a	10	Sn63	8	SS/SS	85/-25	1.091
T11a	16	In/Ag	4	A48/A48	125/-55	
T11b	10	In/Ag	4	SS/SS	125/-55	

Table 4 Number of thermal cycles to 5% ACR increase.

T1a	T1b	T2a	T2b	T3a	T3b	T4a	T5a	T5b	T8a	T8b	T8c	T9a	T9b	T10/T11
15	9	10	5	32	11	500+	211	500+	4	219	407	2	76	1000+
39	24	12	6	35	12	500+	346	500+	5	255	473	3	76	1000+
69	24	14	6	45	18	500+	372	500+	6	279	578+	3	109	1000+
70+	67	19	12	70+	21	500+	463	500+	7	578+	578+	3	131	1000+
						500+	480		9			4	170	1000+
						500+	500+		9			5	358	1000+
						500+	500+		12			5	416	1000+
						500+	500+					10	430+	1000+