Thermoelectric Cooling for Low Temperature Space Environment

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Abstract

The paper presents a multi-incremental work on the thermoelectric cooler (TEC) development for planetary space instrumentation. The technical specifications designated for cooling an infrared focal plane array detector involved strict dimensional, electrical and thermal constraints. The latter ones are the following: the operational temperature range is 160-180K and the cold side temperature to maintain is not higher than 140K at the heat nominally to be pumped 50mW. Within this guidance the optimum TEC was elaborated. That is a three-stage module with different pellets occupation density based on the low temperature optimized thermoelectric materials and improved thermal conductance substrates. The technology and assembling update was carried out. The reliability testing was performed. The compliance of the theory and experiment was verified and the results allow concluding that Mars-type mission requirements are met.

Introduction

Space equipment often implies sensors operation at low ambient temperatures. The problem dealt with here is to provide a thermoelectric cooler (TEC) capable of maintaining an IR focal plane array designed for a Mars mission at 120-140K.

Cooling down to significant temperature difference in such environment involves supreme requirements for the TEC design optimization and low temperature efficiency. The latter means shifting figure-of-merit peak to lower temperature values. This task was taken over, for example, by Vedernikov, Kutasov et al.[1] and by Anukhin [2] but still the problem of thermoelectrics yeilding delta-temperature more than 30 K in supercold plannet atmospheres is a challenge.

The successful elaboration of TEC design, optimisation and production for the IAS CIVA/Mars equipment is the message of this paper. It is laid out as the following increments section by section: the task generation, TEC theoretical elaboration, TEC design development, results on optimimal thermoelectric (TE) material preparation, TEC performance theoretical prediction and final product tests results.

Mission Context and Task Specification

The TEC is intended for cooling a focal plane array (FPA) of the Mars mission infrared microscopic spectral imager. The instrument will be in contact with the local environment. The surface temperatures range from 155 K to 310 K. The instrument will work during night (IR contribution reduced, Mars surface temperatures fall within 135 K; 200 K).

The TEC *mission parameters* must meet thermal, electrical and dimentional requirements. These are the following.

Thermal Constraints

The TEC is supposed to provide active cooling. With the hot side temperature varying 160-180K, its cold side temperature should be maintained lower than 140K. Along with it the heat load should nominally equal 0.05W, maximum 0.1W.

Electric Constraints

The electric limits for TEC supply are rather strict. Current should not exceed 1 A, voltage should be up to 4.5V. Together with these two terms, the input power should be lower than 4W.

Dimensions

The TEC should be of a micro-type. However its cold side surface is to be enough for the FPA to locate on and, thus, not less than 7.5x7.5mm^2. The hot side dimensions should not exceed 13x13mm^2. The TEC must be no higher than 20mm.

TEC weight

The TEC is to weigh less than 5 g.

The lifetime of the mission is ~ 2 Earth years, the operational time of the FPA instrument is ~ 500 hours. The TEC is vacuum-packed together with the detector (internal pressure of the common FPA package < 10^{-5} mbar). The TEC hot plate is connected to one heat sink through the common package. The package external pressure is the Martian one.

The developed TEC should be exposed to tests and qualification procedures at IAS.

Theoretical Grounding for TEC Design and Material Optimization

To develop a TEC within the defined specifications means solving two problems of form and substance, altogether separate and unified: to optimize both TEC design and TE materials.

Let us start with the latter. The criterion to choose a certain thermoelectric (TE) material for the operation at the settled temperature range can be specified in terms of the so-called figure-of-merit Z(T):

$$Z = \frac{(\alpha_n + \alpha_p)^2}{(\kappa_n + \kappa_p)(\rho_n + \rho_p)} \qquad (1)$$

where α - material Seebeck coefficient, κ - material thermal conductivity, ρ - material electric resistivity, indices p and n correspond to the p- and n-types respectively.

Let us survey the thermoelectric materials scale to work with. As a rule, the materials are based on Bi_2Te_3:

n-type is a Bi_2Te_3 - Bi_2Se_3 compound;

p-type is a Bi_2Te_3 - Sb_2Te_3 compound.

There are variants of free carriers concentration and therefore shifted peaks of Z.

Consider two TE materials optimized approximately to 180K and 300K cooling. Let us designate the two options as Z180 and Z300. The optimal carriers concentrations $n_o \sim T^{3/2}$ [3] are the following: Z180: $n_o \sim 3.5\times10^{18} cm^{-3}$ [1], Z300: $n_o \sim 10^{19} cm^{-3}$. In Fig. 1 the temperature behaviour of both options figure-of-merits measured in Saint-Petersburg Ioffe Institute is presented.

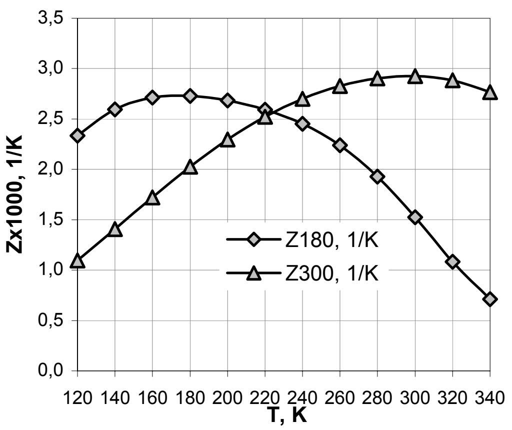

Fig.1. Temperature dependence of figure-of-merits for the Z180 and Z300 materials

Is the Z300 variant really inappropriate?

Here (Figure 2) we offer a comparative analysis of calculated maximum temperature difference provided by exemplary n-cascaded (n=1,2,3) TE coolers based on Z180- and Z300- materials. A four- or more-cascade TEC involves a much more challenging construction, less steadiness and lower survival. Therefore we intentionally eliminated the n>3 variants from the study.

We see that the 300K-optimized TE material fails to cool down to 40K temperature difference from 180K. The Z180 material enables us to have a 10-15K average gain in delta-temperature, which is quite essential for the task considered. Also, selection of the TEC number of stages is more clear-cut now. The case of the hot side temperature equaling 180K is decisive. Single-stage option is eliminated. The two-stage one is too much a borderline. Therefore we suggested the theoretical optimization should be solved for a three-stage TEC.

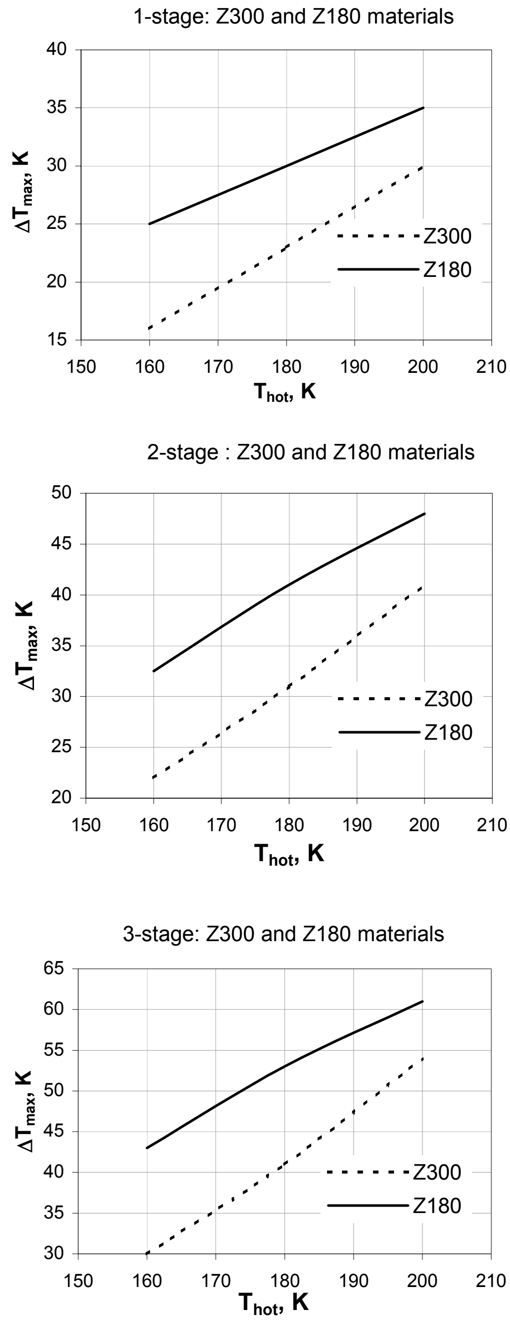

Fig.2 Maximum Delta-temperature (with no heat load) estimates versus the hot side temperature for single-, two- and three-stage TEC. The cascading coefficients for the two- and three stage TEC cases are equal to 3.

Once we choose the three-stage TEC variant we should closer analyze the cascading coefficient problem. The definition of cascading coefficient is:

$$cc_i = \frac{N_i}{N_{i-1}}, \tag{2}$$

where cc_i - the i-th cascading coefficient, i=2,3,…, N_i - pellets number at the i-th TEC stage.

According to the technical specifications the dimensional pyramid is not in favour of high cascading coefficient values. Let us compare the three-stage variant varying by the cascading coefficient. In Fig. 3 we have the temperature difference available for a three-stage TEC, estimated for the Z180 material, for two cascading coefficients values and hot side temperatures 180K and 160K.

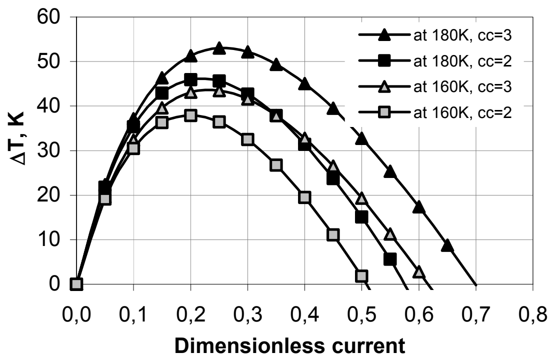

Fig. 3. Temperature difference range for a three-stage TEC based on the Z180-material for different hot side temperatures and cascading coefficients cc=2 and 3.

We see that the cc=2 variant reduces us to the two-stage-like efficiency. So, the way-out is still a three-stage TEC with the cascading coefficient around three.

To specify each stage pellets number and pellets dimensions we have to consider not only thermal but also electrical requirements keeping in mind size limitations. To this purpose we undertake the procedure of the theoretical optimum three-stage TEC construction. The input values for this procedure are the stages number, necessary heat load on the cold side, the total temperature difference on the one hand, and electrical constraints on the other. The pellet cross-section is a guess value. The Z180 TE material is applied. The problem is solved by numerical maximization of the TEC coefficient of performance (COP) by achieving equal COP_i at the cascades [4,5]. The temperature dependences of TE parameters (Eq. 1) are taken into account [6]. The outcome values are: each stage pellets number and pellets length.

The approach results for the three-stage option are given in Table 1. The temperatures numeration starts from the cold side (# 0,1,2,3).

Table 1. Optimal three-stage TEC results

Substrate #	T_i, K	COP
0	137.0	
1	148.6	0.4426
2	162.7	0.4411
3	180.0	0.4519

Here the summed heating capacity coefficient is 34.22, COP is ~ 0.03. If the module cross-section is 0.7x0.7mm^2, pellet lengths distribution for the cascades is 1.15-1.16-1.14 mm. The numbers of pellets couples at the stages are 8-24-66. The optimal current equals 0.66 A. The optimal voltage is 4.17 V. The power is 2.75 W. This is the specification fit. Thus, the resulted optimum TEC for the designated application is elaborated.

The corresponding cascading coefficients are 3 and 2.75.

With the cold and hot sides dimensions 8x8mm^2 and 12x12mm^2 respectively, medium substrates 10x10mm^2 and 12x12mm^2, ceramics width 0.25mm, metal junctions 0.06 mm thick, the average distance between metal tabs 0.03mm, the module mass is m=1.6g, which meets the mass limits.

Armed with all the above studies we are to cope with the two stated problems: first, developing the TEC design; second, obtaining the TE material close to Z180 properties.

TEC Design Developing

In this section we deal with the first problem.

As a design basis we take the optimized three-stage TEC, described above, with pellets length equal the average value 1.15 at all the cascades. Using the fixed nomenclature it can be referred to as 3MC07-098-115.

Dimensional specifications of designed three stage TE module are advised in Table 2.

Table 2. Thermoelectric module 3MC07-098-115

Parameter	Units	Value
Cold side	mm^2	8x8
Hot side	mm^2	12x12
Height	mm	4.8
Pellet cross-section	mm^2	0.7x0.7
Pellet height	mm	1.15
Number of pellets per stage		8-24-66

As for the ceramic substrates we suggest applying Aluminum nitride for the heat capacity gain and better elastic reasons.

For the metallization we use traditional copper. The TEC dimensions do not suggest a three times proportion as the cascading coefficients do, so the distance between pellets is different at the 1st, 2nd and 3d stages. In spite of this non-uniform pellets filling we offer a homogeneous metal tabs tracery in 3MC07-098-115 for better temperature equaling and less mechanical strain reasons. Fig. 4 illustrates it.

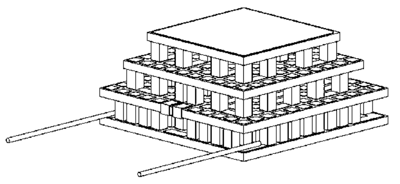

Fig.4. 3MC07-098-115 exterior

Two different kinds of solders: pure Indium and lead-tin are involved by a double-stage assembling method:

First stage: assembling of TE pellets matrix of each stage (first, second and third) on ceramic plate with the standard (183º C) lead-tin solder; *Second stage:* completing integration at the lower melting temperature (Indium soldered surfaces). Fig. 5 conveys this.

Temperature modes of soldering at each stage are optimized depending on the melting point of each solder.

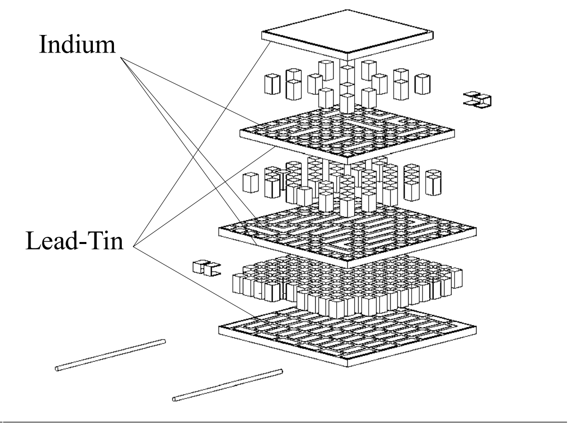

Fig.5 Three-dimensional view of 3MC07-098-115 at the pre-assembly level

Indium is a highly elastic solder. In combination with the traditional lead-tin it provides a more reliable survival under thermal expansion operation. It is demonstrated by Fig. 6

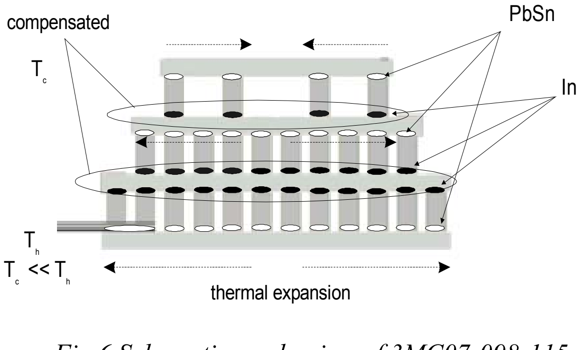

Fig.6 Schematic mechanism of 3MC07-098-115 compensating thermal expansion

Now, the construction as well as the ceramics and metallization materials are clear, we are to deal with TE material optimization.

Thermoelectric p- and n- Materials Optimization

The materials used in TE cooling industry are solid solutions based on chalcogenides of bismuth and antimony. The common (the so-called Z300) materials are optimized for cooling at the room temperature. The Z300 p-type material is $Bi_{0.5}Sb_{1.5}Te$ and that of the n-type is $Bi_2Te_{2.7}Se_{0.3}$ solid solutions. At the room temperature the Seebeck coefficient of these materials $|\alpha|$=190-210μV/K and the electric conductivity σ=980…1150 $Ohm^{-1}cm^{-1}$[3].

The problem of low temperature optimization is solved separately for the n- and p- types. The reason is their much differing composition.

For shifting the maximum of figure-of-merit to a lower temperature it is necessary to decrease the carrier concentration in the TE materials (to increase the absolute value of α up to 270-290 μV/K at the room temperature).

For low temperature n-type material it is efficient to change only the doping level of the donor impurity without varying the Se content. To make intrinsic defects more stable, redundant Te as compared to the stoichiometric composition is doped into the mixture of the $Bi_2Te_{2.7}Se_{0.3}$ solid solution. The Te atoms take places of Bi (antistructural defects) and are donors, so it allows stabilizing the composition at the homogeneity area edge and eliminating the intrinsic defects affecting the final doping level.

As for the p-type it may be shown that the way out is to decrease the antimony component in the solid solution. We may use Se instead of a part of the Te atoms. This change makes the homogeneity area narrower and increases the ion part of the chemical bonds, which prevents antistructural point defects generation. So the optimal p-type composition is a solid solution that should be defined within $Bi_{2-x}Sb_xTe_{3-y}Se_y$, where x varies as 1.2-1.5 and y does as 0.2-0.5.

Electrical conductivity and Seebeck coefficient of every grown sample have been measured at room temperature to make preliminary selection of material that can satisfy the criteria $\sigma \leq$ 400-450 $Ohm^{-1}cm^{-1}$, $\alpha \geq$ 270μV/K.

Table 3 offers the averaged values of α and σ of some resulting TE material samples at 300K comparing with the Z180 parameters.

Table 3. Parameters of the grown TE materials compared with those of Z180.

	α, μV/K	σ, $Ohm^{-1}mm^{-1}$
p-type		
Z180	*280*	*300*
Grown	280	388
n-type		
Z180	*288*	*460*
Grown	295	319

It can be shown that on average temperature dependence of the figure-of-merit is as illustrated in Fig. 7.

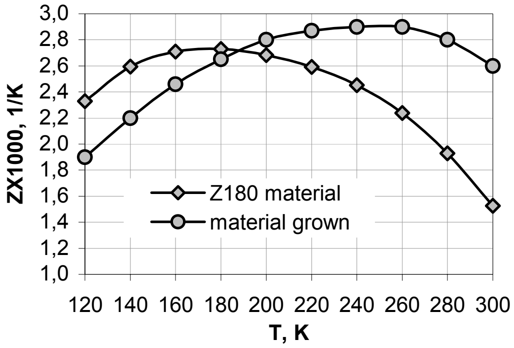

Fig.7. Temperature dependence of figure-of-merits for the Z180 and the grown materials

The grown material reveals figure-of-merit's maximum at 240 K approximately and from this time on we refer to it as the Z240 material. But its absolute (maximum) value is higher than that of the Z180 material. The Z-values difference at 180K is 10^{-4} 1/K. At 160K it is approximately $2.5x10^{-4}$ 1/K. The low temperature Z-decreasing is faster for the obtained material, nevertheless let us consider calculations for 3MC07-098-115 built up by the grown TE material.

Theoretical Results for the TEC 3MC07-098-115 based on the Low Temperature TE Material

Here we offer the calculations results allowing for temperature dependence of thermoelectric parameters of the material (see Eq. 1). In Fig. 8 the temperature difference depending on the supplied current is presented.

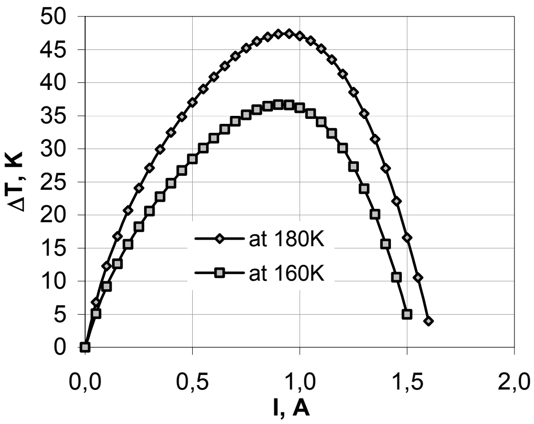

Fig.8. 3MC07-098-115 temperature difference vs current at 160K (ΔT_{max}=37K, I_{max}=0.87A) and 180K (ΔT_{max}=47K, I_{max}=0.91A).

Fig. 9 presents voltage along the temperature difference at the maximum current on the TEC at 160K and 180K.

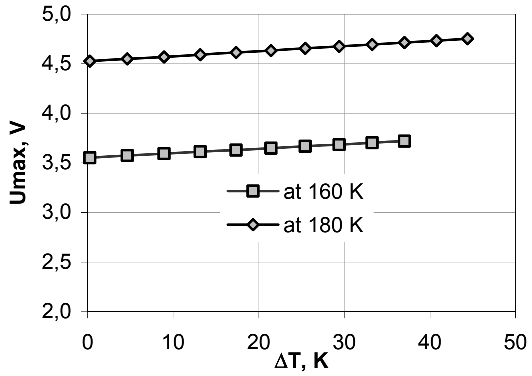

Fig.9. 3MC07-098-115 maximum Voltage vs temperature difference at 160K (U_{max}=3.7V) and 180K (U_{max}=4.8V).

Fig. 10 depicts cooling capacity along the temperature difference available on the TEC at 160K and 180K.

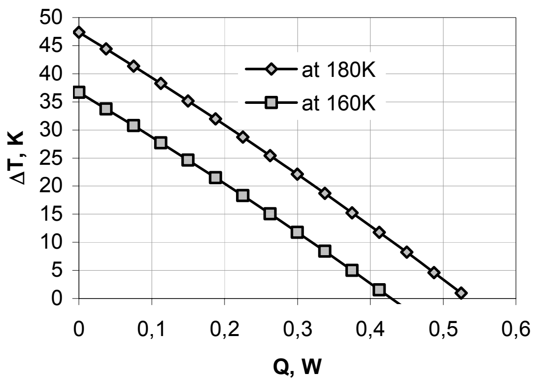

Fig.10. 3MC07-098-115 temperature difference vs heat pumping at the hot side temperatures 160K and 180K

Judging by Fig. 10 we see that if operating at the temperature differences close to maximum and not less than 40K at 180K we can afford cooling 0.05-0.08W. In Fig. 11 we see coefficient of performance at the modes considered.

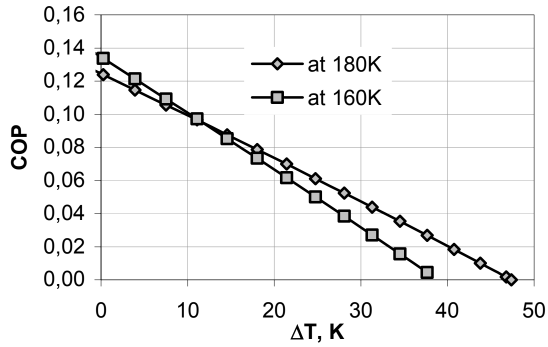

Fig.11. 3MC07-098-115 Coefficient of Performance (COP) vs temperature difference at maximum current values at 160K and 180K

In Fig. 12 – 14 theoretical temperature difference vs current, volt-ampere and power consumption characteristics for the TEC under nominal heat load 0.05W are given.

At the hot side temperature 180K and the nominal heat pumping capacity Q=0.05W the range of the current I (0.7 – 1.1A) is available for the temperature difference not lower than 40K. On the other hand, varying heat to be pumped up to 0.1W is limited (see the standard performance plot Delta-T vs heat pumping at 180K). The power consumption is within the power constraints.

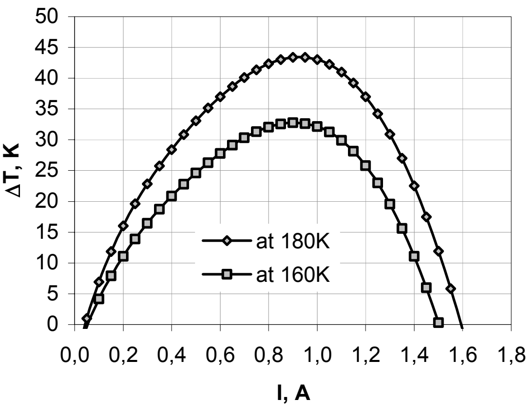

Fig.12. Temperature difference vs current at 160K and 180K under the nominal heat load 0.05W.

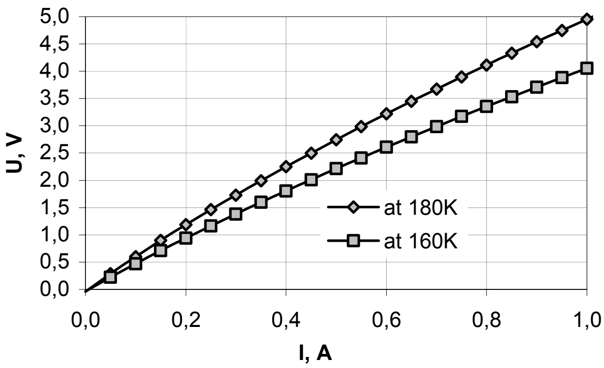

Fig.13. Volt-Ampere characteristics at 160K and 180K under the nominal heat load 0.05W.

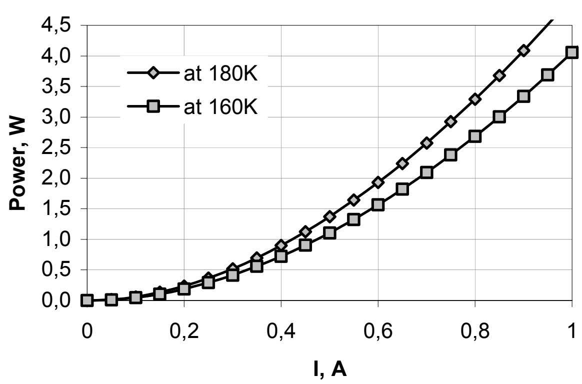

Fig.14. Power consumption at 160K and 180K under the nominal heat load 0.05W.

So we can see that for the nominal heat load (Q=0.05W) the operational parameters actually meet the thermal and electrical constraints imposed. Therefore we conclude that the grown TE material can fit the problem being solved. It is time to check the theory by experiment.

Final Tests Results

The performance parameters of the TEC were measured via thermovacuum tests. For testing two sets of 3MC07-098-115 TE modules have been prepared: optimized type using Z240 material; and modules produced with standard material Z300.

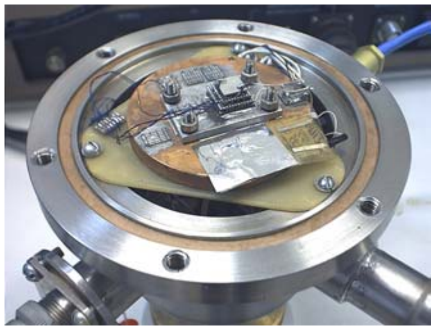

Fig.15. TE module prepared for thermovacuum test.

Fig. 16 shows the measured temperature difference ΔT vs current I for the different stabilized temperatures of the hot side.

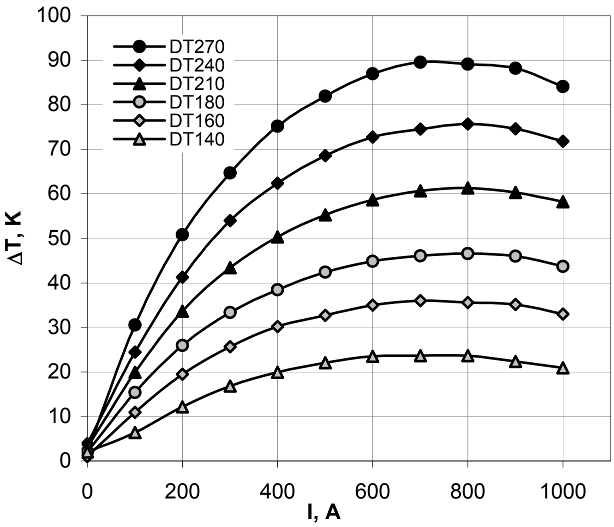

Fig.16. The 3MC07-098-115: temperature difference ΔT vs current I for the different stabilized temperatures of TEC hot side.

Fig. 17 depicts the maximum temperature difference values measured at zero heat load on the cold side. Values correspond to the data in Fig. 15. To make it more demonstrative we place experimental results of the same 3MC07-098-115 TE modules produced using standard Z300 material.

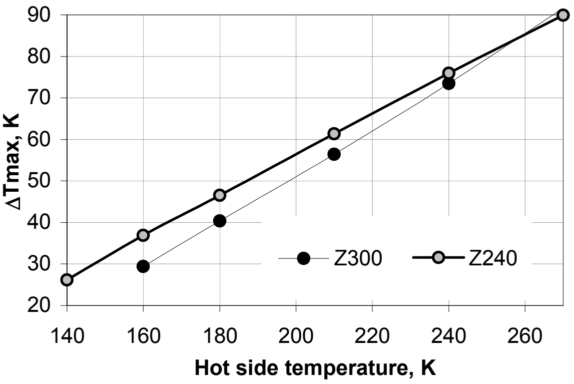

Fig.17. The 3MC07-098-115 ΔTmax along the range 140 – 270K of the different temperatures of hot side.

In Table 4 the Fig. 14 data are presented in specified figures.

Table 4. Maximum temperature difference in the temperature range 140 – 270K for the grown and standard materials.

	T_{hot}, K						
	300	270	240	210	180	160	140
ΔT_{max}, K (Z300)	109.7	91.6	73.5	56.4	40.4	29.4	NA
ΔT_{max}, K (Z240)	NA	89.9	76.0	61.4	46.6	36.9	26.2

Fig. 18 presents maximum current depending on the hot side temperature for the TEC based on Z240 as well as the Z300 materials.

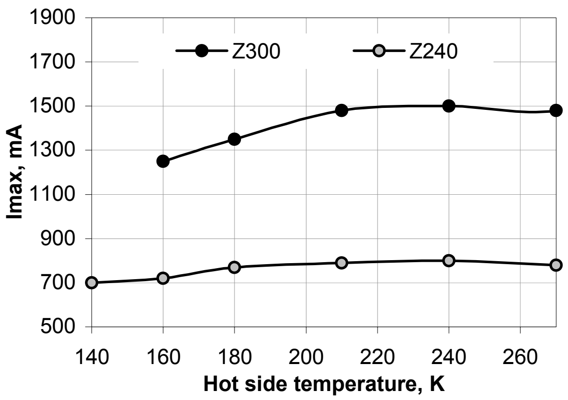

Fig.18. The 3MC07-098-115 maximum current values along the temperature range 140 – 270K of the different hot side temperatures.

In Table 5 the same data are specified.

Table 5. TEC maximum currents at Z300 and Z240 materials.

	T_{hot}, K						
	300	270	240	210	180	160	140
I_{max}, mA (Z300)	1650	1480	1500	1480	1350	1250	NA
I_{max}, mA (Z240)	NA	780	800	790	770	720	700

In Fig. 19 and Table 6 one can see the corresponding data on maximum voltage values.

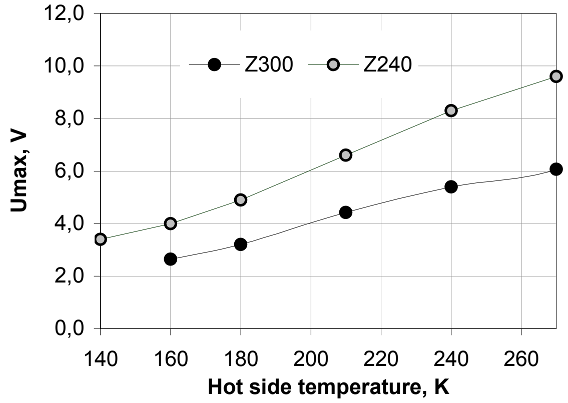

Fig.19. The 3MC07-098-115 maximum voltage along the temperature range 140 – 270K of the different stabilized temperatures of hot side for Z240 and Z300 materials.

Table 6. TEC maximum voltage for Z240 and Z300 materials.

	T_{hot}, K						
	300	270	240	210	180	160	140
U_{max}, V (Z300)	8.13	6.07	5.39	4.42	3.21	2.65	NA
U_{max}, V (Z240)	NA	9.60	8.30	6.60	4.90	4.00	3.40

The temperature difference values at the nominal heat load 50mW are plotted in Fig. 20 and specified in Table 7.

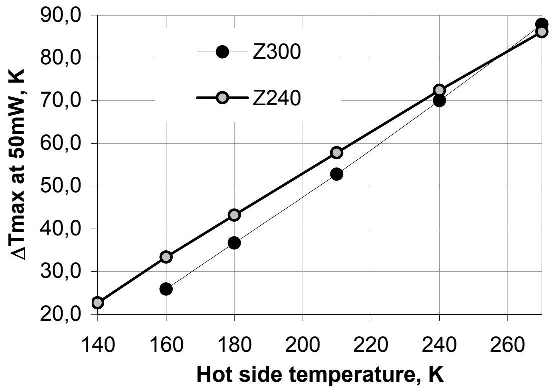

Fig. 20. The 3MC07-098-115 temperature difference values, the heat pumped at the cold side 50mW, along the temperature range 140 – 270K of the diffeternt stabilized temperatures of hot side.

Table 7. The highest possible temperature difference values in the loaded mode (the pumped heat equals 50mW).

	T_{hot}, K						
	300	270	240	210	180	160	140
ΔT, K (Z300)	105.8	87.8	70.0	52.8	36.7	25.9	NA
ΔT, K (Z240)	NA	86.1	72.4	57.8	43.2	33.4	22.7

It is apparent now that the produced TEC fits thermoelectrical requirements. The final 3MC07-098-115 specifications at 180K and 160K are given in Tables 8, 9.

Table 8. The 3MC07-098-115 Specifications @ 180 K

Parameter	Units	3MC07-098-115 result	Tolerance, +/-
Maximum cooling capacity*	W	0.55	
Maximum temperature difference	K	47.0	1.0
Maximum voltage drop	V	4.9	0.1
Maximum current	mA	770	30
Temperature difference @ 50 mW	K	43.0	1.0

Table 9. The 3MC07-098-115 Specifications @ 160 K

Parameter	Units	3MC07-098-115 result	Tolerance +/-
Maximum cooling capacity*	W	0.45	
Maximum temperature difference	K	37.0	1.0
Maximum voltage drop	V	4.0	0.1
Maximum current	mA	720	30
Temperature difference @ Q=50 mW	K	33.0	1.0

The TEC was exposed to GOST induced entry control, mechanical (vibrations and single impact), temperature cycling and endurance testing. Additionally to the standard temperature cycling test the hard cycling has been performed: from ambient 300 K down to 77 K (LN2) temperature.

According to the results the developed TEC's 3MC07-098-115 passed through these procedures successfully. It is the confirmation of thermovacuum, mechanical, thermocycling and life endurance reliability of the modules manufactured. Their structural assessment was confirmed by IAS vibration and shock tests performed on RMT mechanical prototypes.

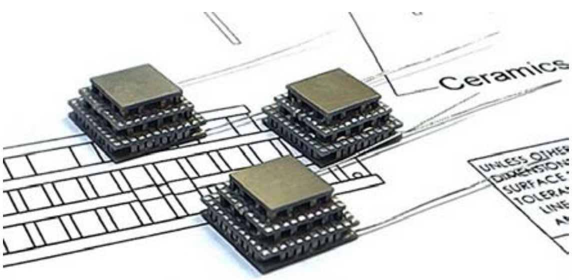

Fig. 21. Samples of 3MC07-098-115 thermoelectric modules.

* calculated value

Conclusions

The high reliability required of all space equipment is achieved by the designs, design margins, and by the manufacturing process controls imposed at each and every level of assembly. The presented paper summarizes the data on constructing and testing the thermoelectrical cooler 3MC07-098-115 meeting the Mars environment constraints.

Ever-increasing space industrial and scientific applications demand that thermoelectricity should keep pace with this field development. However the main stumbling point seems thermoelectric material optimization to space involved low temperature, which is quite a painstaking job. Thus, the progress in this area means that close co-operation is in store for thermoelectric material technologists and end-use thermoelectric coolers manufacturers.

Acknowledgments

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