TE Modules Application Tips

In the given Chapter the basic important points of effective application of TEcooling modules will be considered.

TE modules are effective means of cooling in various applications. In many cases they have no alternatives.

Designs of modules and their efficiency characteristics, TE modules mathematical simulation and optimum TE module choice considered in the above chapters allow consumers to choose an optimal solution for specific requirements.

However a choice of a suitable TE module is only a "half" solution of the problem: its correct application is not of a lesser concern.

The following factors are vital for efficient operation and life time of a TE cooling module/sub-mount:

- *Quality of mounting an object to be cooled onto a TE module and a TE module onto a heat rejecting system*
- *Materials CTE agreement*
- *Temperature losses reduction*
- *Passive heat loads reduction*
- *Heat rejecting system efficiency*
- *TE module correct power supply*

The above factors underestimation or neglection rather often causes ineffeciency of an optimum TE module. Therefore questions of correct TE module application are worth paying a thorough attention to.

1. Quality of Mounting a Cooled Object onto a TE module and a TE Module onto a Heat Rejecting System

The efficiency of TE sub-mount as a whole depends on the quality of mounting an object to be cooled onto a TE module and a TE module onto heat rejecting elements.

Based on RMT's and other manufacturers' (for example, the company Melcor) data the highest extent of TE modules failure is due to an improper process of installation of objects on the module and the module on the appropriate header.

It is necessary to take into account, that at installation some problems are solved, namely:

- *Strong mechanical design, steady at mechanical influence of various kinds while in service (vibration, impacts);*
- *Good thermal contact, which is important both for an object located on the TE module cold side and for effective heat rejecting system.*

There are three widely applied methods that can be used for mounting::

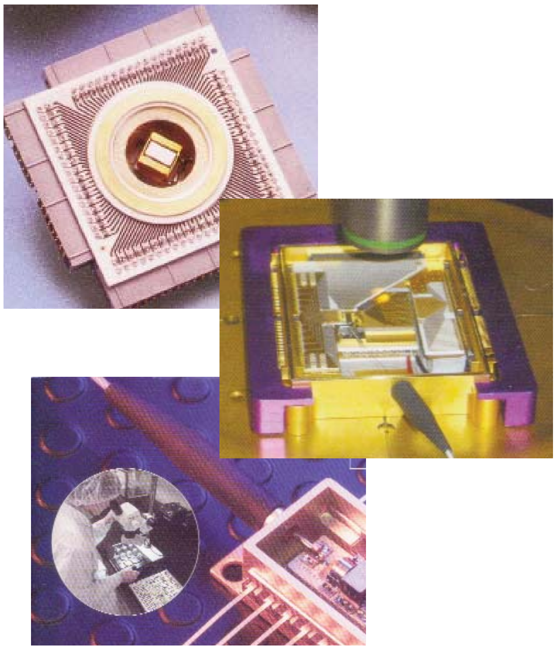
1) Mechanical mounting,

2) Soldering

3) Adhesive bonding.

Each of the listed methods has its own areas of applications, both advantages and shortcoming.

When choosing an optimal way of mounting a TE module and cooled objects it is necessary to be guided by features of the methods.



Examples of TE cooling applications

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1.1. Mechanical (Compression Method)

Description. A TE module is placed between two heat exchangers (plates) fixed by screws or bolts.

For good thermal conductance the clearances between the plates should be filled by some substances of high thermal conductance. As such a thermal grease or a heat-conducting gasket may be used - see Fig. 1.1.1.

Application. The method is widely applied for mounting large single-stage TE modules.

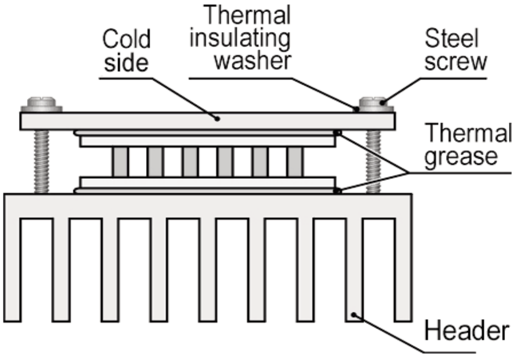

Figure 1.1.1. Mechanical mounting

For micromodules this method has a limited application as fixing elements occupy too much space and cause significant thermal losses. Besides for micromodules the compression should be small and accurately normalized.

Advantages. Advantages of the mechanical method of installation are a possibility to disassemble of the construction and, consequently, maintainability of a design.

Important remarks. It is necessary to take into account the following:

- Preparation of contacting surfaces

The preparation is expressed in terms of requirements for nonflatness and roughness of surfaces as well as exception of alien particles and inclusions.

The nonflatness of contacting surfaces is very important. It concerns ceramic surfaces of a module and metal plates of heat exchangers. Roughnesses or deflections of contacting surfaces at applying pressure can destroy a TE module (Fig. 1.1.2).

Thus it is recommended that the nonflatness of contacting surfaces be not more than 0.02 mm.

The roughness of contacting surfaces is the reason of deterioration of thermal contact between surfaces. The class of roughness not worse than R_a=2.5 is recommended.

For the similar reasons it is necessary to eliminate alien particles and inclusions from contacting surfaces. Even in the best case they increase a clearance between contacting surfaces, in the worst case at pressure applied they can cause mechanical destruction.

- Normalized Compression

It is necessary to take into account that TE modules are rather fragile products. It can endure a limited compression, stretching and sheer effort. Therefore it is required to control compression of the module when mechanically installed. It is also necessary to exclude a compression non-uniformity between the bolts.

- Quality of heat-conducting gaskets and thrmal greases

Quality of thermal contact determines an overall performance of TE module assembly. Taking into account that it is impossible to prepare ideally smooth and even surfaces, heat-conducting substances are necessary between contacting surfaces.

TE modules fragility is determined by mechanical durability of the TE material (Bi_2Te_3). It is known that limiting compression efforts (before destruction) for Bi_2Te_3 is about 1 kg/mm^2.

It is recommended that compression efforts should be no more than 1/2 from maximum. From that it is possible to calculate allowable compression for various TE modules for mechanical mounting (Fig. 1.1.2).

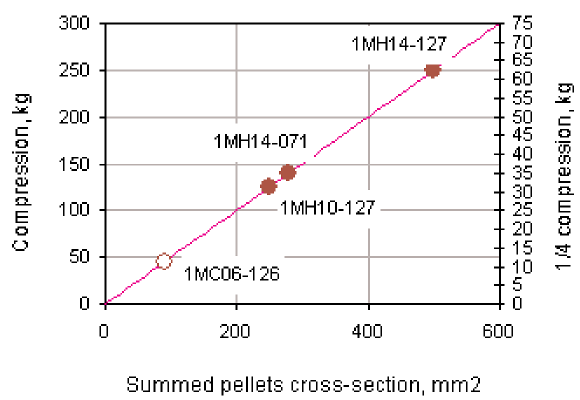

Figure 1.1.2. Allowable compression vs the summed cross-section of the pellets

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The heat-conducting substances are called to compensate the heterogeneity of contacting surfaces and to increase the area of contact. In Tables 1.1.1-1.1.4 examples of the appropriate materials and their properties are given according to manufacturers' information.

At the same time it is necessary to provide minimally reasonable thickness of such gaskets (or layers). All useful properties considered, such materials have rather a high thermal resistance increasing with thickness growth - see Fig. 1.1.3. The increase of gasket thickness worsens mechanical durability of the connection as well.

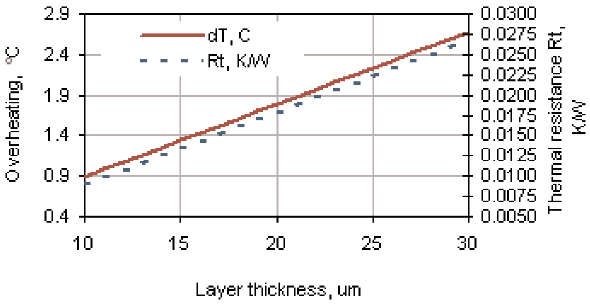

Figure 1.1.3. Thermal resistance of the heat conducting layer and corresponding overheating (temperature difference at the layer) depending on the layer thickness:

- For the TE module 1MH14-127-13 in the maximum temperature difference mode (100 Watt of the heat to be rejected)

- The thermal grease is used (see Table 1.1.1)

◆ Thermal Losses Reduction

In the mechanical way of installation cold and hot sides of the TE module are held down by bolts, which create channels of thermal losses. To reduce such thermal losses it is necessary to apply thermal insulating elements (washers) and make bolts of metals with low thermal conductivity. In Table 1.1.1 for comparison properties of some constructional metals are given. It can be seen that stainless steel is the most advantageous material.

◆ Elastic connection

While operating the mechanical connection of this kind, a thermal expansion (compression) is observed due to temperature change. A compression results in easing the clip and deteriorating the thermal contact, accordingly. An expansion increases the pressure on the module. Therefore it is necessary to apply elastic elements (elastic washers, see the Young's modulus of some materials in Table 1.1.1). Otherwise, the design mechanical destruction or overheating is probable because of loss of the thermal contact.

Restrictions. Unfortunately, the mechanical method of mounting is not applicable to TE micromodules as the mechanical installation demands an additional space. Moreover, it is impossible to exclude passive heat fluxes through the elements of fixtures (bolts), which is crucial for micromodules efficiency, especial in case of multicascade modules.

Table 1.1.1. Some materials properties

Material	CTEx10^{-6}, 1/K	Thermal Conductivity, W/mK
Aluminium	22.5	237
Bismuth Telluride	12.9(⊥)	1.5
Brass	18.0	110
Ceramics Al2O3 - 100%	7.2	30
Ceramics Al2O3 - 96%	7.0	24
Ceramics AlN	4.5	170
Ceramics BeO	7.0	230
Cold-roll steel (CRS)	11.5	50
Constantan	16.9	22.5
Copper	16.7	400
Copper-Molybdenum(15%-85%)	6.9	190
Copper-Molybdenum(25%-75%)	8.0	175
Copper-Wolfram(10%-90%)	6.7	180
Copper-Wolfram(20%-80%)	8.5	200
Gold	14.0	317
Iron	12.0	80
Kovar	5.5	17
Lead	29.3	35
Molybdenum	4.9	138
Nickel	11.9	90
Platinum	9.0	72
Silicon	3.0	150
Silver	18.9	429
Stainless steel	17.1	14.5
Thermal Grease	n/a	0.8-1.2
Tin	23.4	67
Wolfram	4.6	174

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Mechanical Mounting Step by Step

A. The following order of mechanical installation using heat conducting greases can be recommended:

- *Prepare contacting surfaces. Check the planeness of surfaces, remove alien particles. Clear the surfaces with a lint free soft cloth. Use ethanol.*
- *Put a thin layer of a heat conducting gease on the contacting surfaces.*
- *Connect the surfaces. With a small effort grind the surfaces to improve the contact.*
- *Give the elements a final alignment and set them by a slight clamping effort.*
- *Connect the surfaces with bolts. It is necessary to provide a uniform pressing without skrews. The maximal clamping effort should meet the restrictions.*

B. The following order of mechanical installation using heat conducting gaskets can be recommended:

- *Prepare contacting surfaces. Check the planeness of surfaces, remove alien particles. Clear the surfaces with a lint free soft cloth. Use ethanol.*
- *Put an all-over thin layer of the thermal grease on each contacting surface.*
- *Connect the surfaces with the prepared heat conducting gaskets.*
- *Give the elements a final alignment and set them by a slight clamping effort.*
- *Connect the surfaces with bolts. It is necessary to provide a uniform pressing without skrews. The maximal clamping effort should meet the restrictions.*

There are plenty of materials to improve a thermal contact. In Tables 1.1.2-1.1.4 examples of such materials are given:

◆ *Heat conducting greases. Usually these greases are on the basis of organic binding (for example silicone oils) with various filling agents increasing thermal conductivity.*

◆ *Heat-conducting gaskets. Commonly these are elastic polymeric materials of an organic or silicone origin, also doped by some heat conducting agents.*

◆ *Heat-conducting gaskets undergoing a phase transition at a certain temperature and thus becoming plastic. Due to that voids and hollows are better filled and the quality of thermal contact improves.*

Table 1.1.2. Thermal greases parameters

Model	Material	Thermal Conductivity W/mK	Resistivity Ohmcm	Temperature range °C	Lifetime	Manufacturer
TG-001	Zinc Oxide/Silicone	0.74	>5x10^{14}	<150	5 years @25C	Melcor, Inc.
TG-003	Al2O3 / Non-Silicone	2	>10^{13}	<150	1 years @25C	
TG-005	AlN / Non-Silicone	4	>10^{13}	<150	1 years @25C	
CGL70151	Non-silicone paste	2	>1x10^{13}	n/a	1 years @25C	AI Technology, Inc.
CGL7056	Silicone paste	> 4.0	>1x10^{14}	n/a	1 years @25C	
CGR7016	Non-curing paste	4	>1x10^{13}	n/a	n/a	
ELGR8501	Non-curing paste	> 6.0	<1x10^{-3}	n/a	n/a	
Arctic Silver 5	Non-silicon poly-synthetic oils	>7.5	ÍÄ	-50…+150	n/a	Arctic Silver, Inc.
T660	thermal phase change (patented)	0.90	1x10^{14}	-50…+200	n/a	Chomerics North America
T650	n/a	0.80	1x10^{14}	-50…+200	n/a	
КПТ-8	Silicone	0.8-1.2	1x10^{13}	-60…+180	5 years	"Химтек" (Russia)

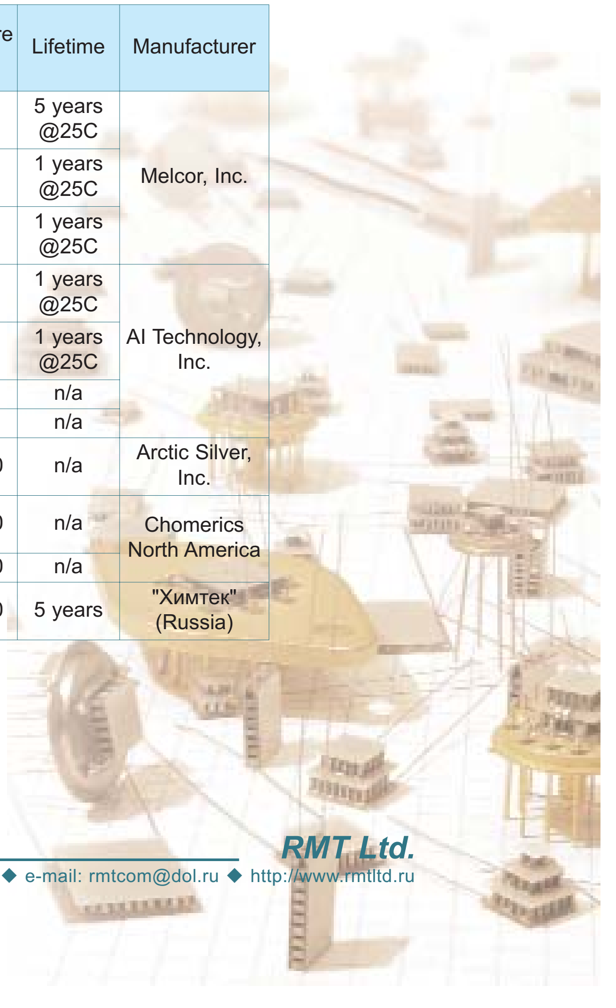

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Table 1.1.3 Heat conducting gaskets parameters

Model	Material	Thermal Conductivity W/m-K	Resistivity Ohmcm	Thickness, mm	Tensile Strength, psi	Temperature range °C	Manufacturer
T444	Silicon/Alumina filled	0.38	$1x10^{14}$	0,08	3000	-60…+150	Chomerics North America
T500	Silicon/Boron Nitride	2.07	$1x10^{14}$	0,25	1000	-60…+200	
ADI-ALO-119-135	Al_2O_3 filled	1.7	n/a	0,10	15…300	<+150	Melcor, Inc.
ADI-ALN-119-135	AlN filled	3.6	n/a	0,10	15…300	<+150	
GRF-600-600	97% Graphite filled	5	n/a	0,13	15…300	<+450	
CPR 7156	n/a	>4.0	$1x10^{14}$	n/a	n/a	n/a	AI Technology, Inc.

Table 1.1.4 Phase changing heat conducting gaskets parameters

Model	Material/Colour	Thermal Conductivity W/m-K	Resistivity Ohmcm	Thickness, mm	Phase Change Temperature, °C	Clamping, psi	Temperature range, °C	Manufacturer
NTE425	Black/self-adhesive layer	0.7	n/a	0.077	+55	10…200	<+120	NTE Electronics, Inc.
T443	Grey/self-adhesive layer	1.0	$5x10^{15}$	0.13	+43	20…60	-60…+125	Chomerics North America
T310	Grey/self-adhesive layer	0.6	$5x10^{14}$	0.18	+46	50…300	-60…+125	
T558	Grey/self-adhesive layer	3	n/a	0.11	+43/+65	n/a	n/a	

When choosing a heat conducting layer it is important to remember that its thermal resistance is in inverse proportion to heat conductivity of the material and in direct ratio to its thickness.

If the clamping pressure is increased, the layer thermal resistance falls. In Fig. 1.1.4 the exemplary dependence of the gasket thermal resistance per surface unit on pressure is shown. However, one cannot overlook that at growth of pressure it is necessary to find an optimum decision, as the clamping effort should not exceed a recommended value.

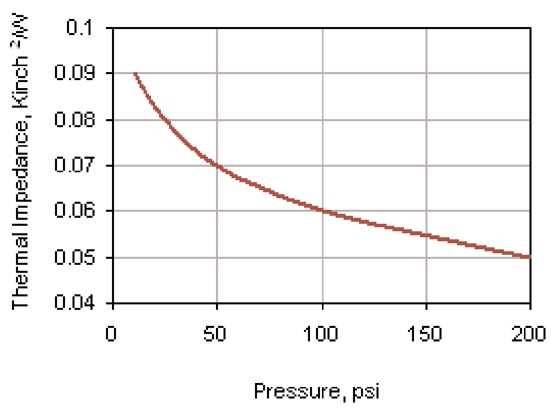

Figure 1.1.4. Exemplary dependence of the gasket thermal resistance on pressure

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1.2. Soldering

Description. The module is soldered by a soft solder to a heat-conducting header, and a cooled object is soldered by a similar way on the cold side of the TE module. The thermal contact and mechanical durability is provided by the used solder.

The soldered surfaces should be prepared:

- Surfaces of the module (the cold and hot sides) should be metallized and have a good solderability. As this metallization we most frequently recommend either a nickel metallization covered by a tin galvanic layer with additives (for example Sn-Bi or Sn-Co), or a thin gold covering atop of a nickel layer.

- Surfaces soldered to the TE module also should have a good solderability. Most frequently soldered objects are made of metals or ceramics whose solderability is also provided with metallizations applied to the module - a tin covering atop of a nickel layer or gilding.

Advantages of the Method. The method of the soldering has a lot of doubtless advantages:

- *Good mechanical durability;*
- *Good thermal contact between the surfaces;*
- *Suitability for vacuum applications as does not cause outgassing;*
- *No need for additional space as in case of mechanical mounting;*
- *Possibility of partly disassemblying.*

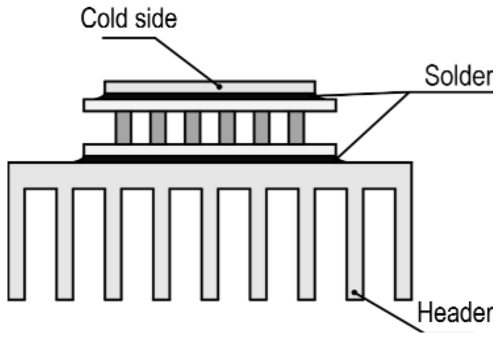

Figure 1.2.1. Soldering method of mounting

Both metallization types (tin-covered and gold plating) provide a good solderability.

- *Gold plating has a longer life-time but can increase cost of this product due to gold contents.*
- *Tin covering is less expensive but has a limited usage-time (usually 6 months) as solderability is worsened due to surface oxidation. It is possible to freshen the surfaces wiping by ethanol and to remove oxide mechanically, it is also possible to apply active fluxes.*

In practice it is necessary to take into account in liquid condition physical and chemical properties of metals contained by solders.

On the one hand interaction of a solder with a layer of metallization of the soldered details is obligatory for a good contact, on the other hand a strong interaction can result in a worsened solderability.

For example, in many solders there is indium or lead. In a liquid condition the given metals interact and dissolve gold of the covering. If the layer of gilding is very thin, even at a very short process of soldering, liquid solder has time to dissolve the covering, and the surface becomes unsolderable. Any further attempts of soldering are practically to no avail: the surfaces are totally damaged.

The second consequence of interaction of covering metals and a solder and a change of the melted solder structure the resulted melting temperatures can change considerably.

As a rule, if during soldering the gold covering is dissolved the temperature of the soldered seam is increased in comparison with the initial melting temperature of the solder. Frequently the difference can be 10 K and more).

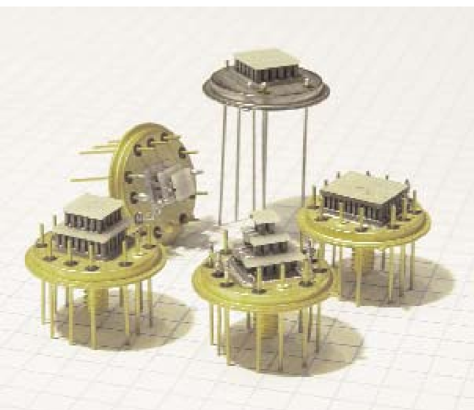

Figure 9.1.2.2. Examples of mounting by soldering on the TO8-style headers

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Application. It is the main mounting method for single- and multistage micromodules. For large modules it is limited due to a risk of mechanical strain owing to a difference of thermal expansions of contacting surfaces.

Important remarks. When the soldering method is used, it is necessary to pay attention to the following:

◆ Preparation of Surfaces

As mentioned above, the solderability of the contacting surfaces, therefore their metallization is absolutely necessary for the method application.

Similarly to the mechanical installation and gluing, the requirement to the planeness and roughness of surfaces, as well as to the particles ingress exception are actual. Excessive roughnesses and heterogeneity results in increasing the soldering seam. It is undesirable as solders' thermal conductivity is frequently much lower than that of contacting details.

◆ Solder Selection

The first requirement is application of solders with melting temperature below that of the internal solder of the module. Otherwise there is a risk of the module destroyment. Thus, the maximal melting temperature of installation solders is determined by the internal solder. In Table 1.2.1 the melting temperatures of the most frequent solders are given.

It should be borne in mind that the most habitual solders containing lead has become forbidden in Electrical and Electronic Equipment (EEE) since the middle of 2006. Therefore the set of solders from the list offered has to be considerably reduced and applicability of other suitable solders is investigated.

Table 1.2.1. Solders and their melting points

INTERNAL SOLDERS		
Solder	Composition	T_{melt}, °C
Tin-Lead	Sn-63%, Pb-37%	183
Tin-Zinc	Sn-91%, Zn-9%	199
Tin-Antimony	Sn-95%, Sb-5%	230
EXTERNAL SOLDERS		
Solder	Composition	T_{melt}, °C
Bismuth-Tin-Lead (Rose)	Bi-50%, Sn-25%, Pb-25%	94
Undium-Tin	In-52%, Sn-48%	117
Bismuth-Tin	Bi-57%, Sn-43%	138
Tin-Lead-Cadmium	Sn-50%, Pb-32%, Cd-18%	145
Indium	In-100%	157
Tin-Lead	Sn-63%, Pb-37%	183

The thickness of solder can be considerably reduced by a strong clip at the solder being melted: the higher the effort , the more the surpluses of the solder can be removed from the contact area.

The control of the solder thickness is possible if monitoring the quantity of the solder (soldering flux) and the subsequent clipping effort.

A more precise control of the soldering seam thickness can be carried out by a metal foil of the given thickness. The thickness of the soldering seam is close to that of the foil.

It is necessary to take into account, that while soldering, the area of two details contact is strongly heated up to temperature above the melting point of the solder. At the subsequent cooling there is a crystallization of the solder at $T=T_{melt}$. Thus, a rigid contact of the soldered surfaces is provided at the raised temperature.

And the further cooling can result in a mechanical strain in soldering area because of the inevitable difference of thermal expansion coefficients of the contacting details. The greater this difference and the higher the melting temperature, the more significant the strain.

Table 1.2.2. Physical properties of solders

Solder (composition, %)	T_{melt}, °C	Density, g/cm^3	Thermal conductivity, W/mK	Specific Heat, J/kgK	Electrical conductivity x10^6, 1/Ohmm	CTEx10^{-6}, 1/K	Ultimate Strength, MPa
Bi(50)Sn(25)Pb(25)	94	9.44	16	151	1.7	20	35
In(52)Sn(48)	117	7.30	73	233	9.4	24	n/a
Bi(57)Sn(43)	138	8.58	41	180	1.7	19	n/a
Sn(50)Pb(32)Cd(18)	145	8.80	60	205	7.5	26	40
In(100)	157	7.31	86	243	13	29	2
Sn(63)Pb(37)	183	9.30	50	170	7.2	26	51
Sn(91)Zn(9)	199	7.27	61	256	3.9	25	54
Sn(95)Sb(5)	230	7.25	28	221	6.9	27	40

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◆ <u>How to Solder</u>

The most simple way is tin-plating the surfaces by a soldering iron with a chosen solder and a suitable flux and further connecting them at the temperature above the solder melting point and then cooling.

The given way is based on manual skills. Thus, the quality and appearance of the soldered connections is far from being perfect.

A more progressive way is applying soldering pastes. The soldering paste is put on one of the surfaces. Surfaces are touched and the connecting area is heated up to the melting temperature.

◆ <u>Soldering Seam Thickness</u>

The thickness of a soldering seam is of vital concern. During the soldering it is possible to adjust the solder thickness in a wide range.

◆ <u>Thermal Expansion Agreement.</u>

The method of soldering is referred to a rigid fixation. In this case it is necessary to bring the coefficients of thermal expansion (CTE) to agreement.

In Table 1.2.3 the data on CTE of materials applicable for installation are given.

<u>Soldering Mounting Step by Step</u>

We can recommend the following prcedure of installation by the soldering method (with a soldering flux):

- *Put a thin all-over layer of the soldering paste on one of the surfaces, commonly on that of the module. The thickness of the layer should be no more than 50-70 microns.*
- *Connect surfaces and slightly grind them in to improve the contact.*
- *Bring the surfaces into a final orientation and elements into a necessary position, press and fix for the period of the soldering.*
- *Place the detail into a furnace or on a heating table.*
- *Provide a short-term heating up to the solder meling temperature.*

Table 1.2.3. Physical properties of materials

Material	CTEx10-6, 1/K	Density, g/cm^3	Thermal Conductivity, W/mK	Specific Heat, J/kgK	Electrical Conductivity, 10^6 1/Ohmm	Ultimate Strength, MPa	Young's Modulus, GPa
Aluminium	22.5	2.7	237	900	36	50	70
Bismuth Telluride	12.9(⊥)	7.85	1.5	188	0.1	20-40	50
Brass	18.0	8.49	110	343	7.1	240-400	102-115
Ceramics Al2O3 - 100%	7.2	3.9	30	800	-	150	280
Ceramics Al2O3 - 96%	7.0	3.75	24	800	-	150	280
Ceramics AlN	4.5	3.3	170	920	-	n/a	350
Ceramics BeO	7.0	3	230	1088	-	105	330
Cold-roll steel (CRS)	11.5	7.85	50	460	7.5	210-240	200-210
Constantan	16.9	8.39	22.5	410	2.08	n/a	n/a
Copper	16.7	8.96	400	385	58	215	120
Copper-Molybdenum(15%-85%)	6.9	10	190	280	18	540	280
Copper-Molybdenum(25%-75%)	8.0	9.8	175	283	17.5	n/a	n/a
Copper-Wolfram(10%-90%)	6.7	17	180	163	19	560	330
Copper-Wolfram(20%-80%)	8.5	15.65	200	n/a	25	490	280
Gold	14.0	19.32	317	128	44	150	80
Iron	12.0	7.87	80	465	11.5	290	200
Kovar	5.5	8.36	17	460	2	n/a	n/a
Lead	29.3	11.34	35	130	5.2	14-18	14-18
Molybdenum	4.9	10.22	138	249	18	670	300-330
Nickel	11.9	8.91	90	448	16.3	200-220	n/a
Platinum	9.0	21.45	72	133	9.2	145	150-175
Silicon	3.0	2.33	150	705	0.4	700	110-160
Silver	18.9	10.5	429	235	60	160	80
Stainless steel	17.1	8.01	14.5	460	7.5	580	n/a
Thermal Grease	n/a	2.8	0.8-1.2	2093	n/a	n/a	n/a
Tin	23.4	7.31	67	226	8.70	30	48
Wolfram	4.6	19.35	174	132	18	500-1000	350-400

1.3. Adhesive Bonding

Description. A TE module is attached to a header/heat sink or an object to be cooled is mounteed onto a module by a thermoconductive glue.

The thermal contact and mechanical durability strongly depend on a glue used. As a rule these are epoxy glue with different fillers, which are called to provide a good thermal conductivity. In Table 1.3.1 examples of applicable glues and their properties are given according to manufacturers.

For adhesive bonding the TE module surface should be lapped though a metallization is admitted unless it worsens the adhesion quality of the glue supposed.

The method of adhesive bonding is widely used both for micromodules (mainly) and for the big modules. Though in the second case its usage is restricted.

The method of adhesive bonding is referred to methods of rigid fixing, therefore the thermal expansion agreement of contacting materials (ceramics of the module, heat-removing surface and a material of a cooled object) is necessary.

Application. The method application is similar to that of soldering: it is mostly applied to single- and multistage micromodules. The application for powerful modules is limited due to possible mechanical strains due to thermal expansion.

Important Remarks. An excessive roughness and heterogeneity of the surface may result in increasing the thickness of the bonding layer that reduces thermal conductance.

◆ Bonding Layer Thickness

Whatever the manufacturers of the glues and pastes invent to highten thermal conductivity, its value remains quite lower than the properties of contacting ceramics metal surfaces. Therefore, on the one hand, the bonding seam should be rather thin, which can be managed by clamping.

On the other hand, limitless minimizing the seam thickness is the extreme to be avoided. The seam thickness should be enough to provide a sufficient strength and a certain compensation of the coefficient of thermal expansion difference between the bonded surfaces.

It is recommended that the bonding thickness should be 10-20 μm.

◆ Agreement of Thermal Expansions of Contacting Materials

The method of adhesive bonding is referred to the rigid fixation. In that case it is necessary to take into account agrreement of thermal expansion coefficients of the pasted surfaces. In Table 1.2.3 the data on thermal expansion coefficients of the materials most frequently used for installation are given.

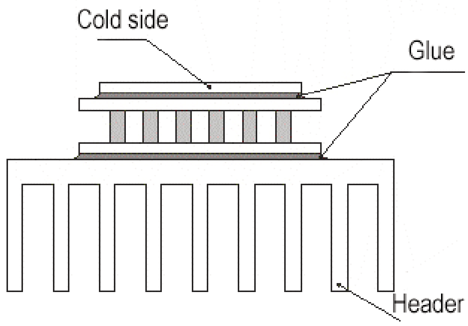

Figure 1.3.1. Adhesive bonding mounting

Adhesive Bonding Mounting Step by Step:

The following procedure s to be recommended:

- *Prepare the surfaces thoroughly: remove alien particles, wipe it with a lint free soft cloth. Use ethanol.*
- *Get ready with a sufficient glue quantity. If the glue is two-component, prepare the composition.*
- *Put a thin layer of the glue on one of the surfaces to be bonded. The layer thickness should not exceed 50-70 μm.*
- *Join the surfaces and slightly grind them in for a better contact.*
- *Bring the surfaces into a final orientation and elements into a necessary position, press and fix for the period of the glue polymerization.*
- *Carefully remove the redundant glue.*
- *Soak the detail in a high temperature condition if it is recommended for the glue given.*
- *After a complete polymerization of the glue remove the tools of temporary fixing.*

For the control of the glue complete polymerization it is necessary to expose the residuals of the prepared glue portion to the same conditions as the bonding. Thus, the final polymerization of the glue can be checked by the polymerization of the glue residuals within a given period of time.

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Advantages of the Method. Adhesive bonding is a reliable and a rather simple method for TE modules mounting:

- *Unlike the mechanical installation it does not demand any additional elements occupying the area.*
- *In contrast to the soldering method it does not demand any intensive heating of the mounted surfaces, accurate control of temperatures and a special equipment for high temperature.*

Limitations. Adhesive bonding has its own shortcomings and disadvantages:

- *Disassembly of the details mounted by this method is complicated. In some cases it is not acceptable.*
- *Gluing is quite a long process (determined by the glue hardening duration, or a cure time), which reduces productivity.*
- *In operation it is necessary to take into account temperature restrictions of the used adhesive connection. Usually it is not recommended to heat it up above 150-160 °C. Otherwise the material of the glue can undergo irreversible changes and consequently the connection durability and thermal properties can degrade . There are also restrictions on the lowered temperature that may cause embrittlement of the epoxy structures.*
- *It is necessary to limit the use of adhesive connections in vacuum designs due to outgassing intensified by temperature growth.*

Table 1.3.1. Thermoconductive glues

Model	Material	Thermal Conductivity W/mK	Resistivity Ohmcm	Die-Shear kg/cm^2	Thermal expansion $10^{-6}/K$	Temperature range °C	Cure Time	Manufacturer
TCE-001	Silver Filled	1.35	0,05	45	49	-55…+125	2 hrs@ 65°C	Melcor, Inc.
TCE-002	Al2O3 Filled	1.73	$>1x10^{14}$	105	140	-20…+130	1 hr@ 85°C	
TCE-003	Al2O3 Filled	1.73	ND	105	140	-20…+130	1 hr@ 85°C	
TCE-004	AlN Filled	3.6	ND	125	120	-25…+130	1 hr@ 85°C	
ESP 7356	AlN, Flexible Epoxy Film	>3.6	$>1x10^{14}$	140	ND	-60…+125	>125°C/10psi	AI Technology, Inc.
TP7095	Flexible Alumina Filled	1.7	$>1x10^{14}$	>70	ND	-55…+125	>120°C/10psi	
ESP 7676-HF	Low Stress, High Flow Epoxy	>3.6	$>x10^{14}$	>210	ND	-55…+125	80-100°C	
ME7668	Low Stress, Epoxy	>3.6	$>1x10^{14}$	>210	ND	-55…+125	80-100°C @30 min	
Arctic Silver	Silver and conductive ceramic particle filled Epoxy	>7.5	ND	ND	ND	-40 …+150	25°C@3-4 min	Arctic Silver, Inc.
1641	One-component	0.9	$1x10^{13}$	ND	112	-70…+200	25°C@48 hours	Chomerics North America
1642	Bicomponent	0.95	$1x10^{13}$	ND	180	-70…+200	100°C@1 hours	

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2 Thermal Expansion Effect

2.1 Thermal Expansion in TE Modules

In any of the mounting methods listed above there is a contact of different materials.

In a TE module operational mode there are significant temperature changes of TE module elements caused by the gradient of temperature between the cold and hot sides of the design.

The materials of the design have different coefficients of temperature expansion (CTE) resulting in inevitable mechanical strains that may destroy the TE module (Fig. 2.1.1).

Mechanical strains arise both in the vertical direction along the heat path and in the plane of the cold and hot sides. It is the difference of CTEs in the plane of the module as its width commonly exceeds its height.

It should always be borne in mind in case "rigid" methods of installation are used, such as soldering or adhesive bonding. It concerns a mechanical method to a lesser extent

The destruction character is typical enough. As the TE material has the least strength (see Appendix A2 - typical properties of materials), at excessive mechanical strains TE elements (pellets) may be destroyed. This process initially manifests itself in an increase of the TE module resistance and a corresponding decrease of the Figure-of-Merit (the time constant of the module remains approximately unvaried). It is the result of microcracks occurrence in the TE material. A total mechanical break of pellets follows.

As an example, we give a photo data on the tests of a set of TE modules mounted on headers (sub-mounts) with an object of cooling on the cold side (Fig. 2.1.2). Tests were carried out by the method of thermal cycling at at electric curremt at a raised temperature (burn-in).

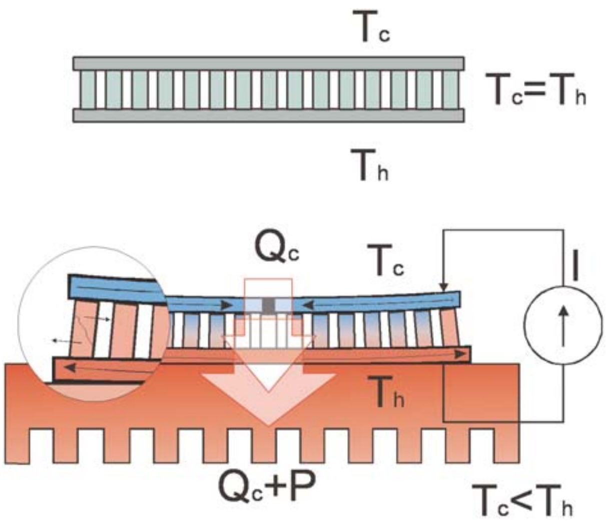

Figure 2.1.1. Mechanical strains in the TE module design

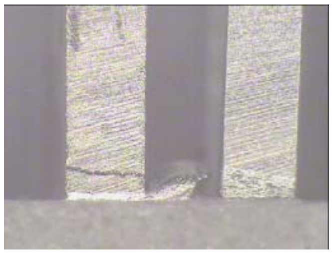

Figure 2.1.2. TE design burn-in test result

2.2 Materials CTE Agreement

The coefficients of thermal expansion (CTE) agreement should be paid much attention to while developing a design with a built-in TE cooling module. The TE module itself has a high reliability and stability to temperature changes and gradients. However in a final design this reliability can be negated by an unreasonable material choice .

The materials connected to the module, namely to the cold and hot side ceramics, are the subject to the CTE agreement.

In Table 2.2.1 the data on properties of the most widely used TE designing materials are given.

Table 2.2.1. Some materials CTE and thermal conductivity

Material	CTEx10^{-6}, 1/K	Thermal Conductivity, W/mK
Aluminium	22.5	237
Bismuth Telluride	12.9(⊥)	1.5
Brass	18.0	110
Ceramics Al2O3 - 100%	7.2	30
Ceramics Al2O3 - 96%	7.0	24
Ceramics AlN	4.5	170
Ceramics BeO	7.0	230
Cold-roll steel (CRS)	11.5	50
Copper	16.7	400
Copper-Molybdenum(15%-85%)	6.9	190
Copper-Molybdenum(25%-75%)	8.0	175
Copper-Wolfram(10%-90%)	6.7	180
Copper-Wolfram(20%-80%)	8.5	200
Gold	14.0	317
Kovar	5.5	17
Nickel	11.9	90
Platinum	9.0	72
Silicon	3.0	150
Silver	18.9	429
Stainless steel	17.1	14.5

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From Table 2.2.1 we see that the application of materials with the best thermal conductivity is not obviously optimal. Such materials as copper, aluminium and some other metals have a very high thermal expansion coefficient. Experience proves that problems with reliability of cooled designs applying these materials are rather often, especially if linear dimensions and temperature gradients are significant.

Thus, in practice, whenever possible, the compromising choice of materials is important. The following tips may be considered:

1) In many cases the best solution is the application of composite materials such as Cu/W or Cu/Mo. These new materials have good thermal conductivity and thermal expansion coefficiwents well correlated with ceramics of TE modules. However their expensiveness is the application essential restriction.

2) In designs with small heat flows (low-power TE modules) the solution is a kovar or a cold-rolled steel. While the thermal expansion of these materials is compatible to that of ceramics, they have a high thermal resistance. However at small heat flows it is not of a vital concern.

3) In designs with small linear dimensions such good heat conductors as copper or aluminium are allowable. However taking additional measures for improving reliability is necessary, for example, an appropriate solder selection. To a certain extent an inevitable mechanical strain can be damped by the use of elastic solders, among which the Indium solder or the Rose alloy.

Table 2.2.2. Some solders CTE and thermal conductivity

Solder (composition, %)	Tmelt, °C	CTEx10^{-6}, 1/K	Thermal conductivity, W/mK
Bi(50)Sn(25)Pb(25)	94	20	16
In(52)Sn(48)	117	24	73
Bi(57)Sn(43)	138	19	41
Sn(50)Pb(32)Cd(18)	145	26	60
In(100)	157	29	86
Sn(63)Pb(37)	183	26	50
Sn(91)Zn(9)	199	25	61
Sn(95)Sb(5)	230	27	28

2.3 TE Design Thermal Expansions Optimization

The larger initial values of linear dimensions L_0, the more significant absolute values of thermal expansions ΔL. Except allowing for the influence of characteristics of materials, the designing task is to optimize geometry of a design taking into account the CTE α of the chosen materials and the given restrictions.

The criterion for elementary estimations can be the following:

$$\Delta L = \alpha \Delta T L_0 \qquad (2.3.1)$$

For a nonrigid installation of a TE module (see Sec. 1.1 and 1.3) the criterion can be calculated as the radius r of allowable curvature of the surfaces (Fig. 2.3.1).

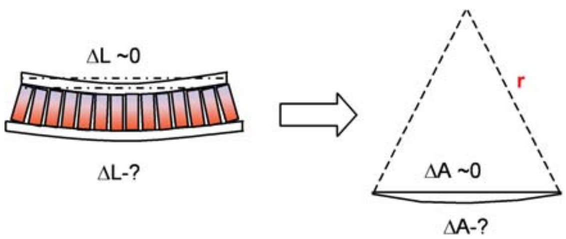

Figure 2.3.1. Explanations for r calculations

In some problems it is necessary "to split" rigid elements of a design for a new constructive concept. Thus, sometimes for cooling planar objects it is reasonable to use not a single TE module but several ones.

Example

Let us consider 6 TE modules 10x12 mm^2 for cooling a CCD matrix whose surface is 10x110 mm^2 (see Fig. 2.3.2).

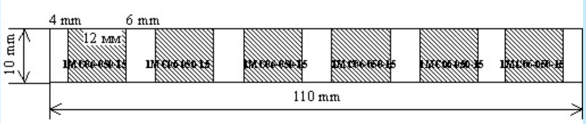

Figure 2.3.2. Planar objects cooling by the system of splitted TE modules

If in the given example a single TE module were used, at the temperature gradient 20 K the change of the linear dimensions would equal 16 μm. Application of a splitted cooling allows almost 2 times reducing this value (8.6 μm).

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2.4 Optical Adjustment and Thermal Expansion

In many optoelectronic devices it is very important to perform an accurate adjustment of the components placed on the TE module cold side.

It is necessary to take into account that during assembly of such designs the adjustments are made under one (equilibrium) temperature conditions, whereas the operation occurs at TE cooling temperature gradients.

Let us consider a practical example - a laser diode, where cooled elements (a pumping laser and a nonlinear crystal) placed on the TE module cold side should be adjusted to each other and to the exit lens aperture.

From Fig. 9.2.4.1 it is visible that at this device operating there is a change of position of optical axes because of different absolute displacement of elements of a design owing to linear expansions.

Therefore the following recommendations are advisable:

- *Usage of the same materials for different constructive elements.*
- *Minimization of the design and various elements vertical dimensions for reducing absolute sizes of thermal expansion displacements.*
- *Avoiding application of copper or aluminium constructive elements because of big mismatches possibility. The best solution are compromising materials with good thermal conductivity and small (coordinated with the TE module) thermal expansion coefficients.*

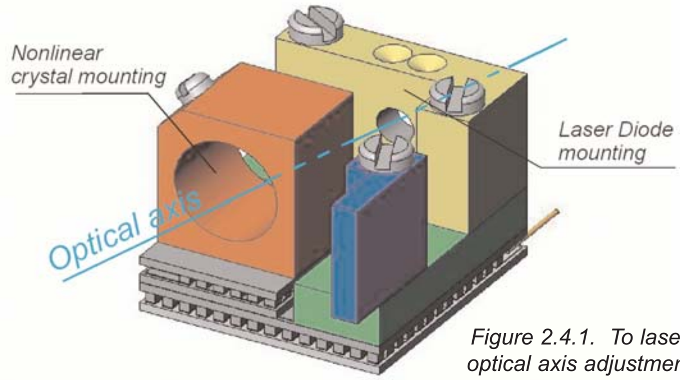

Figure 2.4.1. To laser system and optical axis adjustment (two-cooler thermal stabilization concept)

3. Temperature Losses Reduction

In many applications the size of a cooled object does not coincide with the size of a cooling surface (the cold side of the TE module). It is necessary to take it into account while estimating the efficiency of TE cooling and optimizing cooling systems.

The majority of the used mathematical simulation models solve a 1-dimensional problem of cooling. It is equivalent to an assumption that the cooled object and its heat load are distributed homogeneously on the cooling surface.

Quite frequently in practice this assumption is not true.

Consider two cases:

- *<u>Localized object</u> - object of cooling has a smaller size than the cooling surface. The case is typical for TE coolings of semi-conductor lasers: the size of the laser chip is less than 1 mm.*
- *<u>Planar object</u> - object of cooling has a greater size than the cooling surface. Such situations are typical in detector applications when the cooled object is mounted on a substrate and then on the cold side of the TE module. The size of the substrate usually exceeds the size of the TE module cold side.*

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Example

In the centre of the cold side 16x16 mm^2 of a single-stage RMT TE module 1MC06-126-05 (Q_{max}=28.30 W) there is an object 10x10 mm^2, its heat load 10 W. The object temperature should be 255 K. The TE module hot side is stabilized at T_{hot}=300 K, the module current is 3 A.

1D solution yields that the requirement ΔT=45° can be met. Let us find the temperature 2D field on the module cold side and the value of 2D δT_{losses} - see Fig. 3.1.1.

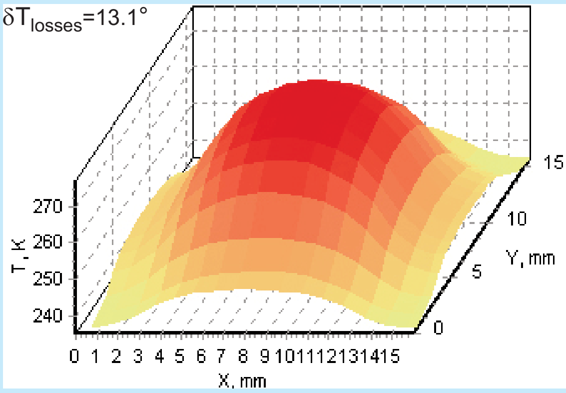

Figure 3.1.1. Example of the 2D temperature field on the TE module cold side with a cooled object localized.

There is overheating in the centre. Heat conductance of the module cold side do not suffice for effective cooling all over the surface.

3.1 Localized Objects Cooling

Here we consider all the objects with the sizes smaller the the cooling surface. The most typical example is the system of a one-cascade TE cooling of the semiconductor laser.

In this case it is necessary to take steps to make the cooled object average temperature approach the average temperature of the heat-absorbing surface of the TE module, that is to reduce two-dimentional (2D) temperature losses δT_{losses} to the minimum (see Sec. 8.5.2). The following ways to do it are available:

1) *Making the size of the contact as close as possible to the heat-absorbing area of the TE module. However at fixed dimensions of the cooled objects the increase of the heat flow density may cause further heat sinking problems.*

2) *Application of special substrates of high thermal conductance (for example, made of such materials as AlN, CuW) placed between the TE module and the cooled object. When choosing the material and the plate thickness the thermal expansion agreement should be remembered (see Sec. 8.2.2), as well as the compromise between one- and two-dimensional temperature losses.*

The 2D analysis can be carried out with the help of the advanced mathematical method of the solution of the 2D problem of cooling for an any arrangement of a rectangular source of heat on the TE module.

Example

The object 20x20 mm^2,material Al_2O_3, its thickness is 0.8 mm, the heat load is 2 W. The RMT TE module 1MC06-050-05 has the cold side 10x10 mm^2. The module hot side temoperature T_{hot}=300 K, electric current 1.4 A.

1D calculations show that the required temperature difference is achievable ΔT=30°. However 2D simulation gives the opposite: the temperature on the object periphery is higher than 270 K (see Fig. 3.2.1).

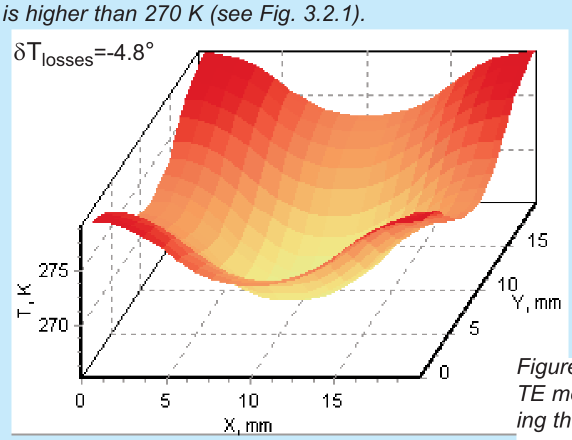

Figure 3.2.1. Example of the 2D temperature field on the TE module cold side with a cooled planar object exceeding the cooling surface.

3.2 Planar Objects Cooling

When the size of the object of cooling exceeds the size of the TE module cold side, it is nonadvisable both owing to additional passive thermal heat flows on the open edges of the object and to 2D-losses: in the centre of the object the cooling is effective but at the edges the temperature is higher.

To heighten the cooling efficiency and 2D-losses reduction it is necesssary to use one of the recommendations described in Sec. 3.1: selecting a CTE optimized substrate of high thermal conductance.

Increasing the substrate thickness reduces 2D losses. However it is necessary to bear in mind that the increase of thickness adds the massiveness of object, results in one-dimensional losses and increases of a surface open for passive heat flows. Therefore in practice search of the optimum is necessary.

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3.3 Uniform Cooling

Such devices are frequently used for registration of thermal emission with resolution 0.01-0.001 K. It is natural that uniformity of cooling should be not worse than the physical parameters of a detector.

A source of non-uniformity is pellets discrete distribution on the substrate surface. The most effective cooling refers to the centre of of a pellet cross-section, reducing towards its periphery. Thus the 2D temperature field has periodical fluctuations.

Appreciable non-uniformity reduction can be achieved by means of AIN for TE module substrates.

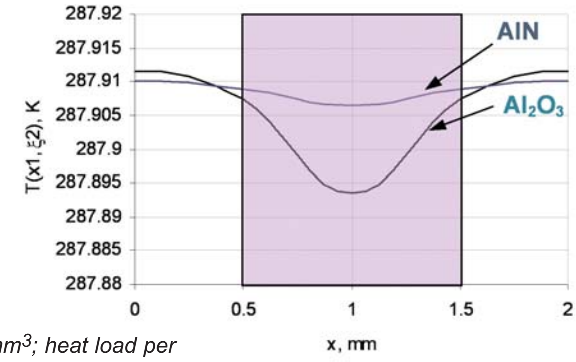

Figure 3.3.1. Temperature on the cold end of the pellet 1x1x2 mm^3; heat load per pellet 0.7 mW, current 1.4 A substrate 0.5 mm thick , made of Al_20_3 and AIN.

4. Passive Heat Load Reduction

As said in Sec. 7.4.8, a full heat load on the TE module is the sum of an active heat flow from the objects demanding cooling and a passive heat flow accompanying processes of heat exchange. Passive heat load results in some drop of cooling efficiency.

4.1. Reducing Thermal Conduction Passive Heat Load

One of the passive heat contributions is thermal conduction by design elements (for example, wires, multiplexers, diaphragms, etc.), connected with a cooled object.

As a rule, these elements have one end connected to the housing (package). For the number N of such elements, heat conductance of an i-th element k_i, package temperature T_{hot}, module cold side T_{cold}, for small currents and not too long wires the following formula can be used:

$$Q_{cond} = \sum_{i=1}^{N} k_i (T_{hot} - T_{cold}) \quad (4.1.1)$$

It is evident that to reduce this heat load means to decrease elements thermal conduction or/and ΔT.

The first is possible by the choice of the proper material. In Table 4.1.1 thermal conductivity of several metals used for leading wires are given.

Table 4.1.1. Some meatals thermal conductivity

Material	Thermal conductivity, W/mK
Platinum	72
Nickel	90
Gold	317
Copper	400
Silver	429

The second variant is a connection of heat-conducting elements to the design details of temperature T lower than T_{hot}: $T_{cold}<T<T_{hot}$. If a multicascade TE moduleis is used, its intermediate cascades can serve as such heat-removing details. This mediate heat-conducting is frequently referred to in engineering terminology as anchoring.

In the simplest case heat-conducting elements are leading wires which, if anchored, are provided with thermal contact on one of intermediate cascades.

The souces of passive heat that do not demand cooling down to low temperatures (T_{cold}) can be taken outside the module cold side. Their heat load can be removed by means of a special heat-conducting bridge applied as an interface between the cooled object and some intermediate cascade.

Example

The souces of passive heat that do not demand cooling down to low temperatures (T_{cold}) can be taken outside the module cold side. Their heat load can be removed by means of a special heat-conducting interface (screen) between the cooled object and some intermediate cascade (see Fig. 4.1.1).

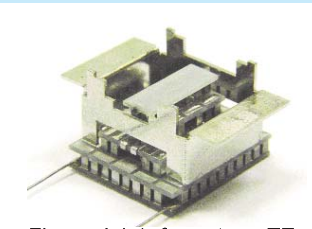

Figure 4.1.1. four-stage TE module with a screen (Patent RF # 41548, U1, application 2004120182, 08.07.2004

In the depicted assembling with the screen the heat load on the TE module cold side is 100 mW, whereas on the cooled screen mounted on the bottom cascade it is 150 mW. In the absence of the screen the summed heat load 250 mW would be rejected by the cold side, thus it would be impossible to provide required cooling down to 200 K.

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4.2 Reducing Gas Environment Passive Heat Load

Vacuum in TE cooling is the best for thermal losses reduction as it eliminates passive heat loads by gas convection and thermal conduction.

If the design is gas-filled or if the system vacuum tightness is violated, its cooling efficiency deteriorates due to the influence of two processes:

- **Thermal conduction through the gaps between pellets**

Let's take into account additional thermal conduction in gas through the gaps between pellets as increased effective thermal conductance of each pellet:

$$k_0' = k_0\left(1 + \frac{\kappa_{gas}}{\kappa_{mater}}\left(\frac{1}{\beta} - 1\right)\right) , \qquad (4.2.1)$$

where k_0 is a pellet thermal conductance, κ_{gas} is gas thermal conductivity, κ is TE material thermal conductivity, β is pellets filling coefficient (the ratio between the summed pellets cross-section and the cold side surface).

In Table 4.2.1 thermal conductivity of some most frequently used gases under normal conditions and an estimation of ΔT_{max} decrease for the single-stage module 1MC04-018-05 (RMT), β=0.25, if ΔT_{max} in vacuum is 70 K. The module hot side is kept at T_{hot}=300 K.

Table 4.2.1. Estimations of ΔT_{max} decrease in gas as compared with vacuum (ΔT_{max} in vacuum is 70 K)

Gas	Thermal Conductivity, W/mK	Decrease of ΔTmax, K
Dry air	0.026	1.4
Argon	0.016	0.9
Xenon	0.0057	0.3

Obviously, the best gas environment among the variants offered is Xenon with the lowest thermal conductivity.

- **Convective thermal exchange between the TE module substrates and gas**

Let us analyze convective heat loads for different gases. The convection heat exchange coefficient per surface unity α_{conv} is given by:

$$\alpha_{conv} = \frac{\kappa}{x} Nu , \qquad (4.2.2)$$

where Nu is the Nusselt number, x is the characteristic size of the TE module substrate, k is gas thermal conductivity (see Table 4.2.1).

Table 4.2.2 gives calculated values of the convection heat exchange coefficient for the same gases as in Table 3.2.1 at the gas temperature 300 K, ΔT_{max}=70 K and x=5 mm (for example, the TE module 1MC04-018-15). There are also given passive heat and corresponding delta-temperature ΔT_{max} reduction estimates.

Table 4.2.2. Calculated value of α_{conv} for some gases at 300 K, ΔT_{max} = 70 K (in vacuum), x=5 mm, and ΔT_{max} decrease as compared with vacuum

Gas	Convection coefficient, W/m^{2}K	Qpas, mW	Decrease of ΔT_{max}, K
Dry air	21.6	49	5.5
Argon	14.8	34	3.2
Xenon	8.5	19	2.2

From Table 4.2.2 we see that it is only xenon that can reduce temperature losses to the extent of the calculation errors.

As we can conclude, the more inert gas is, the less intensive passive heat flows interfering with TE module efficiency. That should be taken into account when selecting a gas for a non-vacuum operational environment of a TE module.

4.3 Reducing Thermal Radiation Passive Heat Load

Unlike convection, radiation is present in vacuum as well. In gas environments the radiation heat load is commonly several times smaller than the convective one. But the problem of its reducing is faced very often.

For reducing passive radiation heat loads screening methods are used.

The radiation flow from object 1 of the temperature T_1 to object 2 of the temperature T_2 can be generally described as:

$$Q_{rad} = \sigma_Б A_{12} F_2 (T_1^4 - T_2^4) , \qquad (4.3.1)$$

where A_{12} is the radiation exchange coefficient (effective emissivity) between object 1 and object 2, $\sigma_Б$ is the Stephan-Botlzman constant, F_2 is the surface of object 2 that accepts the radiation heat load.

It is evident that if the cooled surface F_2 and its temperature T_2 are given, for reducing the radiation impact two ways are possible:

- *Value A_{12} decreasing (for example, applying reflective coating and screens);*
- *Temperature T_1 lowering (for example, applying cold screens and anchoring – see Sec. 4.1).*

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5. Heat Sink Efficiency

A TE module must not be operated without a sufficient heat rejection from the hot side.

As a rule designing a heat sink can be divided into two phases:

- *Determining a value of the heat sink thermal resistance R_t, as necessary to meet operational requirements;*
- *Designing of the heat sink system that has thermal resistance not higher than the obtained value R_t.*

We assume that the operational mode of a TE cooling system is known: a full heat to be pumped Q_{cold} and necessary ΔT in the described conditions and at a known ambient temperature T_a are given. Then we can calculate (see the software TECcad, Chapter 7) the TE module/TE sub-mount maximum hot side temperature $Thot_{max}$ to meet the requirements. Let the corresponding heat to be rejected be Q_{hot}. Then the necessary thermal resistance R_t can be calculated as:

$$R_t = \frac{T_{hot\,max} - T_a}{Q_{hot}} \qquad (5.1)$$

Then an experienced designer-thermophysicist selects or develops a radiator (heat sink) to meet the R_t, makes conclusions on necessary free or induced heat exchange between the heat sink and the ambient, recommending a fan or a liquid exchanger, if needed.

The company RMT has experienced engineers specialized in this problem. If it should be solved do not hesitate to address to the RMT R&D (e-mail: rmtcom@dol.ru).

Example

In Fig. 5.1 there is an example of dependence of the value R_t on temperature T_a at the hot side temperature 55 °C and heat to be removed 19 W.

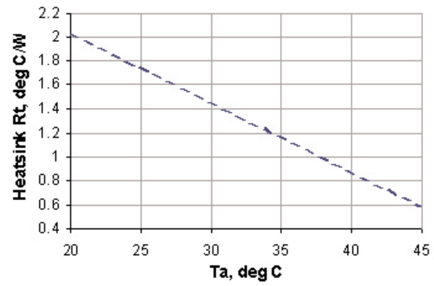

Figure 5.1. Exemplary dependence of the value R_t on the temperature T_a

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6. TE Module Power Supply

A TE module is a DC device. An alternating current of any nature can be detrimental to a TE module efficiency. Let us estimate the decrease in ΔT_{max} if there is an AC component. Let at DC of the value I_0 the maximum temperature difference equals ΔT_{max}(DC). We consider two variants of the current modulation.

6.1 Sinusoidal Modulation

Consider a current rippled in a sinusoidal way – see Fig. 9.6.1, I_0 is the average electric current, the oscillations amplitude around the average is NI_0 (see Fig. 9.6.1.1).

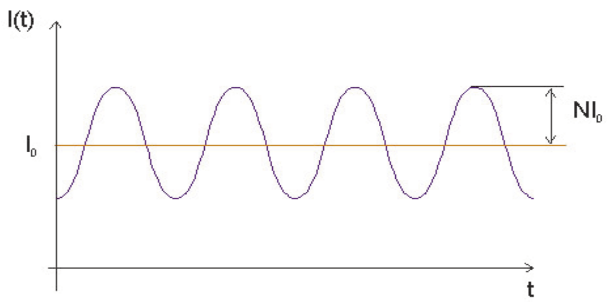

Figure 6.1.1. AC supply vs time (sinusoidal modulation)

The reduction of a TE module performance due to the ripple can be approximated by the following ratio of ΔT_{max}(AC) to ΔT_{max}(DC):

$$\frac{\Delta T_{max}(AC)}{\Delta T_{max}(DC)} = \frac{1}{1+N^2/2} \qquad (6.1.1)$$

Fig. 6.1.2 demonstrates the ripple AC component effect in a range of ripple amplitudes   vs N for a single-stage TE module with ΔT_{max}(DC)=70 K.

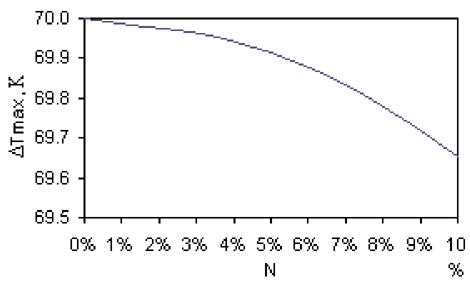

Figure 6.1.2. Detoriation of ΔT_{max} vs N at the nominal ΔT_{max}=70 K in case of sinusoidal modulation.

6.2 Pulse-Width Modulation

Let us consider a current modulated pulse-width, I_0 is the average electric current, the oscillations amplitude around the average is NI_0 (see Fig. 6.2.1); $Q=\tau/T$ is a duty cycle.

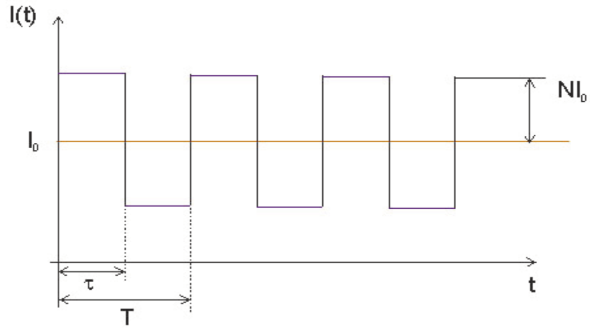

Figure 6.2.1. AC supply vs time (pulse-width modulation)

The ratio of ΔT_{max}(AC) to ΔT_{max}(DC) is:

$$\frac{\Delta T'_{max}}{\Delta T_{max}} = \frac{(1+N(2Q-1))^2}{1+2N(2Q-1)+N^2} \qquad (6.2.1)$$

The results illustrating the efficiency reduction ΔT_{max}(AC) at ΔT_{max}(DC) = 70 K are given in Fig. 6.2.2.

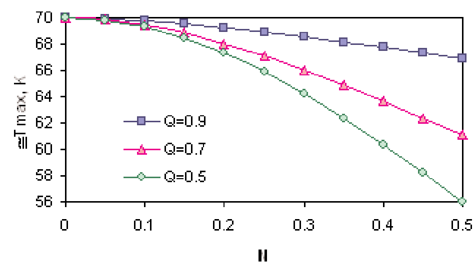

Figure 6.2.2. Detoriation of ΔT_{max} vs N at the nominal ΔT_{max}=70 K. Pulse-width modulation is at various values Q

For Q=0.5 the results (6.2.1) are equivalent to (6.1.1).

It may be shown that at small N (about or less than 1 %) Eq. (6.2.1) can be approximated linearly:

$$\Delta T_{max}(AC) = \Delta T_{max}(DC)(1-N) \qquad (6.2.2)$$

Eq. (6.2.2) is convenient for practical calculations, though for N>1% it underestimates ΔT.

The above study shows that the more intensive the deviation of the electric current from the DC component, the less efficient a Peltier module operation.

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