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Current state of Peltier cooling

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Abstract.

The performances of Peltier cooling depend first of all, on the thermoelectric properties of the thermoelectric (TE) materials and secondly on the thermal design. A survey will be given of present and future TE materials, bulk and thin film. The technologies of manufacturing the materials and of manufacturing TE modules (a rigid assembly of TE couples) will be presented with future trends. Cooling systems from milliwatts to kilowatts with temperature differentials from a few K to more than 100 K will be examined. Present day and pending applications will be reviewed.

The figure of merit Z is the best overall parameter to characterize TE material.

We will examine, for a standard air-air modular cooling unit, the influence of higher values of Z, on the cooling power and the coefficient of performance COP (= cooling power/electrical power). Also the influence on the cost of the system will be estimated. The COP of TE is compared to the COP of a small HFC type compressor.

The aspect of development cost will be addressed as it is a major drawback to the increase of new developments.

1) Introduction

We shall use the abbreviation TE for the word thermoelectric. This paper attempts to satisfy the layman and the specialist. For the past few years there is a renewed interest in Thermoelectricity, also all the work done over the past 30 years in all the countries of the former Soviet Union is slowly emerging. We hope that some of the ideas proposed below will encourage discussion and development.

2) Thermoelectric materials.

2.1 Characterization

The best way to characterize a thermoelectric material is the coefficient of merit $Z = s^2/(\rho * \kappa)$

where s = Seebeck coefficient V/K

ρ = electrical resistivity Ω*m

κ = thermal conductivity W/(m*K)

There has to be an n type material which has a negative Seebeck coefficient and a p type material with a positive Seebeck coefficient. The basic cooling sub-assembly is the thermoelectric couple shown as a sketch in Fig. 1, then comes the thermoelectric module see photograph in Fig. 1 which consists of TE couples in series electrically and in parallel thermally. These are manufactured industrially all over the World.

Thermoelectric semiconductor materials were discovered and developed in the 1950's. For cooling around 300 K bismuth tellluride based compounds are still the best. The improvement since 1960 has essentially been in quality control.

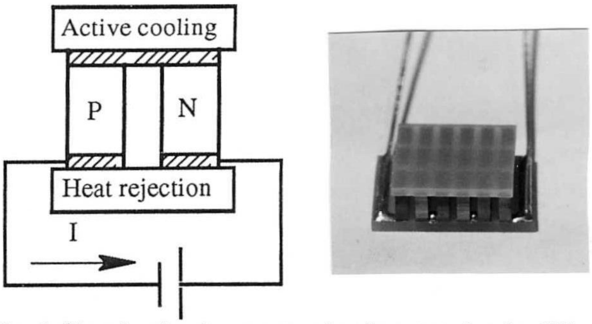


Fig. 1 Sketch of a thermocouple-photograph of a TE module (Thermion) base 8*6 mm

Typical easy to remember values for bismuth telluride at ambient temperature are:

$s = \pm 200$ μV/K

$\rho = 10$ $\mu\Omega$*m

$\kappa = 1.5$ W/(m*K)

$Z = 2.67 * 10^{\wedge -3}$ K^{-1}.

These materials are anisotropic, the performances are obviously better when they are oriented in the most favorable way.

2.2 Experimental characterization

The characterization with high accuracy is very difficult. A paper by Uher [1] gives an excellent survey of all the methods used. The most difficult parameter to measure is the thermal conductivity. Harman [2] developed a method to measure directly the coefficient of merit Z. This measurement is relatively easy to do, it has the tremendous advantage of being a cross check of Z calculated from the 3 parameters s, ρ and κ measured independently. The difference between the calculated Z and the Z measured directly gives one an idea of the inaccuracies involved. Therefore all values announced by a laboratory or a company must be considered with a degree of precaution.

2.3 Manufacturing processes

There are quite a few ways these materials can be manufactured, we will give the most commonly ones used.

The following pertains to bismuth telluride.

1) Crystal grown

There are many ways to grow such crystals. The best crystals are mono-crystals meaning that the manufacturing process produces an ingot consisting of one crystal.

- The Traveling heater method known as THM is considered to produce the best mono-crystals. This method is presently mainly used for research because the method is a very slow one.
- Bridgman, Zone refining and Czchrowlsy are used in industry.

2) Sintered materials

There are 3 methods:

- cold sintering which produces a non oriented material for bismuth telluride compounds this method produces an excellent p type material (Z up to $3.0 *10^{\wedge-3}$ $K^{\wedge-1}$, but the n type material has so far always had a Z that does not exceed $2.4*10^{\wedge-3}$ $K^{\wedge-1}$.

- extruded material

This process is used to manufacture rods of TE material like spaghetti with diameter greater than 1 mm. Interestingly this process produces an oriented material, that can be used directly by slicing perpendicularly to the rod (the current must flow parallel to the axis of the rod).

3) Thin film deposition

There are two categories: the first is by electrodeposition, the second by vacuum deposition. The latter has numerous processes such as sputtering, molecular beam epitaxy etc.

2.4 Temperature ranges of present day TE materials

2.4.1 Bismuth telluride

This material generally includes Selenium for the n type material. Normally the maximum of Z is around 300 K. It can be shifted as a function of temperature by changing the composition and the doping of the material.

This material can be optimized to have a maximum Z of $2.5*10^{-3}$ $K^{\wedge-1}$ at 200 K Anukhin [3].

The maximum of Z as temperature increases is around 350 K, this material is generally used for electricity generation but can be used also for cooling. The maximum temperature at which bismuth telluride can be used is a function of its internal degradation as a function of temperature. It is generally accepted that this TE material should not be continuously used above 250 °C, though certain compositions can withstand short periods up to 275 and even 300 °C. This temperature range is interesting for cyclic cooling and heating to check reliability of electronic components.

2.4.2 Bismuth antimony.

This compound unfortunately only exists as an n type, Lenoir [4] Goldsmid [5] proposed that one can use a superconductor for the other leg, then the overall Z is close to the Z of the n leg.

2.5 Materials of the near future.

After over 30 years of stagnation in the development of TE materials, there is a renewal of interest in this area. There are two families: bulk type material and thin film materials. The following is a brief survey for non material specialists so that they have some idea of the research work that is being done.

2.5.1 Bulk type materials.

An extensive materials search has been done at the Jet Propulsion Laboratory (Pasadena ,California, USA): JPL [6]. The most promising materials are skutterdurites which are a class of compounds based on the mineral skutterdurite : CoAs3. There are nine binary semiconducting compounds in this group, the first one to be studied was IrSb3. Slack [7] has examined the thermoelectric properties of skutterdurites.

These materials of cubic structure have two vacant sites Slack has proposed to place in those sites a "rattling atom" which would considerable reduce the thermal conductivity and lead to materials with a ZT of the order of 1. This value of ZT = 1 is no marked improvement but many specialists feel that one should be able to considerably increase it for skutterdurites.

Numerous other materials are also being studied, in particular intermetallics such as TiNiSn, Kohl [8] and organic compounds. These have been studied for many years but the major obstacle to be solved was their stability in time, it seems that this problem has been solved.

2.5.2 Thin films.

The term thin film is a very simplistic term to cover new families of materials that consist of very thin films that are superlattices one of which is quantum wells. The TE properties are those parallel to the plane. This must not be forgotten so the electrical current and the heat flow are parallel to the plane.

The quantum well was first studied by Hicks and Dresselhaus [9]. At the 1997 Spring Materials Research Society Meeting in San Francisco the theoretical work by Dresselhaus [10] associated with the experimental work on PbTe by Harman [11] constituted a proof of principle of the quantum wells. Dresselhaus considers that the time frame, for this to reach industry, is 10 years away. PbTe was studied because a barrier was available which was not the case for bismuth telluride.

The quantum well consists of a very thin layer of material (between 1 and 100 nm) sandwiched between two barriers. So a system would consist of a stack of alternatively active films and of barrier films.

It is necessary to indicate that the Z values given for 2D materials does not include the barrier. The barrier decreases the Z as heat flows through it and therefore increases the overall thermal conductivity of the films. Until now only the quantum wells have been studied, and the barriers have not yet been optimized.

From the above we see that nothing is on the short term horizon, but there is at last very reasonable hope that we shall see within 7 to 15 years new materials which will considerably increase the performances of cooling systems and will open up new markets.

A cooling system consists of an active TE material and a technology to mechanically and thermally link the material to the heat sources. For the bulk material of the future all present day technology development will contribute to the system design.

For thin films it is another subject, especially as we saw that the plane of the thin films will be perpendicular to the heat sources. This will require the development of a whole new technology.

2.6 Unexplored thermoelectric physical processes.

We must not forget the potential physical processes that have not been studied, Anatychuk [12] presented a table showing all the thermoelectric physical processes. Very few have been studied in fact, essentially those, with an electric field continuous in time. For low temperatures the magnetic enhancements has been studied they are the Nernst, Ettinghausen Riggi etc. effects.

The influence of pressure and of magnetic fields has not been systematically studied. There are areas that should be explored. An area of potential interest is the one with variable electric and magnetic fields. Work has been done in some of these areas Strachan [13] combined an electric field with a variable pressure (piezo-electric) but to date Strachan's results have not been confirmed .

The author believes that these areas are worth studying.

There are two technologies to connect the TE material to the heat sources.[14]. The most common one uses thermoelectric modules as shown in Fig. 1, the other integrates the TE material to the heat exchangers which are used to conduct the electrical current from one piece of TE material (n type) to the next piece of TE material (p type) [15].

3) Thermoelectric modules: single stage

3.1. TE modules with a ceramic

The great majority of thermoelectric modules consist of the assembly of thermoelectric couples between two ceramic plates see Fig. 1. The ceramic must be a good dielectric insulator, have mechanical strength, have a thermal expansion compatible with the copper connectors between the pieces of TE material and have a good thermal conductivity. The compactness of the TE material is generally such that the area of TE material is about 40 % of the area of the ceramic plate

Generally alumina (Al_2O_3) with a thermal conductivity below 25 W/(m*K) is the ceramic. Beryllium oxide which has a much higher thermal conductivity of 250 W/(m*K) is also used but it is expensive and its manufacturing and machining creates a toxic dust. Aluminum nitride is an excellent material with excellent properties and a very high thermal conductivity of 180W/(m*K). The cost of this material which five years ago was very high is now coming down and is a very valid material.

3.2 TE modules without a ceramic

Modules that are manufactured without a ceramic support are more compact as the thermoelectric elements are only separated by a thin electrical insulator with a thickness of about 0.1 mm, so the compactness can exceed 90 %.

These modules nevertheless require an electrical insulation between the copper connectors and the heat exchangers. Generally one uses a thin organic insulator such as Mylar or Kapton.

The performances of a thermoelectric module depend primarily on the quality of the thermoelectric material and to a minor extend on the thermal conductivity of the electrical insulator whether it be a ceramic or an organic electrical insulator. We will address the subject of the interfacing of the module with the heat exchangers further on.

3.3 Interfacing of TE modules.

The interface with the lowest thermal resistance is a soldered interface. Present day applications generally interface modules with a ceramic, with a thermal grease such as a zinc oxide powder in a silicone oil. There are also thermal pads. These interfaces have the advantage of allowing the ceramic to freely expand thermally. This is at the detriment of a certain thermal surface resistance between the ceramic and the metallic heat exchanger which is of the order of $0.35*10^{\wedge-4}$ $K*m^2/W$ (0.35 $K*cm^2/W$).

An alumina ceramic with a thickness of 0.6 mm and a thermal conductivity of 25 W/(m*K) has thermal area resistance of 0.24 cm2*K/W, this is similar to the value of the interface resistance. A Kapton sheet 50 micrometers thick has a thermal bulk surface resistance of 0.5 K*cm2/W, but it has two interfaces of around 0.35 K*cm2/W each.

When both sides are extriorly mehanically independent both sides can be soldered. For certain applications it is possible to solder one of the ceramics to the heat exchanger. In this case the ceramic has a metallization on its outside surface. The soldered interface has a thermal resistance which is decreased by a factor of ten, which make it very interesting. Generally one solders the cold side ceramic, because the thermal expansion is much less than on the hot side. Soldering large surfaces requires considerable care and its application is essentially a matter of cost.

3.4 Integrated heat exchangers.

By this term we mean associating the "ceramic" with the heat exchanger. Until now the market for TE modules was for "universal modules" that can be installed in many different ways to many different heat exchangers.

The trend to day with an increasing market for TE modules estimated at about a 15 % annual increase, is such that soon it may be economically valid to manufacture TE modules for a specific application with the heat exchangers being an integral part of the TE module.

Two technologies are emerging.

3.4.1 Anodized aluminum heat exchangers

With an electrically insulating anodization.

The concept is to manufacture the TE modules onto the heat exchanger [16]. TE modules are commercially sold with an integrated heat exchanger consisting of finned aluminum plates

Thermally this concept is very interesting, the main disadvantage is the difference in thermal expansion between the aluminum and the copper connectors, it may be advantageous to replace the copper connectors with aluminum connectors?. This technology probably very economic has yet to be confirmed from the reliability point of view.

3.4.2 Aluminum nitride heat exchangers.

The advantage of aluminum nitride is that it is an excellent thermal conductor and an excellent electrical insulator combined with a high mechanical strength. It's cost is decreasing every year.

So a TE module can be made with this ceramicmaterial with an appropriate outside surface for the heat exchange.

The cost for prototype parts made with aluminum nitride are still very expensive but for large annual requirements the cost will come down.

This concept leads to a completely new technology for the assembly of several or many modules together. The main difficulties will be

- to have a structure to hold the modules together
- to obtain reliable sealed circuits
- to absorb the thermal expansion.

Such systems are presently being studied and will probably be commercially available in the next few years. The performances will be better than present day assemblies.

4) Multistage TE modules

se TE modules produce a high ΔT and give a low cooling ver. The applications are numerous for spot cooling in icular of detectors.

ne TE companies just sell the multistage modules, other ipanies manufacture and sell detectors with their in house le multistage modules.

lowest temperature one can reach from ambient is around K[17].

other application is to drop the temperature a few K but at y low temperatures. At temperatures below 200 K bismuth uride has a very low Z. The best material today is n type nuth antimony with a superconducting second leg. to our wledge such modules are not available commercially. The nufactures use them for their own detectors. So not much rmation is available about them.

Applications.

ow we have reviewed most present day applications and e divided into categories more or less by cooling power and perature range.

5.1 Electronic chip spot cooling.

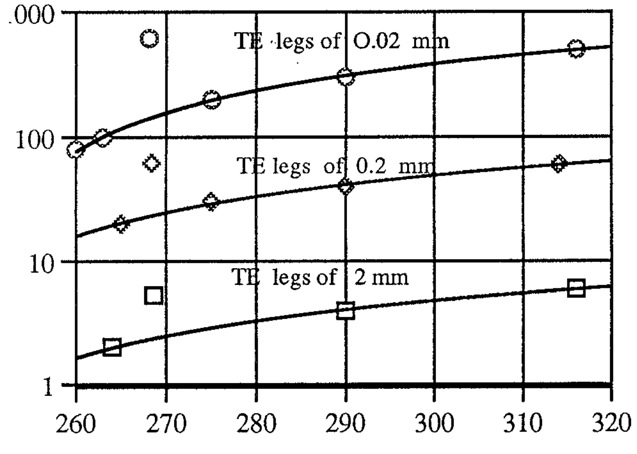
s application is a growing market as more and more iponents require cooling. The main trend is towards higher higher heat flux densities which is requiring development k.

5.1.1 Present day technology.

lay certain CPU's are cooled thermoelectrically. The TE lule cools the CPU and on the heated side there is a heat hangers and generally a small fan. The small unit is either igned for assembly to the CPU during manufacturing or as ommercially sold add on component that clips onto the J. The modules used have TE legs with a length generally veen 1 and 1.5 mm

5.1.2 Micro devices with thick and thin films.

s is a new area of development [18]. The substrates are nond or aluminum nitride: AlN. The advantage of having rter TE legs is that the cooling power density increases as legs get shorter. See Fig. 2



ot = 330 K diamond substrates Cold side temperature K
2 Cooling power density for different leg lengths from[18]

We note that with a ΔT of 50 K the cooling power densi W/m2 increases 10 fold each time the leg length decreases factor of 10 from 2 mm to 0.2 mm to 20 µm. and has a of 3 MW/m^2 (300 W/cm^2), these are very high heat densities. The applications are for the cooling of electr chips. For example an 8 watt chip today dissipates 30 W, and future power amplifiers will dissipate 100 W/cm2. these micro coolers one shall be able to maintain temperature of the active layers of the electronic device fr few degrees to tens of degrees below the temperature of the substrate on which the device is mounted. This reduction i temperature increases reliability, lifetime and clock speed.

5.2 Biological applications

More and more biological samples require cooling for the be conserved and examined often under a microscope.

5.3 Temperature stabilization.

Thermoelectrics is the ideal solution when one need stabilize a temperature and when small cooling and hea powers are required. the field is enormous in particular ir biological sciences where often it is critical that temperature be maintained constant to within a tenth degree C.

Certain electronic components have important properties vary with temperature, the most common one is the laser d that is very sensitive to temperature. This market has developed as fast as people thought. Komatsu of Ja developed a sophisticated robot to manufacture automatic small TE modules of a few mm by a few mm for application. The robot is presently operated well below capacity. The interesting fact is that a robot has b successfully built to manufacture small modules, so expe has been accumulated leading the way for the future w larger modules could be manufactured automatically.

5.4 High ΔT multistage modules.

These modules are generally for detectors of all sorts: infra X ray, gamma ray etc. because lowering the tempera reduces the noise and increases the sensitivity. The objec has been 170 K. This is obtainable, but still requ considerable electrical power. Better TE materials will re the electrical power. Development in this area is due tc military applications.

5.5 Standard range up to 50 W

There is a big World market for TE modules with a cera sizes of 30*30 and 40*40mm. The applications are "infir from industrial applications to consumer products suc picnic coolers. This market is the one that has m thermoelectrics known to many people. A new poter market, especially in the US is the water cooler market.

There is presently no special breakthrough, cost is the r important factor. The manufacturers of the applicat sacrifice performance for cost. They install generally only TE module and operate it close to its maximum cooling pc hence at a very low Coefficient of performance COP

COP = cooling power W / electrical power W

which often gives thermoelectricity a reputation for a very efficiency when it is not quite that bad.

5.6 Range up to 50 W with a higher ΔT.

For quite a few years now two stage modules manufactured generally with three ceramics of the same size have been commercialized. These TE modules allow one to obtain slightly greater ΔT's between the cold ceramic and the hot ceramic. The increase is of the order of 10 to 15 K. A typical application is a refrigerator that makes ice.

5.7 Range 50 to 200 W.

The small home refrigerator has a cooling power of 75 W this increases as the size of the refrigerator. A few months ago the Japanese company Matsushita announced the manufacturing and commercialization of small thermoelectric refrigerators for hotel rooms. The main advantage of TE being the absence of the noise of a compressor. These refrigerators that contain food and drink are quite sophisticated in that they are computer controlled. Matsushita announced a yearly production of 50 000 units. Their publicity was misleading in that they compare their performances with that of "cheap" picnic coolers so announce a considerable improvement in performance which already exists in systems properly designed.

This application is nevertheless very important because it creates an awareness and more and more refrigerators will be thermoelectric though thermoelectricity is not ready to replace the compression cycle from an efficiency point of view.

This example is very interesting because it is a reality and we can use it to make comparisons between compression cycle and thermoelectricity. This is the object of paragraph 7.

This range corresponds to space cooling for electronic cabinets, the World leader in this field is TECA (Chicago Illinois USA) who make off the shelf TE air-air coolers in this range. Their standard product Americool® 4000 See Fig. 3. It is an air to air unit, designed so that they can be stacked, Fig. 3 shows 4 units stacked together

5.8 Cooling powers greater than 200 W

The TECA unit referenced above is designed so that up to 10 units can be installed in parallel on both air circuits. This gives cooling powers in the range of 1 kW.

Marvel has developed a standard TE building block with a nominal cooling power of 150 W with a ΔT = 0 between the inlet air flows and a COP = 1. See Fig. 4 Marvel TEBB AA6 These temperature conditions are standard for electronic cooling when the user wants to keep the inside temperature of the enclosure equal to the outside temperature without any air going from the outside to the inside and vice versa. This TE air-air building block is designed so that it can be assembled in series and in parallel on both air circuits. In this way one can obtain much greater temperature drops than with units that can only be assembled in parallel.

Applications for these building blocks are numerous: first of all they are an economic way to build feasibility prototypes and to obtain small productions series. The design is for all uses including where there is condensation of moisture in the air, so performances are not optimized for a given application, but they are sufficiently good for most applications. Numerous

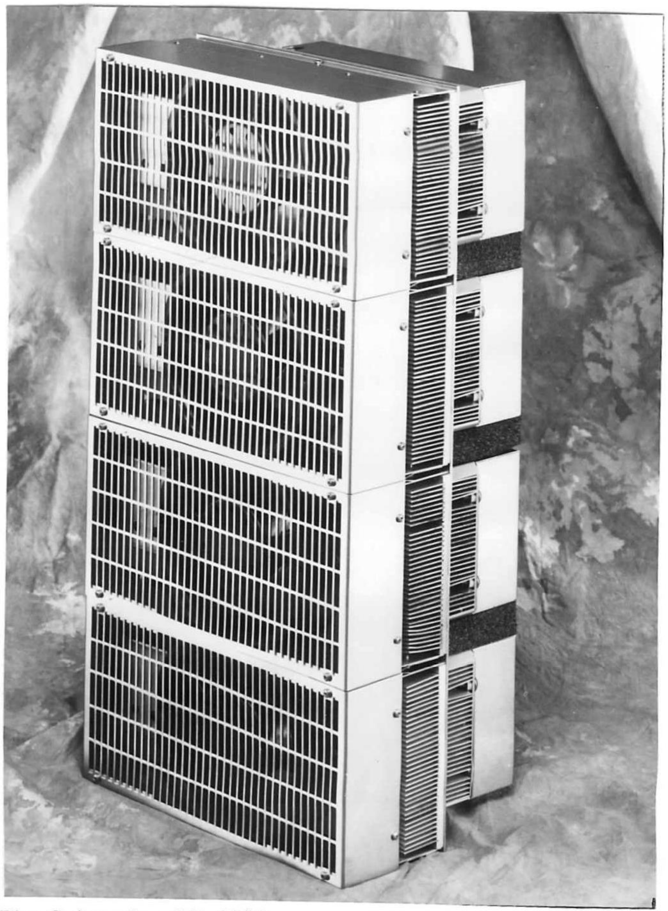


Fig. 3 Americool® 4000

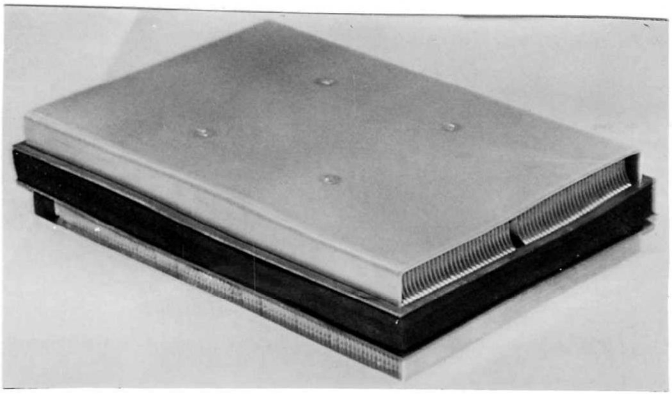


Fig. 4 Photograph of Marvel Thermoelectric building block air-air TEBB6 Dimensions: 275*185*70 mm

drivers cabs of trains. This appears to be an excellent application because the cooling powers do not exceed 10 kW and are generally around 6 kW.

We must not forget that large TE systems were initially developed in the 1960's. The administrative building of S. C. Johnson by Frank Lloyd Wright in Racine Wisconsin USA was equipped in 1965 with 30 units of TE air conditioning with heat rejection to water, manufactured by Carrier Corporation. A photograph was taken by the author in 1973 of a unit placed on the floor. After 8 years they were mainly having power supply problems. A few years later the units

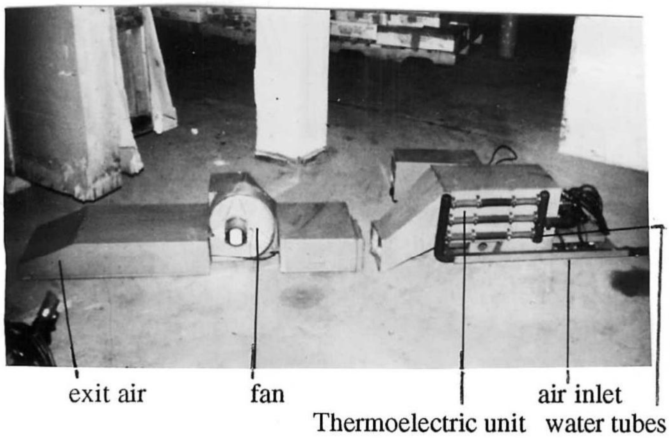


Fig. 5 TE air conditioning at S. C. Johnson by Carrier Corp. Cooling power 1,5 kW heating power 1.8 kW

Then a railway coach was TE air conditioned with 20 kW of cooling and 32 kW of heating, designed and manufactured in the late seventies by Air Industrie [19] see photograph in Fig. 6 below. It was in commercial operation for over 10 years on the French Railways without a thermoelectric failure, there were only maintenance problems with the power supply and the controls.

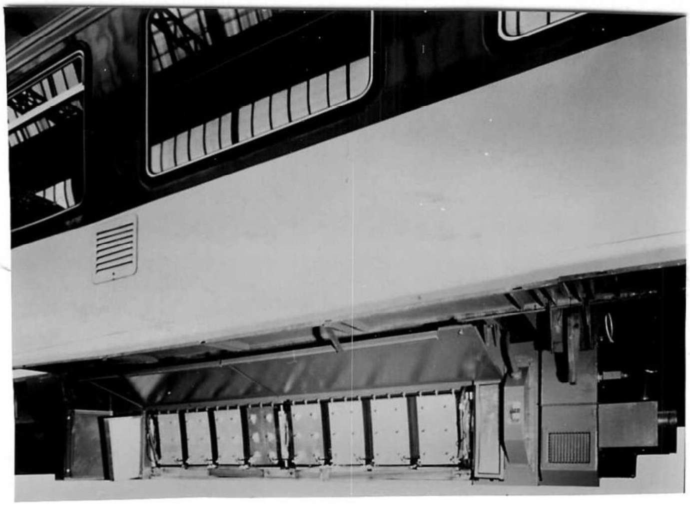


Fig. 6 TE air conditioning unit of a passenger railway coach

For large water cooling units, there are no commercially available units all equipment's are designed for a specific application such as for submarine use. A cabinet is shown in Fig. 7 that produces 15 kW of chilled water with heat rejection to a water circuit [20]. It was developed by the same team that developed the TE railway air conditioning Many of these cabinets are now installed and are in operation on a submarine.

All these applications has proved the technical reliability of such systems, but not the economic. We do not see today any more applications for cooling powers in the tens of kW range. These applications will only emerge economically for specific applications when a new generation of TE materials with Z's at least double of present day materials become industrial.

6) Influence of Z on the performances of a standard TE building block (TEBB)

Fig. 7 TE water cooling cabinet for a submarine application. Dimensions 1800*600*900 mm

The influence of the Z of TE material on the performances of a system vary on the type of system. For a multistage cooler the overall performances depend on the module performances and on the heat exchanger on the hot side. We will not address this example as the module manufacturer can calculate the performances.

We will examine an air to air TE building block designed for 6 large thermoelectric modules. These building blocks are designed so that they can be placed in parallel and in series to make up a big system. We will examine a single building block

6.1 Description of the TE Building Block. (TEBB)

The TEBB is designed to contain 6 TE modules with ceramics ranging in size between 40*40 and 62*62 mm. See Fig. 4 Photograph Marvel TEBB AA6

The air to air TEBB is cross flow so that the TEBBs can be placed in parallel and in series on each of the air circuits. See Fig. 8 Schematic of 8 TEBB AA6 which shows 8 TEBBs.

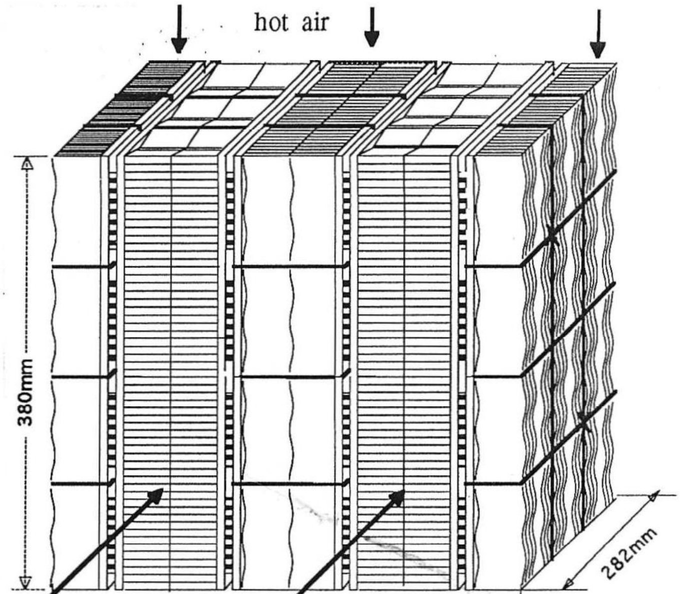


Fig. 8 Schematic of 8 TEBB AA6

6.2 Performances of TE building block.

The performances for the TEBB with a commercial TE module

Melcor CP5-31-06 L are given in Fig. 9 The nominal conditions are those used for electronics:

- both inlet air temperatures are equal to 25 °C.

With a COP =1 the cooling power is of 135 W

- the air flow rates are such that the cooled air velocity is 2 m/s and the heated air flow velocity is 4 m/s.

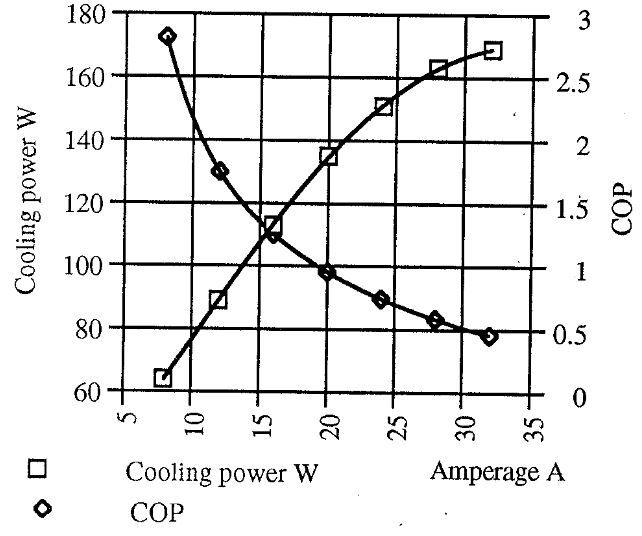
6.3 Influence of Z on the performances.

We have examined the influence of Z between 2.44 and $8.5*10^{-3}$ K^{-1} of a hypothetical TE material to see how it influences the performances of the Marvel air-air TEBB6. We used the simple thermal-thermoelectric mathematical model 21. the air flow velocities through the heat exchangers are of 3 m/s on the cooled side and 6 m/s on the heated side. The thermal resistance's between he ceramics of each Melcor CP5-31-06 TE modules and the air flows are for the cooled side 0.24 K/W and for the heated side 0.17 K/W.

We used the following formulae from Melcor expanded around 23 °C (not from O K as the Melcor formulae are given)

ρ = (10.85+0.0535*(tm_Te-23)
+ 0.0000628*(tm_Te-23)^2)/1000000 Ω*m
s = (210.9+0.344*(tm_Te-23)
- 0.0009904*(tm_Te)^2)/1000000 V/K
κ = (1.659-0.00332*(tm_Te-23)+0.0000413*(tm_Te-23)^2) W/(m*K)

The values of Melcor material at 23 °C correspond to the first number in the expansion.



Air inlet temperatures
hot side 25 °C 50 %RH air 2 m/s: 9.1 g/s ΔP = 24 Pa
cold side 25 °C 50 %RH air 4 m/s 27.3 g/s ΔP = 46 Pa

Fig. 9 Marvel air-air TEBB6 Cooling power and COP.

The hypothetical material has properties ρ, s and κ. We chose the values by taking the initial values of the Melcor material then we multiplied them by the factors given below.

Values of 1000*Z

	2.44	3.02	3.72	4.61	5.7	6.3	8.5
k factor of ρ	1	0,9	0.9^2	0.9^3	0.9^4	0.9^4	0.9^5
k factor of κ	1	0.9	0.9^2	0.9^3	0.9^4	0.9^5	0.9^5
k factor of s	1	1	1	1	1	1	1 1

For each case with the set of values of ρ, s and κ with a corresponding Z, we calculated the Cooling power and COP as a function of ΔT between the two air flows and the electical current through the TE modules.

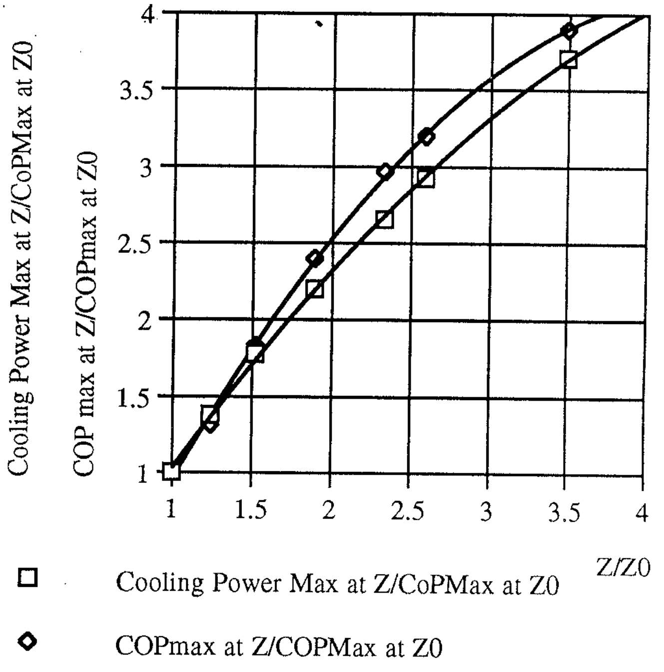
To obtain 2D graphs from 3D data, we chose to present the results for a given ΔT between the two air flows. We chose 30 K as being an industrially valid temperature difference.

$$\Delta T = \frac{\text{(T heated in +T heated out)}}{2} - \frac{\text{(T cold +T cold out)}}{2}$$
$$= 30\ \text{K}$$

With ΔT= 30 K, we calculated for each case the maximum cooling power and the maximum of COP and the corresponding electrical currents through the TE modules.

The nominal values for Z = $2.44*10^{-3}$ K^{-1}.
Are: Maximum cooling power 152 W
COP Max. = 0.39

Fig. 10 gives the relative values



Marvel air-air TEBB with DT = 30 K between the air flows.

Fig. 10 Relative Maximum Cooling power and COP max. for average ΔT between the air flows = 30 K

We must not forget that these two values correspond to two different values of the electrical current. So we examined an "industrial" case, we took the average of these two electrical currents which corresponds to a current that would be used industrially.

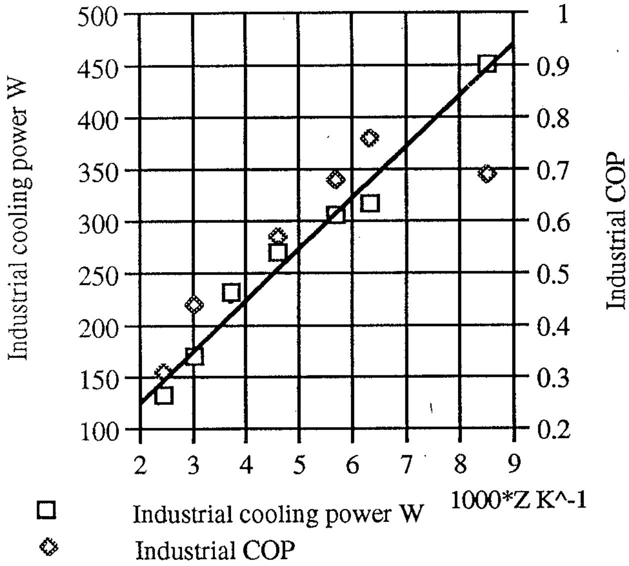
We chose severe conditions. A constant ΔT between the average temperature between the two air circuits of 30 K

We defined an industrial operating point such that

I ind = [I(Pmax) +I (COPmax)]/2

$$\Delta T = \frac{\text{(T heated in +T heated out)}}{2} - \frac{\text{(T cold +T cold out)}}{2}$$
$$= 30\ \text{K}$$

Examining the results of the calculations shown in Fig. 11, we realized that the criteria chosen for the "industrial current" was not ideal, we got a dispersion of points, that can only be explained by the arbitrary choices of ρ, σ and κ. The curves are relatively regular up till Z = 6.3*10-3. Then the COP drops off. The only explanation we can find is that up to a Z of $6.3*10^{-3}$ the s remained unchanged then for Z =$8.3*10^{-3}$ we increased s.



Electrical current= (current of Pmax + current of COP max)/2

Average temperature between the two air flows = 30 K

Fig. 11 Industrial cooling power and Industrial COP with average ΔT between the two air flows of 30 K

This graph shows that from a 1000*Z of 2.4 to 8.5 the cooling power increases by a factor of 3, but the COP then leveled off at 0.7. We examined the results of the calculations and saw that for 1000Z =8.3 we could increase the COP to =1 but the cooling dropped to 338 W.

The ΔT max. which corresponds to zero cooling power was not systematically examined but with a Z of 6.3 $*10^{-3}$ K^{-1}. It exceeds 120 K.

6.4 Estimated influence of Z on the cost of the TE building block.

The cost of a TE unit is proportional to the number of TEBBs and to the yearly production. Examining the above graphs, we consider that assuming a conservative value today of Z = $2.4*10^{-3}$ when Z reaches $6*10^{-3}$ the cost will be divided by more than two and at the same time the COP will have more than doubled.

7) Comparison between a TE module and a small compressor

We are giving this because a lot of general statements are made on the subject but few numbers. So we have examined the COP of small HFC R134a compressors of 60 W and 75 W of electrical power at 60 Hz and 50 Hz (courtesy of Japan air conditioning, heating and refrigeration news). Fig. 12 shows the COP as a function of the temperature difference between condensor at 45 °C and evapoerator, ambient being 32.2 °C.

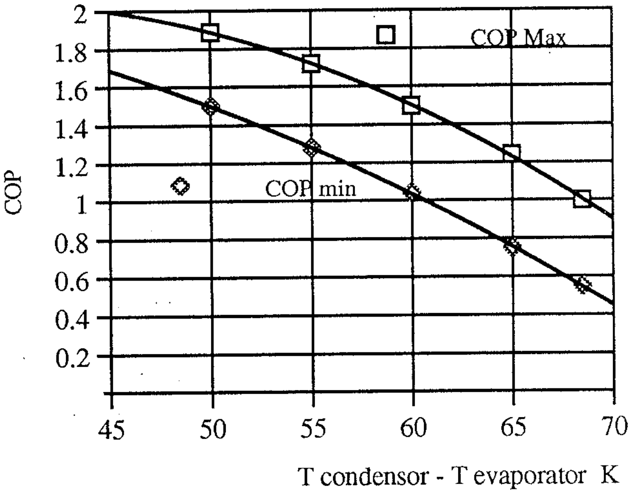


Fig. 12 COP of a compressor with HFC R134a.

It is dangerous to use the same temperature differences for an equivalent TE system, nevertheless it is interesting to compare the above performances with those of a TE module with today's Z = 2.44*10-3. A compressor operates essentially at constant electrical power, but a TE system can be operated with different electrical powers (electrical current) so we must choose a value for the electrical current. See Fig. 13 and 14

We want to compare the compressor operating with a ΔT = 50 K to the above module. We see that with this ΔT and an electrical current of 50 A we obtain 30 W with a COP = 0.18. This is to be compared with a COP between 1.5 and 1.9 for a compressor. The conclusion is that today we are very far from the COP of a compressor for the range of a few hundred watts of cooling.

Nevertheless we must not forget the advantages of a TE system which are reliability, no potentially hazardous fluid, flexibility etc.

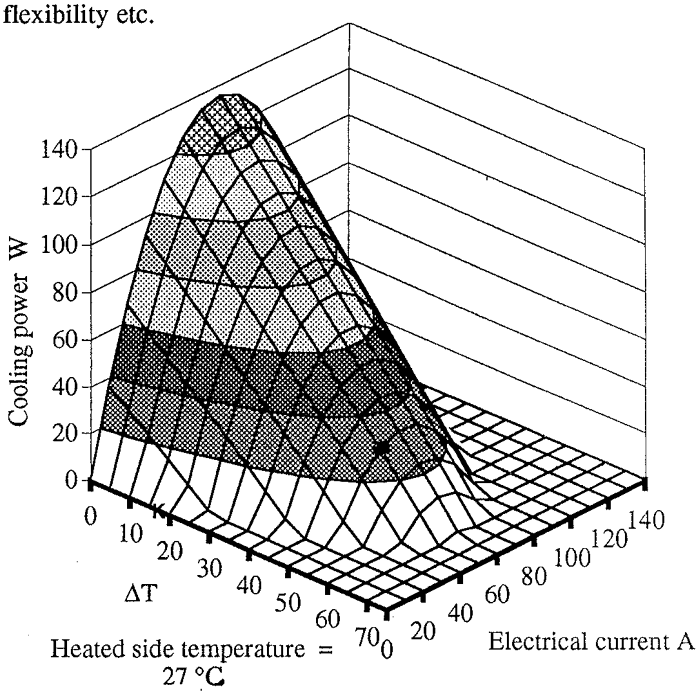
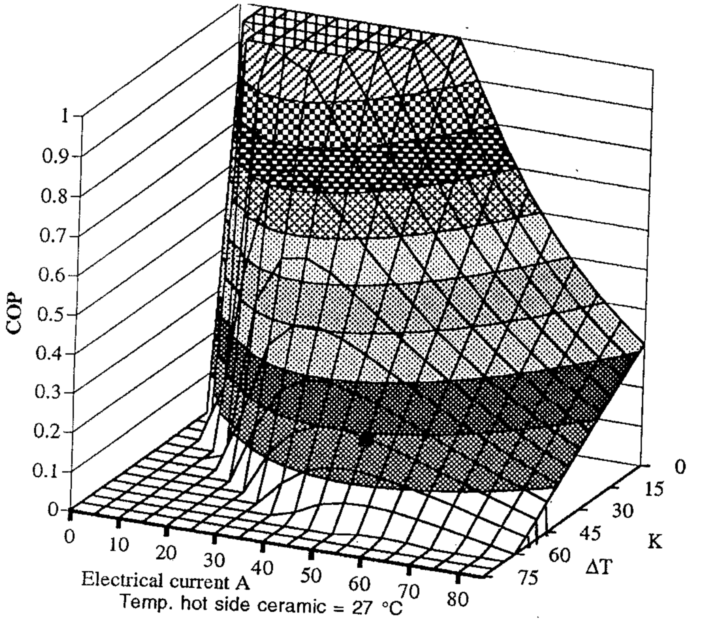


Fig. 13 Cooling power of a Melcor CP5-31- 06

The COP is given in Fig. 14



ΔT Axis goes from 0 to 75 K
ΔT = Temp. hot side ceramic - Temp. cold side ceramic

Fig. 14 Melcor module CP5-31-06 COP

8) Economics of TE cooling and development costs.

A predominant parameter is the annual requirements. As annual
quantities increase the costs go down. For very large annual quantities such as those encountered in the automotive industry the cost is essentially material cost, the manufacturing and assembly costs become the minor component.

8.1 Raw TE material costs

For cooling today bismuth telluride is the only valid material. Material costs vary as a function of purity and of annual quantity, the following values are approximate and correspond to annual quantities per ton and purities between 4 and five nines.

Bi: \$10/kg
Te: \$70/kg
Sb: \$80/kg
Se: \$45/kg

New materials may use:

Zn: \$1.20/kg
Cd: \$1.50/kg
Co: \$43/kg

with these values the raw materials cost for a bismuth telluride that contains Sb and Se will be around \$70/kg.

8.2 TE material costs.

Bismuth telluride is available on the World market, the price per kg for one ton a year is around \$250. This is very variable as it depends on the Z of the material, this value if for a Z = $2.5*10^{\wedge -3}\ K^{\wedge -1}$.

8.3 TE module costs.

One can in a very simplistic way calculate the module cost based on the amount of TE material and come up with a \$/kg of TE material in a module. Comparisons are only valid for very similar modules as the cost increases considerably as the size of the TE elements decrease.

A major parameter is once again the annual requirements. TE module manufacturers generally give cost for orders up to 1000 modules, for larger quantities there is always negotiation. An estimation of the relative cost as a function of quantity is given in[22].

For medium and large cooling power TE modules the cost per kg of TE material assembled into a module is around \$1500, for annual orders corresponding to a ton of TE material in the TE modules.

8.4 TE system costs.

The predominant parameter is the influence of the annual production, but the technology of the system will depend on the annual production. Obviously the level of production at which the technology changes depends on many parameters to simplify when dealing with large cooling systems with cooling powers in excess of hundreds of watts the "magic number is 1000 kg year of TE material.

Today the TE module manufacturers produce TE modules that are relatively universal, this means that they can produce large annual quantities. The user who only requires much smaller quantities profits by the series effect of the TE module manufacturer.

The difference is that the annual quantities so far for TE systems is small except for some devices that require only one TE modules such as specific spot electronic cooling, or the picnic cooler.

8.5 Development costs.

This aspect is generally considerably under estimated. Big systems require extensive R and D. That is why developing a multi-use building blocks is economical, because the thermoelectric R and D has been done and then there is only left to do the mechanical assembly.

Systems require that a test bench be built to measure the overall performances and also endurance testing is a necessity to ensure the reliability of the system.

It is very difficult to estimate on a general basis development costs. When experience in designing and building TE systems is already available then the development cost decreases considerably. Unfortunately there is no book on the Design and Technology of TE cooling systems,

8.6 New TE materials

The new materials which are on the horizon may contain Zn and Cd which are very cheap and Co is about half the price of Te so from the raw material aspect we may see a considerable decrease in cost.

Today we do not know the manufacturing processes that will be required to make from these raw materials a good TE material, but we can hope that the processes will be analogous to those used today so the manufacturing costs should be similar. As the raw materials are cheaper and the performances are considerably better, we should see a big increase in annual quantities and this should also contribute to bring down the cost of the TE material.

Many applications will only develop if the cost of the TE material is considerably lower than today.

9) Conclusions

Peltier cooling has progressed very slowly over the past 35 years. In fact many large applications of the past have proven the advantages of thermoelectrics but the economics are very rarely valid for large systems. For the past 4 years money has been invested into the study of new materials, They are 7 to 15 years away. New areas of thermoelectrics deserve research such as those where there are magnetic fields, variable currents and perhaps mechanical stresses.
Thermoelectrics has not taken off yet. It will come but in probably only 10 to 15 years. Then it may increase like the area of microelectronics today.

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