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FUTURE PROSPECTS IN THERMOELECTIC COOLING SYSTEMS

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Abstract.

Thermoelectric systems are divided into small and large systems based on the amount of thermoelectric material that they contain. Small systems have been considerably developed over the past few years, we will examine how the market can still be expanded. Large systems have been dormant except for a few exceptions. The two available technologies: with thermoelectric modules and with integrated thermoelectric material will be presented. Selection criteria, based on cost, that take into account the amount of thermoelectric material required on a yearly basis, will be given. Prospects will be discussed.

Introduction.

A thermoelectric (abbreviated by TE) cooling system can be a very small TE module, with a cooling power of a fraction of a watt, that cools an electronic component such as a laser diode, or a large system, that air-conditions a passenger railway coach. We have divided the systems into small and large to facilitate the analysis, because their prospects depend on different influencing factors.

There are many ways to divide between small and large, we have chosen as the parameter, the quantity of TE material, because it is the dominating factor in the cost of cooling systems.

1. Categories of thermoelectric cooling systems

We have chosen the dividing line between small and large to correspond to 100 g of TE material, because it corresponds to approximately the smallest compression cycle systems. This value must only be considered as an order of magnitude.

1.1 Small systems

These systems contain less than 100 g of TE material. They represent the quasi totality of the TE cooling market, they all use commercially available TE modules. This technology is presented in paragraph 2. It has the advantage that all thermoelectric expertise is inside the TE module, the industrialist needs only to interface thermally the TE modules with the heat exchangers and installing one or a few modules is not technically difficult.

1.2 Large systems

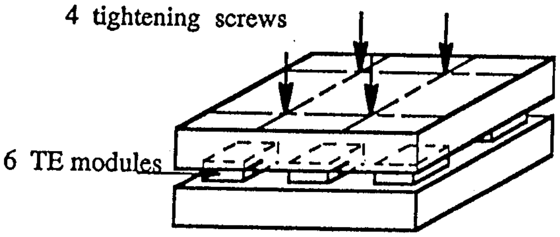
These systems contain more than 100 g of TE material. In this case there are two technologies, one uses thermoelectric modules that are commercially available, the other uses pieces of thermoelectric material that are integrated into heat exchangers that conduct the electrical current from one piece of thermoelectric material to the next along the electrical circuit. Both these technologies are now presented.

2. Thermoelectric module technology.

2.1 Structure

The basic structure is always planar meaning, that when there is more than one module they are assembled in planes (large flat surfaces).

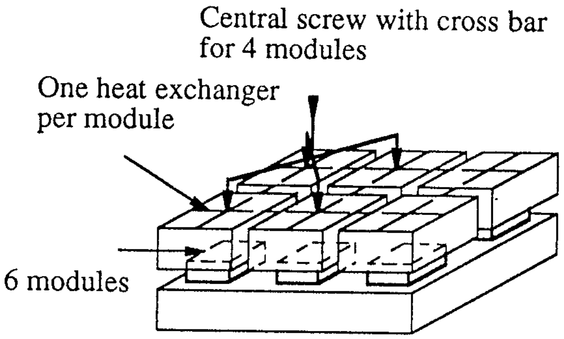
The difficulty of assembling many TE modules in a system comes from the dimensional tolerances of the module: thickness and parallelism of the two outside surfaces of the ceramics. The planar structure is the only one where one can have one big plate on one side onto which one attaches many modules. The most frequent method is to compress and to lock TE modules between two plates of the same size. Fig.1



Two large heat exchangers with 6 modules

Fig. 1 Traditional TE module tightening mechanism

The best tightening mechanism must be such that
1) the pressure is equally distributed over the total surface of the module 2) there are individual heat exchangers on one side of the TE modules. When a system contains many modules, there are several ways of tightening the modules individually with the force applied in the middle of each module. Two examples are given in **Figure 2**, where 2 or 4 modules are tightened with one centrally located screw.



Large heat exchanger with 6 modules

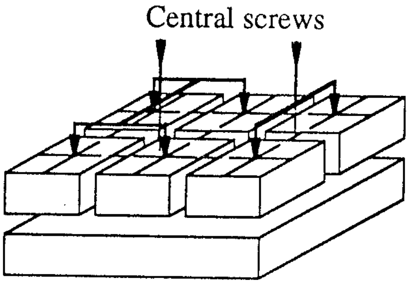


Figure 2. Tightening mechanisms

2.2 Interfacing

The fundamental characteristic is that the modules are electrically insulated from the heat exchangers, so this technology is simple.

The advantages of modules are:

1) The ceramic is a good electrical insulator for low voltage operation

2) The ceramic with a thermally conducting grease has a relatively low thermal resistance between the ceramic and the heat exchanger and allows easy assembly of the TE modules to the heat exchangers.

The main difficulty with modules is that their structure which has a ceramic on each side cannot accept any bending, shear stress must be limited to the weakest shear component of the structure which is the interfacing of the TE elements.

When several modules are assembled between two plates, the modules must all have the same thickness, the ceramics must be parallel to 0.02 mm. and the plates must be parallel, otherwise there is bending and the TE modules will be damaged.

2.3 Reliability

TE modules are extremely reliable [1], assemblies for space applications have met the most severe shock and vibration requirements.

3. Integrated technology

TE systems are constituted by an assembly of TE building blocks. A TE building block consists of thermoelectric material and a heat exchanger on the cooled side and one on the heated side.

The design of the building block depends first on the type of fluid: a gas or a liquid usually air and water, the three combinations are: air-air, air-water and water-water are shown in Figure 3

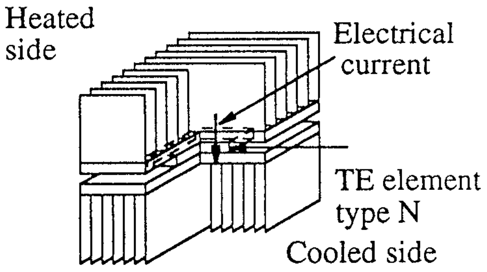


Fig 3 a Air-air building block

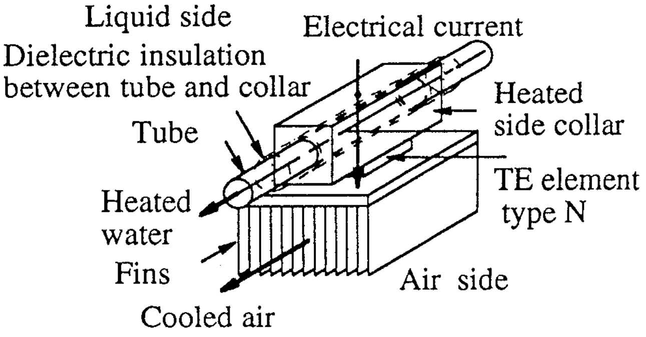


Fig. 3b Water-air building block

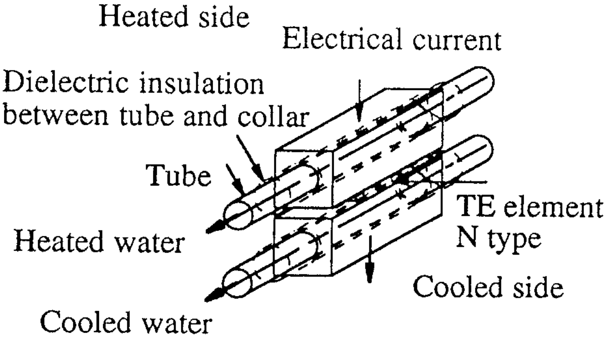


Fig. 3 c Water-water building block

We define 3 types of structures, that are characterized by the relative position of the pieces of TE material that are alternately of type N and of type P. They are presented with air heat exchangers on the cooled and on the heated sides.

Column structure: Figure 4a.

The heat exchangers have two bases and are located in line with the TE material.

Linear structure: see Figure 4b.

The heat exchangers have only one base and are located on the side of the line constituted by the electrical circuit.

Planar structure: see Figure 4c.

The TE material is situated in a plane and the electrical current goes alternatively up and down through the material.

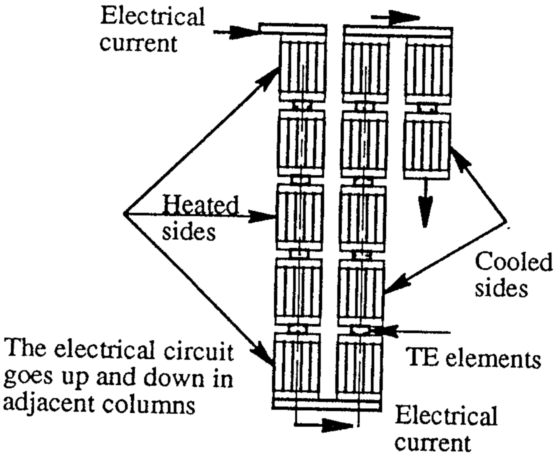


Figure 4 a Column structure.

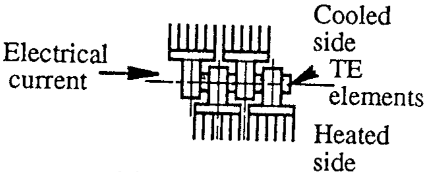
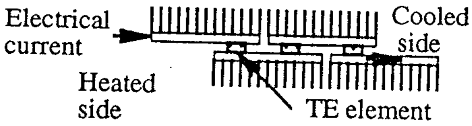


Figure 4 b Linear structure



The electrical current goes up and down through TE elements that are in a plane

Figure 4 c Planar structure.

Fig. 4 Structures

The structure must be such that:

1) The TE material must always be under compression. This is obtained by tie rods and bolts.

2) The TE material should only be, under a small shear stress. This requires that the structure include all the necessary means for absorbing thermal expansion.

Air heat exchangers are represented, because should there be any shear stress due to the differential thermal expansion it can be absorbed by an elastic seal, located between each heat exchanger.

One can have liquid heat exchangers instead of air gas heat exchangers in these three types of structures, on the condition that the shear stress is absorbed by the structure and not transmitted to the TE material.

4. Thermoelectric material

The only material for cooling around ambient is bismuth telluride. It has been available for over 30 years. Most of it is produced by a crystal growing process. Some is produced by hot sintering, by cold pressing and by extrusion..

4.1 Thermoelectric material characterization

These materials are characterized by their coefficient of merit Z

Typical set of values

$Z = s2/(\rho*\kappa)$	$2.5*10^{-3}$.	K^{-1}
s= Seebeck coefficient	$200*10^{-6}$	V/K
ρ = electrical resistivity	$10*10^{-6}$	Ω*m
κ = thermal conductivity	1.60	W/(m*κ)

The best commercially available material, is polycrystalline, it has a Z equal to or greater than $2.5*10^{-3}$ K^{-1}. Small samples with Z= $3.0*10^{-3}$ K^{-1} are obtainable.

4.2 Cost

The cost of thermoelectric material depends on:

- the raw materials,
- the manufacturing process.
- the quantities produced per year

Bismuth telluride generally contains Bi, Te, Se and Sb. A typical composition [2].

P type: $Bi_{0.5}Sb_{1.5}Te_3$.
N type $Bi_2TE_{3.7}Se_{0.3}$.

Using average European and American prices for quantities, of these raw materials, in excess of 500kg, with a purity of 99.999, the raw material cost is estimated between $75 and $100/kg.

The manufacturing cost to make a good quality thermoelectric material depends on the process and the manufacturer's capabilities. The cost of thermoelectric material in bulk form varies tremendously. The selling price of bulk thermoelectric material from the CIS countries with a Z > $2.5*10^{-3}$ K^{-1} is between $ 200 and $ 400 per kg, but the price of their raw materials may be presently below the values given above.

5. Thermoelectric elements and thermoelectric modules

5.1 Characterization

A TE module and a TE element are characterized in the following simple model, besides the material characteristics ρ, s and κ, by two other parameters:

N = number of TE elements in the module, N = 1 for a TE element
GF = the geometric factor of the TE elements
= A_Te/L_Te m

The TE component is therefore characterized by:
$Re = N^* \rho/GF$ Electrical resistance Ω
$S = N^*s$ Seebeck coefficient V/K
$C = N^*GF^*\kappa$ Thermal conductance W/K

These parameters can be measured directly on a TE element and on a TE module [3].

5.2 Cost.

a) TE elements

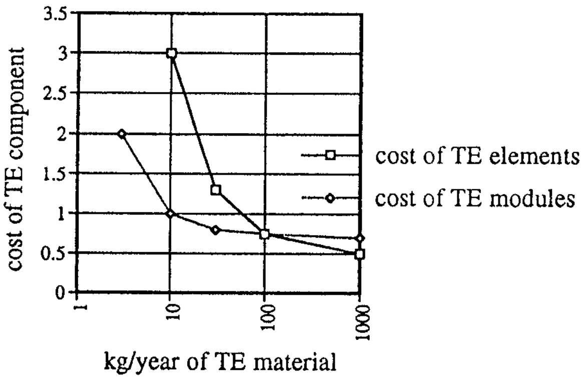
The cost of TE elements with a diffusion barrier, ready for soldering, varies considerably with the quantities and the size of the elements. The range in cost is estimated to be between \$500 and \$ 1000 per kg.

b) TE modules

The cost of thermoelectric material in a large thermoelectric module, with elements of cross section between 20 and 25 mm^2 and the height of around 1.5 mm, for large series is around \$ 1500 per kg of thermoelectric material.

5.3 Component cost comparison

Thermoelectric modules are presently mass produced in quantities of millions per year requiring tons of thermoelectric material, this is not the case of TE elements that are ready for interfacing or capped.
The relative costs of large TE modules and of TE elements per kg of TE material and per year are given in Fig. 5.



F ig. 5 Cost of TE component.

The intersection between the two cost curves is located at 100 kg/year of TE material, this value is given as an order of magnitude, the object is to show that below a certain quantity per year of TE material the technology with TE elements is not economically valid.

6) System cost

A comparison of the cost for the two technologies: TE modules, Integrated elements as a function of the TE material per year, is given in Fig. 6. The intersection **A** between the curves that separate the choice between technologies is indicative.

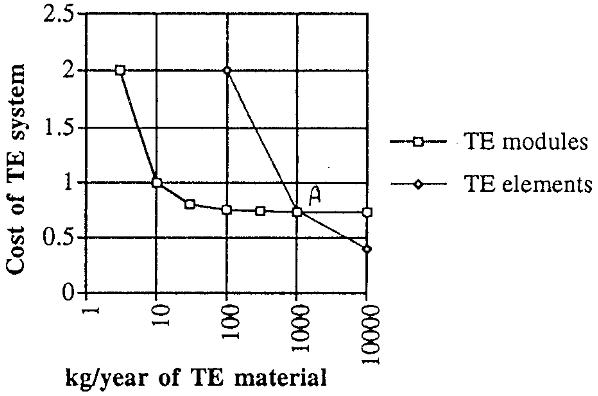


Fig. 6 Cost of TE system

An improvement in the Z of the TE material reduces the amount of TE material required and hence the "amount" of heat exchangers, so it will reduce the overall cost. If Z improves by 10 % then the gain in system cost could be of about 20 %.

The author has had experience with very large systems where the integrated technology with TE elements was used. The final costs were high for these systems because only a few units were manufactured. This underlines the importance of the quantities to be manufactured per year. It is the quantity to be manufactured per year that determines the most appropriate technology and its economic validity.

Fig. 7 is a schematic of the steps to be followed in choosing the technology.

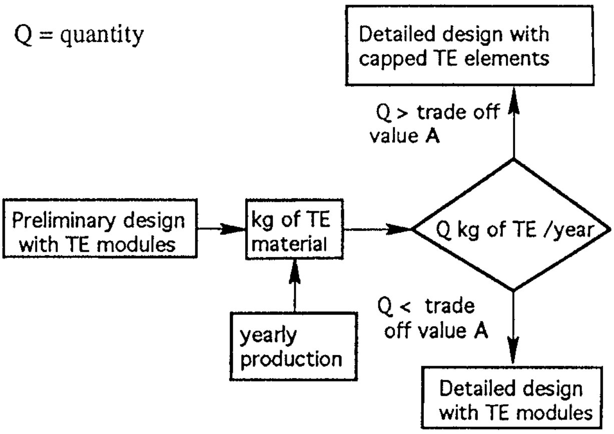


Fig. 7 Steps for choosing technology

7. Thermoelectric material improvement

Over the past 30 years there has been no marked improvement in TE material characteristics. If the market with bismuth telluride increases considerably there is no problem concerning the availability of bismuth or antimony, while tellurium could be a problem. The tellurium world production is around 300 tons a year, thermoelectrics only uses several tons. When thermoelectrics requires tens of tons per year there will be an influence on the market price. The largest cooling systems today require about 100 kg of tellurium, these market can be developed several fold before they will affect the price of tellurium, but if some systems are mass produced such as for the car industry the requirements for TE material could increase by a factor of 10 or more and might create supply and cost problems.

Recent theoretical work in solid state physics leads us to believe that we are on the eve of having new thermoelectric materials with coefficients of merit Z that could be doubled. We must be realistic it takes time to go from theory, to the laboratory, then to industrial manufacturing. A reasonable time scale is a minimum of 5 years and it may take 15 years. Never the less such an improvement will rapidly increase the number of technically and economically viable applications.

We do not know today what the materials of the future will be. They may still be based on bismuth telluride that has fundamentally a good solid state structure for the properties that are required.

8) Perspectives

The factors that will increase the markets are:

- inherent characteristics
- awareness
- cost
- performance

8.1 Inherent features

TE systems are static, highly reliable, are modular in design with built-in redundancies. The cooling power is adjustable with a COP increasing fast as the cooling power is decreased. The system becomes a heater by changing the direction of the electrical current..
These features exist already, but they will continue to make TE cooling an emerging technology.

8.2 Awareness

There is still a general lack of awareness in industry of the possibilities of thermoelectric cooling. The International thermoelectric society, the International thermoelectric conferences, the manufacturers of thermoelectric modules and equipment's are all promoting thermoelectric cooling, nevertheless there is still a lot to be done. Consumer products, such as the picnic cooler, have been the greatest publicity so far for thermoelectrics. There are other such products that should emerge in the near future

In large systems there must be a NEED to use thermoelectrics, it will be one of its advantages.

8.3 Cost

a) Small systems

There are many applications that require few cooling systems a year, they are generally highly specialized, this is a growing market where the TE module manufacturer assists technically the potential client.

Some applications require many systems, these are the interesting markets to develop, they only emerge after considerable development. A typical example in industry is the TE module that stabilizes the temperature of laser diode amplifiers.
Some applications have not expanded for performance reasons.

Cost is the determining factor for products produced in large quantities. The development of small systems is continuing, thermoelectric modules are used in more and more scientific equipment's.
The future is in mass produced products of small systems such as those indicated in 8.2 Awareness

b) Large systems

In the area of large cooling where CFC's are used today, thermoelectrics is an ideal product and should be promoted because they are solid state.

At the present time, thermoelectric cooling is only competitive in the power range below a few hundred watts which is on the borderline between small and large. The question is: Can something be done to change this situation?

Yes, Fig.5 shows how the TE component cost varies with the annual requirement of TE material. It is difficult to put an absolute value on the scale, nevertheless for large systems we will consider that unity on the cost of TE component scale corresponds to around \$ 1500/kg. This gives us a basis to calculate the cost of the system. Depending on the series, excluding auxiliaries such as power supply controls fans and pumps, a system cost, is for example 2 or 3 times the component cost. This gives a reference cost to start with. The system can then be compared cost-wise and technically with a compression cycle system.

In the case of very large systems, as long as the production series are small, the technology must be with TE modules, an integrated technology can only be considered with annual production series in excess of 300kg a year of TE material.

Applications:

- Air conditioning of aircraft parked at a terminal gate, such applications will require quantities of TE material in the tens of kg per system. The market is considered to be quite important so hundreds of systems a year would require several tons a year of TE material. This is an example where an integrated technology might be more economical.
- Air conditioning of driver's cabs of trains and underground trains, for small automatic transit people movers. These systems with cooling powers below 10 kW will emerge before the larger systems. Their development must be pursued, whenever possible. Partial funding from state organizations should be considered.
- comfort cooling and heating in electric cars may represent a potential market, it is being examined by several companies.

- Naval applications.

These applications have been developed ever since bismuth telluride became commercial. There are several aspects of thermoelectrics that constitute important advantages for the navies. For example in submarines, quietness is of major importance and TE systems are static except for water pumps and fans, so a cost premium is acceptable.

8.4 Performances

In small systems TE cooling is the predominant system. For most applications the electric power which is small is perfectly acceptable.

The electrical power required being large, it represents a high operating cost so the coefficient of performance COP is very important. TE systems with TE material of $Z = 2.5*10^{-3}\ K^{-1}$ cannot compete with the performance of a compression cycle system. There are circumstances where TE cooling can prevail.

- when the outside temperature is very high compression cycle systems have problems.
- in moderate climates where it rarely gets very hot, a TE system will operate most part of the time at partial load. The cooling power is adjustable by varying the electrical current. At half load the COP is considerably greater than at full load, the performance can compete with the compression cycle system under these conditions.

8.5 Future applications

8.5.1 Consumer

In consumer products, the classic example which has not yet emerged is the drinking fountain cooler. There are numerous other equipment's that could emerge

- the butchers meat grinder
- the cheese conservation
- wine" chiller and warmer" before serving
- wine cellars are on the borderline between small and large

8.5.2 Industrial

An application on the horizon for a long time, is the small multistage TE module to cool the detector for night vision equipment, the present limitation is the performance. This market will really expand when better TE materials are available.

Recently the development of large two stage TE modules has opened up the possibility of TE systems for deep freeze rooms at - 20 °C and lower. This is an example where TE modules are very interesting because manufacturing a two stage integrated technology system is today, unthinkable.

9. Conclusions

There will be in the next five years laboratory thermoelectric materials that will increase the performances and hence open up markets. It will start with expensive thermoelectric materials that will be only valid for expensive equipment's, an example could be multistage coolers for infrared detection and night vision. Over a period of years these materials will either become cheaper as industrial manufacturing processes are improved or other similar materials with cheaper raw materials and easier to manufacture will emerge.

Today we are a few years away from a marked increase in the number of applications and a marked increase in the overall market of thermoelectric cooling.

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