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NAVAL THERMOELECTRICS

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ABSTRACT

The principles of Thermoelectric systems are described. The types of Thermoelectric equipments operating with air and water with their applications to air conditioning and to the cooling of electronic cabinets are presented.
The advantages and disadvantages with respect to compression cycle systems are given. The advantages for submarine and surface ship are reviewed. The development done for the French Navy and the long term development is examined.

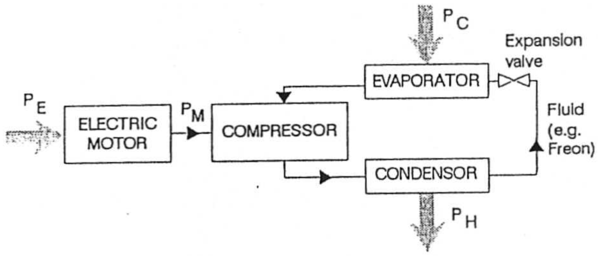
1 - PRESENTATION OF THERMOELECTRICS

Thermoelectric systems like compression cycle systems are heat pumps that transfer heat from one level of temperature to another level of temperature.

1.1. SCHEMATICS OF COMPRESSION CYCLE AND THERMOELECTRIC SYSTEMS

The two systems are shown schematically below in Fig. 1.

a) Compression cycle system



b) Thermoelectric system

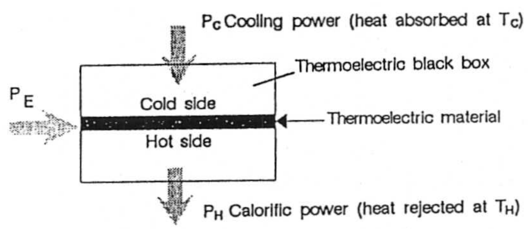


Fig. 1 Schematics of :
a) Compression cycle system
b) Thermoelectric system

A thermoelectric system is considerably simpler than a compression cycle system.

1.2. EQUATIONS FOR THERMOELECTRIC HEAT PUMPS

The above black box is ruled by the following equations :

$Pc + Pe = Ph$ equation of energy conservation

where P stands for power (W) and the indices : c for cooling (useful), h for heating wasteful, e for electrical.

$$Pc = s.I.Tc - R.I^2/2 - C.(Th - Tc)$$

$$Ph = s.I.Th + R.I^2/2 - C.(Th - Tc)$$

$$Pe = s.I.(Th - Tc) + R.I^2$$

The heat pump is reversible in that by reversing the electrical current, heat is produced on the useful side and cooling on the wasteful side.
The piece of thermoelectric material is characterized by :

s = Seebeck coefficient (V/K)
R = electrical resistance (ohms)
C = thermal conductance (W/K)
Tc = absolute temperature of cooled side in K
Th = absolute temperature of heated side in K
I = electrical current in amperes

The cooling power Pc, which we are most interested in, contains 3 terms.

The first one : $s.I.Tc$ is the total power pumped by the Peltier effect, which is proportional to the Seebeck coefficient, to the current intensity and to the absolute temperature of the thermoelectric material cold side.
The following two terms unfortunately must be substracted from the first and they reduce it.
The second one $R.I^2/2$ represents the unavoidable Joule effect.
The last one C.(Th - Tc) is the result of the thermal conductivity of the thermoelectric conductor due to the temperature difference (Th - Tc).
This effect reduces the cooling and heating powers,

because it transfers heat from the hot side to the cold side.
The curves in Fig. 2A show the Peltier cooling, and the effect of the Joule heating and heat conduction.

The curves in Fig. 2B show how the cooling power and COP of a system varies with electrical current.

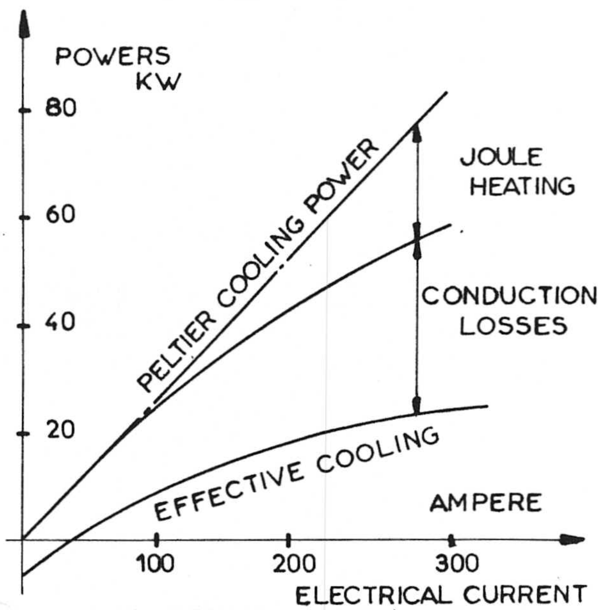


Fig 2A Effective cooling power with effect of Joule heating and heat conduction versus electrical current.

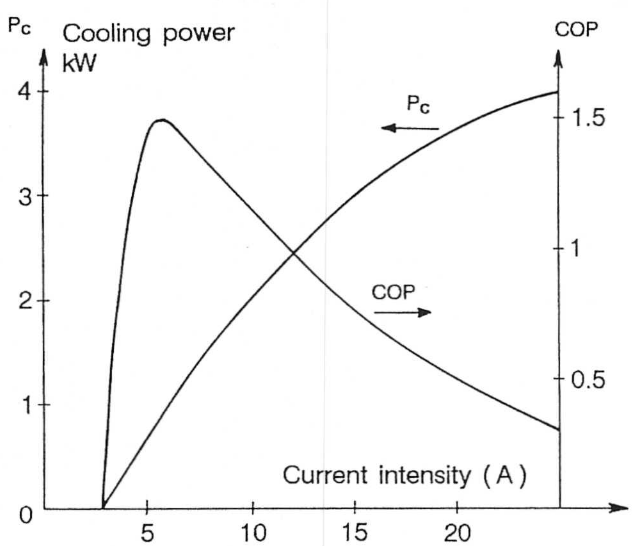


Fig. 2B Typical cooling power Pc and coefficient of performance COP versus electrical current.

1.3. MATERIAL PROPERTIES

The PELTIER effect is obtained at the junction between two different materials that form a couple, one material is of type N the other of type P.
Each material is characterized individually but it is the characteristic of the couple that counts.
An overall parameter, the coefficient of merit Z is the best practical way to characterize thermoelectric material, it has the dimensions of 1/K :

$$Z = s^2 / (\rho . k)$$

where :
s : Seebeck coefficient (V/K)
ρ : electrical resistivity Ohm.m
k : thermal conductivity W/(m.K)

Materials from most manufacturers were characterized by the authors (1).

Typical values are
$s = 200\ \mu V/K$
$\rho = 10\ \mu\Omega.m$
$k = 1.6\ W/(m.K)$
$z = 2.5*10^{-3} K^{-1}$

Most materials that are used today have a Z at room temperature between $2.5*10^{-3}\ K^{-1}$ and $2.8*10^{-3}\ K^{-1}$.

There are 2 manufacturing processes, one that makes a polycristaline material by a crystal growing technique such as Bridgman or Zone refining, the other is a sintering process that produces a sintered material.
The best commercially available material is at the present time polycristaline but a good economic sintered material may emerge in the near future.

2 - TYPES OF THERMOELECTRIC EQUIPMENTS

Thermoelectric equipment design depends first on the type of fluid : a gas or a liquid. Here we will only consider water (which can sometimes contain additives such an antifreeze) and air (dry and wet). There are only three possible combinations air-air, water-air and water-water.

2.1. AIR INDUSTRIE BUILDING BLOCK TECHNOLOGIES

AIR INDUSTRIE has developped building block technologies for the 3 combinations. An example is shown below in Fig. 3 where a water-air block shows the combination with a liquid and with a gas. The air-air and water-water building blocks use the same concept except that the heat exchangers on the 2 sides of the thermoelectric material are similar.

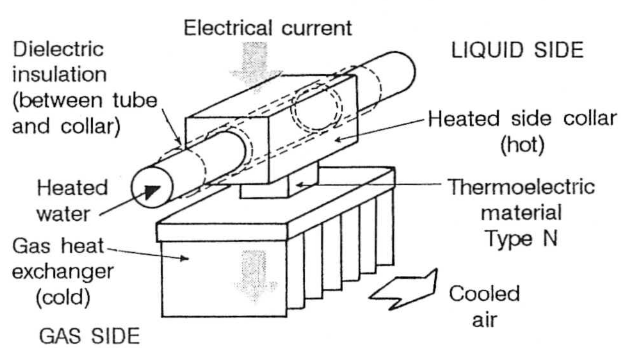


Fig.3 Building block (water-air).

Each liquid building block "uses" a small length of the tube upon which a thermally and electrically conducting collar is tightly fixed. In fact the blocks are assembled onto Continuous Insulated Pipes (CIP) which support the other components. This technology for a liquid circuit is extremely robust and reliable (see paragraph 2.3.1.).

Adjacent air heat exchangers are positionned by a seal, as shown in the photograph below for air-air subunits.

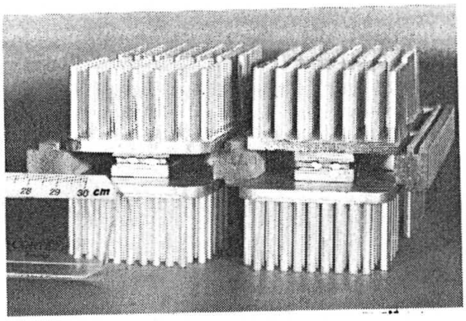


Fig. 4 Photograph of buidings blocks (air-air)

2.2 AIR-AIR

Air Industrie Thermoelectrics started in 1973 to develop thermoelectric air conditioning for a passenger railway coach 2.
A laboratory made prototype was installed and was operational on the French railway late 1977. In 1980 a prototype designed for industrial production was installed. The cooling power is of 20 kW (nearly 6 tons of refrigeration) and the heating power of 29 kW (100.000 Btu/h). The coach has operated daily and has never had a single thermoelectric breakdown.

The unit contains 32 subunits (drawers that pull out).In all the unit has 6144 building blocks each consisting of a piece of thermoelectric material, a hot side air heat exchanger and a cold side heat exchanger.
The coach has been operated for aver 20,000 hours and has covered 2 million kilometers which expressed in buiding block hours is around 2.10^8 building-block x hours.

The problems encountered were not on the thermoelectric units where there has not been a single failure, but on the auxiliairies such as the dual current power supply which operates from 1500 V 50Hz AC or DC but with spikes reaching 8000 volts. The controls which also can get voltage spikes have also been damaged and repaired.

The environment of a railway coach is in fact much more severe than on a ship. The equipments were initially tested for vibration on a vibrating table. A frequency scan from 1 Hz to 133 Hz was done, a highly damped resonnance around 80 Hz was found. Several scans were done and the unit was vibrated at 80 Hz for several hours with a peak to peak acceleration of 10 g.

During the vibration tests, the electric resistance of the subunit is monitored. No change was noted. After the test, the subunit was rechecked thermally and no difference was found.

This shows the ruggedness and reliability of this building-block technology.
A photograph of the side of the railway coach is shown below in Fig 5

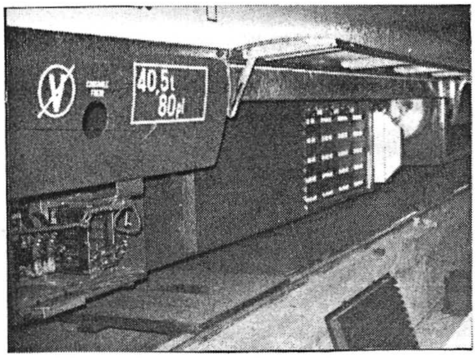


Fig. 5 Photograph of a passenger railway coach with thermoelectric air conditioning.

The French Navy learnt about this passenger railway coach with 20 kW of thermoelectric air conditioning and realized that to develop large scale thermoelectric cooling for submarines was no longer unrealistic.

2.3 WATER-WATER

The experience obtained from the development of the robust railway thermoelectric equipment confirmed that thermoelectrics had become insdustrial.The acquired experience was put to profit in developing a water-water system.

The program started in 1980 after an extensive bibliographical study on water-water systems that had been developped in the past. The work done by Westinghouse was remarkable in that they showed with the large equipment installed on the USS Dolphin in the nineteen seventees that thermoelectric systems could be made and operated for many years.

We carefully analyzed their technologies called "Direct Transfer", which is based on :

.direct transfer from thermoelectric material to the water with no electrical insulator.
. bellows between conduction blocks to absorb mechanical stresses.

The direct transfer concept when applied directly to an equipment gives excellent performances. It is fine when it works but the slightest deviation in quality leads to difficulties and when operating parameters change, problems arise.

The more, technological realities are introduced, the further away one is from the initial concept and the more the performances are reduced.

Thermoelectric material with its soldered interfaces is relatively fragile, its mechanical properties are like those of concrete, in that it is extremely robust when prestressed.

Knowing the problems created by having a water circuit in direct contact with different voltages (electro-corrosion) and the lack of long term reliability of bellows in such an environment, we adopted the policy corresponding to Admiral HORLICK's saying (which reached me by hearsay)

" WHAT YOU DON'T INSTALL DOESN'T CAUSE YOU ANY PROBLEMS".

This means, that rather than to solve problems, it is better to eliminate their origin to start with.

To start with, we accepted to loose some performance but so as to increase quality reliability.
This means :
. grounded water circuit : This avoids the problem of the quality of the water.
. No bellows to protect shearstress-wise the thermoelectric material because thousands of miniture bellows present a reliability risk.
. A design capable of using industrially manufactured parts with industrial tolerances so as to have reliability in quality and to reduce cost.

All our work has been based on this policy.

2.3.1. Assembly structure

The building block is repeated again and again. First along the tubes which have from 10 to 30 collars. The number of tubes above each other generally varies from 2 to 9. The number of tubes on the same level goes from 2 to 6 or more. A schematic cross section of a set of 5 layers of tubes is given in Fig. 6 below.

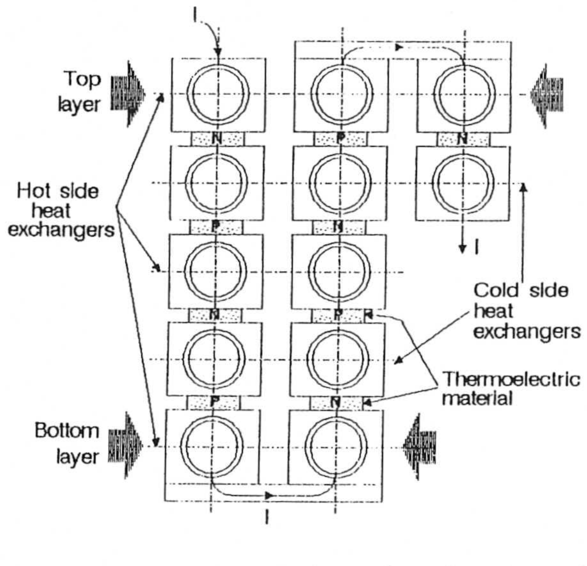


Fig. 6 Cross section of thermoelectric water-water system.

The thermoelectric material is always maintained prestressed, this garanties the stability and the performances in time under continuous cycling.

The number of building blocks in the three axes can be customized. The size limitations arise from pratical considerations, such as easy manipulation weightwise. The average subunit therefore contains about 500 pieces of thermoelectric material or polarized modules.

This is the first time that a thermoelectric water-water technology can have more than three layers of tubes. To obtain a maximum compactness, the tubes should be as long as possible but limited to one meter. The minimum number of tubes on one layer is 2, 4 is very good and 8 for manufacturing reasons is a maximum. The main originality of this structure, is that it can contain yp to 10 layers of tubes with the same compression on all the thermoelectric elements in a column. This gives high compactness and an overall rigidity so that the structure satisfies Military Shock and Vibration Specifications.

The faculty of being able to assemble a robust and reliable array from robust building blocks leads to a complete adaptability to meet all configurations.

2.3.2. Standard subunit PE925

A typical subunit PE925 is shown in Fig. 7 in the photograph below.

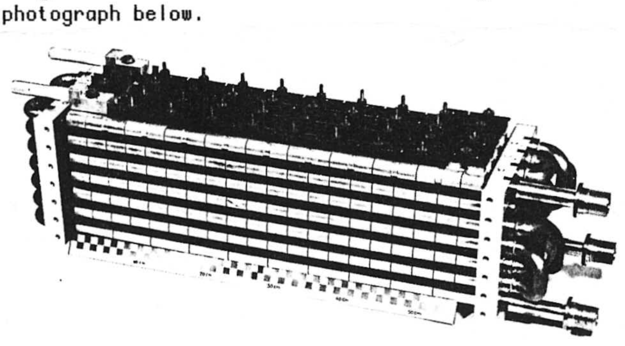


Fig. 7 Photograph of subunit PE925 without casing.

This subunit is composed of 7 layers of 4 tubes, each tube has 20 collars, there are 480 pieces of thermoelectric material that have a cross sectional area of 1.5 cm^2 and a thickness of 1.5 mm. All the cold tubes are in series (3 layers of 4 tubes) and all the hot tubes (4 layers of 4 tubes) are in series. The tubes of this subunit have an I.D of 17 mm and are made of titanium.

The water flow rate of each circuit can vary between 0.14 and 0.55 kg/s (0.5 and 2 m^3/h).
(2 to 9 gpm).

This subunit can be operated over a wide range of temperatures from above freezing, up to around 40°C. For subunit PE925 the electrical current can vary from 50 A up to 300 A. The system can withstand constant operation at 400 A without any deterioration.

2.3.3 Standard water cooling cabinet 10T925

The basic subunit was initially designed , so that two subunits could be placed side by side in a total width of 600 mm. A 1800 mm high cabinet contains 10 subunits.

A temporary prototype cabinet was built to permit laboratory long term testing.

The photograph Fig. 8 of a prototype cabinet is shown below.

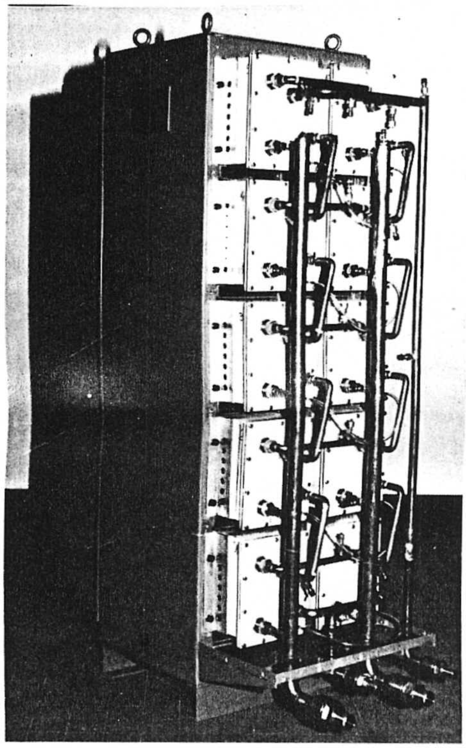


Fig. 8 Photograph of prototype cooling cabinet 10T925 with 10 subunits without front panel.

A new cabinet has been designed and is being built, where the vertical water distribution tubing is located in the lateral walls. The advantage is that the access to the subunits is much easier.

The depth of the cabinet bas been reduced from 1100 mm to 950 mm.

The nominal cooling power is around 15 kW (4.25 tons), it can be produced in different ways. The series-parallel fluid circuitry between the subunits permits one to cover a range of cold water flow rates and a range of temperature drops between inlet and outlet of the cold water circuit.

The performances depend on the operating conditions so they are given with the applications in paragraph 4.1.

The subunits have plug in electrical connectors at the back where all the electrical circuitry is located and were the power leads enter the cabinet. All the water circuitry is in the front, so should there ever be a water leak at a connector the water cannot easily reach the electrical wires.

2.4 WATER-AIR

The technology of continuous insulated pipes (CIP) as used in the water-water configuration, is associated with air heat exchanger as shown in paragraph 2.1.3.

2.4.1. Assembly structure

A shematic of an assembly is given in Fig. 9. The drawing shows how the electricity goes from an air heat exchanger through a piece of TE material and through a block (water heat exchanger) to the next piece of TE material. The blocks located on the continuous tubes, are in good thermal contact with the tubes but electrically insulated from them. The water circuit has the following advantages : simplicity, water-tightness, robustness and reliability.

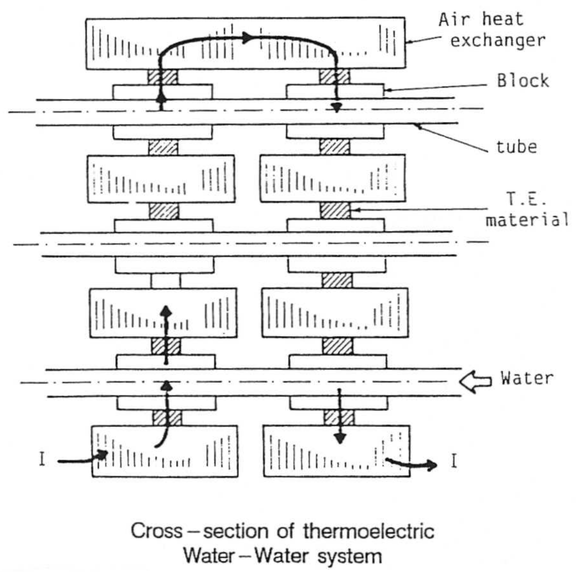


Fig. 9 Schematic of water to air assembly

2.4.2. Subunits

Water-air subunits have been built and tested thermally and mechanically on a vibrating table.

It is necessary to have two types of air heat exchangers, those designed for no condensation which is the case when one cools the air around electric components and those designed for condensation. For air conditioning especially in a closed circuit one must condense the moisture in the air and it is absolutely necessary to eliminate the condeensate, as it is produced from the air heat exchangers, otherwise it is entrained and causes problems. This is possible with Air Industrie's high performance air heat exchangers of patented design. A photograph of a subunit EA 408 for air conditioning is shown below.

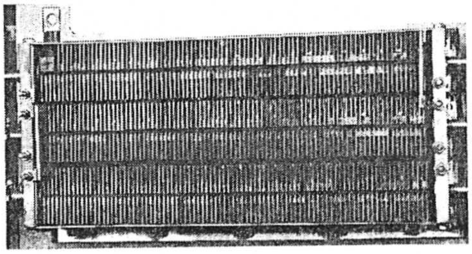


Fig. 10 Water-air subunit EA 408

When there is no condensation, which is the case when electronics are cooled, simpler and better suited air heat exchangers are used. A photograph of one of these subunits is shown below.

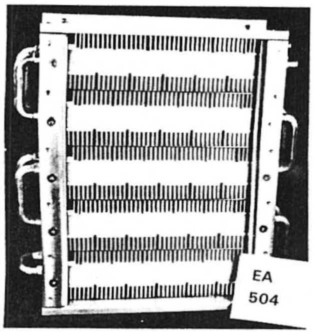


Fig. 11 Water-air subunit EA 504

2.4.3. Water-air system

When the cooling power is in the kilowatt range, a single subunit is installed in a casing, for large cooling powers subunits can be arranged in parallel and in series. The air cooling system shown in Fig. 12 has 2 air circuits in parallel and each circuit has 3 subunits in series. Such a unit has a nominal cooling power of 15 kW.

To date no complete water-air system has been built. The following system unit design was dimensionned for the U.S.S. Dolphin to replace an existing unit that requires subunit replacements.

2.4.4. State of the water-air development

This combination (water-air) was the last one of the 3 to be developed. It happens to be the most logical one to leave till last because one can fully profit from all the useful aspects of the industrially built air-air and water-air systems. Since 1984 3 laboratory prototypes have been built and a fourth one is being assembled early 1988.

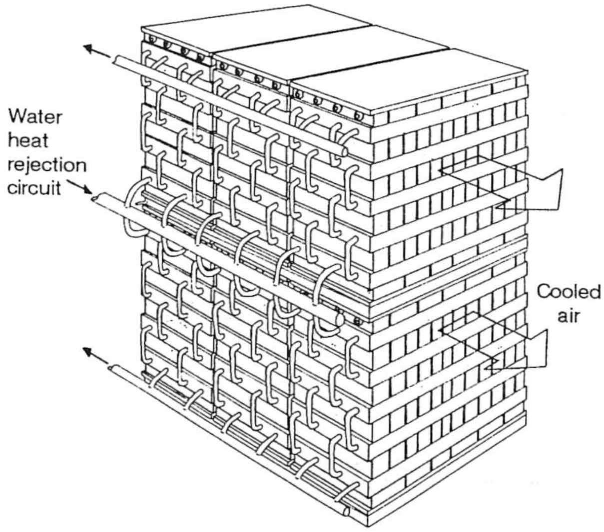


Fig. 12 Air-water unit for air conditioning

The heat transfer aspects are already well known through our extensive experimentation. The prototypes are oriented towards the mechanical structural aspects. Subunits must be operated under severe conditions and must be turned on and off many thousands of times to ensure that the MTBF is sufficiently great.

3 - ADVANTAGES AND DISADVANTAGES OF THERMOELECTRICS

It is so obvious that quietness and reliability are the deciding factor in choosing thermoelectrics that we won't elaborate on these two advantages.

The advantages of thermoelectric systems over compression cycle systems are the following :

3.1. QUIETNESS AND SAFETY

Thermoelectric cooling units have no moving parts except for the water, so by concept are absolutely quiet.
The main hazard of compression cycle systems is the risk of a leak, (that may be a health hazard), due to all the components on the freon cicuit. Thermoelectric systems contain no such thermal compression fluid.

3.2. REDUNDANCY AND RELIABILITY

On surface ships to obtain a high reliability of compression cycle syustems an extra unit is sufficient. On submarines a complete back-up is installed such a requirement doubles the volume of the installation and also doubles the cost.
Thermoelectric systems are static and, when properly designed and built, have a very high reliability with a MTBF exceeding several hundred thousand subunit-hours.

As an example the French Railways have operated an Air Industrie air-to-air unit, for over 6 years and have accumulated over 600 000 subunit-hours of operation without a thermoelectric failure.

To the overall reliability on can add the following advantage resulting from the natural redundandies built into the system. Should a subunit in a cabinet fail for some reason or other, it can be electrically and or fluid-wise bypassed.
When the cabinet is again operated minus a subunit but with the same voltage, the voltage of each subunit increases by 10 %, but the overall cooling power of the cabinet only drops by 5 %.

There is no routine maintenance so this reduces the maintenance work of the crew, also very little maintenance is expected on board.

3.3. MODULARITY AND DISPERSABILITY

3.3.1. System sizes

The C.I.P. building block concept enables a certain continuity in the dimensions of subunits and of cabinets.
The smallest subunits generally have a volume of less than 100 dm^3 (3.5. cft). The cooling power is generally between 1 and 3 kW, (0.3 tons and 1 ton of refrigeration).
According to the size of the system there can be two other levels of modularity. For cooling powers of 10 to 30 kW, cabinets with about 10 subunits are built. For higher cooling powers, cabinets can be grouped together.

3.3.2. Consequences

There are three interesting aspects :

a) The modularity allows the use of available space however small.

b) The cooling equipment can be located in the proximity of the survivability installations.

c) Retrofit is facilitated by installing wherever one can.

3.4. FLEXIBILITY OF OPERATION

Compression cycle systems have different performances depending on the type of compressor (piston, screw or centrifugal) but a general characteristic is that the coefficient of performance COP decreases as the cooling power is reduced.
On the other hand thermoelectric systems have two very important characteristics :

. When the cooling power is reduced the COP increases, which means that the electrical power decreases much more than the cooling power. See Fig. 13.

. When the required cooling power is greater than the nominal value, the voltage on the equipment can be increased by a factor of two and the cooling power is increased by 30 to 50 %. This increase in cooling power does decrease the COP, nevertheless it is a very important asset of thermoelectric systems.

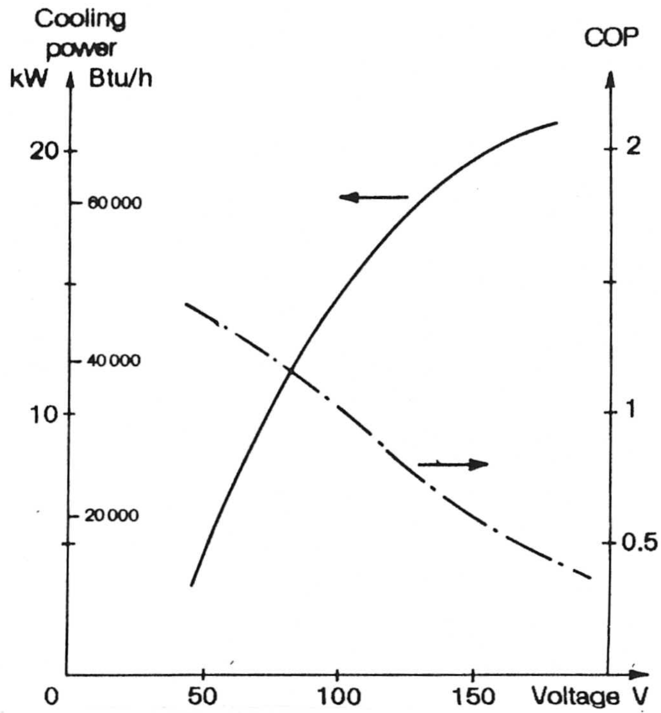


Fig. 13 Cooling power and COP versus voltage

3.5. OPERATING VOLTAGE

Thermoelectric subunits and therefore cabinets can be designed to operate with a very wide range of voltages, from several volts up to several hundred volts. The electrical power input must be DC.
When battery power is available the design allows the operation directly from the battery, even though the voltage varies with the level of charge; the voltage may vary within + or - 20 % without any problem and consequently the cooling performance varies as can be seen in Fig. 13.

When available power is AC, an AC to DC converter is necessary, but fortunately the DC can have up to a 5% ripple without affecting the performance of the thermoelectric system.
With a 3 phases AC, a diode bridge type rectification is sufficient. With a single phase AC, selfs are required to reduce the AC ripple,so as to avoid too great a drop in cooling power.

3.6. TRANSIENT MODE

Thermoelectric systems designed by their, have little thermal inertia since the thermal paths on both sides of the thermolectric material are very short. At startup the temperature difference between the hot side and the cold side is less than the steady state one so the cooling power is much greater than that of the steady state mode, see Fig. 14.

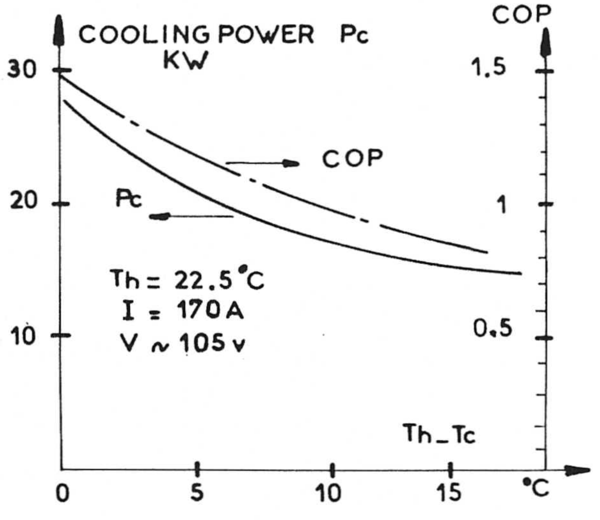


Fig. 14 Cooling power and COP versus temperature difference between the 2 water circuits of PE 925 subunit.

At startup the cooling power can be increased even more by increasing the voltage, so the steady state mode is reached in about half the time required with an equivalent compression cycle system.

The drawbacks of a thermoelectric system compared to a compression cycle system are :

. under identical operating conditions and at full power requirements, it is known that thermoelectrics needs much more electrical power than that required by a compression cycle system, but thermoelectric systems are generally more efficient (higher COP) than compression cycle systems when the cooling power is equal or below 50 % of the nominal. An important advantage of thermoelectric systems is that they start-up with an electrical current which is within 20 % of the nominal current.

Therefore the power supplies do not require oversizing as with freon systems.

3.7. COST

3.7.1. Capital cost

. The capital cost on a one to one unit basis is systematically higher than for a compression cycle system, but it varies considerably with the applications and the size of the series. This extra cost is considerably reduced because partial or complete back systems are not required.

3.7.2. Total cost

. The overall cost (capital plus maintenance) must always be taken into account, especially as the maintenance costs of thermoelectric systems are considerably lower than those of compression cycle systems because of simplicity and reliability. The elimination of routine maintenance constitutes a savings.
Nevertheless the disadvantages are outweighed by the numerous advantages given above such as : quietness - reliability - dispersability - flexibility.

4 - APPLICATIONS

A presentation by the types of equipments is chosen, because there are only 2 types : water-water and water-air. The applications concern either submarines or surface ships and the cooling pertains either to air conditioning or to electronic cooling.

The water-water equipments have passed the development stage. A preliminary small production has produced aver 20 subunits for long term evaluation. The industrial production is in its initial phase.

The water-air units are laboratory prototypes that have been thermally and mechanically tested. Small scale production will start when equipments are required.

4.1. WATER-WATER

4.1.1. Submarines

In submarines a thermoelectric water cooler can partially or totally replace a centralized freon system. An advantage is that it uses the same chilled water loop to distribute the cold water. Cabinets of 15 kW of cooling can be centralized or decentralized, they can be placed in a row or separetely to obtain the required cooling power the Fig. 15 below shows a system.

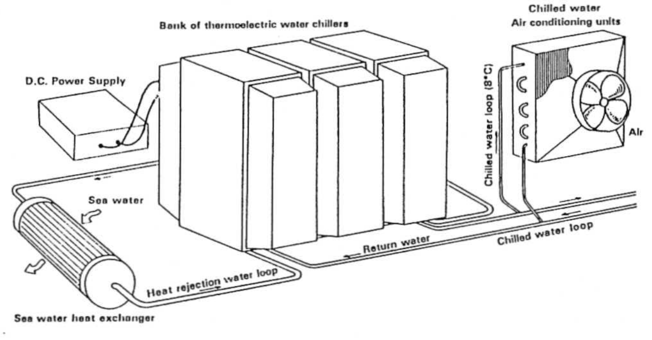


Fig. 15 Submarine centralized thermoelectric water chillerfor air conditioning.

The industrialized version of cabinet 10T925 has the following dimensions :

. height : 1800 mm (70.9 inch)
. width : 600 mm (23.6 inch)
. depth : 950 mm (37.4 inch)

Volume : 1.026 m^3 (36.2 ft^3).
Mass (without water) varies with the materials used to make the cabinet between 750 kg and 900 kg. Each of the ten subunits weighs 50 kg (110 lbs).

The performances of this cabinet for 85 and 125 V DC operating voltages are given in Fig. 16. This graph contains the cooling power and electrical power as a function of heat rejection loop inlet temperature. The cold water loop produces cold water at 8°C.

This cabinet can be operated from 70 to 190 V DC. The cooling power increases with the voltage but simultaneously the coefficient of performance COP decreases.

$$COP = \frac{\text{Cooling power (watts)}}{\text{Electrical power (watts)}}$$

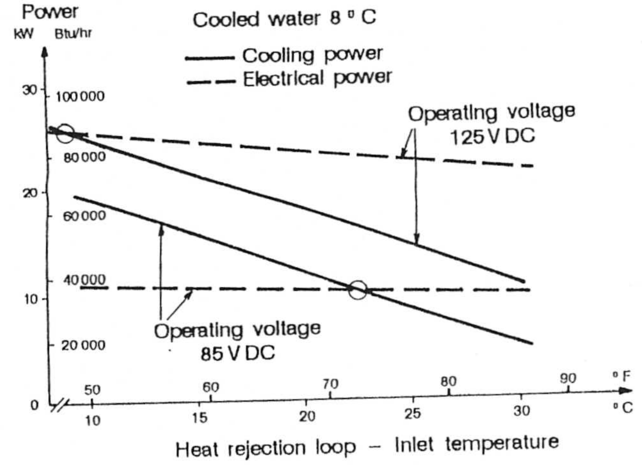


Fig. 16 Thermoelectric water chiller 10T925 performances

The circles (O) on the graphs correspond to COP = 1, which is used to determine a nominal cooling rating for a given voltage.

On a submarine one can consider that the heat rejection loop is 5°C above the sea temperature. When the sea temperature is 15°C, the heat rejection loop enters the cabinet at 20°C. Under these conditions a cabinet operated at 125 V DC :

. cooling power 18 kW (5.1 tons of refrigeration)
. electrical power 23 kW.

The volume per unit cooling power is :
. 57 litre/kW of cooling (7 ft^3/ton of ref)

For electronic cooling the performances are given below in Fig. 17.

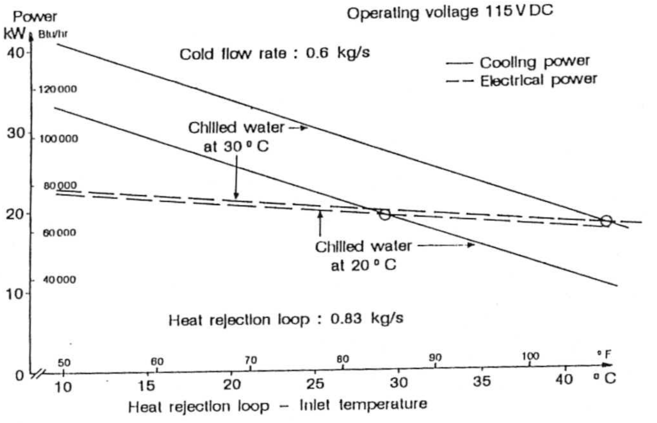


Fig. 17 Thermoelectric water chiller 10 T 925 performances for electronic cooling.

The cooling power is of 18 kW when cold water at 20°C is produced, with the heat rejection loop at 30°C. The volume per unit cooling power is 57 l/kW of cooling (7 ft^3/ton of Ref).

4.1.2. Surface ships

Thermoelectric units can be dispersed over the ship. An application is for operational control rooms where it is necessary to have air conditioning for the personnel and cooling for the electronics. The unit uses the sea water fire-line for heat rejection. Two cold water loops exit the cabinet, one with water at 8°C for the air conditioning heat exchanger and one at 20°C for the cooling the electronic cabinets.

The size of the cabinet depends on the cooling powers required and on the electrical power available.

A cabinet similar to the one shown in Fig. 8 operating with sea water at 30°C (86°F) is :

. 2 drawers to produce water at 8°C (46°F) for air conditioning, with cooling power of 2,5 kW of cooling .

. 8 drawers to produce water at 20°C (68°F) give 20 kW of cooling.

The size is :

. width : 600 mm
. height : 1800 mm
. depth : 950 mm

A schematic is given in Fig. 18

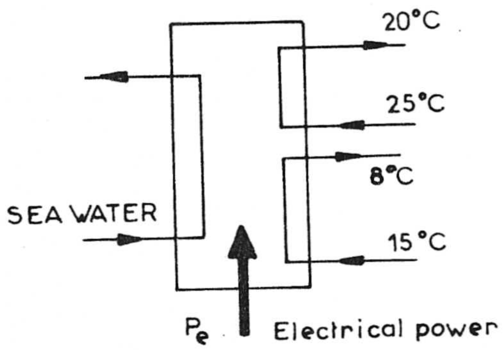


Fig. 18 Thermoelectric dual exit water chiller 8T925

4.2. WATER-AIR

4.2.1. Submarines

For air conditioning it is advantageous to decentralise water-air systems because the "right" air can be produced at the "right" place, this avoids unnecessary ducting.

The production of air directly in a thermoelectric unit requires the cold side of the thermoelectric material to be much less cold that what it would have to be to produce cold water at 8°C. The difference in cold side temperature of the thermoelectric material increases the COP by 30 % or more.

This means that it requires less electrical power than a water-water system. It is particularly well suited for humidity control because after having cooled the air to the saturation temperature corresponding to the required level of humidity, the air is then heated in the thermoelectric system.

A typical assembly is shown in Fig. 12 of pararaph 2.4.3.

4.2.2. Surface ships

The applications are similar to those for submarines exept that the heat rejection loop can be sea water. The units can be more or less centralized.

4.3. DUAL THERMOELECTRIC WATER AND AIR UNIT

The application for a control room on a surface ship where air conditioning and electronic cooling is required is a typical example of a thermoelectric unit requiring all the available technologies to produce an efficient system.

The layout of such a unit is shown below in Fig. 19

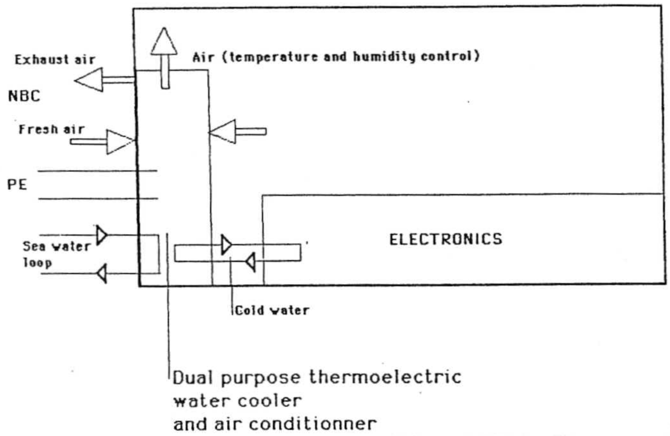


Fig. 19 Control room layout with dual thermoelectric water and air unit

5 - TECHNICAL AND ECONOMIC ADVANTAGES AND DISADVANTAGES

The applications given in paragraph 4 present certain technical and economic advantages. They are examined by category of vessel.

5.1. SUBMARINES

The most important technical advantage is acoustical. Then comes the absence of freon which eliminates all the problems related to freon leaks in a closed environment. The third advantage is the reduction of on board maintenance.

5.2. SURFACE SHIPS

Thermoelectrics has two advantages : reduces vulnerability and reduces cost because the costly priority cold water loop that is needed for combat systems rooms would be suppressed and the existing highly redundant main sea water loop would be used for the heat rejection.

Therefore decentralized thermoelectic air conditioning and cooling is very interesting for control rooms that have people and electronics such as for communications, radars, defense and attack systems.

5.3. MASS AND VOLUME

5.3.1. Water-water systems

The specific mass kg/kW (lb/ton of ref.) and the specific volume dm^3/kW (ft^3/ton of ref.) are given in Fig. 20 for water cooling plants producing water at 8°C (46°F) that reject the heat to a water circuit at 31°C (88°F).
The solid lines correspond to existing equipments while the dashed lines correspond to equipment being developped. No distinction has been made between equipments for surface ships and for boats.
Thermoelectric units require more volume and mass

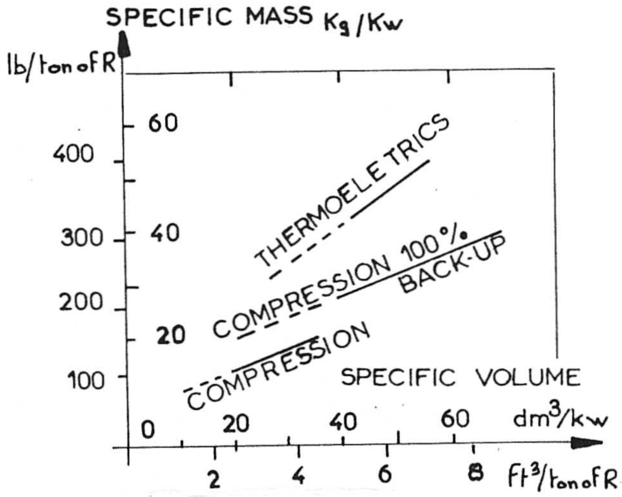


Fig. 20 Specific mass and volume for water chillers

than compression cycle systems. The fact that compression cycle systems require up to 100 % back-up has lead us to draw the line corresponding to systems with 100 % back-up.

5.3.2. <u>Water-air systems</u>

The presentation of the specific mass and specific volume is the same as above, Fig. 21 gives values for units that produce air at 13°C (55°F) with heat rejection to water at 35°C (95°F). The specific volume for compression units increase as the units are smaller, this is much less true for thermoelectric systems, the dashed line corresponds to systems designed, that use subunits that have been built. It appears that thermoelectric units with small cooling powers take up less room than equivalent compression cycle systems.

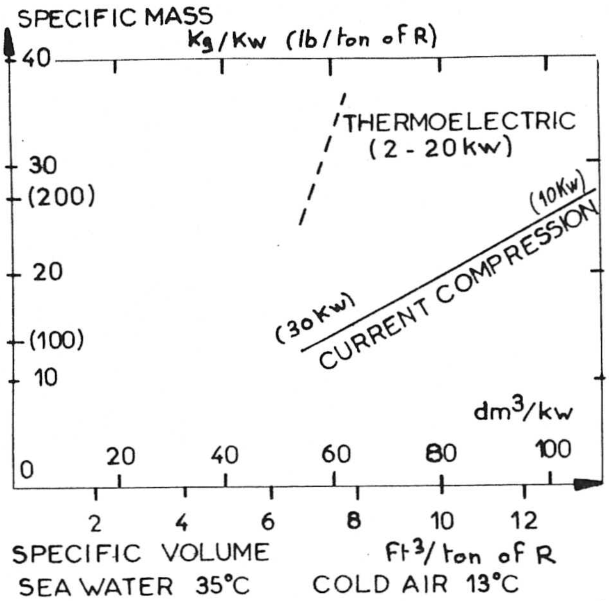


Fig. 21 Specific mass and volume for air cooling equipments.

5.4. POWER CONSUMPTION

The power consumption of thermoelectric systems depends ont the volume available. In general for air conditioning the COP (watts of cooling/watts electrical) is between 0.7 and 1 (3.5 to 5 kW/ton of ref.). When the air is cooled directly the COP increases by about 50 %.

6 - LONG TERM DEVELOPMENT - THE FUTURE OF THERMOELECTRICS

There are several potential areas for development, the one bearing the most direct impact on performances concerns thermoelectric materials, the others concern system optimization and also technology.

6.1. THERMOELECTRIC MATERIALS

Tremendous advances have been made in solid state physics since the early sixties when thermoelectric material research stopped. Today if sufficient means are given to solidistate specialists, new materials should emerge.

Recently at the First European Conference on Thermoelectrics (University of Wales - Cardiff Sept. 1987) several papers on the fundamentals of bismuth telluride were presented, better bismuth telluride is around the corner, the material used today has a
$Z = 2.5 \ 10^{-3} \ K^{-1}$. A 20 % improvement has already been obtained on industrial size samples. We can hope to see this in industry within a year or two. Materials with a $Z = 3.4 \ 10^{-3} \ K^{-1}$ seem possible in several years time.

A thermoelectric material improvement in Z of 10 % increases approximately the cooling power by the same percentage. Improved pieces of thermoelectric material are directly substituable with existing thermoelectric material in the technologies we have developed.
Obviously a 20 % gain in cooling power means approximately a 20 % reduction in volume, in mass and in cost.

6.2. TECHNOLOGY IMPROVEMENTS

The improvements will be in :

1) In simplification and in cost reduction,
2) In increasing the reliability and in volume reduction.

6.3. OPTIMISATION

Mathematical models for our robust highly reliable technology have been developed using extensive experimental datas. Optimisation can therefore be initiated on paper, in practice the optimisation consists in a compromise between many parameters the main ones being cooling power - COP - volume and cost.

The optimisation is done at three levels, the building block, the subunit and the unit level. Most cases can be covered with basic 3 sizes of building blocks, but when one of the parameters is at a high premium, the building block must be highly optimized. The subunit contains several hundred building blocks, the fluid circuitry must be adapted to obtain acceptable operating parameters such as flow rates, pressures drops and required temperature changes.

The unit must contain sufficient subunits so that the nominal cooling power is obtained.
The complete system which consists of the thermoelectric unit, the power supply and the controls must satisfy a given set of parameters that vary from case to case.
The foremost parameter and obligatory is the cooling power. After that there is a compromise between volume, electrical power and cost. Mass is proportional to volume but when mass is at a very high premium it can be reduced at the expense of electrical power and cost.
Naval applications require different compromises between volume (and mass) electrical power and cost.
The water-water unit (10 T 925) which is undergoing long term testing is in its initial stages of industrial production : Is a typical compromise. The emphasis was on obtaining a compact unit using the building block considered to be a good compromise between volume and performance (COP). To conclude a lot of work needs to be done to define equipments where a set of parameters have an order of weighted priority.

6.4. DEVELOPMENT EFFORT

Air Industrie Thermolectrics started in 1973.

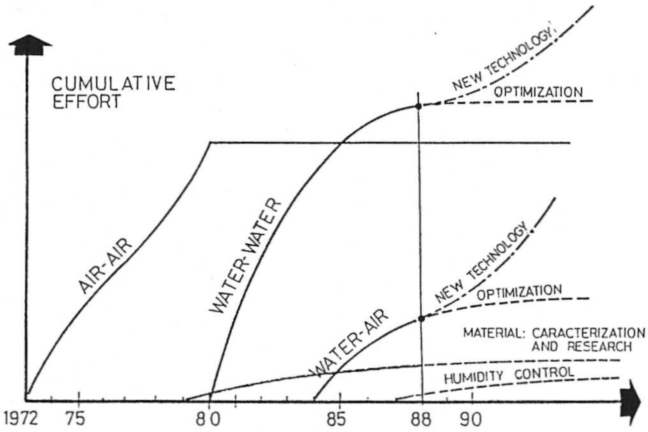


Fig. 22 Development effort.

by studying air-air, in 1980 water-water was studied and since 1984 water-air is being developed.
An air-air technology has been proven by 10 years of daily operation on a passenger railway coach without a single thermoelectric failure
(20 kW air conditioning with 29 kW of heating).

A water-water technology has now been in operation for 2 1/2 years at a French Naval test and Evaluation Center. This technology is being commercialized. A second generation is being examined for development.

The water-air systems are still at the laboratory made prototype stage using available parts from the 2 previous technologies. The emphasis in 1988 will be on the optimization so as to reduce volume, mass and cost.

7 - CONCLUSION

The advantages of thermolectrics are considerable :
- quietness and safety
- redundancy and reliability
- modularity and dispersability
- flexibility of operation.

There is a potential for material improvement that would lead to thermoelectric system characteristics such as cost volume and mass that would be equal or better than those of compression cycle systems.

Naval Thermoelectrics has transformed thermoelectrics, which was initially developed as "high tech", into a simple robust common industrial product.

We believe with the French Navy that it is an old but now an emerging technology rich in potential. We do not yet measure all the potential applications that its advantages deserve.

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