13 - Naval large scale thermoelectric cooling. J. G. Stockholm , P. M. Schlicklin . French Naval Material Exihibition and Conference. Washington D. C., November 1985 . Unpublished, copy available on request.

NAVAL LARGE SCALE THERMOELECTRIC COOLING

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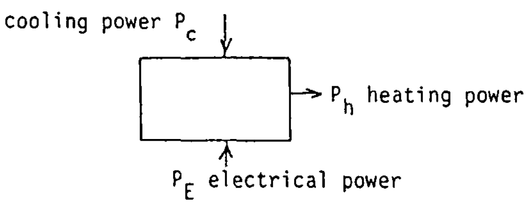
ABSTRACT

The fundamentals of thermoelectricity are briefly presented to underline the fact, that thermoelectric equipments are heat pumps, that, using electricity, transfer energy from one temperature to another. A review of prior art is given. Air Industrie's development program concerning the air conditioning of railway coaches and especially the systems with heat rejection to water developed for the French Navy are described. For each type of equipment : water-to-water water-to-air and air-to-air, the following aspects are examined : technology, equipment design, application to air conditioning and application to electronic cooling. Electricity generation using the same equipment design is also briefly presented. The pros and cons of thermoelectric equipments are given.

1. PRINCIPLE OF OPERATION

Thermoelectric systems are in fact static heat pumps that transfer heat from one level of temperature to another level of temperature. They are like a "black box" as shown below :



The law of energy conservation requires :

$$P_E + P_c - P_h = 0$$

The mathematical equations for the 3 powers are given in the Appendix with the physical interpretation of each term of the equations.

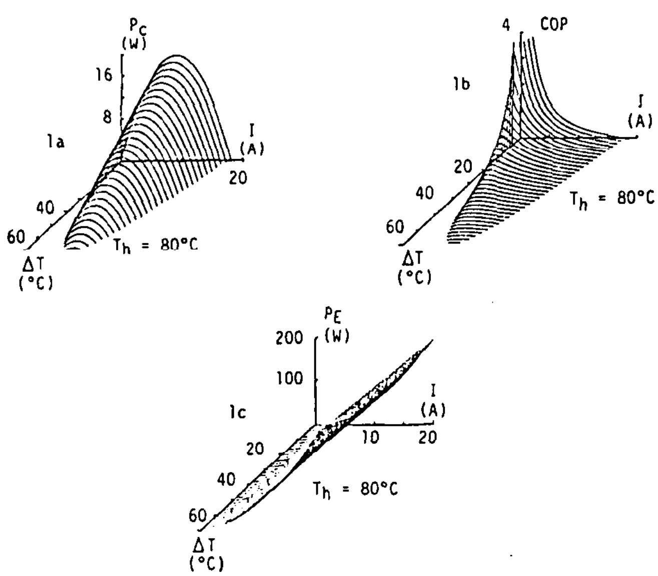


Fig. 1 : THREE-DIMENSIONAL CHARACTERISTICS

Fig. 1 a : Cooling power
P_C decreases as ΔT increases and P_C passes through a maximum as electrical current increases
Fig. 1 b : COP
COP decreases very strongly with ΔT. Systems are operated on the right-hand side of the surface, so COP always decreases with I.
Fig. 1 c : Electrical power P_E
P_E increases with I.

A thermoelectric system is a juxtaposition of pieces of thermoelectric (TE) material as shown schematically below.

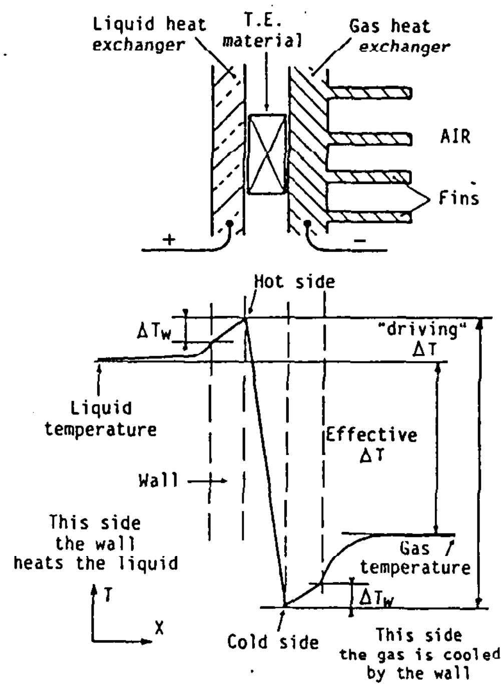


Fig. 2 : SCHEMATIC WITH TEMPERATURE PROFILE

We have a system which transports energy from one level to another, this is obtained by the thermoelectric material which when traversed by an electrical current has one side that becomes hot and the other side that becomes cold. This temperature difference is the driving ΔT. The whole architecture of the system is based on ways to reduce the negative tendencies which are :
-one has created a driving ΔT but the heat tries to go back from the hot side to the cold side
-Resistance (Joule) heating : electrical resistances when on the cold side reduce the cooling power elsewhere they increase the electrical power
-On both sides of the TE material, all thermal resistances create parasite ΔT's which reduce as shown in Fig. 2 the driving ΔT to the effective ΔT.

2. PRIOR ART

Thermoelectric cooling dates back to 1834 when it was discovered by Jean Peltier, it is also called "Peltier cooling". A decisive step was made in the 1930's by Ioffe in the Soviet Union; he developed laboratory thermoelectric materials which are now knownas semiconductors. In the mid 1950's, doped bismuth tellurides emerged as the first industrial material for cooling. Scientists predicted fantastic future materials that would lead to thermoelectric cooling equipments with performances analogous to those obtained with freon compressors[1].The pioneering Company was Radio Corporation of America and many other companies started up activities in this field, the big Companies were Carrier Corporation, Whirlpool, Borg-Warner, Westinghouse etc ... In the early 1960's it became apparent that the miracle thermoelectric material was not "round the corner", so the companies only interested in domestic applications dropped this activity. A few major companies interested in industrial developments pursued an activity. Two basic technologies emerged in the 1960's the first use preassembled thermoelectric modules such as the Melcor modules shown below.

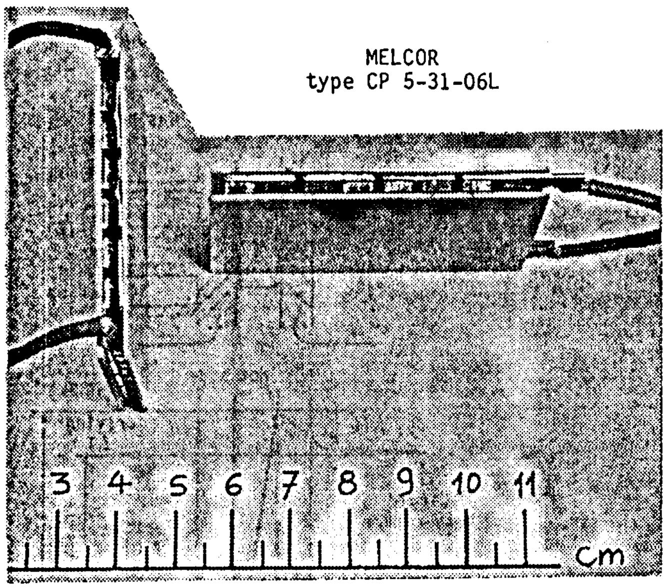


Fig. 3 : PREASSEMBLED MELCOR MODULES

The second technology integrates the thermoelectric materials directly to the heat exchangers which also conduct electrical current.

2.1. Technology with preassembled Thermoelectric modules. This is the first one that was developed because it diassociates the source of cooling from the heat exchangers, in particular, the heat exchangers are insulated electrically from the electric circuit, this electrical advantage unfortunately becomes a thermal disadvantage because all electrical insulators are bad heat conductors. For powers below a few hundred watts, it is still the best technique. Carrier Corporation in the late 1950's had a US Navy contract to study a water-to-water-unit and a water-to-air unit. A remarkably detailled paper[2] was presented in 1960 on the subject. It gives a very sound basis to compare new technologies. Carrier Corporation installed in 1965 at the Headquarters of S.C. Johnson and Co. in Racine, Wisconsin 20 to 30 water-to-air units to air condition its offices. We visited in 1973 the installation which was still in daily use. Such systems cannot compete economically with freon compressor systems, but for the first time technical validity was confirmed for air conditioning with heat rejection to water.

2.2. Technologies with integrated heat exchangers

These technologies are the most suited for large systems where the cooling power requirements are in excess of several kW. In large systems the overall efficiency which is characterized by the Coefficient of Performance (COP) defined in the Appendix is important because the electrical power is generally costly [3,4]. High efficiencies are only obtained with low electrical and thermal resistances. The thermal resistances characterize thermal barriers existing between the thermoelectric material and each fluid and correspond to drops in temperature as already shown in Fig. 2.
In this technology the electrical current goes directly through the heat exchangers, this eliminates electrical wires which are a source of parasite electrical resistances, which also decreases the COP.

Besides the efficiency constraint this technology must satisfy the following basic constraints :
- the electrical circuit that goes through the thermoelectric material and the heat exchangers, must be insulated from the walls of the fluid circuits
- the mechanical means of absorbing shear stress on thermoelectric materials because they withstand low shear stress.

. For gas circuit it is easy to have a compressible seal between heat exchangers,which is also an electrical insulator and absorbs the mechanical stresses, see Fig. 4.

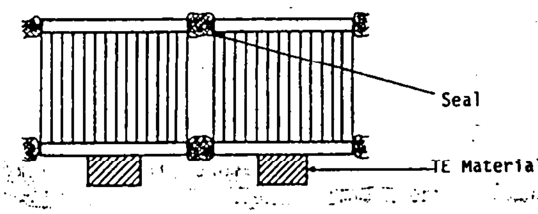


Fig. 4. : SCHEMATIC OF AIR HEAT EXCHANGERS

. For liquid circuit heat exchangers the above constraints are much more difficult to satisfy.

There are two ways of solving them which are shown below in Fig. 5.

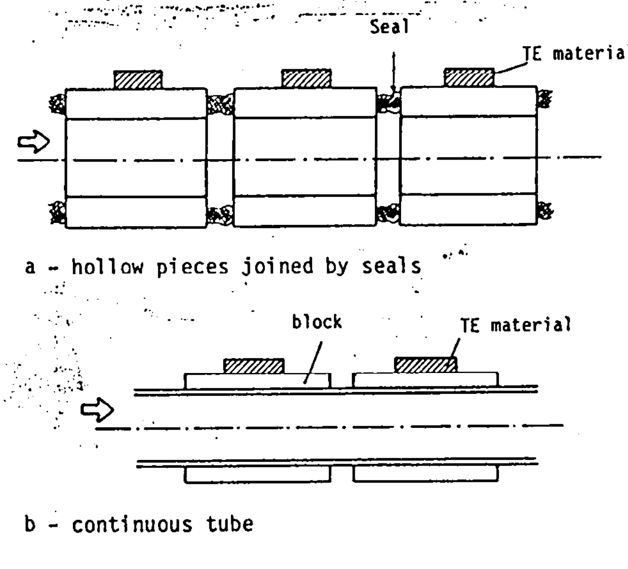


Fig. 5 : SCHEMATICS OF WATER HEAT EXCHANGERS

The first way is to join together hollow pieces with a seal. The second way is to have a continuous tube bearing blocks in good thermal contact with the tube but electrically insulated from the tube.
Westinghouse was the pioneer of the first way, that they called "Direct transfer" ; their first published paper was in 1964 and the last in 1972 [5,6,7,8].

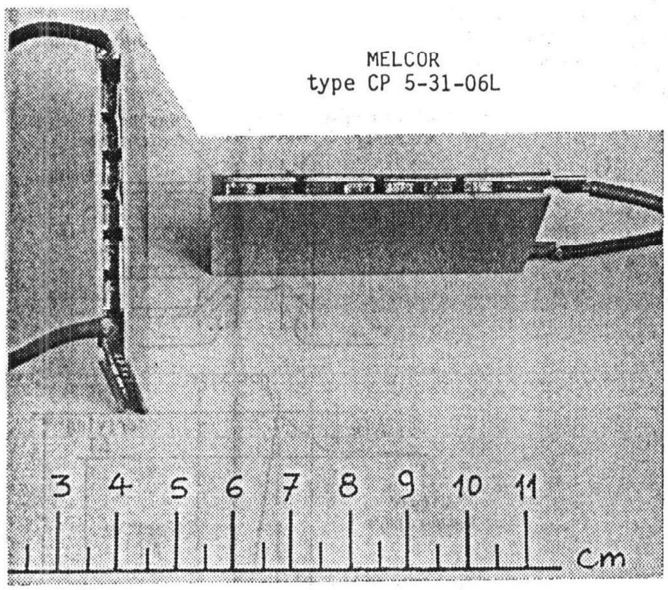


Fig. 3 : PREASSEMBLED MELCOR MODULES

Westinghouse's technology uses metallic bellows as seals ; this requires high resistivity water so that the water heat exchangers through which the electrical current flows can be in direct contact with the water. Westinghouse manufactured thermoelectric equipments with heat rejection to water especially for the US Navy. Water cooling units such as 20 GS produce cold water. Air conditioning systems of type 21 were built. Some of these equipments were installed for long term evaluation on U.S.S. Dolphin.
Westinghouse had the great merit to prove the feasibility and the endurance of large scale thermoelectric systems with the integration of thermoelectric materails onto the heat exchangers.
Borg Warner also developped some equipments about which not much is known.
All theses developments terminated more or less in the late seventies.

3. DEVELOPMENT PROGRAM OF AIR INDUSTRIE

Air Industrie initiated a very important thermoelectric development program in 1973.
The first application was for the air conditioning of railway coaches[9].In summer the inside air is cooled and heat is rejected to the outside air. In winter the inside air is heated and the outside air is cooled. The system is designed to switch within minutes from the heating to cooling mode and vice versa. A passenger railway coach was equipped in 1978 with a thermoelectric air conditioning unit of 20 kW of cooling and 32 kW of heating and has operated since without a single thermoelectric incident.
In 1980 the Franch Navy contracted Air Industrie to develop large scale thermoelectric water cooling units with heat rejection to water. A subunit PE 925 was developed and underwent extensive in house thermal shock and vibration tests. Standard Naval Shock Tests were done at a Naval Testing Center. A prototype Cabinet 10T925 containing 10 such subunits with a cooling power of 15 kW was delivered to the Franch Navy in early 1985. It is now undergoing prolonged evaluation and endurance testing.
This contract was followed by one to develop air cooling systems with heat rejection to water or sea water. The new technologies developed by Air Industrie are presented and compared with prior art.
These are 3 types of equipments :
- water-to-water for producing cold water
- water-to-air for producing cooled air (air conditioning)
- air-to-air for producing cold or hot air.
The latter type has very few application in the Navy and will briefly be described when used for electronic cooling.

4. WATER COOLING

We are concerned with systems where the heat is rejected to a water circuit.

4.1. Technology - The stipulation of the Naval contract was to develop a technology with 3 technological goals :
-No bellows on the water circuit
-Grounded tubing
-High dielectric insulation
In such a way that :
-With no bellows the water circuit would be simple economic and reliable
-Whith grounded tubing there is no electro-corrosion as with materials under voltage in contact with water
-With dielectric insulation the operating voltage can be of several hundred volts. This increases the COP compared to systems limited to 50V.

To achieve these 3 technological goals was difficult, time consuming and costly as many laboratory prototypes had to be built and tested ; but having succeeded in developing a technology with a continuous grounded tube (see Fig.6) so we now have a system which is:
-simple, water-tight, robust and reliable
-industrially designed and manufacturable at reasonable cost
-efficient

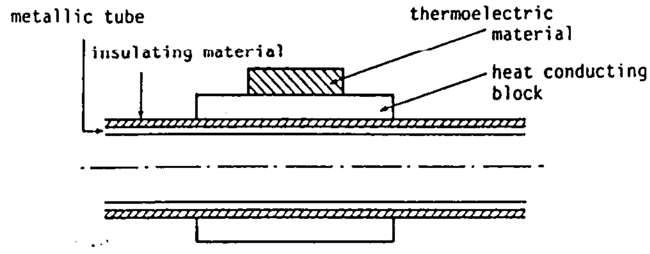


Fig. 6 : CONTINUOUS TUBE WATER HEAT EXCHANGER

4.2. Equipments - A subunit PE 925 designed to be installed in a cabinet has been developed.

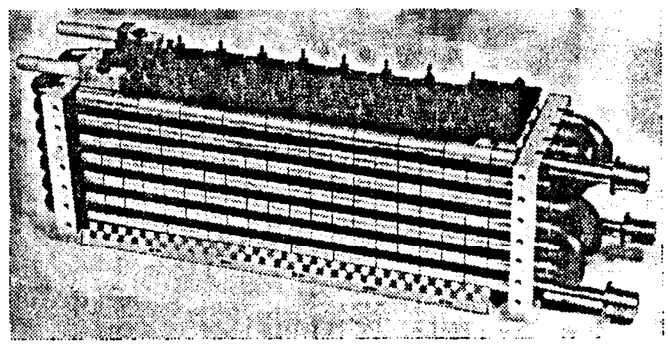


Fig. 7 : PHOTOGRAPH OF SUBUNIT PE 925

The industrial cabinet has the vertical water columns inside the structure alongside the subunits so a photograph of the prototype cabinet which shows all the water piping as the front panel is removed. See Fig. 8 on next page.

4.3. Application to air conditioning[11]-The cooling cabinet 10T925 is designed to be installed in banks for producing large quantities of cold water (at 8°C), that will be distributed to water-to-air heat exchangers for air conditioning.
The drawing below shows a bank of 3 cabinets that produces cold water for air conditioning equipments. The heat is rejected to a water loop going through a seawater heat exchanger.

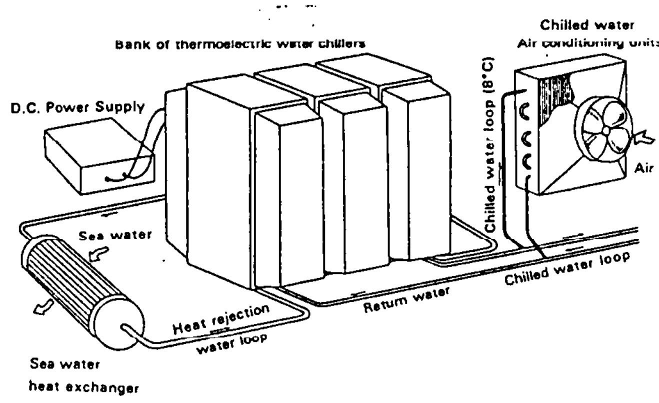


Fig. 9 : SUBMARINE CENTRALIZED THERMOELECTRIC WATER CHILLER FOR AIR CONDITIONING

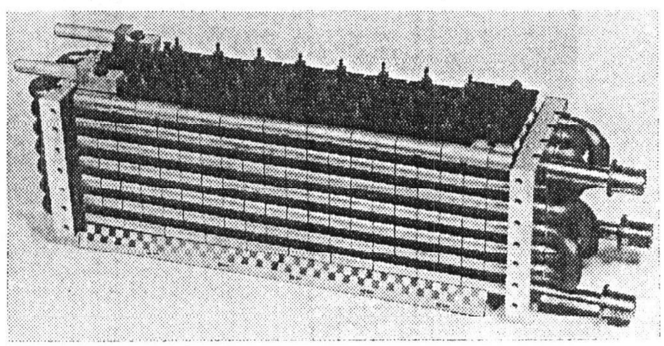


Fig. 7 : PHOTOGRAPH OF SUBUNIT PE 925

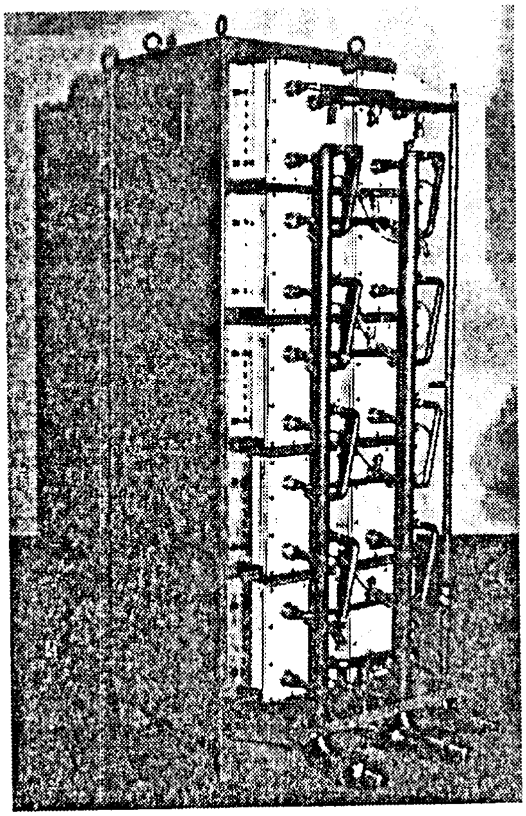


Fig. 8 : PROTOTYPE COOLING CABINET WITHOUT FRONT PANEL

Cabinet characteristics
. width : 600 mm (2 ft)
. depth : 1100 mm (3 ft 8 in)
. height: 1800 mm (5 ft 10 in)
. mass : 1200 kg
. flow rates :
  - chilled water loop : 0.3 kg/s (5 US GPM)
  - heat rejection loop : 0.83 kg/s (13 US GPM)

This cabinet has 3 important advantages :
-safety (no freon)
-reliability
-quietness

The performances are given in Fig. 11.

4.4. Application to electronic cooling[12] -Electronic cooling power requirements vary considerably, generally 20°C water is used. The cabinet 10T925 is the standard equipment. For large cooling powers, cabinets 10T925 are arranged in banks. For the range below 10 kW special cabinets using the same subunits are built with widths of 300 or 600 mm. For surface ships the heat can be rejected directly to sea water. The cabinet cooling power for sea water at 30°C is of 15 kW. For submarines a closed heat rejection loop in connection with a sea water heat exchanger is required. The cabinet 10T925 cooling power with sea water at 30°C is 12 kW.
A drawing showing a centralized thermoelectric water chiller to cool electronic cabinets for submarines is given in Fig. 10.
The drawing shows the cold water distribution loop, that supplies chilled water at 20°C to water-to-air ordinary heat exchangers located in electronic cabinets . Certain electronic cabinets are now directly cooled with water, which is much more energy efficient than going through a water-to-air exchanger.

4.5. Cabinet 10T925 performances - The performances of cabinet 10T925 are given below for submarine application. These curves are calculated assuming that the average temperature of the heat rejection loop water circuit is 7.5°C above the sea water temperature and that the operating voltage is 115 V DC.

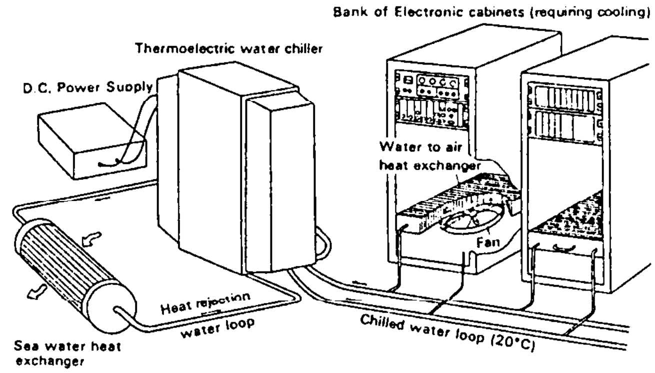


Fig. 10 : SUBMARINE CENTRALIZED THERMOELECTRIC WATER CHILLER TO COOL ELECTRONIC CABINETS

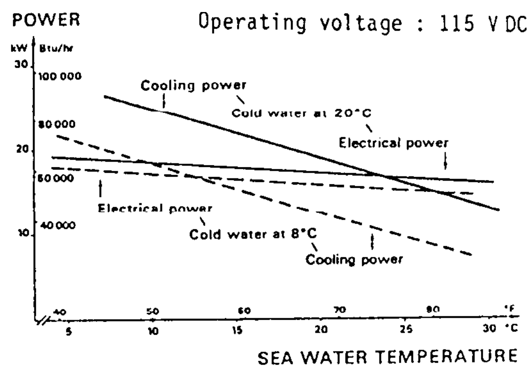


Fig. 11 : THERMOELECTRIC WATER CHILLER 10T925 PERFORMANCES

The cooling and electrical powers are given for cold water production at 8°C (air conditioning) and 20°C (electronic cooling) as a function of sea water temperature.
The cabinet can be operated at voltages in the range 60 to 170 V DC, the higher the voltage, greater is the cooling power but the COP drops ; at lower voltages, the cooling power decreases but the COP increases.

5. AIR COOLING

Air Industrie developed in the seventies, for thermoelectric air conditioning, high performances air heat exchangers, which evacuate by gravity condensate as it is produced.

5.1. Technology - Associating these air heat exchangers with the technology of grounded continuous tubes, used in subunit PE925, constitutes a tremendous step forward in thermoelectric air conditioning technology. A schematic of an assembly is given next page, Fig. 12.
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-thightness, robustness and reliability.

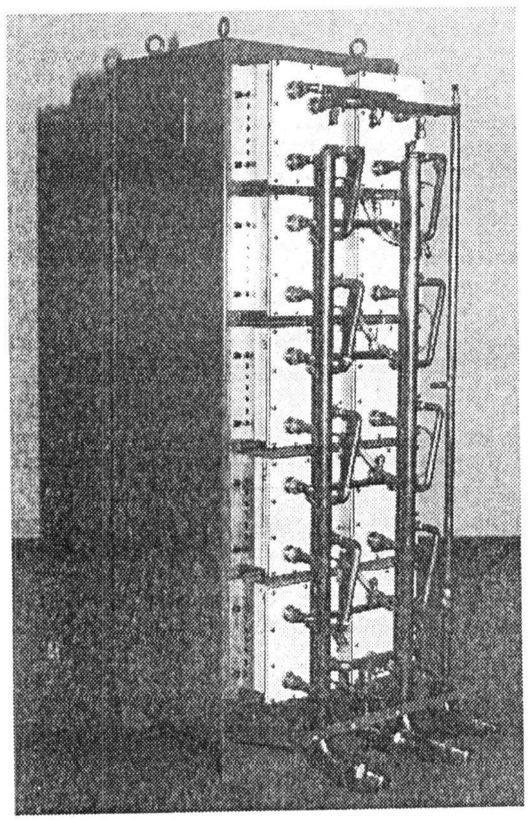


Fig. 8 : PROTOTYPE COOLING CABINET WITHOUT FRONT PANEL

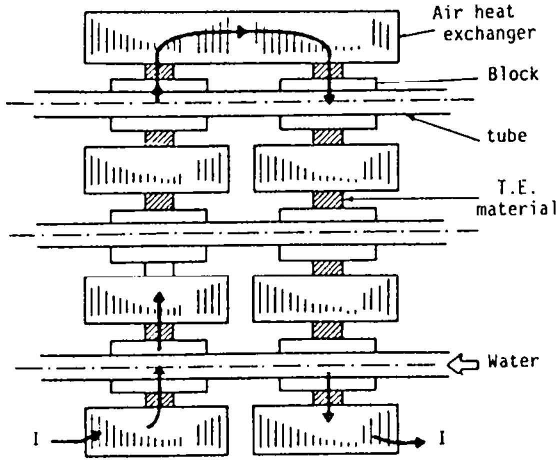


Fig. 12 : SCHEMATIC OF WATER TO AIR THERMOELECTRIC ASSEMBLY

5.2. Equipments - Cooling of air will often condense its humidity. This is the case in air conditioning, where the condensed humidity must be eliminated as it is produced, otherwise it is entrained and causes problems. This is possible with Air Industrie's high performance air heat exchangers of patented desing. A photograph of a subunit EA 408 for air conditioning is shown below.

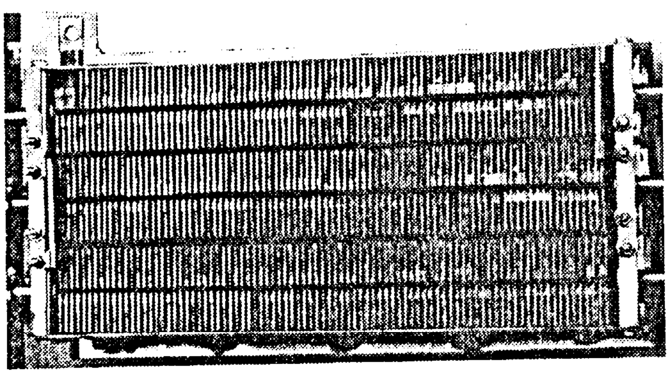


Fig. 13 : SUBUNIT EA 408

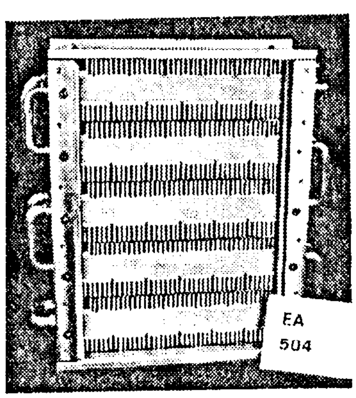
When there is no condensation, which is the case when electronics are cooled, simpler and better suited air heat exchangers are used. A photograph of one of these subunits is shown below.

Fig. 14 :

ELECTRONIC COOLING

SUBUNIT

EA 504



5.3. Application to air conditioning - An important advantage of thermoelectric air conditioning is that with one heat rejection loop (water or sea water) individual and centralized units can be connected to this loop. An individual unit is composed for instance of 1 or 2 subunits. A centralized unit would consist of 10 or more subunits. The drawing below illustrates this example.

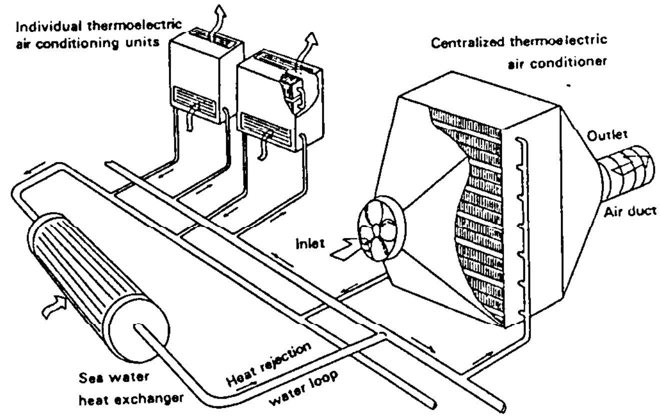


Fig. 15 : SUBMARINE THERMOELECTRIC AIR CONDITIONING

The overall characteristics and performances for a cabinet 10T403 containing 10 subunits EA 403 similar to EA 408 are given below.

Dimensions :
. width : 550 mm (22 in)
. depth : 410 mm (16 in)
. height : 1800 mm (71 in)

Mass : 950 kg

Air circuit :
. flow rate 1.32 kg/s (2330 cfm)
  - nominal inlet temp. : 30°C 50 % rh

Heat rejection loop :
. flow rate : 2.0 kg/s (31.7 US GPM)
. inlet temp. : sea water +5°C
. outlet temp. : inlet temp. +5°C

Operating voltage : 115 V DC

The cooling and electrical powers are given as a function of sea water temperature. The heat rejection water loop is assumed to have an average temperature 7.5°C above the sea water.

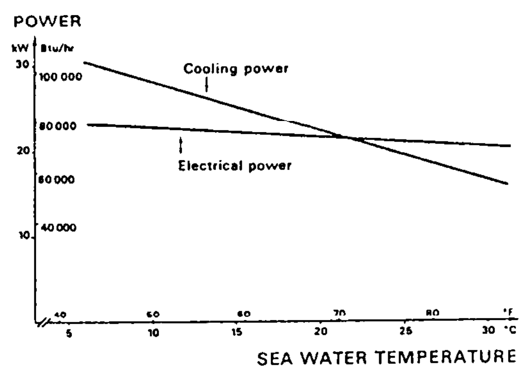
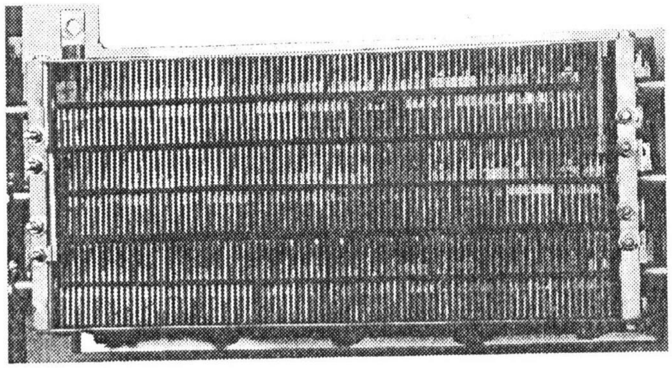


Fig. 16 : PERFORMANCES OF AIR CONDITIONING CABINET 10T403



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ELECTRONIC COOLING

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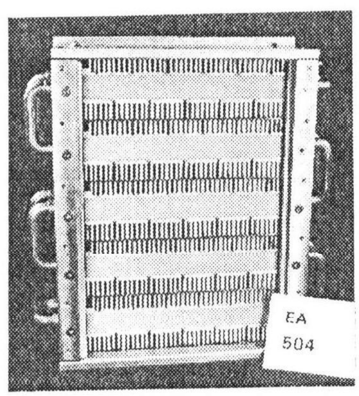
EA 504



5.4. Application to electronic cooling - In this case, the air must not be cooled below its dew point. A compact technology has been designed and built to fit into 19 inches racks. The unit can operate either with fresh water or sea water. The drawing below shows thermoelectric units placed inside electronic cabinets. A fan is located below the unit to circulate the air through lateral ducts to the top of the cabinet. These thermoelectric units are designed to replace passive water-to-air heat exchangers requiring an outside cooling system that cools water to 20°C. The overall characteristics of subunit EA504 and its cooling power are given below.

Dimensions :
. width : 480 mm (19 in)
. depth : 510 mm (20 in)
. height : 170 mm (6.7 in)
Mass : 34 kg
Air circuit :
. flow rate : 0.5 kg/s (800 cfm)
. nominal inlet temp. : 30°C 50 % rh
Heat rejection loop :
. flow rate 0.5 kg/s (7.9 US GPM)
. inlet temp. : sea water +5°C
. outlet temp. : inlet temp. +5°C

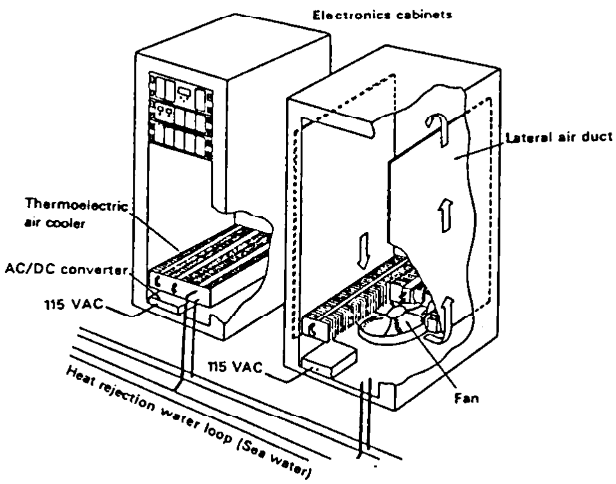


Fig. 17 : THERMOELECTRIC AIR COOLING FOR ELECTRONIC CABINETS

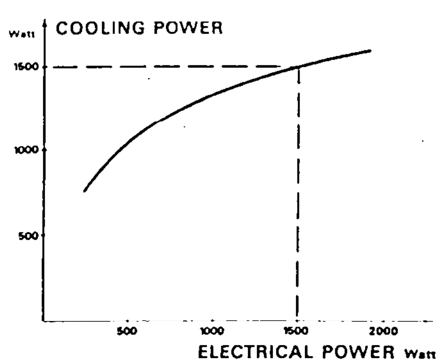


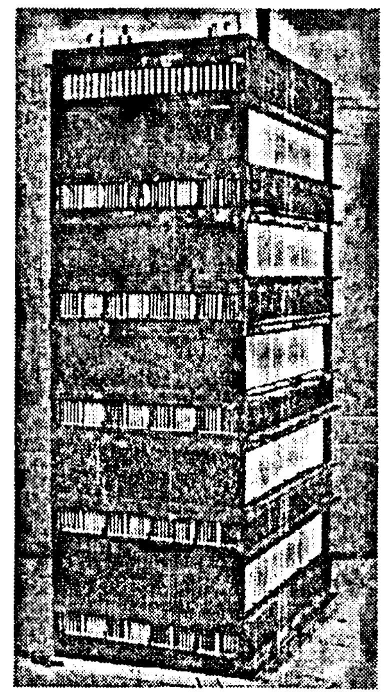
Fig. 18 : COOLING POWER 19 INCHES RACK-UNIT EA 540

The curve above corresponds to an inside temperature of the cabinet of 30°C (inlet temperature to thermoelectric unit) and a sea water temperature of 30°C. Under these conditions the EA 504 unit has a cooling power between 1 and 1.5 kW.

6. AIR COOLING WITH HEAT REJECTION TO AIR

There are cases in the Navy where it is interesting to cool electronics and to reject the heat to air. It is necessary to emphasise that a unit rejecting heat to air is much less efficient than one rejecting heat to water. There are 2 reasons : air temperatures are generally greater than water temperatures and the heat transfer is more efficient to a liquid than to a gas. A unit PR2 was developed for railway air conditioning, where it has given entire satisfaction. It is specially suitable for air conditioning or simple air cooling of mobile enclosures, when vibration and shock endurance is fundamental with very high reliability. The characteristics and a photograph of standard PR2 subunit are given below.

Fig. 19 : PR2 SUBUNIT



The cooling power of 4 subunits PR2 assembled together (unit 4TPR2) is shown.

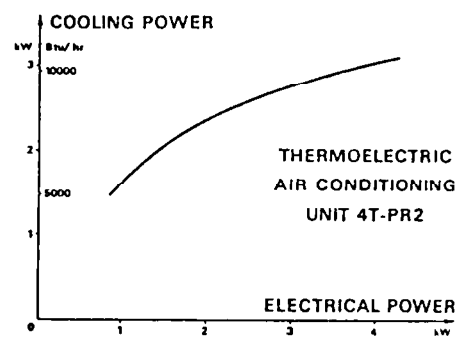


Fig. 20 : COOLING POWER OF 4T PR2 UNIT

The curve corresponds to the following operating conditions for air conditioning :
- enclosure temperature 26°C humidity 50 % r.h
- outside temperature 30°C humidity 60 % r.h
- cooled air flow rate : 0.24 kg/s (425 cfm)
- outside air heat rejection flow : 1.8 kg/s (3100 cfm)

There is also air renewal. A thermoelectric cooling unit 4T PR2 operating in a closed air loop, which is the case in electronic cooling (no air renewal),will have a cooling power approximately increased by 25 % or more.

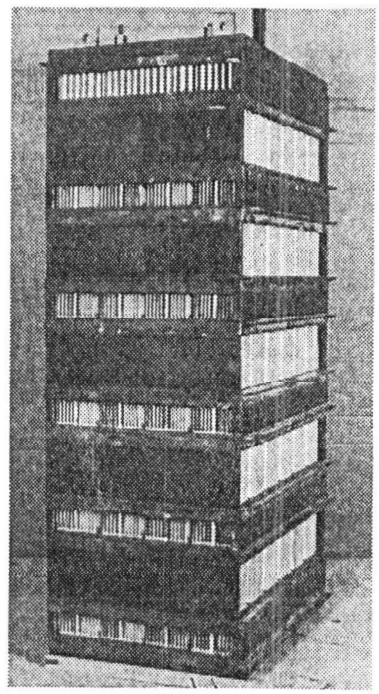


Fig. 19 : PR2 SUBUNIT

7. ELECTRICITY GENERATION

The experience acquired by Air Industrie in the use of bismuth telluride materials for cooling, is valid for the usefull temperature range of this material from well below 0°C up to 200°C. The technologies developed can be used for generating electricity when two heat sources at different temperatures are available. The efficiency η of such a systel is of a few percent.

$$\eta = \frac{\text{Electrical Power}}{\text{Thermal power}}$$

There are some very specific cases where it is valid to generate small electrical powers (below a kW) using two available heat sources. Air Industrie operated a water-to-water thermoelectric unit PE904 in the generating mode [13].

An application is for a back-up power supply for safety devices. For relativity large powers, it is valid that a part of the generated electricity be used for pumping the two liquids. For small powers, pumps can be avoided and natural convection must be used to transfer the heat. There are also applications from water to gas and gas to gas.

8. PROS AND CONS OF THERMOELECTRIC SYSTEMS

Large scale thermoelectric is no longer a risky adventure as Air Industrie has made the process industrial. A comparison with freon systems requires the examination of many factors.

8.1. **Performance** - At the nominal rating of a system a thermoelectric unit requires considerably more electrical power than a freon compression unit ; but thermoelectric units present a tremendous advantage in that they are extremely flexible. When the cooling power requirement decreases the voltage on the thermoelectric unit can be decreased and the COP will increase considerably, this is not possible with a freon system. Also should the cooling requirement increase above the nominal the cooling power is easily increased by 30 % by increasing the voltage [14].

8.2. **Capital cost-Operating cost** - Depending on the relative cost of capital and electrical power one can taylor the size of a system to a specific situation. For example a systems is required to produce 150 kW of cooling (42 tons of refrigeration). By installing 10 cabinets, the capital cost is of 10 cabinets, the electrical power for given operating conditions might be of 150 kW. If one installs 15 cabinets instead of 10 to produce the 150 kW of cooling then the electrical power will drop considerably. Vice-versa if volume is a premium and electrical power less important then one can install 7 cabinets and still obtain the 150 kW of cooling but more electrical power is required.

8.3. **Equipment volume** - Its basic volume is greater than that of the freon compressor, there is a power supply and an electrical control panel but obviously no freon controls. The access volume is much less, it need only be a passage-way in front of the cabinets.

8.4. **Overall advantages** - The list below constitutes the main advantages :

-Reliability with high resistance to shock and vibration

-Quietness

-Abscence of freon as it can be a hasard for health and also for equipments

-Modularity : as can be decentralized and especially for cooling water the cabinets are easy to place

-Always ready to start up especially as there are no moving parts.

9. CONCLUSIONS

Large scale thermoelectrics started in the United States in the early sixties. After a peak of activity it declined to a stand still in the late seventies. Westinghouse was the pioneer and leader in the developing of large systems.

Air Industrie in 1973 started by studying in detail all published documents and met most of the people who had been active in this area of thermoelectrics. Lessons had been learnt over the years, so we were able to use this experiences as a starting point and then forge a head and develop highly efficient, reliable equipments designed to be built in an industrial way and at reasonable cost. Our air conditioning equipments with heat rejection to outside air have been in industrial use for over 7 years. The performances and reliability have been proven. Air Industrie can study any application for an air-to-air system and especially for mobile equipment. Water cooling units with heat rejection to water have been developed, tested and built. A prototype cabinet 10T925 containing 10 units with a cooling power of 15 kW is undergoing long term evaluation and endurance testing at a French Naval Testing Center. Taking into consideration the intensive in house accelerated endurance testing, the reliability is already assured. The unit PE925 is now perfected.

For air conditioning and air cooling systems with heat rejection to water, two laboratory prototypes have already been built and tested. One more especially designed for air conditioning and the second for air cooling without condensation (electronic cooling). Thermoelectric equipments for the air cooling of electronics will be industrialized in the near future. The air conditioning still requires industrialization which needs development funding, that can be covered only by future mass production for a specific market.

APPENDIX
THERMOELECTRIC EQUATIONS

Conservation of energy requires :

$$P_E + P_C = P_h$$

The basic equations can therefore be written (1)

$$P_c = + s * I * T_c - \frac{1}{2} R * I^2 - C * (T_h - T_c)$$

$$P_h = s * I * T_h + \frac{1}{2} R * I^2 - C * (T_h - T_c)$$

$$P_E = s * I * (T_h - T_c) + R * I^2$$

where :

TE is an abbreviation for : thermoelectric

s = Seebeck coefficient of TE material (V/K)

I = Intensity of DC current (A)

R = electrical resistance of TE material (Ω)

C = thermal conductance of TE material (W/K)

T_h = absolute temperature of hot side of TE material (K)

T_c = absolute temperature of cold side of TE material (K)

(1) The asterisk (*) is used as multiplication sign.

These equations permit a physical interpretation of the phenomena. For cooling power P_C :

. + $s * I * T_C$:

"driving power" due to the Peltier effect ; it is proportional to the Seebeck coefficient, to the electrical current I and to the absolute temperatureof the cold side T_C.

$\frac{1}{2} R * I^2$:

Joule heating due to the electrical resistance R of the TE material. It goes half to the cold side and half to the hot side.

. - $C * (T_h - T_C)$:

Heat loss through TE material due to the temperature gradient created by the Peltier effect.

Industrial equipments operate generally in ranges where these 3 terms have the following values, when the Peltier term : $s * I * T_C = 100$

$\frac{1}{2} R * I^2 = 15$ to 20

$C * (T_h - T_C) = 30$ to 35

the net cooling power is of the order of 50.

Electrical term PE :

. $s * I * (T_h - T_C)$ is the electrical power used up to create the Seebeck effect.

. $R * I^2$ is the everlasting Joule effect.

To evaluate the performances of a thermoelectric unit (like for all heat pumps) one generally uses the coefficient of performance COP:

$$COP = \frac{\text{useful power}}{\text{driving power}}$$

for thermoelectric cooling this becomes :

$$COP = \frac{\text{cooling power}}{\text{electrical power}} = \frac{P_C}{P_E}$$

It is interesting to visualize how the cooling power, heating power and electrical power vary as a function of electrical current and temperature difference between the hot and cold sides of the TE material $\Delta T = T_h - T_C$. Figures 1a to 1c on the first page are three-dimensional representations.

To the above 3 equations, more equations must be added that relate the fluid temperatures to the TE material surface temperatures. The set of simultaneous equations must be solved to obtain the cooling, the heating and the electrical power of an industrial unit.

The basic equations require the knowlegde of the 3 properties of the thermoelectric material , s, ρ, k

- Seebeck coefficients s in V/K
- Electrical resistivity ρ in $\Omega * m$
- Thermal condutivity k in $W/(m * K)$

The materials commonly used (doped bismuth telluride) have the following values

$s = 190$ to $220\ \mu V/K$

$\rho = 9$ to $15\ \mu\Omega * m$

$k = 1.3$ to $2\ W/(m * K)$

The material is caracterised by the coefficient of merit Z :

$$Z = \frac{s^2}{\rho * k} \text{ in units } \frac{1}{K}$$

$$\text{Exemple : } \left.\begin{array}{l} s = 220\ \mu V/k \\ \rho = 10\ \mu\Omega * m \\ K = 1.5\ W/(m * k) \end{array}\right\} Z = 2.67 * 10^{-3} K^{-1}$$

This is an average value for good material available commercially. In the laboratory samples have been obtained with a Z greater than $Z = 3 * 10^{-3} K^{-1}$.

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