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THERMOELECTRIC WATER COOLING FOR AIR CONDITIONING AND ELECTRONICS

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Abstract

The principle of thermoelectric systems is described and a comparison with compression cycle systems that use a Freon is given.
A new generation of thermoelectric equipments, that produce cooled water and reject the heat to a water circuit, with subunits based on a proven robust building block concept, is described in detail.
The technology has two fundamental characteristics, the first is that the electrical circuit is highly insulated from the water circuits for operation up to 750 V DC, the second is that the thermoelectric material is integrated into the heat exchangers ; it can either be, for systems of tens of kilowatts, in the form of thermo- elements of 1.5 cm² area or, for smaller systems of several kilowatts, in the form of polarized modules, which compared to thermoelements increase the operating voltage by a factor of 10 or more.
Thermoelectric cabinets, either standard or customized are shown. They can produce chilled water at 8°C for air conditioning or water between 20°C and 30°C for the cooling of electronics, their performances are given.
A thermoelectric water cooling unit that is integrated into the bottom of an electronic cabinet is described with its performances.

1. Thermoelectricity versus compression cycle

Both these systems are heat pumps that transfer heat from one level of temperature to another level of temperature.

1.1. Presentation of the systems

The first difference between the two systems is that a compression cycle system requires mechanical energy which can be obtained by an electrical motor, while a thermoelectric system operates directly from electrical power.

The second difference is that a compression cycle requires an internal fluid loop, while thermoelectricity transfers the heat by putting electrical power into appropriate semiconductors associated with heat exchangers.

Schematics of both systems are shown in Fig. 1, followed by a brief description how each system operates.

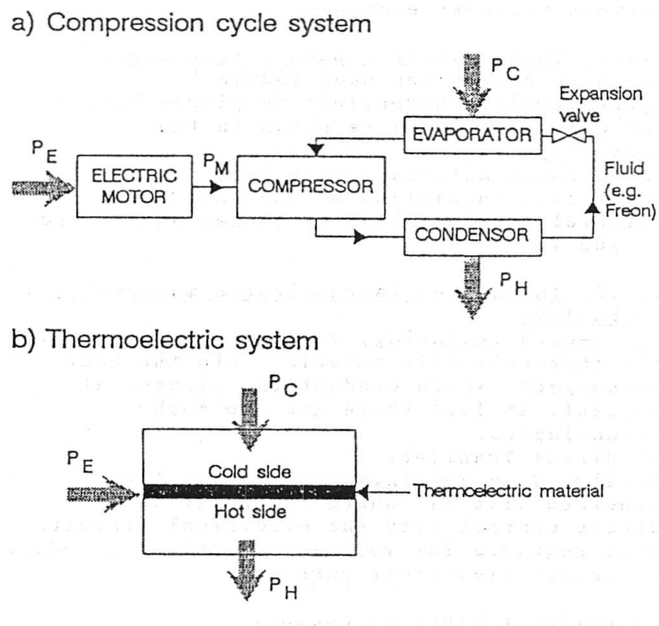

Fig. 1 Schematics of :
a) compression cycle system
b) thermoelectric system

A compression cycle system (Fig. 1a) consists of :
- An electrical power input P_E, and an electrical motor which delivers a mechanical power P_M to the compressor. The most commonly used fluid is a Freon (halogenated hydrocarbon). It goes through a thermodynamic cycle. At the compressor exit the fluid is a hot gas, it then goes through the condensor where it is cooled to the liquid state with heat rejection P_H, then it is expanded and becomes a cool gas and absorbs heat P_C in the evaporator and then returns to the compressor which absorbs the mechanical power P_M.

A thermoelectric system (Fig. 1b) only consists of a sandwich composed of a hot side heat exchanger, thermoelectric material and a cold side heat exchanger.

1.2. Thermoelectric technologies

The principle of a thermoelectric water to water system is shown in Fig. 2, where the heat exchangers are tubes located on either side of the thermoelectric material.

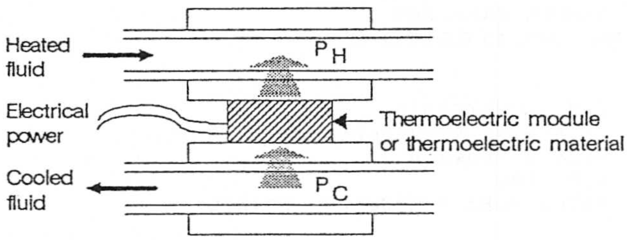

Fig. 2 Principle of thermoelectric water to water system.

There are two basic technologies concerning the sandwiching of thermoelectric material between the heat exchangers.

1.2.1. Thermoelectric module technology

The most common one uses modules[1] (preassembled thermoelectric pieces between two ceramic plates) as shown in the photograph Fig. 3. (module)
The ceramic material constitutes an electrical insulation of the thermoelectric material from the heat exchanger of the order of 100 V

1.2.2. Integrated thermoelectic material technology

The second technology consists in integrating the thermoelectric material into the heat exchangers, which conduct the electrical current. In fact there are two such technologies.
a) Direct Transfer.
Developed by Westinghouse[2] in the late nineteen sixties, where the water is in direct contact with the electrical circuit. This requires low voltage operation to reduce parasitic electrical currents.

b) Building block technology
Developed since 1980 by Air Industrie with the Pont-à-Mousson Research Center[3] it insulates the electrical circuit from the water circuit for operation up to 750 V DC. It is presented in paragraph 2.

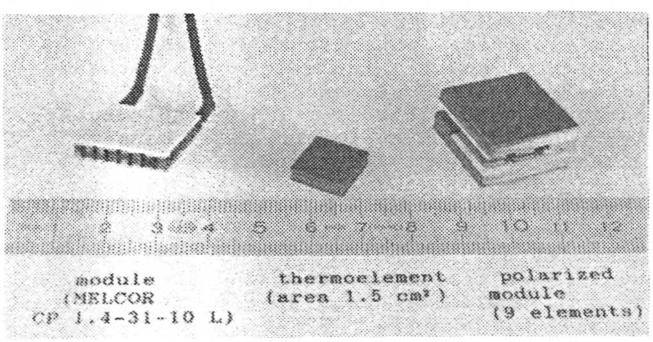

Fig. 3 Photograph of a thermoelectric module, one piece of thermoelectric material (thermoelement) and a polarized module.

2. Air Industrie Technology

This new technology consists of building blocks assembled onto Continuous Insulated Pipes (C.I.P)
Each liquid circuit consists of a continuous tubing which supports the other components. This insures robustness, water tigthness and high reliability.

2.1. C.I.P Building block concept

Air Industrie developed thermoelectric water to water equipments of an advanced technology[10] under contract for the French Navy. The design has several levels of modularity, the basic component is the building block shown in Fig. 4.

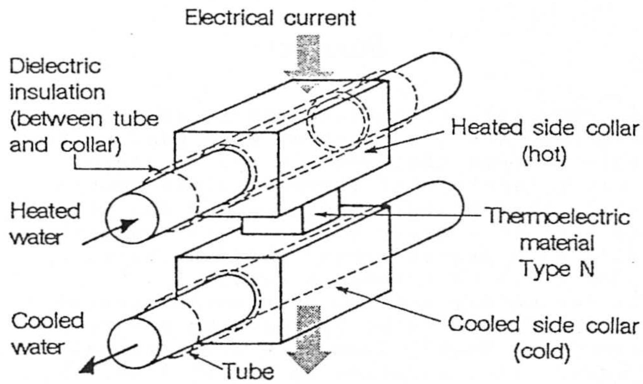

Fig. 4 Building block

The building block consists of a tube (titanium, copper, etc) with heated water, a heated side collar (copper or aluminium) electrically insulated from the tube but with good thermal heat transfer between the tube and the collar. An electrical current I goes through the hot collar, through the thermo-electric material of type N in this case, as we want to produce cooling at the collar after the thermoelectric material along the electrical current path.

Each building block uses a small length of the tube, upon which a thermally and electrically conducting collar is tightly fixed. The collar is electrically insulated from the tube to withstand testing at 2500 V DC, which enables operation up to 750 V DC.

Our standard building block uses tubing with an ID of 17 mm and collars that fit onto the outside. There are two options concerning the thermoelectric material :
- for large systems (greater than 10 kW)[4] single pieces of thermoelectric material are used (cross section 1.5 cm², thickness 1.5 mm. See Fig. 3 (thermoelement)). An average current would be around 180 A, the voltage across two consecutive collars (one piece of thermoelectric material) would be around 20 mV.

- For small system (several kW)[5,6]. Polarized modules are used because the material cross-section that the electrical current goes through is reduced and because the elements are in series electrically.

The photograph Fig. 3 shows a polarized module with nine elements with a total cross section of 1.5 cm² (9 x 16.7 mm²).
In this way the voltage is multipled by 9 compared to a system using single thermoelements of 1.5 cm².
We have developed polarized modules where the numbers of elements are equal to :
9 ; 15 ; 25 ; 35 and 49. In this way we can design systems to operate in a very wide range of voltages.

2.2. 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 two to six or more. A schematic cross section of a set of 5 layers of tubes is given in Fig. 5. below.

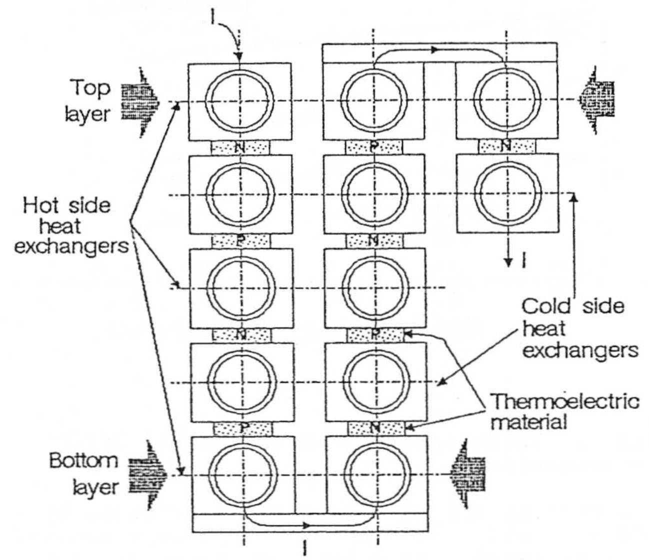

Fig. 5 Cross section of thermoelectric water-water system.

The thermoelectric material is always maintained prestressed, this garanties the stability and the performances in time under continous 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 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 up to 10 layers of tubes. 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. Standard subunit PE925

A typical subunit PE925 is shown in Fig. 6 in the photograph below.

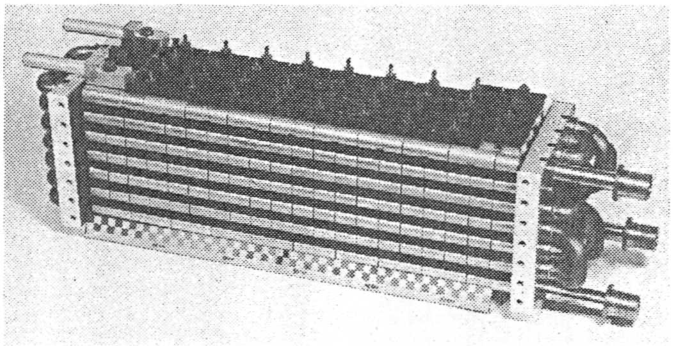

Fig. 6 Photograph of subunit PE925 without casing

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 cm² 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 m³/h).

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.

3. Air conditioning applications

The main application is for the air conditioning of submarines when quiet operation is required.[4]
A cabinet was built for the French Navy.
It is the first industrial prototype. The cabinet 10T925 containing 10 subunits built with our technology is undergoing long term evaluation at a French Naval Test and Evaluation Center. After some teething problems concerning the dielectric insulation between the thermoelectric circuit and the grounded water tubing, the tests have accumulated 35000 subunit-hours. The endurance tests have covered 10000 on and off cycles. Early 1987, following a failure of the auxiliaries, the tests were suspended for 3 months.

On board the chilled water is produced either by a compression cycle system, or when quiet operation is required, by the thermoelectric system, which is in parallel with it.

3.1. Standard water cooling cabinet 10T925

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

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

The photograph Fig. 7 of a prototype cabinet is shown below.

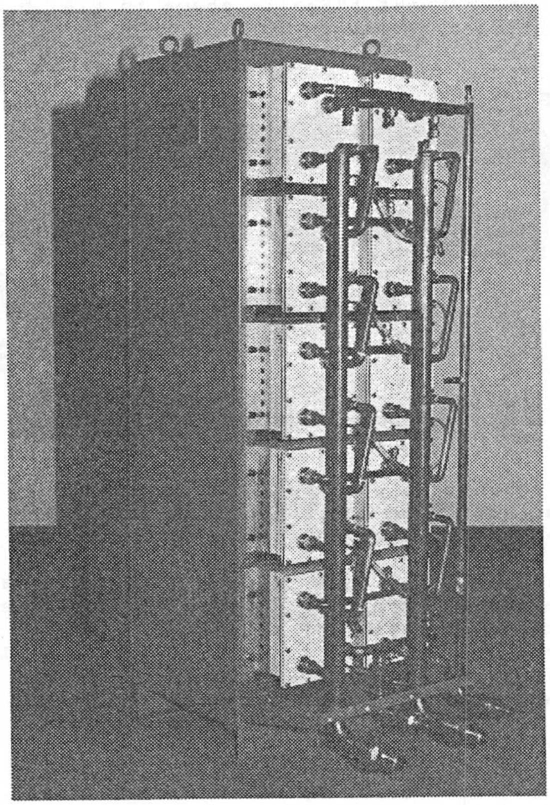

Fig.7 Photograph of prototype cooling cabinet 10T925 with 10 subunits without front panel

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 has been reduced from 1100 mm to 870 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 nominal cooling power is around 15 kW (4.25 tons of refrigeration), 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 ten subunit cabinet 10T925 has two standard fluid configurations :

a) Configuration 1
The cold water circuit consists of 2 parallel circuits each containing 5 subunits in series. The hot water circuit consists of 5 parallel circuits, each containing 2 subunits in series
This corresponds to the circuitry in the photograph Fig.7.
A typical cold water flowrate is
Q_c = 0.6 kg/s

The performances of this cabinet for 85 and 125 V DC operating voltages are given in Fig. 8. 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 easily operated from 70 to 170 V DC. The cooling power increases with the voltage but simultaneously the coefficient of performance COP decreases.

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

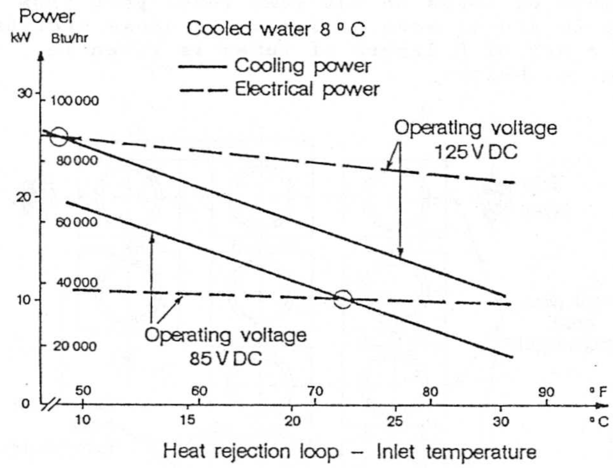

Fig. 8 Thermoelectric water chiller 10T925 performances.

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

b) Configuration 2
The hot and the cold water circuits each consist in 5 circuits in parallel. This circuitry is suited for cold water flowrates of around 1 kg/s.
A typical flowrate is Q_c = 1.1 kg/s.

3.2. Customized cabinets with standard subunits PE925

Cabinets can be tailored to a wide variety of dimensions, so as to fit into the available spaces.
The frame can be a permanent fixture but subunits are always removable. Height is limited by access to the top subunits.

The basic subunit permits cabinets to be made with widths that are multiples of 300 mm.

The cooling power is approximately proportional to the number of subunits. The mass of the subunit is close to 50 kg. The mass of the cabinet with its piping will increase the mass per subunit by about 50 % .
When mass is at a premium a certain mass reduction can be obtained by using aluminium whenever possible.

3.3. Cabinet layouts

The best layouts are those where each cabinet (standard or other) is fluid-wise and electrically independant. This means that, in the overall cold circuit, each cabinet should be in parallel and, in the overall hot circuit, each cabinet should also be in parallel. Electrically the cabinets can either be independently powered, connected in parallel or connected in series, on the condition that the overall voltage does not exceed 750 V DC.

A drawing showing three cabinets and a centralized air conditioning unit is given in Fig. 9.

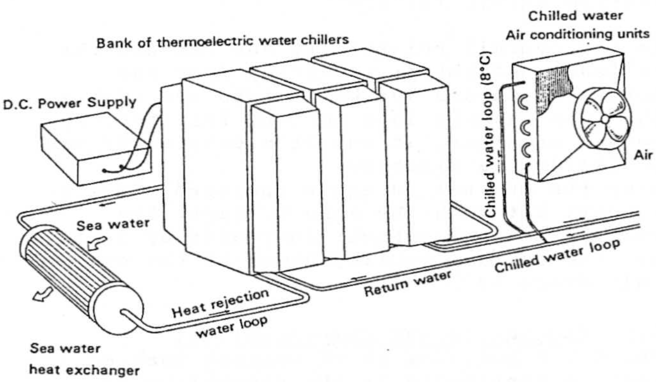

Fig. 9 Centralized thermoelectric submarine water chiller for air conditioning.

4. Centralized thermoelectric cooling for electronics

Water cooling cabinets to produce chilled water for the cooling of electronics are the same as for air conditioning. The difference is in the cold water temperature.
The cooling of an electronic cabinet can be done by circulating air inside the cabinet. In this case the chilled water is generally produced around 20°C. The other method which is more efficient is to circulate water directly through the circuit-boards. In this case the water is often warmer, around 30°C.

A drawing Fig. 10 shows the thermoelectric water chiller with the chilled water loop (between 20 and 30°C), the electronic cabinet on the left contains a water to air heat exchanger so the cabinet is cooled by cooled

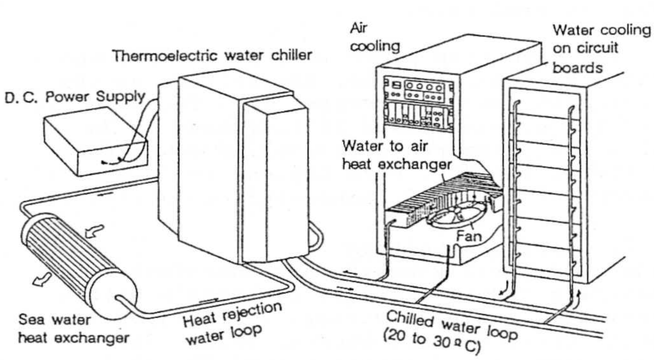

Fig. 10 Centralized thermoelectric submarine water chiller to cool electronic cabinets.

recirculating air. The cabinet on the right has its circuit-boards directly cooled by chilled water from a thermoelectric unit.
The cooling performances and the electrical power as a function of the heat rejection loop inlet temperature for chilled water at 20 and 30°C are given Fig. 11 below.

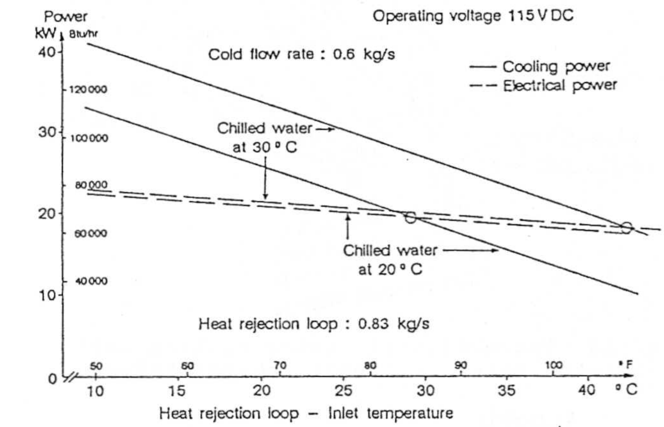

Fig. 11 Thermoelectric water chiller 10T925 performances for electronic cooling.

Electronic cooling requires cold water between 20 and 30°C. Such temperatures being considerably higher than the temperatures required for air conditioning, the performances of thermoelectric systems are acceptable with sea water temperatures reaching 30°C. It appears therefore that these systems are also particularly well suited for surface ships. Our technology uses titanium tubing which means that the hot water loop can simply be sea water.

5. Thermoelectric integrated electronic cooling

In many cases it is interesting for electronic cabinets to have their own autonomous cooling. The electrical power supply for these cabinets can be used for the thermoelectric cooling equipment. If the available power is AC then the cabinet must contain an AC to DC converter. There must be a heat rejection loop that can be either sea water or a water circuit linked by a heat exchanger to sea water. We have designed a unit PE940, that fits in the bottom of the cabinet. Its dimensions are :

495 x 495 x 340 mm

and it contains 1152 polarized modules that each have 15 elements of 7.84 mm².

A drawing showing a cabinet with such an integrated thermoelectric unit is given Fig. 12. We have shown the cold water circuit on the front of the cabinet. See next page.

This unit uses the standard building block of subunit PE925, but there are only 12 collars per tube instead of 20, and there are 9 layers of tubes instead of 7. It contains electrical subunits, that can be wired in series or in parallel, so that the operating voltage can be between 100 and 160 V.

The performances are given next page Fig. 13, for operation at 107 and 160 V.

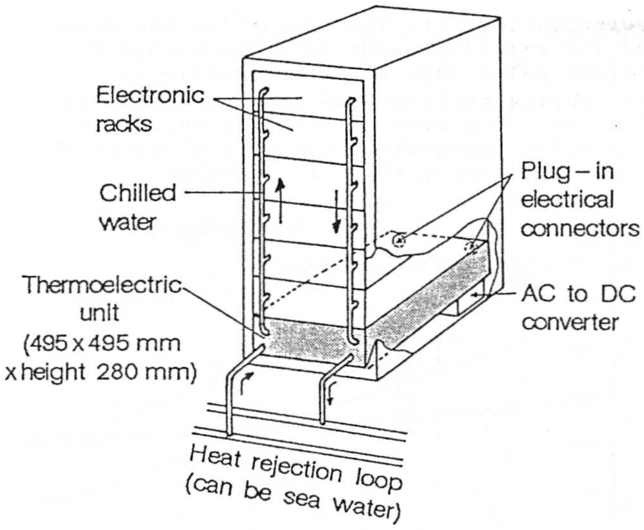

Fig. 12 Thermoelectric water cooling unit integrated into electronic cabinet PE940.

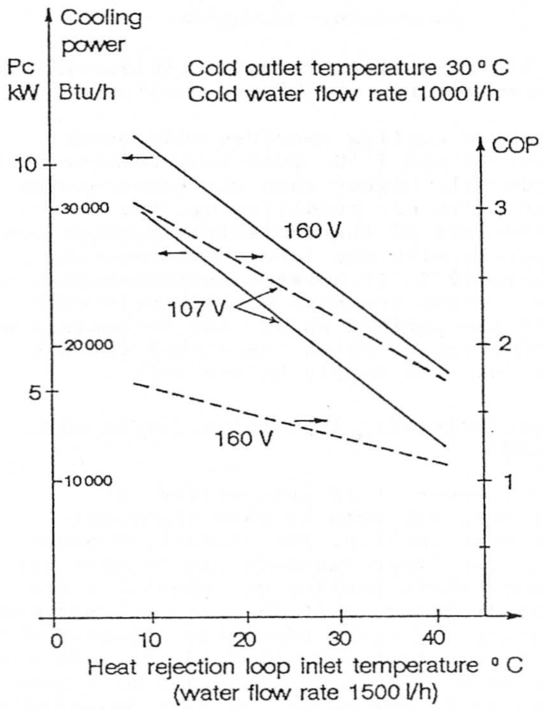

Fig. 13 Performances of integrated thermoelectric water cooling cabinet unit PE940.

The design is a typical example of what can be done to integrate a thermoelectric water cooling unit into a cabinet.

6. Pros and cons of thermoelectric systems

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

6.1. Quietness and safety

Thermoelectric systems have no moving parts except for the water pumps, so by concept are very 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 circuit.

Thermoelectric systems contain no thermal compression fluid such as a Freon that could constitute a health hazard.

6.2. Redundancy and reliability

To obtain high reliability, compression cycle equipments require a complete back-up unit. 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 500 000 subunit-hours of operation without a thermoelectric failure[7].

To the overall reliability one can add the following advantage resulting from the natural redundancies 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 % .

6.3. Modularity and dispersability

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 (litres). The cooling power is generally between 1 and 3 kW.
The modularity permits the distribution of cooling powers where they are required.
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.

6.4. 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[8] :
- when the cooling power is reduced the COP increases, which saves electrical power. See Fig. 14 next page.

- When a cooling power is greater than the required 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.

6.5. 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 ± 20 % without any problem, and consequently the cooling performance varies as can be seen in Fig. 14.

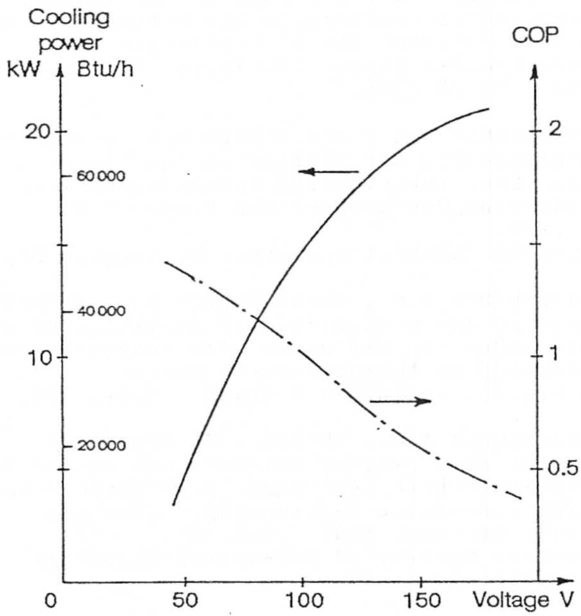

Fig. 14 Cooling power and COP versus voltage

When the grid 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 single phase AC, selfs are required to reduce the AC ripple.

6.6. Transient mode

Thermoelectric systems designed as they are, have little thermal inertia since the thermal paths on both sides of the thermoelectric material are very short. As a consequence and as the temperature difference between the hot side and the cold side is less than the nominal value at start up, thermoelectrics has a high COP and the cooling power is much greater than that of the steady state mode[9].

When necessary it is easy to increase the voltage at start up and obtain the steady state mode in a time that is half or less than 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 more electrical power (about twice as much) 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 below the nominal. Therefore the power supplies do not require oversizing as with freon systems.
-the capital cost is systematically higher than for a compression cycle system, but it varies considerably with the applications and the size of the series. The main savings is that no complete back-up system is required.
-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.

Nevertherless these disadvantages are offset by the numerous advantages given above such as :
- quietness - reliability - dispersability - flexibility.

7. Prevailing characteristics

Some characteristics are essential for certain applications.

7.1. Surface ship combat survivability

The reliability of a combat system decreases when components are dispersed around the ship. Thermoelectric cooling located in the combat system only requires electricity and sea-water, which are both highly redundant. Such a thermoelectric system reduces the vulnerability of the ship's combat system, because it gets rid of the inherent risks of a large compression cycle cooling distribution system widely spread out over the ship and hence highly vulnerable.

7.2. Quietness

Quietness especially for Submarines is a major objective. Thermoelectric cooling being static has no noise-making moving parts.
The strength of the thermoelectric compact prestressed structure enables it to hold up to accelerations of 100 g and more.

7.3. Retrofit

The ease with which a thermoelectric water cooling cabinet can be installed leads one to say that it satisfies the three W's : what, where and when.

WHAT - A thermoelectric equipment it sized so that the cooling power exactly fits the requirements.

WHERE - The thermoelectric cabinet or cabinets because of their quietness can be placed even in places where a compression unit would be a nuisance ; the equipment can be divided up into cabinets and placed in different available locations.

WHEN - Electric power and a water heat rejection loop are available.

Often electronic equipment is modified and the cooling requirements are increased, putting an excess load into the centralized cooling system. Decentralized thermoelectric cooling avoids an extra load and when installed on some of the electronic equipments will therefore reduce the overall cooling load.

8. Conclusions

Large scale thermoelectric cooling started in the nineteen sixties. Sometimes equipments were installed too soon, often with insufficient development involving mishaps. In those days it acquired a bad reputation for being expensive and not reliable. Since then and now with Air Industrie equipments, one must consider thermoelectrics in a completely different way. It is now obvious that thermoelectrics provides advantages over compression cycle systems. It is a common error to consider thermoelectric cooling as an all purpose system, it must only be installed where its advantages are prevailling. The introduction of the Continuous Insulated Pipe (C.I.P) has brought this technology to maturity, enabling the use of thermoelectric cooling with all its advantages : quietness, safety, reliability, modularity and dispersability.

ACKNOWLEDGMENTS

The authors thank M. Michel Bénicourt for his suggestions concerning the best presentation of the advantages and limitations in the use of thermoelectric water cooling systems.

BIBLIOGRAPHY

1. BUIST R.J., FENTON J.W., LEE J.S. A new concept for improving thermoelectric heat pump efficiency. - International Conference on Thermoelectric Energy Conversion. Arlington - Texas - Sept. 1976. IEEE Catalog N° 76 CH 1156-9-REG5.

2. MOLE C.J., MEENAN D.F. Direct transfer thermoelectric cooling. ASHRAE Semiannual Meeting New Orleans La. - Jan. 1964 - N° 1871.

3. BUFFET J.P., STOCKHOLM J.G. Industrial thermoelectric water cooling - 18 th Intersociety Energy Conversion Engineering Conference. Orlando - Fa. Aug. 1983. (American Institute of Chemical Engineers ; New York)

4. STOCKHOLM J.G., SCHLICKLIN P.M. Naval large scale thermoelectric cooling. Presented at French Naval Material Exhibition and Conference Washington D.C. Nov. 1985. (Unpublished, available from the authors).

5. STOCKHOLM J.G., SCHLICKLIN P.M. Industrial thermoelectric cooling in the kilowatt range. 6th International Energy Conference on Thermoelectric Energy Conversion - Arlington Texas - March 1986.

6. STOCKHOLM J.G., SCHLICKLIN P.M. Industrial thermoelectric air cooling in the kilowatt range. 21st Intersociety Energy Conversion Engineering Conference. San Diego - Ca Aug 1986. (American Chemical Society ; Washington DC)

7. STOCKHOLM J.G., PUJOL-SOULET L., STERNAT P. Prototype thermoelectric air conditioning of a passenger railway coach. 4th International Conference on Thermoelectric Energy Conversion. Arlington - Texas - March 1982.

8. STOCKHOLM J.G., BUFFET J.P. Transient response of a railway driver's cab cooled by a thermoelectric heat pump. 16th Intersociety Energy Conversion Engineering Conference Atlanta Ga. Aug. 1981 - Vol. 2. (American Society of Mechanical Engineers ; Warrendale Pa.)

9. STOCKHOLM J.G., BUFFET J.P. Transient response of enclosures heated by a thermoelectric heat pump. 15th Intersociety Energy Engineering Conference. Seattle Wa. Aug. 1980. (American Institute of Aeronautics and Astronautics ; New York)

10. PATENTS : EP 119502 - US 4 420 940 US 4 499 329 and patents pending.

CONVERSION OF UNITS

1 kg/s (water) = 15.85 Gpm

1 kW = 3413 Btu/h

1 kW = 0.284 tons of refrigeration.