THERMOELECTRIC COOLING

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ABSTRACT

Interest in thermoelectric cooling has been growing steadily for a number of years. The French Navy has recently completed an extensive development programme, resulting in the production of centralized submarine thermoelectric cooling plant. The Montreal Protocol agreement, which will restrict the production and use of chlorofluorocarbons (CFCs), has also influenced the Sea Systems Controllerate's decision actively to pursue thermoelectric cooling. This article explains the principle, documents the development process, indicates the progresses made in the U.K., and outlines the potential of thermoelectric cooling for the future.

Introduction

In 1834, Jean-Charles-Athanase Peltier discovered that, when an electric current passes through two different conductors connected in a loop, one of the two junctions between the conductors cools, and the other warms. If the direction of the current is reversed, the effect also reverses.

As a result of follow-on experiments, carried out by Quintus Icilius in 1854, it was proven that the rate of heat output or intake at each junction is directly proportional to the magnitude of the current.

Peltier, born in France in 1785, retired from the clockmaking business at the age of 30 to devote his time to scientific investigations. As a physicist, his discovery of the Peltier effect was followed, in 1840, by the introduction of the concept of electrostatic induction. He wrote numerous papers on atmospheric electicity, waterspouts, the boiling point of water at high elevations, and related phenomena.

The thermoelectric cooling principle harnesses the Peltier effect and is consequently often called Peltier cooling. Thermoelectric equipments are static heat pumps which transfer energy from one temperature level to another temperature level using electrical energy passing through semiconductors. Three basic configurations exist:

- water heat exchanger with heat rejection to water;
- air heat exchanger with heat rejection to water;
- air heat exchanger with heat rejection to air.

Since 1973, a French multi-national company, Tunzini Nessi Entreprises d'Équipments (TNEE), has been undertaking an extensive development programme in the field of thermoelectrics. This has resulted in a proven range of industrial coolers which lead the market.

The vulnerability and poor performance of surface ship chilled water systems is well known. This, together with the increased use of sensitive electronic components, has led MOD to investigate the feasibility of autonomous cooling systems for remote items of equipment. The intention is to decentralize equipment supplies, by removing them from the chilled water main. These dedicated units will ensure a quality and integrity of supply which cannot, at present, be guaranteed. Thermoelectric cooling is one of the options being pursued.

Pioneering Work

In the mid 1950s the first semiconductor materials, such as bismuth tellurides, were used for small-scale industrial thermoelectric cooling. Scientists predicted fantastic future materials which would lead to thermoelectric equipments with performances analogous to those obtained with vapour compression (Freon) units. The Carrier Corporation and the Radio Corporation of America both pioneered this early work, but in the 1960s it became evident that the future materials were not as fantastic as first thought and these small-scale cooling studies ceased.

Since that period, three companies have continued to study systems with cooling powers in the kilowatt range. The Westinghouse Corporation filed and obtained many patents during the late 1960s. Papers were written and subsequent prototype equipment was installed and has been running in the U.S. Navy for 20 years. U.S.S. *Dolphin* was the thermoelectric cooling trials vessel for this period. The York Corporation built several units for military applications and patents were obtained, but activity stopped in the early 1970s. TNEE Air Industrie Thermoelectrics started an important research and development programme in 1973 which has led to the proven kilowatt range of today. The first application of large-scale units was for the air conditioning of passenger railway coaches. These 5 to 30 kW heaters/coolers have been running without problems on the French railway network since 1978.

Module Development

A thermoelectric cooling module is defined as that part of the system which contains the thermoelectric semiconductor material and forms the hot and cold junction when a steady state d.c. voltage is applied.

Low cooling power modules consist of many pieces of thermoelectric material connected in series electrically and in parallel thermally. The bismuth telluride pieces (normally 1.5 mm thick) are compressed between two electrical insulators, the most common being alumina, to make a self-contained heating/cooling unit. This preassembled construction, used in early modules, is still widely available commercially and provides the best technique for applications from a few milliwatts (for laser diode cooling) to 300 watts (module size: 55 mm × 55 mm). The Materials Electronic Products Corporation of Trenton, New Jersey (MELCOR), manufactures the majority of preassembled thermoelectric modules, type CP 5-31-06 being specially designed for military applications.

Difficulties arise when preassembled module technology is applied to larger cooling powers. Thermoelectric material compression requirements restrict the size and hence power of the module, whilst manufacturing tolerances ensure that individual modules cannot be assembled in groups under common hot and cold junctions. The need for module compression pressures of at least $1 MN/m^2$ ($150 lb/in^2$) and reliable thermal conductance (achieved as a direct result of very close tolerances), led to the development of the more complex but more efficient integrated module.

Any preassembled module gains in simplicity are far outweighed by the thermal disadvantage at higher powers. Electrical insulators are bad heat conductors and hence the principle of the integrated module, whereby the electrical circuit goes directly through the heat exchangers, is a basic design advantage.

The integrated technology must satisfy a number of basic constraints. Firstly, the electrical circuit that passes through the Thermoelectric material and the heat exchangers must be insulated from the walls of the fluid circuits. Secondly, a means of absorbing shear stress must be built into the system as thermoelectric material has inherently low thresholds.

FIG. 1 shows the TNEE method of meeting both constraints using integrated modules. The thermoelectric material (bismuth telluride) is in direct contact with the heat exchanger and is connected to the insulated fluid tube by a heat-conducting block assembly which absorbs the shear stress. This continuous grounded tube design with high dielectric insulation, perfected in 1984, improved upon the Westinghouse 'direct transfer' method patented in 1964 and last used in 1972, where pieces of tube were joined by insulated shock absorbing seals (FIG. 2).

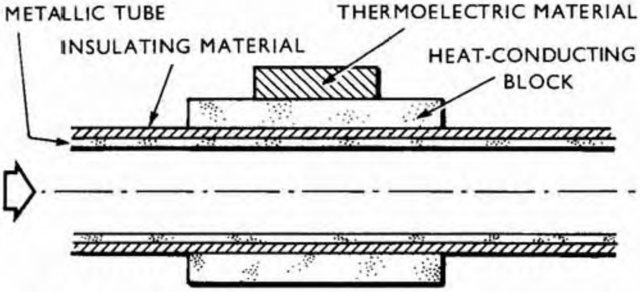

FIG. 1—TNEE DESIGN OF CONTINUOUS GROUNDED TUBE WATER HEAT EXCHANGER (1984), IN WHICH SHEAR STRESS IS ABSORBED BY HEAT-CONDUCTING BLOCKS

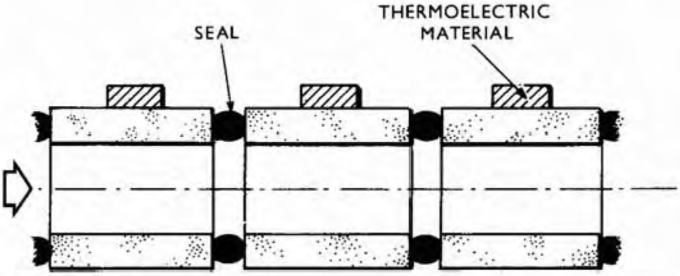

FIG. 2—WESTINGHOUSE 'DIRECT TRANSFER' DESIGN OF HEAT EXCHANGER OF 1964, IN WHICH SHEAR STRESS IS OBVIATED BY COMPRESSIBLE SEALS BETWEEN THE PIECES OF TUBE

Module Performance

In metals, the Peltier cooling at a junction is usually completely masked by the irreversible joule heating in the bulk of the metal and is of no practical use. Semiconductors, however, have Fermi energy levels much more critically dependent on temperature than those for metals. As a result, metal/semiconductor junctions exhibit much larger thermoelectric effects. The so-called Peltier Coefficient or Coefficient of Merit is correspondingly larger and hence practical refrigerating junctions can be constructed. The low thermal conductivity of semiconductors also helps to insulate the cold junctions.

Four main semiconductor alloys have applications as material for thermoelectric junctions. These are bismuth telluride (the most common), bismuth selenide, antimony telluride and antimony selenide. TNEE are actively investigating new alloys. Performance improvements of up to 20% are considered feasible in the near future. The effectiveness of such materials is measured by the Figure or Coefficient of Merit (Peltier Coefficient), Z, defined by,

$$Z = a^2/kp \text{ kelvin}^{-1}$$

where a is the Seebeck coefficient (volts/kelvin)
k is the thermal conductivity (watts/metre kelvin)
p is the electrical resistance (ohms/metre)
of the material.

Current materials yield Z in the region of $0 \cdot 0024\ K^{-1}$ and $0 \cdot 0028\ K^{-1}$. However, by careful selection of material, $0 \cdot 003\ K^{-1}$ is achievable. A figure of $0 \cdot 0026\ K^{-1}$ gives Coefficients of Performance (COPs) for thermoelectric cooling approximately half those for vapour compression (Freon) cycles. The improvement of insulator materials will also increase the performance of thermoelectric junctions. A number of ceramic-based materials (especially aluminium nitride) show particular promise and are likely to replace traditional insulators in the near future.

Naval Applications

Both water/water and air/water thermoelectric heat exchangers are suitable for naval equipment cooling. Water/water units can be used as a direct replacement for centralized chilled water plant or as a method of providing distributed equipment cooling, whilst air/water units can be used as individual compartment air conditioners, cabinet/spot coolers or as alternative Air Treatment Unit (ATU) heating and cooling elements.

These two thermoelectric systems are based on integrated module technology and use the continuous grounded tube design for water circuits. Module and tube assemblies are built up into layers which form the element of a thermoelectric system known as a sub-unit. All electrical circuits are highly insulated from ground to allow operation at 115 volts d.c. nominal. The construction of water/water heat exchangers is more complex; consequently their development process will be discussed in preference to that of air/water units.

Water/Water Sub-Unit Development

Designated PE 925, the sub-unit is intended to be cabinet-mounted in stacked parallel banks. The nominal cooling power of each sub-unit is 1·5 kW at the design voltage of 11·5 volts d.c. Sea water can be passed through the titanium tube fluid circuits. Support for the module and tube structures is provided by a steel mounting frame which also locates the sub-unit within the cabinet.

Intensive design effort to produce the PE 925 sub-unit (FIG. 3) commenced in 1980. Development of the prototype was finalized in 1984 and led to the

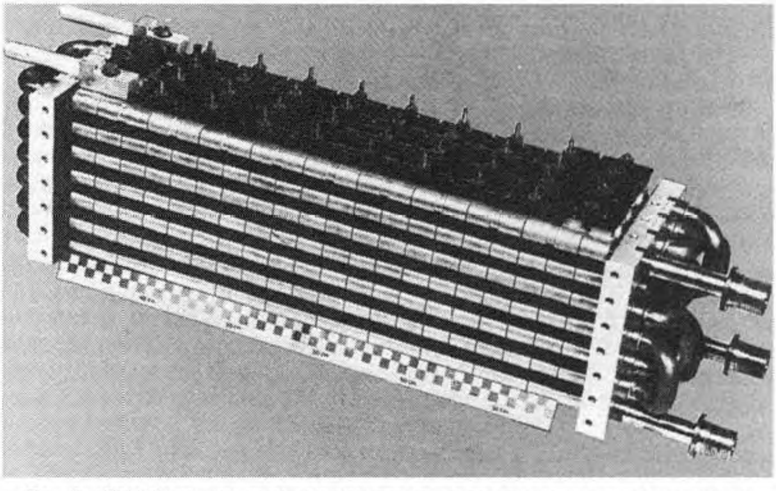

FIG. 3—PE 925 SUB-UNIT WATER/WATER HEAT EXCHANGER, WITHOUT CASING; CM SCALE AT BASE

production of the first thermoelectric water/water cooling cabinet. The basic sub-unit component is a linear assembly comprising titanium tubing, with a wall thickness of 0·5 mm, and 20 aluminium collars which are fixed on to the insulated tube. The collars form the stress-absorbing medium for the thermoelectric material. Four of these assemblies build up to form a layer and seven layers form a sub-unit. The electrical circuit goes alternately through a collar and a piece of thermoelectric material. There are 480 pieces of thermoelectric material (alternately N and P type) which form the 240 couples in a PE 925 sub-unit.

Thermoelectric Cooling Cabinet

The first water/water cabinet, produced in 1984, used 10 PE 925 sub-units and was consequently designated 10T 925. No significant modifications have been made to the basic 2 × 5 configuration, but notable redesigns have been carried out to the header assemblies which join the sub-unit fluid circuits together within the cabinet structure (FIG. 4). A more rational header layout has reduced cabinet depths from early values of 1100 mm to 925 mm for the latest cabinet designated 10T 928. This size reduction has been accompanied

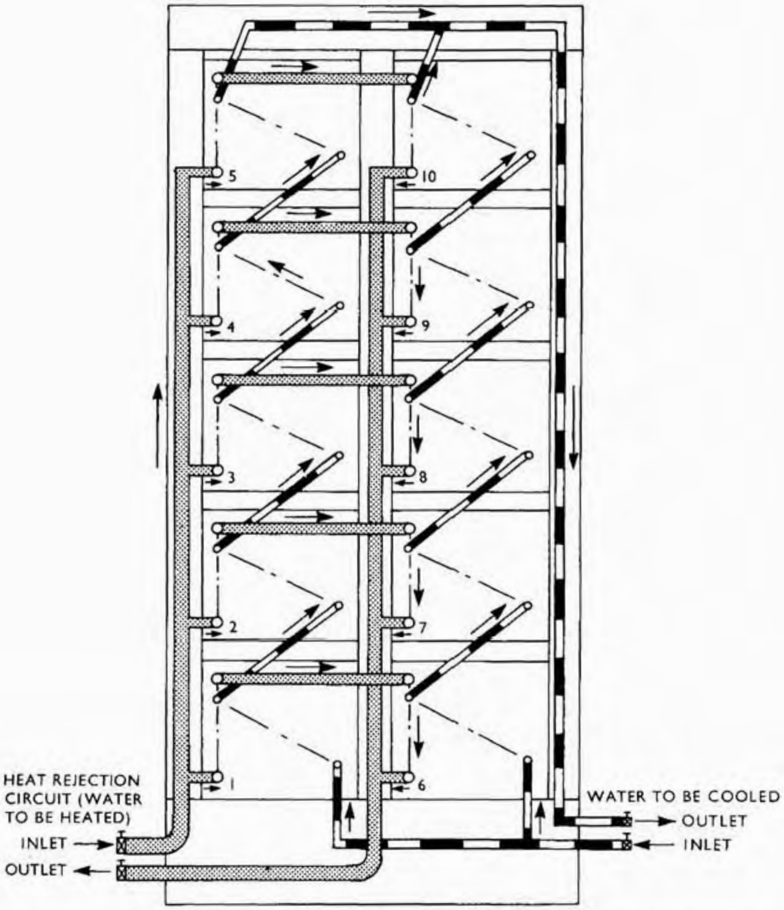

FIG. 4—THERMOELECTRIC CABINET 10T 925; DIAGRAM OF THE TWO WATER CIRCUITS (FRONT VIEW)

by a reduction in weight. The dry weight is now 850 kg, a saving of 350 kg over the original production unit. Existing headers, located at the front of the cabinet, are manufactured from 713 stainless steel, but copper nickel will be used for non-development cabinets.

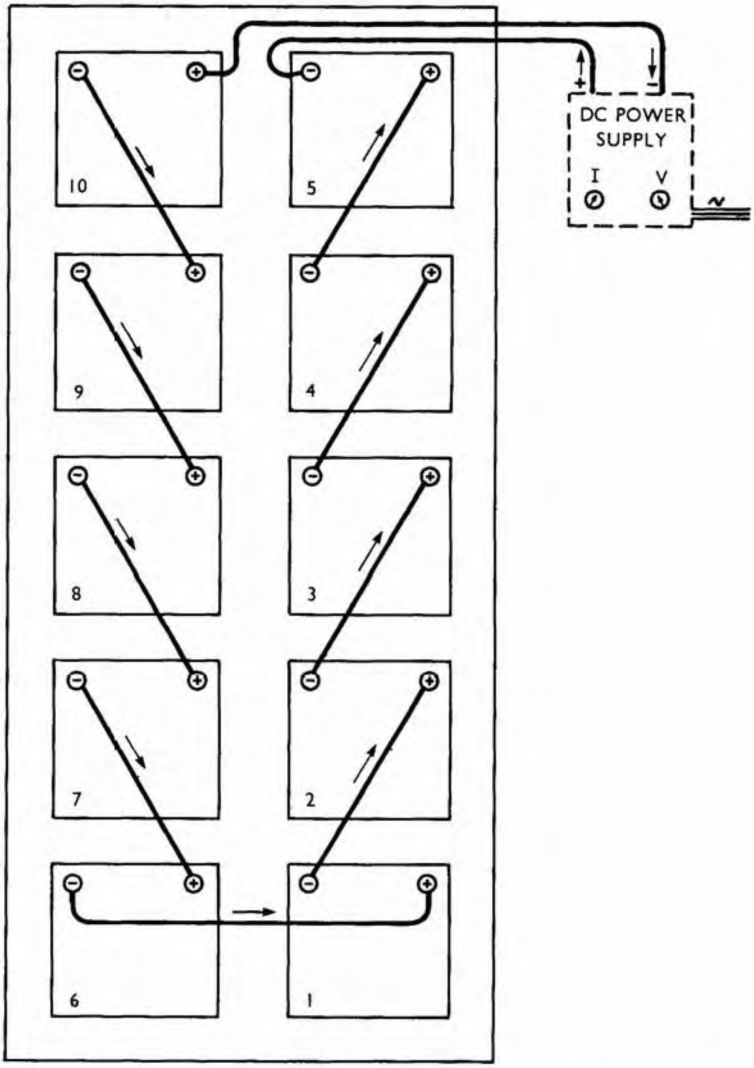

FIG. 5—THERMOELECTRIC CABINET 10T 925; DIAGRAM OF ELECTRICAL CONNECTIONS (REAR VIEW)

All electrical connections between sub-units are on a frame at the rear of the cabinet (FIG. 5). The insulated male plug-in connectors on the frame mate with two female connectors on the back of each sub-unit. The sliding drawer principle, on which sub-unit withdrawal is based, is ideally suited to this type of electrical joint.

Testing and Evaluation

Understandably, TNEE and the French Navy have been concentrating recent efforts on proving the system by means of a testing and evaluation programme. Initial proof and performance testing was carried out at the TNEE Pont-à-Mousson research centre during 1984, in order to obtain confidence in predicted levels. This initial phase included mechanical testing (vibration and shock), performance testing (cooling and electrical power), hydraulic testing (watertightness and pressure drop), dielectric insulation, and thermal and electrical cycling.

The successful conclusion of TNEE in-house testing (mid 1985) led to the installation of a 10T 925 cabinet at the French Naval research centre (CETEC) within DCAN Cherbourg. The objectives of this endurance testing phase were to accumulate running hours, accumulate on and off operations, and monitor a number of parameters including electrical resistance of the thermoelectric circuit, dielectric insulation with respect to ground, and cooling performance. A total of over 52 000 sub-unit running hours has been accumulated (August 1988) with only one failure which was traced to a faulty electrical control circuit leading to massive over-current through the sub-unit.

The endurance testing phase has revealed that the most effective method of measuring mechanical degradation of the thermoelectric material is to monitor the electrical resistance of each sub-unit. Microstrain cracking at the material/insulator interface leads to an increase in resistance which can be more easily detected than by periodic visual inspection of the modules.

Control Requirements

The control and protection activities for a thermoelectric cooling system are inherently more simple than those required for a vapour compression chilled water plant. Parameters that need to be monitored in order to give sufficient protection are minimum chilled water flow, maximum temperature in the cabinet, maximum electric current, maximum supply voltage, and chilled water outlet temperature.

The maximum temperature which can be sustained within the cabinet is governed by the module soldering operations and is limited to 135°C. The maximum supply current is limited to 400 amps. Normal operation requires approximately 150 amps, but during the current overload failure, sub-units were subjected to 750 amps without major damage. Maximum supply voltages are limited by Joule heating effects which reverse the thermoelectric process. 130/140 volts is considered the practical maximum, which is close to the normal operating level of 115 volts. The minimum chilled water outlet temperature is 3°C. This avoids freezing within the fluid coils; a phenomenon which is much more of a problem in vapour compression chilled water plants where 5·5°C is considered the limiting value.

Plant control tasks can be achieved by either of two methods. The first involves keeping the supply current and voltage constant and increasing the heat rejection circuit capacity to decrease cooling power artificially. The second involves the use of variable power supplies, which gives a higher efficiency, but requires the use of a more complex electrical system. TNEE are involved in the design and development of a control, protection and surveillance system to be used on production Thermoelectric cabinets.

U.K. Progress

A thermoelectric cooling feasibility study was carried out for the Ministry of Defence by Ernest West and Beynon during 1980/1981. The modules were supplied by Westinghouse, but the results achieved did not meet intended performance targets; consequently the study was dropped. Since the TNEE development work, interest has been renewed and studies have been restarted.

Vickers Marine Engineering APG (Advanced Programme Group) have recently negotiated a teaming agreement with TNEE, through which French modules or sub-units are supplied to form the basis of U.K. thermoelectric cooling packages. Detailed cabinet design and control arrangements will be carried out by Vickers APG.

In order to further MOD learning, a feasibility study investigating distributed cooling systems has been placed with Vickers APG. A parallel study, requiring the solution to be based on latest vapour compression equipment, will provide the comparison.

The primary U.K. application of thermoelectric cooling is fundamentally different to the French. During a recent visit to the Cherbourg test site, the U.K. delegation were somewhat sceptical of the principle being adopted. 20–30 water/water thermoelectric chillers are to be located in a centralized bank providing a submerged cooling capacity on the new generation SSBN. It is believed that this application does not make full use of the advantages of thermoelectric cooling. A number of small distributed chillers, cooling essential combat systems on surface ships will provide a stern test in the light of recent operational directives such as reduced manpower, low noise signature and increased ARM levels.

Advantages and Disadvantages

Thermoelectric cooling has a number of advantages when the principle is applied to military systems. However, these advantages are diluted when practicalities are considered.The reliability of large thermoelectric coolers is well documented and has now been proven as a result of French testing. Cabinets have a high resistance to both shock and vibration, giving a degree of robustness not normally associated with cooling plant. As there is a total absence of moving parts, the system is abnormally quiet. Flow noise is the only possible source. An absence of Freon yields advantages on both safety grounds and in the light of the Montreal Protocol agreement. This absence of Freon, coupled with the lack of moving parts, leads to a system with very low maintenance levels. When maintenance is required, the sub-units can be easily withdrawn from the front of the cabinet. The access envelope needs only to cater for this withdrawal operation and is consequently small. The autonomous nature of thermoelectric cooling allows plant to be de-centralized, reducing vulnerability. This modularity and low maintenance also assists the installation procedure. The lack of moving parts helps to provide a no warm-up, instant start facility, as well as simplifying the control task. A simple reversal of current flow can alter the cabinet effect from cooling to heating. This flexible performance is further enhanced by the fact that the supply voltage can be easily reduced to limit the degradation in coefficient of performance or increased to meet transients above the nominal load.

The disadvantages of thermoelectric cooling are centred around a less efficient process and a lack of manufacturing expertise. The lower values for coefficient of performance (COP) associated with the thermoelectric cooling process lead to a greater electrical power requirement at the nominal rating. COPs are approximately half those for the vapour compression cycle and consequently electrical loads are at least doubled. Electrical supplies must be d.c. and of high quality. To operate efficiently, the current fluctuation must not exceed ± 10%. Thermoelectric plant occupies a greater equipment volume. Ratios vary from 1·5 or 2 for individual cooling units to 3 or 4 for centralized plant, compared to 1 for vapour compression equipment. This size disadvantage is accompanied by a weight penalty. Centralized thermoelectric cooling systems can be as much as ten times heavier than conventional fits. Smaller distributed systems are less bulky. The relatively inefficient cycle leads to higher operating costs, although reduced maintenance levels offset this. However, the high initial procurement cost cannot be overlooked. This is partly due to the newness of the concept and the associated development costs. No costings are available at this stage, but estimates reveal an order of magnitude increase over current plant.

Conclusions

This article has been written at a time when interest in thermoelectric cooling is high. Although the development process is in its infancy in the U.K., the explanations and progress outlined above should serve to clarify the perceptions of readers. The U.K. had entered the thermoelectric cooling market at a relativley late stage, but can take heart in the fact that French application of the thermoelectric principle during the research and development stages has been very sound. TNEE are currently working in conjunction with French universities to produce a more advanced thermoelectric material. Improvements in performance of up to 20% in the short term are likely.

Improvements in French cabinet design are not expected over the next few years. However, Vickers Marine Engineering will bring a fresh approach to the packaging of French modules and sub-units. Reductions in equipment size are expected as a result.

In terms of potential for the future, the thermoelectric cooling process has applications in the field of submarine cooling, both as centralized plant and as a replacement for existing Air Treatment Units. Extensions to current surface ship applications are also possible as production costs reduce. Until this time, the comparative feasibility study being carried out by MOD will progress and should reveal the potential of thermoelectric cooling in the light of more stringent operational directives.