d. The figure of merit, $Z = \alpha^2/\rho K$, involving the three parameters previously discussed, is used for describing the merit of a thermoelectric material and should be as large as possible. A similar concept in compressor performance is the volumetric efficiency as affected by all three characteristics already discussed, i.e., piston blowby and valve leakage, friction losses contributing to gas superheating, and re-expansion losses.

(e) The maximum temperature difference, $\Delta T_{max} = \frac{1}{2}ZT_h^2$, that can be developed under no load conditions. This is similar in concept to the maximum pressure difference obtainable in a compressor, also in an unloaded condition, and is dependent on the volumetric efficiency and the suction pressure.

ADVANTAGES AND APPLICATIONS OF THERMOELECTRIC COOLING

The heating and cooling functions of the condenser and evaporator in a mechanical system can be interchanged by reversing the direction of refrigerant flow. This cannot be achieved without considerable difficulty and expense. Since the motor and compressor involve rotary and reciprocating motion, wearing of parts and noise may also present a problem. The containing of the refrigerant requires a hermetic system which must be leakproof. A further inherent limitation of this system is that it cannot be readily made in miniature to economically provide a small amount of refrigeration.

The heating and cooling functions of a thermoelectric system can easily be interchanged by reversing the polarity of the direct current applied to it. Since there are no moving parts, there is nothing to wear out and nothing to generate noise. There is no refrigerant to contain, and the pressure-tight tubing has been replaced by electrical wiring. Since the cooling capacity of a single thermoelectric couple is very small, it is practical to make a system of very low refrigerating capacity. The thermoelectric system can also be made in large capacities by using many couples.

Capacity control in a thermoelectric system can be achieved by varying the voltage applied to the couples. The current flow is thus changed and the capacity changes (see Fig. 6).

Another advantage is that a thermoelectric system will operate under zero gravity, or many times the force of earth gravity, and will operate in any position. This is important in considering cooling applications for use in space travel. A thermoelectric system also operates satisfactorily at high temperature levels up to 220 F.

Along with the advantages there are some disadvantages. One is that, at this time, a thermoelectric system requires more power than a compression system to produce a given cooling capacity. Fig. 5 gives an approximate comparison of the coefficients of performance of a compression system and thermoelectric systems using materials with various figures of merit. The current figure of merit is approximately 0.003 per C degree.

Since a thermoelectric system has no moving parts and nothing to wear out, it might be expected to have an infinite life. Individual couples and some devices have operated without a noticeable change for a few years. However, there are some things that, if not controlled, may cause a degradation of performance. It is known that copper will diffuse into a thermoelectric material and adversely affect its thermoelectric properties. The solders for joining thermoelectric material to copper straps must be carefully selected so that they do not diffuse into the thermoelectric material and eventually result in a joint failure. These effects can be minimized, and probably eliminated, by nickel plating the ends of the couple legs prior to soldering. The solders must also be selected with regard to the temperature range of operation of the system.

Thermal expansion and contraction of the materials on the opposite faces of a system will induce stresses. If the function of a particular system is to alternately cool and heat, there will be a reversal of these stresses. Materials must be selected to withstand this.

For many applications, the advantages of thermoelectric cooling will outweigh its chief disadvantage of a relatively low coefficient of performance. For some cooling requirements, a thermoelectric system is the only practical means.

Some of the applications of thermoelectric cooling are: air conditioning and refrigerating systems for use on submarines, temperature control of electronic components, cooling of scientific instrument components and small specialty appliances.

The U. S. Government has sponsored the development of many thermoelectric systems. Among these are: an 8500-Btuh unit[3] for possible use as the refrigerating method for frozen food storage rooms on nuclear submarines, a 9-ton air conditioner for a small submarine, prototypes of air conditioners for submarines[4], and temperature control of crystal oscillators in frequency standards, to improve their life and sensitivity. Thermoelectric applications in the scientific instrument field include: immersion cooler for cooling liquid in a beaker, thermocouple reference junction at 32 F, instrument for measuring dew point, and microscope stage cooler.

There are also applications in commercial and appliance refrigeration. Some of these are: a drinking water cooler[4] for use on Diesel locomotives, a small bottle-type water cooler for offices, and a small ice maker for use in hotel rooms.

The latter unit was capable of freezing one tray of water (approximately one pound) in 6 hours. Small portable refrigerators with less than one cubic foot internal volume have been marketed by two manufacturers. Both of these could be operated from a 120-volt alternating-current source, or from a 12-volt direct-current automobile electrical system. A 2 cu ft unit which can be used either as a refrigerator or a warming oven has also been produced. The cabinet air temperature is 35 F on the cooling cycle and 160 F on warming.

In the commercial and appliance areas, thermoelectric cooling is best suited to small specialty devices. The products mentioned in the previous paragraph illustrate this. Currently, thermoelectric cooling is economically practical in only low capacity systems.[7] As the capacity increases to over 200 or 300 Btuh, a compression system will probably be the more economical. An increase in the figure of merit and a decrease in the cost per couple will be necessary to change this relationship. Fig. 10 gives the maximum temperature difference that has been achieved over the years. This can be converted to the figure of merit by using Equation 14. Based on data currently available (1964), the maximum temperature difference shown for 1961 has not been exceeded. There have, however, been reductions in the cost of thermoelectric couples, due to improved manufacturing techniques.

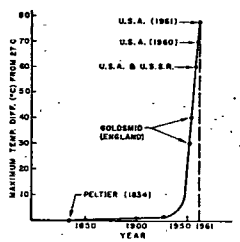

Fig. 10 .... Maximum Temperature Difference Achieved with a Thermoelectric Couple Over the Years

Semiconductor materials used for thermoelectric cooling couples are currently made from alloys of bismuth, tellurium, and antimony for p-type, and of bismuth, tellurium, and selenium for n-type. Usually minute quantities of other materials are added to improve the thermoelectric properties. There has been a very great research effort to find improved materials and to develop a knowledge of the fundamental characteristics of these materials. While this knowledge has been increased, it is still not adequate to enable scientists to predict when higher figures of merit will be available or to estimate how high a figure of merit may be possible.

GUIDE TO THE DESIGN OF DEVICES

Information similar to that required for the design of a compression refrigerating system must also be established in order to design a thermoelectric system. Some of the factors to be considered are: ambient temperature, means of heat removal from hot junctions, means of heat absorption at the cold junctions, and the power available. Fig. 11 is a schematic view of a thermoelectric assembly including couples and fins for absorption and dissipation of heat.

A very important item in device design is heat transfer between the thermoelectric junctions and the heat source or heat sink. For example, the temperature difference over which a couple operates is larger than the temperature difference between ambient and the interior of a refrigerator. From Fig. 12, it can be seen that, with a fixed current, a change in temperature difference across the couple has an appreciable effect on cooling capacity. The couple temperature difference must be minimized to obtain the best performance.

The couple temperature difference in the assembly shown in Fig. 11 equals the sum of these temperature differentials: air temperature on hot side to air temperature on cold side, hot side fin base to ambient, hot junction to hot side fin base, cold side fin base to cold junction, cabinet air to cold side fin base. The electrical insulation between the couples and the fin bases must be a good thermal conductor, to minimize these temperature differences. A satisfactory material is difficult to find, since most electrical insulators are relatively poor thermal conductors. Anodized aluminum, epoxy coatings, and others are being used. The heat transfer surfaces can be calculated by conventional means.

In designing the thermoelectric couples, the designer must consider two basic variables. These are current, I, and the ratio of the cross-sectional area to the length of the couple legs, A/L. There are an infinite number of combinations of these two variables which yield the same total heat pumping capacity. There are two limiting modes of operation, namely, operation at maximum coefficient of performance and maximum heat pumping capacity, which are of special interest. (See Fig. 6.) These two operating conditions fix I with respect to A/L, but the choice of A/L can still remain arbitrary; more precisely, the choice of A remains arbitrary since L is governed by contact resistance considerations already discussed.

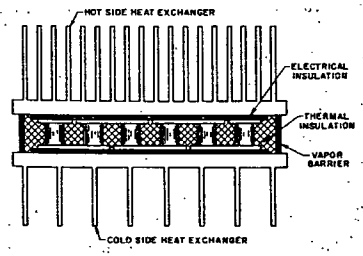

Fig. 11 .... Cross Section of Thermoelectric Module and Heat Transfer Surfaces

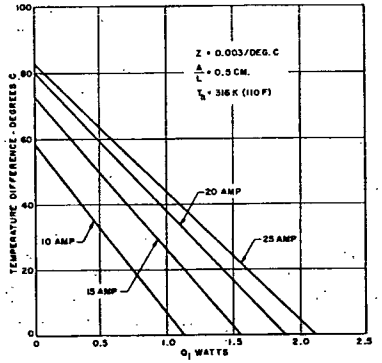

Fig. 12 .... Heat Pumping Capacity of a Thermoelectric Couple as a Function of Temperature Difference and Current

As A/L is increased, the number of couples required decreases, since the heat pumping rate per couple is proportional to A/L. An increase in A/L increases the current requirements.

Once the temperature difference is established and a current is selected, it is possible to calculate the A/L to give maximum cooling capacity or maximum CP by differentiating Equations 5 or 7 with respect to A/L, equating to zero, substituting the proper values, and solving for A/L.

Another approach to the design of a thermoelectric unit is to select thermoelectric modules that are made by any one of several manufacturers. A module is defined as an assembly of thermoelectric couples. A typical eight couple module is shown in Fig. 13.

Each manufacturer has his own design and often provides standard modules in different current ratings and different numbers of couples. The manufacturer will provide performance data similar to that shown in Figs. 6 and 12. It is

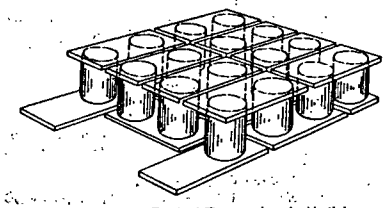

Fig. 13 .... Typical Thermoelectric Module