LOW POWER 145° KELVIN THERMOELECTRIC COOLER

by

R. Buist and J. Fenton
Borg-Warner Thermoelectrics
Des Plaines, Illinois

Introduction

Recently, there has been an activated interest in cooling electronic components to intermediate cryogenic temperatures using multi-stage thermoelectric cascades. The Night Vision Laboratory, Fort Belvoir, Virginia, has funded programs designed to produce a low power thermoelectric cascade that can cool a substrate to 145 K from an ambient of 325 K. Borg-Warner Thermoelectrics has delivered such a unit to NVL, under contract DAAK02-70-C-0189, that has met or surpassed all the contract objectives and represents the most recent state-of-the-art advance in thermoelectric cooling.

The Borg-Warner Thermoelectrics' technology for the production prototype thermoelectric coolers involves six major phases--1) determination of operating boundary conditions, 2) selection and characterization of materials, 3) generation of an optimum design, 4) computerized simulation of performance, 5) fabrication and 6) testing. These phases must be accomplished in chronological order, and the accuracy and reliability of each step must be maintained as each new phase is initiated. The general characteristics and conditions of each phase are discussed in this paper, utilizing the NVL unit as an example.

Boundary Conditions

There are three boundary conditions that must be specified before any meaningful calculations can be made--1) the heat sink temperature, T_h, 2) the cold spot temperature, T_c and 3) the total effective thermal load, Q. These quantities are normally specified by the application. However, most applications specify a range of temperatures under which the device must operate. Unfortunately, a device can be optimized only for a specific set of boundary conditions. Many designs can be generated within the temperature range of interest, so that compromises can be studied. The standard technique, however, is to design the cooler for the worst case conditions--highest expected T_h, lowest expected T_c, and largest expected Q.

The goal of the NVL contract was to cool a 0.2 x 0.4 inch substrate to 145 K from a 325 K ambient with less than 50 watts input power. Since this unit was a feasibility study, operation at other temperature conditions was not considered. There was to be no externally applied thermal load to the system; thus, it was necessary to accurately estimate the passive radiation load.

The specification of Q for large ΔT devices is very important. That is, the efficiency falls off rapidly with increasing ΔT. It will be shown later that the 180° ΔT NVL cooler required about 4 watts of input power for every milliwatt of heat load. Thus, steps were taken to minimize Q as much as possible.

A method of determining effective radiation loads had been developed by Borg-Warner Thermoelectrics utilizing various thermoelectric configurations. A shielding system for the NVL cooler was concurrently developed in order to minimize the radiation effect. The calculated effective thermal load to the 145 K cooler was 10 milliwatts.

Thermoelectric Materials

With the boundary conditions specified, the next step in the process was to select and characterize the thermoelectric material. Borg-Warner Thermoelectrics has a wide variety of different

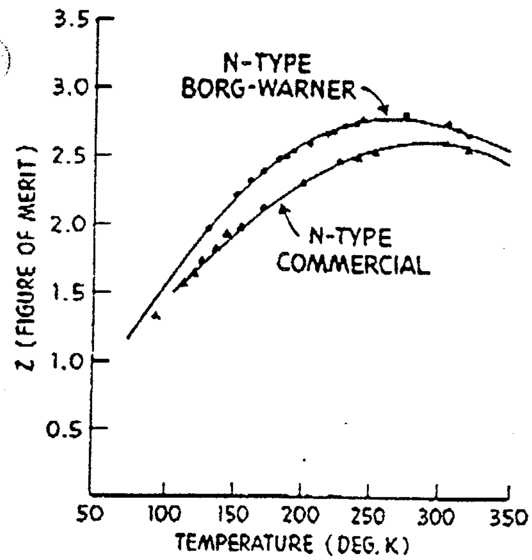

Fig. 1. Figure of merit versus temperature--Z is calculated from simultaneous measurements of Seebeck coefficient, electrical conductivity and thermal conductivity.

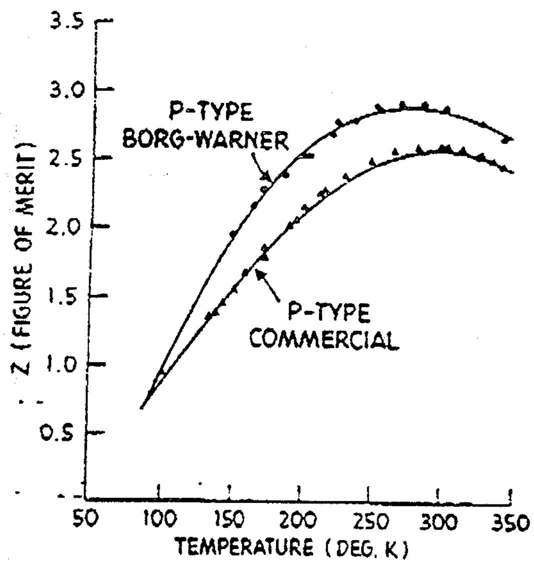

Fig. 2. Figure of merit versus temperature--Z is calculated from simultaneous measurements of Seebeck coefficient, electrical conductivity and thermal conductivity.

thermoelectric materials available, from both commercial suppliers and from the Borg-Warner supported materials research program. The Seebeck coefficient, electrical resistivity and thermal conductivity were measured on a set of Borg-Warner and commercial materials approximately every 10 C in the temperature range of interest. These data are collected by a unique system that operates completely automatically and collects data on paper tape.

The figure of merit determined from these data is illustrated in Fig. 1. The lower curve is the Z versus temperature curve of commercial N-type material, while the top curve is from N-type material made at the Borg-Warner Research Center. The significance of these curves is that, to a first order approximation, the performance quality of a device is improved as Z is increased. Figure 2 is a similar plot for P-type materials.

The higher quality Borg-Warner materials are, at present, produced only in laboratory quantities. Thus, every attempt is made to design using commercial materials and to employ the Borg-Warner materials only when it is necessary to achieve a maximum performance level.

Design and Performance Simulation

Historically, thermoelectric device theory has been based on the simplifying assumption that the thermoelectric parameters are invariant with temperature. This was done for two main reasons--the theory is greatly simplified, and temperature dependent measurements, especially thermal conductivity, are very difficult. It is clear from Figs. 1 and 2 that this assumption is only approximated for very narrow bands of temperature. Even if Z were constant, the temperature variance of the individual parameters, S, σ and K still affect performance. Nevertheless, many design engineers in the field today still utilize the standard simplified theory.

In contrast to standard methods, the device design program at Borg-Warner accounts for the full effect of the temperature dependence of the thermoelectric parameters. This is accomplished by a computerized numerical solution of the fundamental equilibrium equation. This departure from constant parameter theory was found to be necessary for an accurate description of multi-stage large ΔT systems.

The criteria for cascade optimization described in the literature is valid only for constant Z; therefore, cascade optimization was achieved by an iterative process, utilizing a numerical calculation procedure. This process produced designs that were significantly improved over the design formulas derived from constant Z assumptions.

Optimum designs were generated as a function of the number of thermoelectric stages for both classes of materials. The results are shown in Fig. 3. The optimum

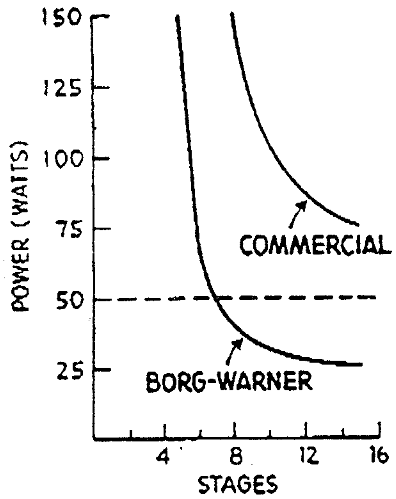

Fig. 3. Effect of staging on optimum design--these calculations are based on data illustrated in Figs. 1 and 2.

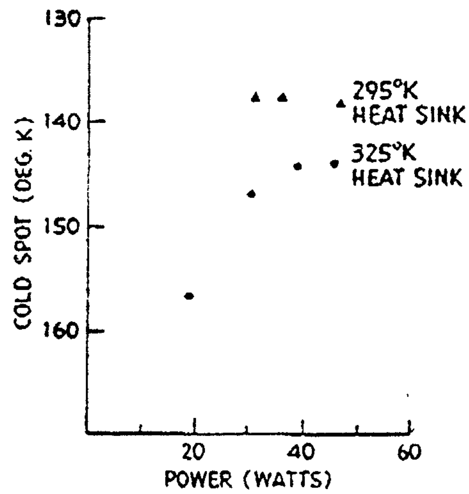

Fig. 4. Measurement test data on NVL cooler--the cold spot temperature was measured as a function of input power for two different constant heat sink temperatures.

number of stages is theoretically infinite. However, in practice, there does exist a finite optimum number of stages. This occurs because the gain in performance due to staging will eventually be smaller than the losses due to the additional thermal and electrical junctions. This "optimum" number of stages is dependent on T_h, T_c and the thermoelectric material used. Thus, Fig. 3 is meaningful only for the conditions specified.

The effect of material quality is quite evident. The factor, at least 3 in C.O.P., is a result of a 10-20% Z improvement over commercial materials. These curves also illustrate the fact that relatively small improvements (or errors) in Z reflect large improvements (or errors) in a multi-stage system.

The need for precise measurements and theory is obvious. It is also clear that the requirement of 50 watts input power cannot be met with commercial materials. In contrast, Borg-Warner materials can satisfy the power requirements using a minimum of seven stages. For an added safety factor, the 8 stage, 38.7 watt optimum design was selected.

The performance simulator program is as complex as the design theory. The constraints were inputted and a simulated test was made. The results indicated that the device would produce 145 K at the substrate, with only 39 watts input power.

Fabrication and Testing

The Borg-Warner Thermoelectrics production personnel have evolved a fabrication technology that minimizes electrical and thermal losses in the assembled device. All critical phases of the fabrication were accomplished by a single, highly skilled technician, and each subassembly was subjected to rigid quality control checks.

The size of the assembled thermoelectric cascade cooler was 1.35 inches square at the base by 1.4 inches high. The thermoelectric unit weighed 84 grams. Before the unit was tested, the shielding system was installed, and a vacuum of 10^{-5} torr was maintained. The initial test results are shown in Fig. 4. The circles are the data taken while maintaining the heat sink at 325 K, while the triangles are those for a 295 K heat sink.

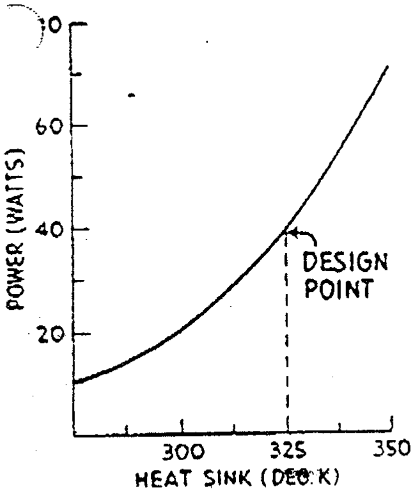

Fig. 5. Effect of heat sink temperature on optimum design—each print on the curve is a different optimum design. The cold spot temperature is 145 K, and the thermal load is 10 milliwatts for all designs.

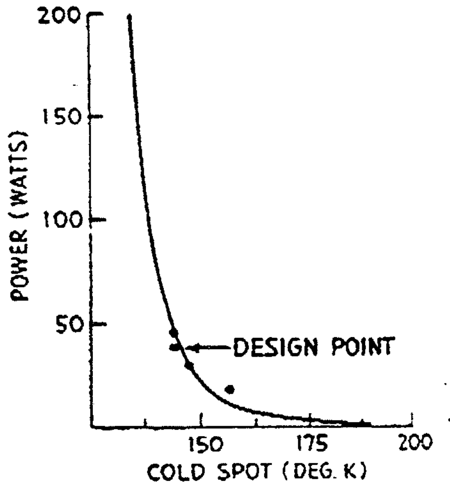

Fig. 6. Effect of cold spot temperature on optimum design—each point on the curve is a different optimum design. The heat sink temperature is 325 K, and the thermal load is 10 milliwatts for all designs.

It is observed that the 38.95 watt, 144.3 K measurement test point is in excellent agreement with predictions. The two sets of data illustrate the remarkable effect ambient temperature has on performance. Calculations have shown that only half the input power is required to cool the substrate from a room temperature ambient. Although this device can be operated at other heat sinks, cold spots and power levels, it is optimized for the particular boundary conditions specified.

Figure 5 illustrates the effect of changing only one condition, the heat sink temperature, on the optimum design. Each point on this curve is a different optimum design. The NVL cooler design point is indicated. The actual performance curve for any of the fixed designs will fall outside this curve except for the design point. Thus, the curve can be viewed as the locus of outlier performance.

A similar curve is shown in Fig. 6. This curve illustrates the effect of changing only the cold spot temperature. Again, the curve is a locus of optimum designs. The actual performance data of the NVL cooler shown earlier are plotted as circles. It is observed that the performance is actually slightly better than expected, with the design point falling inside the outlier curve. The expected deviation from this curve is clearly visible in the far right data point. This illustrates the fact that if one wanted to operate at a cold spot of 156.7 K, a power reduction from the measured 18.3 watts to 10.1 watts would be realized with a redesign.

Summary

More extensive data on the cooler were taken later at the Night Vision Laboratory after the unit had been installed in a vacuum enclosure. The unit performed even better at NVL due to the beneficial radiation shield effect of the enclosure. Table 1 summarizes the contract objectives as required, predicted and measured. The success of this project was due to the improved Borg-Warner materials, a working theoretical design and the skills of the Borg-Warner Thermoelectrics' fabrication technology.

Since the time of construction of this cascade, further significantly improved materials have been produced and characterized by our laboratories. Calculations have shown that over 50% power

Table 1. Summary of contract objectives versus results.

	Required	Predicted	Measured
Heat sink	325 K	325 K	325 K
Cold spot	145 K	145 K	144.3 K
Power	<50 watts	38.7 watts	39.0 watts
Cool-down time	10 minutes	-	6 minutes
Weight	<1.5 pounds	-	84 grams (cooler only)
Substrate	200x400 mils	-	200x400 mils

reductions are presently available, while initial measurements on the very latest materials indicate that a still further improved performance may be expected in the near future.

Richard James Buist is a Research Physicist in the Thermoelectric Materials Research Group at Borg-Warner Research Center. He has recently been concerned with thermoelectric device design and analysis, and functions as Engineering Manager for Borg-Warner Thermoelectrics.