The Where and the Why of Cooling Thermoelectrically

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The Where And The Why Of Thermoelectric Cooling

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Preface:

The principles, applications, and design possibilities of thermoelectric cooling are discussed in this booklet. To place these in proper perspective, however, it is first necessary to know how thermoelectric cooling systems differ from their conventional refrigeration counterparts.

Like conventional refrigeration, thermoelectrics obey the basic laws of thermodynamics, and in a later section of this booklet, these laws are more fully discussed. Both in result and principle, then, thermoelectric cooling has much in common with conventional refrigeration methods — only the actual system for cooling is different.

Perhaps the best way to show the differences in the two refrigeration methods is to describe the systems themselves. In a conventional refrigeration system, the main working parts are the freezer, condenser, and compressor. The freezer surface is where the liquid refrigerant boils, changes to vapor and absorbs heat energy. The compressor circulates the refrigerant and applies enough pressure to increase the temperature of the refrigerant above ambient level. The condenser helps discharge the absorbed heat into surrounding room air.

In thermoelectric refrigeration, essentially nothing is changed. The refrigerant in both liquid and vapor form is replaced by two dissimilar conductors. The freezer surface becomes cold through absorption of energy by the electrons as they pass from one semiconductor to another, instead of energy absorption by the refrigerant as it changes from liquid to vapor.

The compressor is replaced by a battery or dc power source which pumps the electrons from one semiconductor to another. A heat sink replaces the conventional condenser fins, discharging the accumulated heat energy from the system.

The difference between the two refrigeration methods, then, is that a thermoelectric cooling system refrigerates without use of mechanical devices, except perhaps in the auxiliary sense, and without refrigerant.

However, several questions remain. What components make up a thermoelectric cooler, and how do they operate? Where can thermoelectric coolers be used? Why cool thermoelectrically? What practical applications exist for this refrigeration method?

What Specifically are Thermoelectric Coolers and how do they operate ?

The components of a thermoelectric cooler can be shown best through a cross-section of a typical unit, such as that shown in Figure 1.

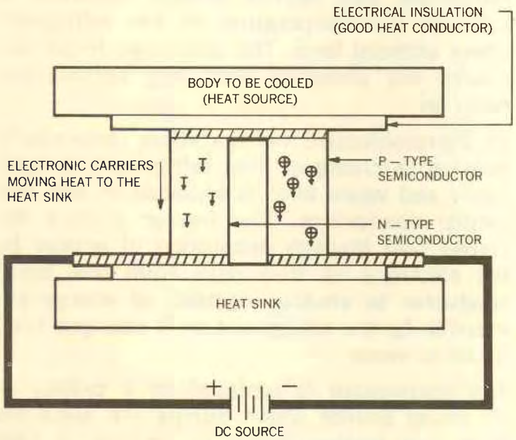


Fig. 1 — Cross-Section of a Typical Thermoelectric Cooler.

Thermoelectric coolers such as this are actually small heat pumps which operate on physical principles established over a century ago. The basic laws of thermodynamics apply to these devices just as they do to conventional heat pumps, absorption refrigerators and other devices involving the transfer of heat energy.

Stated as simply as possible, in a thermoelectric cooler, semiconductor materials with dissimilar characteristics are connected electrically in series and thermally in parallel, so that two junctions are created (Figure 1).

The semiconductor materials are N and P-type, and are so named because either they have more electrons than necessary to complete a perfect molecular lattice structure (N-type) or not enough electrons to complete a lattice structure (P-type). The extra electrons in the N-type material and the holes left in the P-type material are called "carriers" and they are the agents that move the heat energy from the cold to the hot junction.

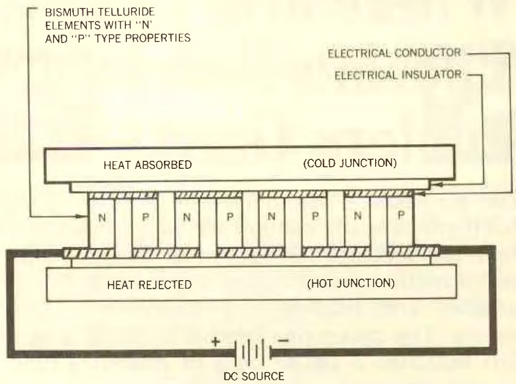


Fig. 2 — Typical Module Assembly. Elements Electrically in Series and Thermally in Parallel.

Heat absorbed at the cold junction is pumped to the hot junction at a rate proportional to carrier current passing through the circuit and the number of couples. Good thermoelectric semiconductor materials such as bismuth telluride greatly impede conventional heat conduction from hot to cold areas, yet provide an easy flow for the carriers. In addition, these materials have carriers with a capacity for carrying more heat.

It is, in fact, only since the refinement of semiconductor materials in the early 1950's that thermoelectric refrigeration has been considered practical for many applications.

In practical use, couples similar to the single couple shown in Figure 1, are combined in a module where they are connected in series electrically and parallel thermally (Figure 2). Normally, a module is the smallest component available. The user can tailor quantity, size or capacity of the module to fit his exact requirements without buying more total capacity than he actually needs.

Modules come in a great variety of sizes, shapes, operating currents, operating voltages, number of couples, and ranges of heat pumping levels, although the present trend is toward a larger number of couples operating at a low current.

Where are Thermoelectric Coolers Used ?

For purposes of simplified illustration, uses for thermoelectric coolers can be grouped into four basic categories; electronic components, temperature control units, commercial refrigeration, and medical and laboratory instruments. The categories overlap in some areas, but establish a better base of reference than overall grouping.

Some sample applications within each category are as follows:

ELECTRONIC COMPONENTS

Cold traps for vacuum chambers
Crystals
Discrete silicon components
Inertial guidance systems
Infrared detectors
Integrated circuits
Lasers
Masers
Nuclear radiation detectors
Parametric amplifiers
Photomultiplier tubes
Vidicon tubes

TEMPERATURE CONTROL UNITS

Constant temperature chambers
Environment chambers
Integrated circuit test chambers

Temperature baths

COMMERCIAL REFRIGERATION

Aircraft water coolers
Cream coolers
Display cabinets
Ice cube makers
Photo developing solution coolers
Picnic baskets
Restaurant service-stand coolers

MEDICAL AND LABORATORY INSTRUMENTS

Blood coagulators
Cold probes
Dew point hygrometers
Microscope cold plates
Mobile drug coolers
Surgical instrument-coolers
Test tube coolers

What Forms do Thermoelectric Coolers take ?

Modules normally contain eight to 100 couples with ceramic-metal laminate plates (Figure 3) at both the hot and cold junctions to provide good thermal conduction and good electrical insulation. A module has a single pair of connecting leads.

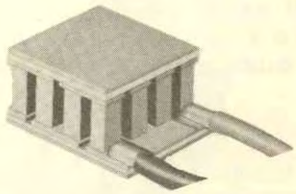


Fig. 3 — Borg-Warner Model 492 Module.

If modules are to be used in cooling chambers or large components, a total surface area of virtually any size can be made by placing the appropriate number of modules side by side.

The interfaces at the cold junction and the hot junction must be constructed to transfer heat in and out of the module with little difference in temperature. Borg-Warner has done this with metal-ceramic laminate plates that give strength and permit good solder bonding between the two interfaces. The outer plate surface is usually tinned to facilitate soldering to heat sinks. Where soldering is not practical, as in the case of thermal expansion differences, heat transfer grease is recommended. Epoxy bonding agents are available where a more permanent solderless bond is required.

Just What is Cascading ?

The single-stage module is capable of pumping heat where the difference in temperature of the cold junction and the hot junction is 70°C or less; however, in those applications which require higher ΔT's the modules can be cascaded.

Cascading is a mechanical stacking of the modules so that the cold junction of one module becomes the heat sink for a smaller module placed on top (Figure 4). The practical limitation is about five stages of cascading although experimental units have been built with as many as seven stages.

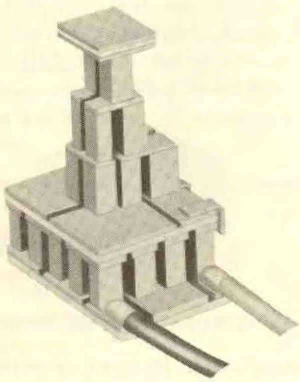


Fig. 4 — Borg-Warner Model 670 Four-Stage Cascade.

As the number of stages increases, each additional stage has a smaller temperature difference and the law of diminishing returns takes over. Practical ΔT's of approximately 125°C are possible through cascading, and as thermoelectric materials improve, further gains will be made.

Why Cool Thermoelectrically ?

Thermoelectric cooling units have many unique advantages over other types of coolers in their application area.

SIZE

They can be tailored to fit the application by easy addition or subtraction of modules to fill the need accurately and avoid waste.

POWER INPUT

Due to tailored modular construction, power requirements can be reduced to a minimum. Power is provided through a single pair of leads.

RELIABILITY

There are no parts that wear or clog, and no delicate moving parts. Gases, corrosive liquids or chemicals that will leak or dissipate with age are also eliminated. These features result in greatly reduced maintenance requirements.

LOGISTICS

There are no requirements at the load for pumping refrigerant or for a source of coolant such as liquid nitrogen to be added during operation of the system.

REMOTE CONTROL

The unit and heat sink are required in the cooling area; the power supply and most other control equipment can be mounted and operated remotely.

COOLING RANGE

Thermoelectric coolers are capable of operating from any heat-sink temperature from +100°C to −100°C.

TEMPERATURE CONTROL

Simple electronic control schemes allow control within a fraction of a degree of desired load temperatures above or below ambient.

What Extraneous Heat Sources ? Affect The Cooler

The load to be cooled should be isolated from other sources of heat in order that the thermoelectric cooler function efficiently.

Other than the load, there are three losses to consider when applying thermoelectric coolers. Each loss is weighted differently for each application.

CONDUCTION LOSSES

These losses are present in virtually every application and result from the fact that heat energy has a natural tendency to flow from the higher temperature heat sink back to the load at the cold junction. This loss is directly proportional to the temperature difference between the hot and cold junctions and to the thermal conductivity of the materials in between. Thus, at high ΔT's conduction losses increase in importance. Further, insulating materials with minimum thermal conductivity should be used. Electrical leads to the load should be optimized with regard to electrical and thermal conductivity. Losses through the structural support between the cold plate and the heat sink can be minimized by using nylon screws or low thermal conductivity metals.

CONVECTION LOSSES

These losses are caused by movement of the higher temperature air or gases across the lower temperature cold plate and are greatly reduced when the cold plate is protected from the gaseous environment by some form of insulation; insulation can take the form of polyurethane foam, inert gas, or vacuum.

Roughly, convection losses are equivalent to 1 milliwatt multiplied by the area of the cold plate in square centimeters and the temperature difference in degrees C between the cold plate and the ambient ($1 mw/cm^2$–°C).

RADIATION LOSSES

Even when conduction and convection losses have been minimized, radiation losses may still be important. They are approximately equivalent to 50 milliwatts per square centimeter, at cold-plate temperatures near −75°C in an ambient of +27°C.

Any one of the above losses can act to substantially reduce a heat pump's cooling capacity. However, in some applications it is possible to virtually eliminate two of the above losses by using a vacuum.

VACUUM OPERATION

When the devices operate in an evacuated enclosure, distinct advantages are gained including virtual elimination of convection losses. If shielding is used, radiation losses are also reduced.

To keep convection losses at a low level a vacuum better than 10^{-3} torr (one micron) is required. Borg-Warner enclosures normally have vacuums 10^{-6} torr. Vacuum units made of Kovar or glass have provisions for brazed ceramic-insulated terminals and windows such as sapphire capable of transmission in desired regions of the spectrum.

Why is a Heat Sink Necessary ?

This question sometimes arises because of a failure to remember two basic facts. First, heat is a form of energy and thus a "hot" body is simply one which has more energy than a "cold" body. Second, heat (or energy) naturally flows from a "hotter" to a "colder" region. Thus, the energy transported from the cold junction to the hot junction by the electronic carriers will naturally tend to flow back to the cold junction. A means (called a heat sink) of dissipating the energy at the hot junction to an alternate environment, which is "colder" than the hot junction, must be provided. In short, all the cooler does is move energy from the load to the heat sink where it must be dissipated to another medium. The cooler alone does not eliminate heat.

In fact, the heat-sink design is of equal importance with the design of the thermoelectric cooler. The ideal heat sink would absorb an infinite amount of heat and not change in temperature. Since this is impossible, the next best approach is to have a heat sink that will carry heat away with a minimum of temperature rise.

Heat sinks come in many forms from massive blocks of material, free and forced convection cooled fins to liquid cooling systems. The main object is to remove heat from the hot junction so that the thermoelectric system realizes maximum use of the module. Liquid cooling is often desirable, but requires tubing, a pump, and in small systems may defeat the inherent size advantage of thermoelectrics.

Forced convection is most commonly used with a finned heat sink and blower. In general it provides a heat transfer coefficient five to ten times greater than free convection. Free convection should only be used with very light loads or very small ΔT's.

In some applications having intermittent duty, a massive block of material can be used that has enough mass to absorb the required amount of heat before reaching equilibrium. This can reduce space requirements.

What Type of Power Supply is Needed

Power-supply capabilities range from the simple open-loop dc supply with a switch, to sophisticated feedback systems with close temperature regulation and fast response. Portable power supplies are made that will operate both from ac or dc power. The only limitation on the supply is that ripple be maintained at a point lower than 10-15%. Open loop systems will generally contain a transformer, rectifiers, choke, and chassis with heat sink for the rectifiers.

In feedback systems, a thermistor is used to sense temperature at the cold junction, and this signal is compared with the desired temperature setting to obtain an error signal. The amplified error signal determines the power applied to the thermoelectric cooler.

Practical Application of Thermoelectric Products

Once the decision to use a thermoelectric cooler has been made, the actual selection of suitable modules and related hardware is relatively simple. It is the function of this section to show how easy it is to specify and select for application each of the Borg-Warner thermoelectric components available.

Generally, Borg-Warner thermoelectric components are divided into two main categories: modules (in single stage and cascaded form) and heat pumps. For each category, this section provides a more complete description, including areas of application and performance curves. Consideration is given to changes in: heat load, temperature requirements, heat sink capacity, and environment temperature.

Important related equipment is also discussed, with the emphasis on: power supplies to provide the low ripple direct current required, temperature controllers to regulate input power for controlling the thermal load temperature, and useful information on heat sinks.

A set of tables provided in the final section gives thermocouple conversion constants and material properties to aid designers in obtaining pertinent information for the rapid design of thermoelectric products for specialty applications.

Borg-Warner Thermoelectric Modules

A module is simply an assembly of numerous thermoelectric couples with the required electric bus bars, leads, and heat transfer plates at the hot and cold junctions. Borg-Warner was the first to use the highly efficient alumina ceramic plates for heat transfer. Modules are generally available in two forms: single stage and cascade.

SINGLE-STAGE MODULE

Several of the many single-stage coolers available from Borg-Warner Thermoelectrics are shown in Figure 5. Each unit may also be used as an efficient heater by reversing polarity.

Model No.	492	837	840
Suggested Cooling Applications	Electronic Components	Battery Powered for Electronic Components	Dew Point Indicator
Heat Sink Required at +27°C	2.8 watts plus load	1.75 watts plus load	3.4 watts plus load
Input Power	3.5 amps at 0.8 volts	1.75 amps at 1 volt	1.0 amps at 3.4 volts
Load De-Rating °C Per Milliwatt	.025°C	.066°C	.021°C
Cold and Hot Plate Mounting Surface (in. x in.) respectively	0.50 × 0.50 0.50 × 0.60	0.25 × 0.25 0.35 × 0.25	0.53 × 0.53 0.53 × 0.60
Height (in.)	0.35	0.16	0.19

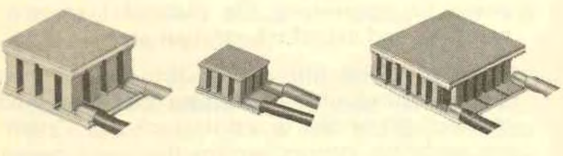


Fig. 5 — Typical Single-Stage Borg-Warner Thermoelectric Coolers.

There are two modes of operation which characterize module performance: operation at maximum heat pumping capacity (Q_c), and operation at maximum coefficient of performance (COP).

The latter term is used by refrigeration engineers to measure the efficiency of the cooling process. COP, which generally ranges from 0.1 to 1.0 for thermoelectric cooling applications, is the ratio of the amount of heat absorbed by the cold face of a module to the electrical power supplied.

The important parameters for establishing module performance are total heat load, module current and voltage, required cold-side temperature, hot-side ambient temperature and COP.

The graphs shown in Figures 6a and 6b illustrate the graphical relationship among these parameters for the Borg-Warner module model number 920 at 27°C hot junction. Similar curves for other modules and other hot-junction temperatures are also available. To illustrate the utility of such curves consider the following example problem:

A user wishes to select a module for use as a diode cooler. Required operating temperature of the diode is —8°C and the hot-junction temperature can be maintained at +27°C. The module required must pump a total heat load of 6.0 watts from the diode and surrounding environment.

In Figure 6b, draw a horizontal line through the $\Delta T = 8+27 = 35°C$ point and a vertical line through $Q_c = 6$ watts. At the point of intersection read COP=0.5 and I=5 amperes.

Notice that the COP curve is relatively flat in this region and that Q_c and I may be varied somewhat without appreciably affecting COP. The power supply voltage is now easily selected.

In Figure 6a, draw a vertical line through I=5 amps to a point halfway between ΔT_{max} (70° from Figure 6b) and $\Delta T=0$; then project a horizontal line to the voltage axis and read 2.35 volts.

A heat load of 60 watts at the same $\Delta T=35$ °C and I=5 amps could be cooled by using 10 modules in parallel thermally and series electrically with a power supply of 23.5 volts (10 modules × 2.35 volts/module).

Borg-Warner has available performance curves on modules at temperatures other than 27°C. However, these curves can be constructed by considering that the load line intersections on the ΔT and Q_c axes change by approximately $+\frac{1}{2}\%$ per degree centigrade increase in hot-junction temperature.

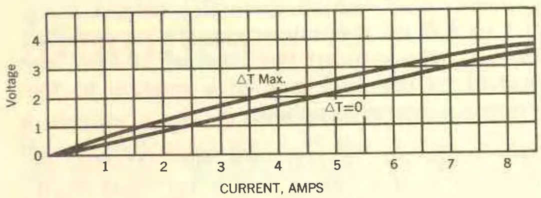


Fig. 6a — Module Voltage.

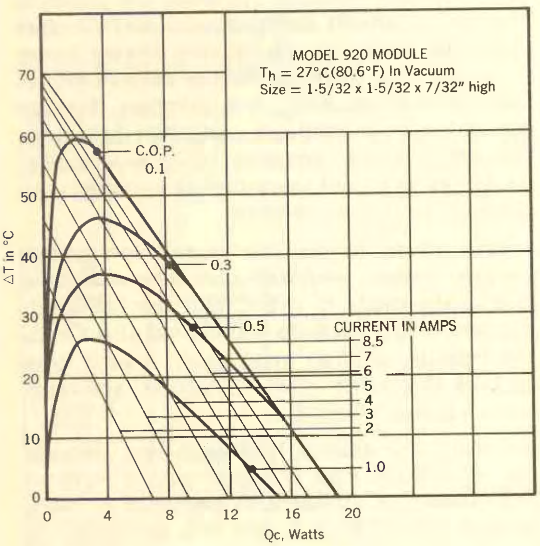


Fig. 6b — Module ΔT vs. Module Heat Pumping Capacity for Various COP and Current Values.

CASCADED MODULE

In general, cascaded modules are used where the desired low temperatures cannot be reached with a single-stage module. Borg-Warner's cascade design provides the largest temperature differential with a small package using a minimum of electrical power.

Typical performance for several of Borg-Warner's cascaded modules is illustrated in Figures 7a-7e. In these cascaded units, the component to be cooled may be bonded directly to the top plate, while the base will accommodate the direct attachment of fins or other heat-sink devices. The cascades illustrated have been designed to cool infrared detectors; however, cascades of much higher capacity are available.

The performance curves in Figures 7a-7d illustrate module capability with and without a vacuum at a heat-sink temperature of +27°C. Since the cold-surface temperature is much colder than the ambient temperature, caution must be taken to insulate the cold surface from extraneous heat loads (generally radiation and convection from the surrounding ambient).

Borg-Warner engineers recommend encapsulating cascade modules in vacuum packages where feasible. Vacuum packages available from Borg-Warner are completely guaranteed for one year. Almost any number of feed-through terminals can be provided for the leads to the cooled components, thermocouples, and thermistors.

Performance of high efficiency cascades in ambients other than in a vacuum is difficult to predict accurately since the cold-side temperature varies greatly with the air density, ambient temperature, relative humidity, frost load, and convective air currents. Performance of a cascaded thermoelectric device is substantially decreased by operation in dry nitrogen or dry air at atmospheric pressure due to convection.

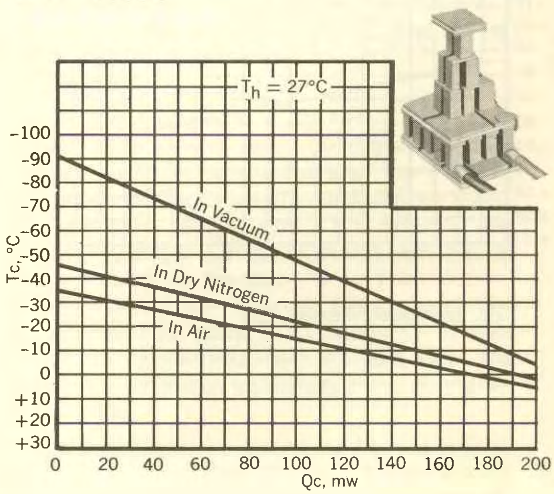


Fig. 7a — Model Number 670 .

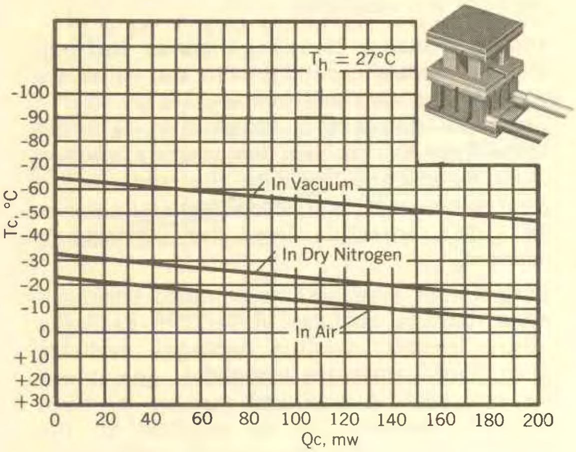


Fig. 7b — Model Number 447.

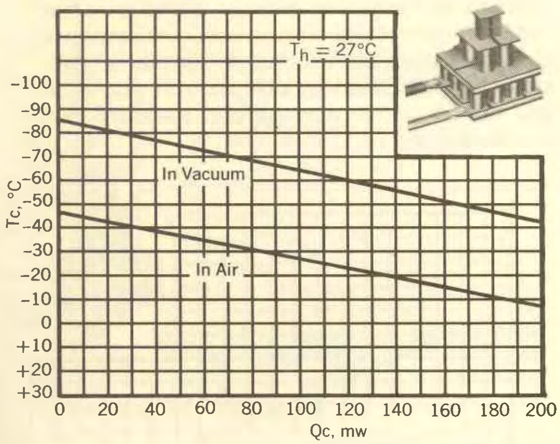


Fig. 7c — Model Number 623.

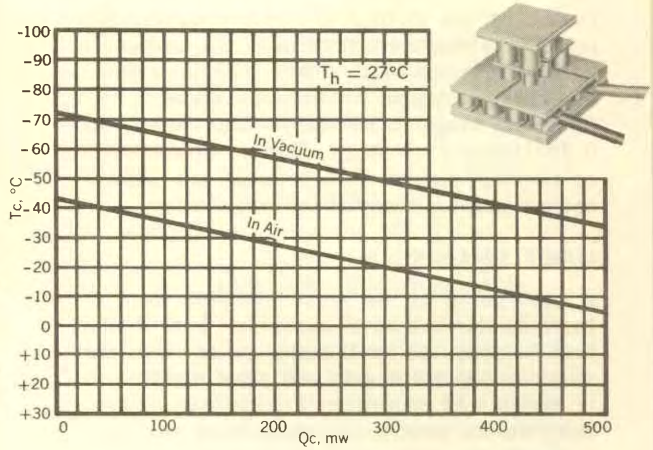


Fig. 7d — Model Number 724 .

Model Number	670	447	623	724
Suggested Cooling Applications	Small Area Infrared Detector Arrays	Dew Point Indicator	Large Area Infrared Detectors	Immersed Lens Infrared Detectors
Heat Sink Required at +27°C	5.4 watts plus load	3.85 watts plus load	7.2 watts plus load	12 watts plus load
Input Power	4.5 amps at 1.2 volts	3.5 amps at 1.1 volts	8.0 amps at 0.9 volts	12 amps at 1.0 volt
No load Cold Plate Temp.	-90°C	-65°C	-86°C	-72°C
Load De-rating °C per milliwatt	0.40	0.09	0.23	0.07
Cold and Hot Plate Mounting Surface (in. × in.) Respectively	0.25 × 0.25 0.50 × 0.80	0.50 × 0.50 0.50 × 0.60	0.12 × 0.22 0.60 × 0.60	0.50 × 0.50 0.80 × 0.80
Height (in.)	Four Stage 0.96	Two Stage 0.57	Three Stage 0.67	Three Stage 0.65

Fig. 7e — Typical Performance Data on Borg-Warner Thermoelectric Cascade Coolers.

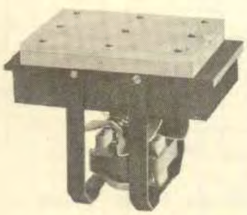
Performance curves such as those given in Figures 7a-7d readily determine the cascade model needed for a specific application. Select the cold-side temperature (T_c) desired and draw a horizontal line from the selected T_c to the load curve. At the point of the intersection, draw a vertical line down to the Q_c axis. The Q_c value at this point is the quantity of heat which can be pumped from the cold side. The known and unknown quantities may, of course, be reversed .

In the event that the operating heat-sink temperature is other than 27°C, a correction for the cold-junction temperature is necessary.

Generally, the change in the unloaded cold-junction temperature relative to the change in heat-sink temperature from +27°C is 0.60 degrees per degree for a single stage, 0.48° for a two stage, 0.32° for a three stage and 0.25° for a four stage. Specific information concerning temperature effects on loaded coolers can be provided by Borg-Warner.

HEAT PUMPS

A heat pump is the most complete form of thermoelectric device available, and if the form is practical for the application, it is the most convenient one to use since installation is simple. As shown in Figure 8, a typical Borg-Warner heat pump consists of: the thermoelectric modules, a ground flat cold plate common to all the modules absorbing heat from the load, and a common forced-air cooled fin-fan assembly for removing heat from the module hot side to the ambient air used as a heat sink. Free convection air-cooled fins or a liquid-cooled sink may be used as alternatives. Heat pumps of the form shown are generally used to cool loads in the 10 to 200 watt range with typical temperature differentials of 30°C.



Borg-Warner Model 1010. Power requirements are 115 volts AC for the fan and 25 volts, 6.5 amperes DC for the thermoelectric assembly.

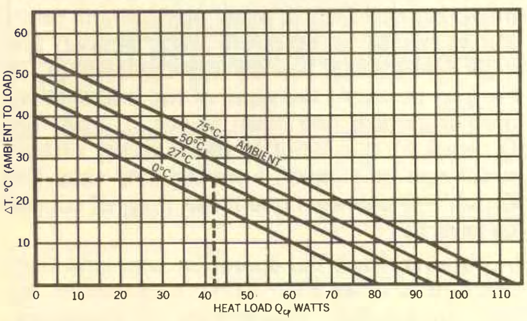


Fig. 8 — Performance of Borg-Warner Model 1010 Heat Pump.

Typical performance curves shown in Figure 8 are easy to use. The temperature differential between the ambient air and the load is plotted as a function of the thermal load for various ambient temperatures. The given fixed recommended current is the largest current that will allow the fin or fin-fan assembly to efficiently transfer the heat from the hot side of the module to the ambient air. A lower current will provide a more efficient heat sink but will reduce the ΔT and Q_c obtainable.

The total load to be considered consists of the actual load to be cooled and any losses due to leakage through the heat pump insulation, mounting assembly, or exposure to ambient. The leakage through the heat pump insulation and assembly is already taken into account in the performance curves.

An application of the performance curves is given in the following example problem:

Select a Borg-Warner heat pump that will provide a +2°C environment for an insulated chamber and also be capable of cooling a 1 lb sample of blood contained in a 0.4 lb stainless steel container from +27°C to +2°C in thirty minutes. The insulated chamber is shown in Figure 9. Assume the following: ambient air is at 27°C; the blood has thermal properties similar to those of water; the thermal resistance of the inside and outside chamber shell is negligible.

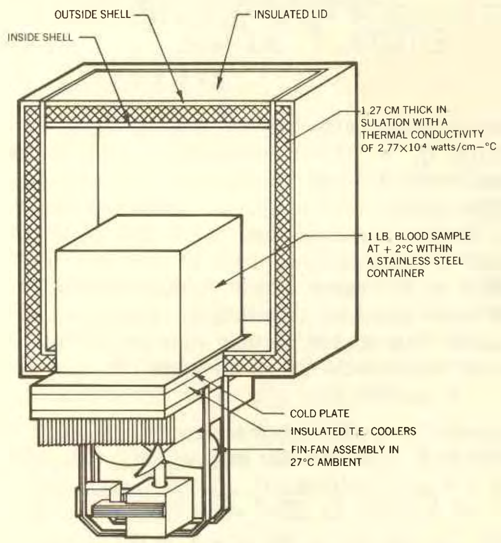


Fig. 9 — Insulated Chamber for Storing Blood Samples.

The performance curve of Borg-Warner model 1010 heat pump in Figure 8 may be used to determine the allowable load Q_c. Subtract the desired chamber temperature (+2°C) from the ambient temperature (27°C). Extend a horizontal line from the $\Delta T=25°C$ point to the 27°C ambient curve. At the point of intersection, extend a vertical line down to the Q_c axis and read $Q_c=42$ watts.

This value is the maximum heat load that can be pumped for the given ΔT and ambient conditions. Next, to determine if the given heat pump will be satisfactory without modifications, find the actual heat load on the chamber.

The actual load Q_c, is composed of two main parts: the steady-state heat leakage through the insulated chamber Q_i; the transient heat load consisting of reducing the temperature of the blood Q_b and the stainless steel container Q_{SS}. The section on **Heat Sinks** will be useful in determining Q_i, Q_b and Q_{SS} in Figure 9. Determine Q_i from Equation (1) on page 30 in the **Heat Sinks** section. This calculation accounts for the combined conduction through the insulation and convection at the outside surface. Assume h=5.0 BTU/hr-ft^2–°F=28.4 × 10^{-4} watts/cm^2–°C. Substituting in Equation (1) gives:

$$\frac{Q_i}{A} = \frac{25}{\frac{1.27}{2.77\times10^{-4}} + \frac{1}{28.4\times10^{-4}}} = .00506 \text{ watts/cm}^2$$

The external area of the box is 2800 cm^2. Thus, Q_i = .00506 (2800) = 14.2 watts. Next use Figure 15 to find Q_b and Q_{SS}. This shows the heat transfer required to cool or heat a pound of material in one hour. Extend a vertical line from the ΔT = 45°F point to the water and stainless steel curves. At each point of intersection, extend a horizontal line to the vertical axis and read for each substance: Q_b = 13 watts/lb and Q_{ss} = 1.5 watt/lb.

Hence, for a cool-down time of thirty minutes and 1 lb and 0.4 lb respectively, calculate:

$$Q_b = 13 \times 1 \times \frac{60}{30} = 26 \text{ watts and}$$

$$Q_{ss} = 1.5 \times \frac{4}{10} \times \frac{60}{30} = 1.2 \text{ watts.}$$

The total power of 27.2 watts is that capacity required if a constant value of heat flow is removed during the thirty minute cool-down time. However, as explained in the section **Heat Sinks,** the thermoelectric heat pump does not pump a constant heat load during cool-down due to the changing load temperature. Instead, its heat pumping capability during cool-down is more accurately stated as that at a median temperature difference:

$\Delta T = \frac{1}{2}$(Initial ΔT + Final ΔT). In this case, the cool-down capacity of the 1010 heat pump is 68 watts at ΔT = 12.5°C.

Thus, the 1010 heat pump meets both the requirements of 27.2 watts cool-down transient and 14.2 watts steady-state load. When the actual load is much smaller than the heat pump capability the operating current can be reduced providing a higher COP or a smaller unit selected.

Power Supply and Temperature Control

POWER SUPPLY

The largest component in a thermoelectric cooling system usually is the power supply. Its function is to convert the available ac (normally 120v, 60 cycle) to the dc required by the module. Design currents for a system may run from 1 to 100 amperes and voltages from 0.1 to 100 volts. Maximum cooling capacity of the module is attained when the ripple in the dc is less than 10%.

Figure 10 illustrates the effect of dc ripple on the temperature difference a single-stage module may attain. The vertical axis is a ratio of the temperature difference attained with ripple (and $Q_c = 0$) to the maximum ΔT which occurs for Q_c = 0 and zero ripple.

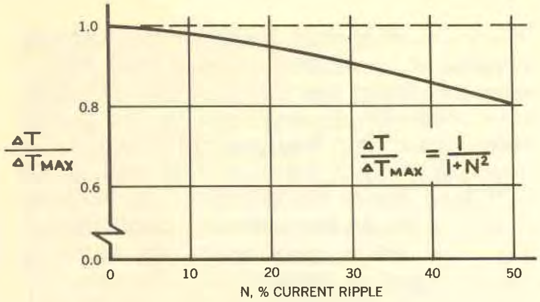


Fig. 10 — Current Ripple Effect on Temperature Differential.

Figure 11 shows the minimum inductance L, required to attain 10% ripple as a function of the thermoelectric resistance for a full-wave power supply at 60 and 400 cps line frequency.

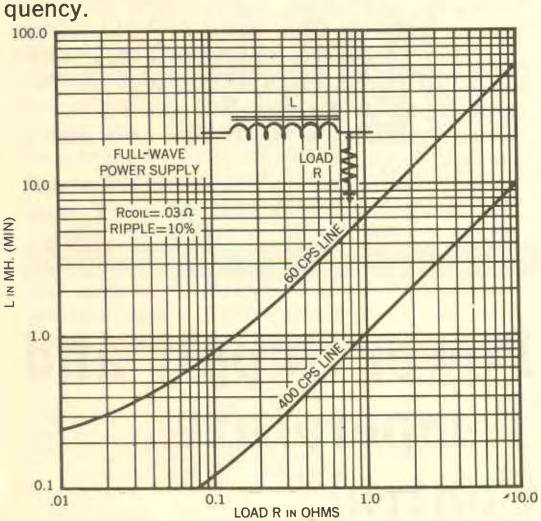


Fig. 11 — Minimum Inductance Versus Load Resistance for 10% Ripple with a Full-Wave Power Supply.

The power supply circuits take several forms depending on the application.
Figure 12, for example, shows one of the simplest power supplies, a typical full-wave center-tap rectifier circuit with a choke-input filter supplying a thermoelectric load.

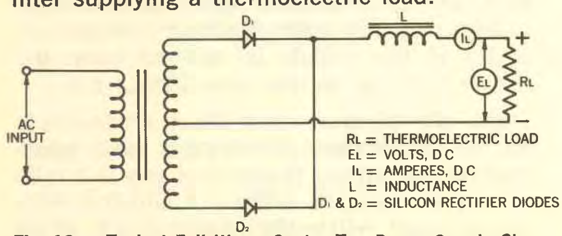
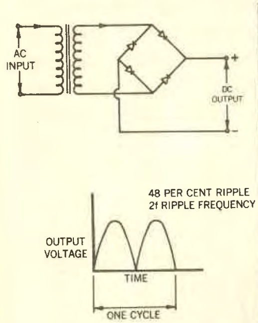


Fig. 12 — Typical Full-Wave, Center-Tap Power Supply Circuit with Choke-Input Filter.

The full-wave center tap is an efficient and economical circuit to use for single-phase ac to dc conversion for low-voltage thermoelectric devices. The full-wave bridge circuit (Figure 13a) is at a disadvantage because it requires four rectifiers instead of two and the two rectifiers in series cause a greater power loss.

However, the bridge circuit has the advantage in higher voltage applications. The inverse voltage of the rectifiers is only half that of rectifiers in the full-wave circuit due to the series elements. The bridge transformer is smaller due to sinusoidal secondary currents and lower voltage.

Figures 13a and 13b show two basic full-wave bridge-rectifier circuits for single and three-phase ac inputs respectively. Notice that the three-phase full-wave bridge rectifier does not require filtering since the theoretical output ripple is already less than 10%.



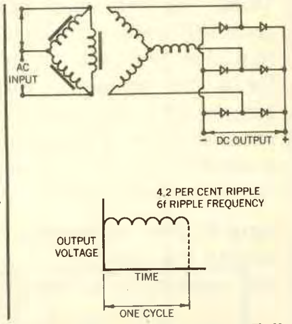


Fig. 13a — Single-Phase Full-Wave Bridge Rectifier Circuit.

Fig. 13b — Three-Phase Full-Wave Bridge Rectifier Circuit.

The cost of a thermoelectric power supply will depend primarily on the amount of output power it must produce because transformers, chokes, rectifiers, and capacitors must be sized accordingly. Borg-Warner engineers can recommend a power supply to provide a most efficient thermoelectric system.

TEMPERATURE CONTROL

After the thermoelectric device and power supply have been selected, the question of controlling the device performance will probably arise. Methods of control are basically divided into two main categories: manual and automatic. These are sometimes referred to as open-loop control and closed-loop control respectively. In either method, the device parameter which is easiest to detect and measure is the temperature (or its voltage equivalent). Thus, the cold-junction temperature (or hot-junction temperature for a heater) is used as the basis for control. A reference temperature is established in either basic method. The cold-junction temperature is compared to the reference temperature, the difference being referred to as the error.

In the open-loop method, an operator manually adjusts the power supply to reduce the error to zero, while in the closed-loop method, various electrical circuits are connected to the power supply so the error is automatically reduced to zero.

The various types of control circuits are too numerous to discuss here. Basic elements range from a simple thermocouple and potentiometer or thermostatic switches to sophisticated thermistor bridge control circuits utilizing transistors and a differential amplifier.

Thus, the degree of control and consequent cost will vary considerably with the application. For instance, the control circuit needed for a thermoelectric refrigerator is relatively simple while the precise temperature control necessary for a thermoelectric dew-point hygrometer requires a very sophisticated and costly control circuit.

Borg-Warner engineers will assist you in selecting the most efficient and economical control system for your application.

Heat Sinks

The design of the heat sink or heat exchanger is a very important aspect of a good thermoelectric system.

Figure 14 illustrates the steady-state temperature profile across a typical thermoelectric device from the load side to the ambient.

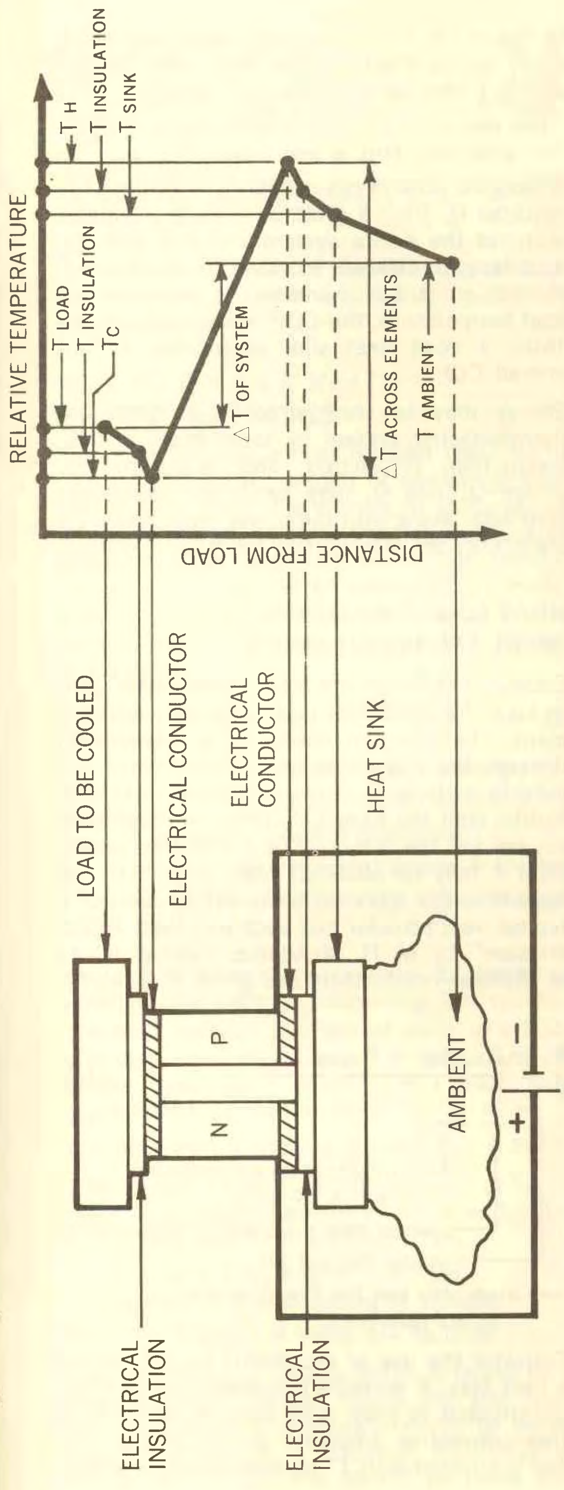


Fig. 14 — Typical Temperature Relationship in a Thermoelectric Cooler.

In Figure 14, the total steady-state heat which must be rejected by the heat sink to the ambient may be expressed as follows:

heat rejected (Q_s) = heat absorbed from load (Q_c) + power input (V•I) + heat leakage (Q_l)

If the heat sink is not capable of rejecting the required Q_s from a given system, the temperature of the entire system will rise and the load temperature will increase. If the thermoelectric current is increased to maintain the load temperature, the COP tends to decrease. Thus, a good heat sink contributes to improved COP.

Energy may be transferred to or from the thermoelectric system by three basic modes: conduction, convection, and radiation. The values Q_c and Q_l may easily be estimated; their total along with the power input gives Q_s, the energy the hot-junction fin must dissipate.

HEAT GAIN OR LOSS WITH INSULATED CONTAINER

Equation (1) shows the total steady-state gain or loss of a conductor in a convective environment. The equation accounts for conduction through the conductor and convection at the outside surface. If convection effects are negligible, omit the term 1/h. Order of magnitude values for the average heat-transfer coefficient h may be obtained from Table I in the appendix. For more accurate values consult a typical heat transfer text such as "Heat Transmission" by W. H. McAdams. Typical values of thermal conductivity are given in Table 7.

$$\frac{Q}{A} = \frac{T_{ambient} - T_{inside}}{\frac{\Delta x}{k} + \frac{1}{h}} \qquad (1)$$

h — average heat-transfer coefficient (BTU/hr-ft^2-°F)
k — average thermal conductivity (BTU/hr-ft-°F)
Δx — conductor thickness (ft)
Q/A — steady state heat flux through exterior surface (BTU/hr-ft^2)

Consider the use of equation (1) in calculating a heat loss. A portable insulated case is to be constructed to keep drug samples at 60°F in free-convective ambients up to 110°F. The box is covered with 1" of foamed polyurethane

(k = .02 BTU/hr-ft-°F). The external area is .7ft^2. From Table 1 assume h = 1 BTU/hr-ft^2-°F; this will yield a conservative estimate. Thus,

$$Q_1 = \frac{.7\ (110\text{-}60)}{\left(\frac{1}{12}\right)\left(\frac{1}{.02}\right)+\left(\frac{1}{1}\right)} = \frac{35}{5.17} = 6.77\ \text{BTU/ hr} = 1.98\ \text{watts}$$

The module(s) must be capable of pumping this heat loss in addition to the Q_c load from the drug samples.

TIME TO COOL OR HEAT VARIOUS MATERIALS

Figure 15 shows the heat transfer required to cool or heat a given weight of known material in one hour without a change of state. When a change of state occurs (freezing, melting or vaporizing) the additional heating or cooling capacity required can be estimated by multiplying the weight of the given material by the appropriate latent heat. The equation plotted in Figure 15 is:

$$Q\ \Delta t = m\ C_p\ \Delta T \qquad (2)$$

ΔT — required temperature change (°F)
C_p — average specific heat (BTU/lb-°F)
m — weight of material (lbs)
Δt — time interval (assume = to 1 hour)
Q — heat removed or supplied (BTU/hr)

Using this formula, it is easy to design a photographic bath for processing film rapidly. The bath consists of 2 lbs of water in a 1 lb stainless steel container. The bath must be cooled from 110°F to 60°F in 1 hour. How much heat must be removed?

The temperature change is (110-60) = 50°F.

Enter Figure 15 on the horizontal axis at 50°F. Move vertically to the stainless steel and water curves and read on the vertical axis:

15 watts/lb × 2 lbs of water = 30 watts
1.6 watts/lb × 1 lb of stainless = 1.6 watts

Thus, for 1 hr, 31.6 watts are required.

The time provided by this graph is based on a constant heat transfer during the one hour period. Actually, a thermoelectric cooler would not pump heat at a constant level due to change in ΔT and this should be taken into account in a design. An effective heat pumping capacity of a thermoelectric cooler can be **estimated** as the heat pumping capacity at a temperature difference equal to one-half of the final operating ΔT (usually, initial ΔT = 0). Borg-Warner can provide assistance in more accurate transient design.

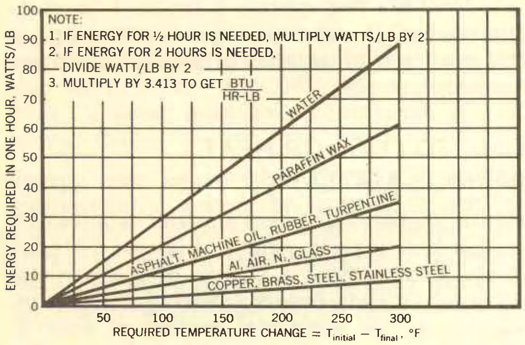


Fig. 15 — Energy to be Added or Removed Thermoelectrically in One Hour for Various Materials.

HEAT TRANSFERRED TO OR FROM A SURFACE BY CONVECTION WITH AN AMBIENT ENVIRONMENT

Equation (3), which applies to a liquid or gas, is the basic relationship used for forced or free convective heat transfer. This equation proves very useful in estimating the area of the hot-junction fin required to dissipate Q_s.

$$Q = hA_s\,(T_{surface} - T_{ambient}) \qquad (3)$$

- A_s — surface area, ft²
- h — heat-transfer coefficient, BTU/ hr-ft²-°F
- Q — heat transferred, BTU/hr

The utility of equation (3) can be illustrated by using two examples. Suppose the water and stainless steel container are placed in the insulated enclosure discussed in illustrating equation (1). Assume that 70 watts of electrical power must be supplied to the thermoelectric system. Then the energy the hot-junction fin must dissipate is:

$$Q_s = Q_c + Q_1 + \text{power input} \qquad (4)$$

$$31.6 + 1.98 + 70 = 103.6 \text{ watts} = 354 \text{ BTU/hr.}$$

Substituting equation 4 into equation 3 and solving for the required surface area gives:

$$A_s = \frac{354}{h(T_{surface} - 110)} \qquad (5)$$

In equation (5), one must fix $T_{surface}$ and h in order to determine A_s. Obviously, the actual choice of $T_{surface}$ and h will vary widely with the design application and discretion of the designer; hence, a rigid rule for their selection is not given. But generally, it is desirable to select $T_{surface}$ within 25°F of $T_{ambient}$. In this case, let us assume $T_{surface}$ = 125°F. Then equation (5) becomes:

$$A_s = \frac{354}{h(125\text{-}110)} = \frac{23.6}{h} \qquad (6)$$

From the h values in Table 1 in the appendix it is apparent that if one chooses a forced, convection coefficient h=10 BTU/hr-ft²-°F, then A_s = 2.36 ft². The designer must now design a fin with about 2.36 ft² of surface area and select a fan and duct system to move air past the surface area at a rate sufficient to give an h of about 10 BTU/hr-ft²-°F.

It is not within the scope of this booklet to discuss the actual fin design and detailed calculations for h. A picture of a typical Borg-Warner heat sink designed for forced convection in air is shown in Figure 8.

In relationship to the above discussion, Table 2 in the appendix is useful for estimating surface-area requirements for various ΔT and h combinations. Table 2 is a tabulation of equation (3) for 1 watt.

APPLICATION ASSISTANCE

From the above discussions, the designer realizes that a knowledge of several engineering areas may be necessary to design some thermoelectric systems. Borg-Warner engineers can provide expert application assistance if the problem is properly defined. Borg-Warner engineers will first be interested in knowing as much about the system operation as possible, including specifications such as:

a. load temperature
b. heat-sink temperature
c. ambient conditions
d. type of heat load
e. heat-sink configuration and type

of heat transfer

f. coefficient of performance desired

g. special requirements on transients, temperature stability, power supply, space, and weight.

With this information Borg-Warner engineers can rapidly fill your needs and provide the most efficient standard or customized unit tailored to your application.

TRY US!

Appendix

TABLE INDEX

TABLE 1

HEAT TRANSFER COEFFICIENT h — ORDER OF MAGNITUDE

Situation	h(BTU/ hr-ft^2-°F)	h(watts/cm^2-°C)
Free Convection		
Gases	1-5	$5.68 \times 10^{-4} - 28.4 \times 10^{-4}$
Liquids	20-120	$114 \times 10^{-4} - 682 \times 10^{-4}$
Boiling Water	200-4000	.114 – 2.27
Forced Convection		
Gases	2-20	$11.4 \times 10^{-4} - 114 \times 10^{-4}$
Viscous Fluids (oil, etc.)	10-100	$56.8 \times 10^{-4} - 568 \times 10^{-4}$
Water	100-2000	568×10^{-4} – 1.14
Condensing Vapors	200-20,000	.114 – 11.4

TABLE 2

SURFACE AREA IN IN^2 TO DISSIPATE 1 WATT OF HEAT FOR VARIOUS h AND ΔT VALUES

h—BTU/ hr-ft^2-°F	ΔT, °F					
	5	10	15	20	25	30
1	98.3	49.2	32.8	24.6	19.7	16.4
5	19.7	9.83	6.55	4.92	3.93	3.28
10	9.83	4.92	3.28	2.46	1.97	1.64
20	4.92	2.46	1.64	1.23	.983	.819
50	1.97	.983	.655	.492	.393	.328
100	.983	.492	.328	.246	.197	.164
200	.492	.246	.164	.123	.0983	.0819

Note: Multiply table value by actual watts for other than 1 watt.

TABLE 3

TEMPERATURE CONVERSION TABLES

Tables 3a and 3b allow the conversion of a Centigrade temperature to Fahrenheit and vice-versa. Because the magnitude of 1°C equals 1.8°F and +32°F corresponds to 0°C an addition or subtraction of 32 is necessary in each table. If the decimal point is moved in the index, it must be moved the same number of positions in the same direction in the body of the tables.

3a. Centigrade to Fahrenheit: °F = 1.8°C + 32
(Add +32 to table value after using)

DEGREES CENTIGRADE

	0	1	2	3	4	5	6	7	8	9
0	0	1.8	3.6	5.4	7.2	9.0	10.8	12.6	14.4	16.2
1	18.0	19.8	21.6	23.4	25.2	27.0	28.8	30.6	32.4	34.2
2	36.0	37.8	39.6	41.4	43.2	45.0	46.8	48.6	50.4	52.2
3	54.0	55.8	57.6	59.4	61.2	63.0	64.8	66.6	68.4	70.2
4	72.0	73.8	75.6	77.4	79.2	81.0	82.8	84.6	86.4	88.2
5	90.0	91.8	93.6	95.4	97.2	99.0	100.8	102.6	104.4	106.2
6	108.0	109.8	111.6	113.4	115.2	117.0	118.8	120.6	122.4	124.2
7	126.0	127.8	129.6	131.4	133.2	135.0	136.8	138.6	140.4	142.2
8	144.0	145.8	147.6	149.4	151.2	153.0	154.8	156.6	158.4	160.2
9	162.0	163.8	165.6	167.4	169.2	171.0	172.8	174.6	176.4	178.2

Example: (a) Convert 10°C to °F
From Table 10°C = 18 + 32 = 50°F
(b) Convert 106.5°C to °F
From Table at 10°C move decimal one place to right and read 180. At 6°C read 10.8. Interpolating read .5°C = .9. Thus 106.5°C = 180 + 10.8 + .9 + 32 = 223.7°F.

3b. Fahrenheit to Centigrade: $°C = \left(\frac{°F - 32}{1.8}\right)$
(Subtract +32 before using)

DEGREES FAHRENHEIT

	0	1	2	3	4	5	6	7	8	9
0	.0000	.5556	1.1111	1.6667	2.2222	2.7778	3.3333	3.8889	4.4444	5.0000
1	5.5556	6.1111	6.6667	7.2222	7.7778	8.3333	8.8889	9.4444	10.0000	10.5556
2	11.1111	11.6667	12.2222	12.7778	13.3333	13.8889	14.4444	15.0000	15.5556	16.1111
3	16.6667	17.2222	17.7778	18.3333	18.8889	19.4444	20.0000	20.5556	21.1111	21.6667
4	22.2222	22.7778	23.3333	23.8889	24.4444	25.0000	25.5556	26.1111	26.6667	27.2222
5	27.7778	28.3333	28.8889	29.4444	30.0000	30.5556	31.1111	31.6667	32.2222	32.7778
6	33.3333	33.8889	34.4444	35.0000	35.5556	36.1111	36.6667	37.2222	37.7778	38.3333
7	38.8889	39.4444	40.0000	40.5556	41.1111	41.6667	42.2222	42.7778	43.3333	43.8889
8	44.4444	45.0000	45.5556	46.1111	46.6667	47.2222	47.7778	48.3333	48.8889	49.4444
9	50.0000	50.5556	51.1111	51.6667	52.2222	52.7778	53.3333	53.8889	54.4444	55.0000

Example: Convert −65°F to °C.
Subtract 32°F first to get an index of −97. Then read at index of −97, −53.8889. Thus, −65°F = −53.89°C.

TABLE 4

CONSTANTS AND CONVERSION FACTORS RELATING METRIC AND BRITISH UNITS

Constants

$e = 2.71828$

$\pi = 3.14159$

$\ln(x) = 2.3 \log_{10}(x)$

Mechanical equivalent of heat

$J = 4.18 \times 10^7$ erg/cal $= 778.16$ ft-lb/BTU

Acceleration of gravity

$g = 32.17$ ft/sec^2

980.67 cm/sec^2

4.17×10^8 ft/hr^2

Universal Gas Constant

$R_u = 1544$ ft-lb/lb-mole-°R

8314 kg — m^2/sec^2

Conversion Factors

	Multiply	by	To Obtain
Density	lb/in^3	27.68	g/cm^3
	g/cm^3	62.43	lb/ft^3
	g/cm^3	1.00	specific gravity at 4°C
	Specific Gravity	62.40	lb/ft^3 at 60°F
Pressure	lb/in^2	2.31	ft of water at 60°F
	lb/in^2	0.0703	kg/cm^2
	lb/in^2	2.04	in Hg at 32°F
	lb/in^2	27.81	in water at 60°F
	lb/in^2	51.71	mm Hg at 32°F
	atmosphere (atm)	14.69	lb/in^2
	g/cm^2	0.01422	lb/in^2
	micron	1.9×10^{-5}	lb/in^2
	1 mm Hg	1.00	torr
Energy	British Thermal Unit (BTU)	252.00	calories (cal)
	BTU	778.00	ft-lb
	BTU	107.60	kg-m
	BTU	1055.00	Joules
	BTU	0.252	kg-cal

Conversion Factors

	Multiply	by	To Obtain
Length	inch (in)	2.54	centimeter(cm)
	meter (m)	39.37	in
	feet (ft)	30.48	cm
	mile	1.61	kilometer (km)
Area	in^2	6.45	cm^2
	ft^2	0.0929	m^2
	(mile)^2	2.59	km^2
Volume	in^3	16.39	cm^3
	ft^3	0.028	m^3
	ft^3	7.48	gallon (gal)
	ft^3	28.32	liters
	gal (U.S.)	3.79	liters
	gal (U.S.)	231.00	in^3
Mass	gram (g)	15.43	grains
	g	0.035	ounce (oz)
	pound (lb)	453.59	g
	lb	0.454	kg

	Multiply	by	To Obtain
Energy	BTU/min	12.97	ft-lb/sec
	BTU/min	0.02358	hp
	BTU/min	0.01758	kw
	BTU/lb-°F	1.00	g-cal/g-°C
	g-cal	4.186	Joules
	g-cm	980.60	erg
	horsepower (hp)	0.746	kw
	Joules	$1. \times 10^7$	ergs
	kw	3413.00	BTU/hr
Thermal Conductivity	BTU/hr-ft^2-°F/in	12.40	kg-cal/hr-m^2-°C/cm
	BTU/hr-ft-°F	0.0173	w/cm-°C
	g-cal/cm-sec-°C	242.00	BTU/hr-ft-°F
Heat Transfer Coefficient	BTU/hr-ft^2-°F	5.68×10^{-4}	w/cm^2-°C
	BTU/hr-ft^2-°F	1.36×10^{-4}	g-cal/cm^2-sec-°C
	BTU/hr-ft^2-°F	4.88	kg-cal/hr-m^2-°C

TABLE 5 THERMOCOUPLE CONVERSION TABLES FOR COPPER - CONSTANTAN

COPPER vs. CONSTANTAN THERMOCOUPLE

Degrees Centigrade — Reference Junction 0° C.

°C	0	1	2	3	4	5	6	7	8	9
					Millivolts					
-150	-4.603	-4.625	-4.647	-4.669	-4.690	-4.712	-4.733	-4.754	-4.775	-4.796
-140	-4.377	-4.400	-4.423	-4.446	-4.469	-4.492	-4.514	-4.537	-4.559	-4.581
-130	-4.138	-4.162	-4.187	-4.211	-4.235	-4.259	-4.283	-4.307	-4.330	-4.354
-120	-3.887	-3.912	-3.938	-3.964	-3.989	-4.014	-4.039	-4.064	-4.089	-4.114
-110	-3.624	-3.651	-3.678	-3.704	-3.730	-3.757	-3.783	-3.809	-3.835	-3.861
-100	-3.349	-3.377	-3.405	-3.432	-3.460	-3.488	-3.515	-3.542	-3.570	-3.597
-90	-3.062	-3.091	-3.120	-3.149	-3.178	-3.207	-3.235	-3.264	-3.292	-3.320
-80	-2.764	-2.794	-2.824	-2.854	-2.884	-2.914	-2.944	-2.974	-3.003	-3.033
-70	-2.455	-2.486	-2.518	-2.549	-2.580	-2.611	-2.642	-2.672	-2.703	-2.733
-60	-2.135	-2.167	-2.200	-2.232	-2.264	-2.296	-2.328	-2.360	-2.392	-2.423
-50	-1.804	-1.838	-1.871	-1.905	-1.938	-1.971	-2.004	-2.037	-2.070	-2.103
-40	-1.463	-1.498	-1.532	-1.567	-1.601	-1.635	-1.669	-1.703	-1.737	-1.771
-30	-1.112	-1.148	-1.183	-1.218	-1.254	-1.289	-1.324	-1.359	-1.394	-1.429
-20	-0.751	-0.788	-0.824	-0.860	-0.897	-0.933	-0.969	-1.005	-1.041	-1.076
-10	-0.380	-0.417	-0.455	-0.492	-0.530	-0.567	-0.604	-0.641	-0.678	-0.714
(-)0	0.000	-0.038	-0.077	-0.115	-0.153	-0.191	-0.229	-0.267	-0.305	-0.343
(+)0	0.000	0.038	0.077	0.116	0.154	0.193	0.232	0.271	0.311	0.350
10	0.389	0.429	0.468	0.508	0.547	0.587	0.627	0.667	0.707	0.747
20	0.787	0.827	0.868	0.908	0.949	0.990	1.030	1.071	1.112	1.153
30	1.194	1.235	1.277	1.318	1.360	1.401	1.443	1.485	1.526	1.568
40	1.610	1.652	1.694	1.737	1.779	1.821	1.864	1.907	1.949	1.992
50	2.035	2.078	2.121	2.164	2.207	2.250	2.293	2.336	2.380	2.423
60	2.467	2.511	2.555	2.599	2.643	2.687	2.731	2.775	2.820	2.864
70	2.908	2.953	2.997	3.042	3.087	3.132	3.177	3.222	3.267	3.312
80	3.357	3.402	3.448	3.493	3.539	3.584	3.630	3.676	3.722	3.767
90	3.813	3.859	3.906	3.952	3.998	4.044	4.091	4.138	4.184	4.230
100	4.277	4.324	4.371	4.418	4.465	4.512	4.559	4.606	4.654	4.701
110	4.749	4.796	4.843	4.891	4.939	4.987	5.035	5.083	5.131	5.179
120	5.227	5.275	5.323	5.372	5.420	5.469	5.518	5.566	5.615	5.663
130	5.712	5.761	5.810	5.859	5.908	5.957	6.007	6.056	6.105	6.155
140	6.204	6.254	6.303	6.353	6.403	6.453	6.503	6.553	6.603	6.653
150	6.703	6.753	6.803	6.853	6.904	6.954	7.004	7.055	7.106	7.157
160	7.208	7.258	7.309	7.360	7.411	7.462	7.513	7.565	7.616	7.667
170	7.719	7.770	7.822	7.874	7.926	7.978	8.029	8.080	8.132	8.184
180	8.236	8.288	8.340	8.392	8.445	8.497	8.549	8.601	8.654	8.707
190	8.759	8.812	8.864	8.917	8.970	9.023	9.076	9.129	9.182	9.235
200	9.288	9.341	9.394	9.448	9.501	9.555	9.608	9.662	9.715	9.769
210	9.823	9.877	9.931	9.985	10.039	10.093	10.147	10.201	10.255	10.309
220	10.363	10.417	10.471	10.526	10.580	10.635	10.689	10.744	10.799	10.854
230	10.909	10.963	11.018	11.073	11.128	11.183	11.238	11.293	11.348	11.403
240	11.459	11.514	11.569	11.624	11.680	11.735	11.791	11.847	11.903	11.959
250	12.015	12.071	12.126	12.182	12.238	12.294	12.350	12.406	12.462	12.518
260	12.575	12.631	12.688	12.744	12.800	12.857	12.913	12.970	13.027	13.083
270	13.140	13.197	13.254	13.311	13.368	13.425	13.482	13.539	13.596	13.653
280	13.710	13.768	13.825	13.882	13.939	13.997	14.055	14.112	14.170	14.227
290	14.285	14.343	14.400	14.458	14.515	14.573	14.631	14.689	14.747	14.805
300	14.864	14.922	14.980	15.038	15.096	15.155	15.213	15.271	15.330	15.388

COPPER vs. CONSTANTAN THERMOCOUPLE

Degrees Fahrenheit — Reference Junction 32° F.

°F	0	1	2	3	4	5	6	7	8	9
					Millivolts					
-200	-4.111	-4.125	-4.138	-4.151	-4.165	-4.179	-4.192	-4.206	-4.219	-4.232
-190	-3.972	-3.986	-4.000	-4.014	-4.028	-4.042	-4.056	-4.069	-4.083	-4.097
-180	-3.829	-3.844	-3.858	-3.873	-3.887	-3.901	-3.915	-3.929	-3.944	-3.958
-170	-3.684	-3.698	-3.713	-3.727	-3.742	-3.757	-3.771	-3.786	-3.800	-3.815
-160	-3.533	-3.548	-3.564	-3.579	-3.594	-3.609	-3.624	-3.639	-3.654	-3.669
-150	-3.380	-3.396	-3.411	-3.426	-3.441	-3.457	-3.472	-3.488	-3.503	-3.518
-140	-3.223	-3.238	-3.254	-3.270	-3.286	-3.301	-3.317	-3.333	-3.349	-3.365
-130	-3.062	-3.078	-3.094	-3.110	-3.127	-3.143	-3.159	-3.175	-3.191	-3.207
-120	-2.897	-2.914	-2.931	-2.947	-2.964	-2.980	-2.997	-3.013	-3.030	-3.046
-110	-2.730	-2.747	-2.764	-2.781	-2.797	-2.814	-2.831	-2.847	-2.864	-2.881
-100	-2.559	-2.577	-2.594	-2.611	-2.628	-2.645	-2.662	-2.679	-2.696	-2.713
-90	-2.385	-2.402	-2.420	-2.437	-2.455	-2.472	-2.490	-2.507	-2.525	-2.542
-80	-2.207	-2.225	-2.243	-2.260	-2.278	-2.296	-2.314	-2.332	-2.349	-2.367
-70	-2.026	-2.044	-2.063	-2.081	-2.099	-2.117	-2.135	-2.153	-2.171	-2.189
-60	-1.842	-1.860	-1.879	-1.897	-1.916	-1.934	-1.953	-1.971	-1.989	-2.008
-50	-1.654	-1.673	-1.692	-1.711	-1.729	-1.748	-1.767	-1.786	-1.804	-1.823
-40	-1.463	-1.482	-1.502	-1.521	-1.540	-1.559	-1.578	-1.597	-1.616	-1.635
-30	-1.270	-1.289	-1.308	-1.328	-1.347	-1.367	-1.386	-1.406	-1.425	-1.444
-20	-1.072	-1.092	-1.112	-1.132	-1.152	-1.171	-1.191	-1.210	-1.230	-1.250
-10	-0.872	-0.893	-0.913	-0.933	-0.953	-0.973	-0.993	-1.013	-1.033	-1.053
(-)0	-0.670	-0.690	-0.710	-0.730	-0.751	-0.771	-0.792	-0.812	-0.832	-0.852
(+)0	-0.670	-0.649	-0.629	-0.608	-0.588	-0.567	-0.546	-0.526	-0.505	-0.484
10	-0.463	-0.442	-0.421	-0.401	-0.380	-0.359	-0.339	-0.318	-0.297	-0.275
20	-0.254	-0.233	-0.212	-0.191	-0.170	-0.149	-0.128	-0.107	-0.085	-0.064
30	-0.042	-0.021	0.000	0.021	0.042	0.064	0.086	0.107	0.129	0.150
40	0.171	0.193	0.215	0.236	0.258	0.280	0.302	0.324	0.346	0.367
50	0.389	0.411	0.433	0.455	0.477	0.499	0.521	0.543	0.565	0.587
60	0.609	0.631	0.654	0.676	0.698	0.720	0.743	0.765	0.787	0.809
70	0.832	0.854	0.877	0.899	0.922	0.944	0.967	0.990	1.012	1.035
80	1.057	1.080	1.103	1.126	1.148	1.171	1.194	1.217	1.240	1.263
90	1.286	1.309	1.332	1.355	1.378	1.401	1.424	1.448	1.471	1.494
100	1.517	1.540	1.563	1.587	1.610	1.633	1.657	1.680	1.704	1.727
110	1.751	1.774	1.798	1.821	1.845	1.869	1.893	1.916	1.940	1.963
120	1.987	2.011	2.035	2.059	2.083	2.107	2.131	2.154	2.178	2.202
130	2.226	2.250	2.274	2.298	2.322	2.346	2.370	2.394	2.418	2.443
140	2.467	2.491	2.516	2.540	2.565	2.589	2.614	2.638	2.663	2.687
150	2.711	2.736	2.760	2.785	2.810	2.835	2.859	2.884	2.908	2.933
160	2.958	2.982	3.007	3.032	3.057	3.082	3.107	3.132	3.157	3.182
170	3.207	3.232	3.257	3.282	3.307	3.332	3.357	3.382	3.407	3.433
180	3.458	3.483	3.508	3.534	3.559	3.584	3.610	3.635	3.661	3.686
190	3.712	3.737	3.762	3.787	3.813	3.839	3.864	3.890	3.915	3.941
200	3.967	3.993	4.018	4.044	4.070	4.096	4.122	4.148	4.174	4.199
210	4.225	4.251	4.277	4.303	4.329	4.355	4.381	4.408	4.434	4.460
220	4.486	4.512	4.538	4.564	4.590	4.617	4.643	4.670	4.696	4.722
230	4.749	4.775	4.801	4.827	4.854	4.880	4.907	4.934	4.960	4.987
240	5.014	5.040	5.067	5.094	5.120	5.147	5.174	5.200	5.227	5.254
250	5.280	5.307	5.334	5.361	5.388	5.415	5.442	5.469	5.496	5.523

TABLE 6 THERMOCOUPLE CONVERSION TABLES FOR CHROMEL - ALUMEL

CHROMEL vs. ALUMEL THERMOCOUPLE

Degrees Centigrade — Reference Junction 0°C.

Millivolts

°C	0	1	2	3	4	5	6	7	8	9	10
-150	-4.81	-4.84	-4.86	-4.88	-4.90	-4.92	-4.95	-4.97	-4.99	-5.01	-5.03
-140	-4.58	-4.60	-4.62	-4.65	-4.67	-4.70	-4.72	-4.74	-4.77	-4.79	-4.81
-130	-4.32	-4.35	-4.37	-4.40	-4.42	-4.45	-4.48	-4.50	-4.52	-4.55	-4.58
-120	-4.06	-4.08	-4.11	-4.14	-4.16	-4.19	-4.22	-4.24	-4.27	-4.30	-4.32
-110	-3.78	-3.81	-3.84	-3.86	-3.89	-3.92	-3.95	-3.98	-4.00	-4.03	-4.06
-100	-3.49	-3.52	-3.55	-3.58	-3.61	-3.64	-3.66	-3.69	-3.72	-3.75	-3.78
-90	-3.19	-3.22	-3.25	-3.28	-3.31	-3.34	-3.37	-3.40	-3.43	-3.46	-3.49
-80	-2.87	-2.90	-2.93	-2.96	-3.00	-3.03	-3.06	-3.09	-3.12	-3.16	-3.19
-70	-2.54	-2.57	-2.61	-2.64	-2.67	-2.71	-2.74	-2.77	-2.80	-2.84	-2.87
-60	-2.20	-2.24	-2.27	-2.30	-2.34	-2.37	-2.41	-2.44	-2.47	-2.51	-2.54
-50	-1.86	-1.89	-1.93	-1.96	-2.00	-2.03	-2.07	-2.10	-2.13	-2.17	-2.20
-40	-1.50	-1.54	-1.57	-1.61	-1.64	-1.68	-1.72	-1.75	-1.79	-1.82	-1.86
-30	-1.14	-1.17	-1.21	-1.25	-1.28	-1.32	-1.36	-1.39	-1.43	-1.47	-1.50
-20	-0.77	-0.80	-0.84	-0.88	-0.92	-0.95	-0.99	-1.03	-1.06	-1.10	-1.14
-10	-0.39	-0.42	-0.46	-0.50	-0.54	-0.58	-0.62	-0.66	-0.69	-0.73	-0.77
(-)0	-0.00	-0.04	-0.08	-0.12	-0.16	-0.19	-0.23	-0.27	-0.31	-0.35	-0.39
(+)0	0.00	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40
10	0.40	0.44	0.48	0.52	0.56	0.60	0.64	0.68	0.72	0.76	0.80
20	0.80	0.84	0.88	0.92	0.96	1.00	1.04	1.08	1.12	1.16	1.20
30	1.20	1.24	1.28	1.32	1.36	1.40	1.44	1.49	1.53	1.57	1.61
40	1.61	1.65	1.69	1.73	1.77	1.81	1.85	1.90	1.94	1.98	2.02
50	2.02	2.06	2.10	2.14	2.18	2.23	2.27	2.31	2.35	2.39	2.43
60	2.43	2.47	2.51	2.56	2.60	2.64	2.68	2.72	2.76	2.80	2.85
70	2.85	2.89	2.93	2.97	3.01	3.05	3.10	3.14	3.18	3.22	3.26
80	3.26	3.30	3.35	3.39	3.43	3.47	3.51	3.56	3.60	3.64	3.68
90	3.68	3.72	3.76	3.81	3.85	3.89	3.93	3.97	4.01	4.06	4.10
100	4.10	4.14	4.18	4.22	4.26	4.31	4.35	4.39	4.43	4.47	4.51
110	4.51	4.55	4.60	4.64	4.68	4.72	4.76	4.80	4.84	4.88	4.92
120	4.92	4.96	5.01	5.05	5.09	5.13	5.17	5.21	5.25	5.29	5.33
130	5.33	5.37	5.41	5.45	5.49	5.53	5.57	5.61	5.65	5.69	5.73
140	5.73	5.77	5.81	5.85	5.89	5.93	5.97	6.01	6.05	6.09	6.13
150	6.13	6.17	6.21	6.25	6.29	6.33	6.37	6.41	6.45	6.49	6.53
160	6.53	6.57	6.61	6.65	6.69	6.73	6.77	6.81	6.85	6.89	6.93
170	6.93	6.97	7.01	7.05	7.09	7.13	7.17	7.21	7.25	7.29	7.33
180	7.33	7.37	7.41	7.45	7.49	7.53	7.57	7.61	7.65	7.69	7.73
190	7.73	7.77	7.81	7.85	7.89	7.93	7.97	8.01	8.05	8.09	8.13
200	8.13	8.17	8.21	8.25	8.29	8.33	8.37	8.41	8.46	8.50	8.54
210	8.54	8.58	8.62	8.66	8.70	8.74	8.78	8.82	8.86	8.90	8.94
220	8.94	8.98	9.02	9.06	9.10	9.14	9.18	9.22	9.26	9.30	9.34
230	9.34	9.38	9.42	9.46	9.50	9.54	9.59	9.63	9.67	9.71	9.75
240	9.75	9.79	9.83	9.87	9.91	9.95	9.99	10.03	10.07	10.11	10.16
250	10.16	10.20	10.24	10.28	10.32	10.36	10.40	10.44	10.48	10.52	10.57
260	10.57	10.61	10.65	10.69	10.73	10.77	10.81	10.85	10.89	10.93	10.98
270	10.98	11.02	11.06	11.10	11.14	11.18	11.22	11.26	11.30	11.34	11.39
280	11.39	11.43	11.47	11.51	11.55	11.59	11.63	11.67	11.72	11.76	11.80
290	11.80	11.84	11.88	11.92	11.96	12.01	12.05	12.09	12.13	12.17	12.21
300	12.21	12.25	12.29	12.34	12.38	12.42	12.46	12.50	12.54	12.58	12.63

CHROMEL vs. ALUMEL THERMOCOUPLE

Degrees Fahrenheit — Reference Junction 32°F

Millivolts

°F	0	1	2	3	4	5	6	7	8	9	10
-200	-4.29	-4.31	-4.32	-4.34	-4.35	-4.36	-4.38	-4.39	-4.41	-4.42	-4.44
-190	-4.15	-4.16	-4.18	-4.19	-4.21	-4.22	-4.24	-4.25	-4.26	-4.28	-4.29
-180	-4.00	-4.01	-4.03	-4.04	-4.06	-4.07	-4.09	-4.10	-4.12	-4.13	-4.15
-170	-3.84	-3.86	-3.88	-3.89	-3.91	-3.92	-3.94	-3.95	-3.97	-3.98	-4.00
-160	-3.69	-3.70	-3.72	-3.73	-3.75	-3.76	-3.78	-3.80	-3.81	-3.83	-3.84
-150	-3.52	-3.54	-3.56	-3.57	-3.59	-3.60	-3.62	-3.64	-3.65	-3.67	-3.69
-140	-3.36	-3.38	-3.39	-3.41	-3.42	-3.44	-3.46	-3.47	-3.49	-3.51	-3.52
-130	-3.19	-3.20	-3.22	-3.24	-3.25	-3.27	-3.29	-3.31	-3.32	-3.34	-3.36
-120	-3.01	-3.03	-3.05	-3.06	-3.08	-3.10	-3.12	-3.13	-3.15	-3.17	-3.19
-110	-2.83	-2.85	-2.87	-2.89	-2.90	-2.92	-2.94	-2.96	-2.98	-2.99	-3.01
-100	-2.65	-2.67	-2.69	-2.71	-2.72	-2.74	-2.76	-2.78	-2.80	-2.82	-2.83
-90	-2.47	-2.49	-2.50	-2.52	-2.54	-2.56	-2.58	-2.60	-2.62	-2.63	-2.65
-80	-2.28	-2.30	-2.32	-2.34	-2.36	-2.37	-2.39	-2.41	-2.43	-2.45	-2.47
-70	-2.09	-2.11	-2.13	-2.15	-2.17	-2.18	-2.20	-2.22	-2.24	-2.26	-2.28
-60	-1.90	-1.92	-1.94	-1.96	-1.97	-1.99	-2.01	-2.03	-2.05	-2.07	-2.09
-50	-1.70	-1.72	-1.74	-1.76	-1.78	-1.80	-1.82	-1.84	-1.86	-1.88	-1.90
-40	-1.50	-1.52	-1.54	-1.56	-1.58	-1.60	-1.62	-1.64	-1.66	-1.68	-1.70
-30	-1.30	-1.32	-1.34	-1.36	-1.38	-1.40	-1.42	-1.44	-1.46	-1.48	-1.50
-20	-1.10	-1.12	-1.14	-1.16	-1.18	-1.20	-1.22	-1.24	-1.26	-1.28	-1.30
-10	-0.89	-0.91	-0.93	-0.95	-0.97	-0.99	-1.01	-1.03	-1.06	-1.08	-1.10
(-)0	-0.68	-0.70	-0.72	-0.75	-0.77	-0.79	-0.81	-0.83	-0.85	-0.87	-0.89
(+)0	-0.68	-0.66	-0.64	-0.62	-0.60	-0.58	-0.56	-0.54	-0.52	-0.49	-0.47
10	-0.47	-0.45	-0.43	-0.41	-0.39	-0.37	-0.34	-0.32	-0.30	-0.28	-0.26
20	-0.26	-0.24	-0.22	-0.19	-0.17	-0.15	-0.13	-0.11	-0.09	-0.07	-0.04
30	-0.04	-0.02	0.00	0.02	0.04	0.07	0.09	0.11	0.13	0.15	0.18
40	0.18	0.20	0.22	0.24	0.26	0.29	0.31	0.33	0.35	0.37	0.40
50	0.40	0.42	0.44	0.46	0.48	0.51	0.53	0.55	0.57	0.60	0.62
60	0.62	0.64	0.66	0.68	0.71	0.73	0.75	0.77	0.80	0.82	0.84
70	0.84	0.86	0.88	0.91	0.93	0.95	0.97	1.00	1.02	1.04	1.06
80	1.06	1.09	1.11	1.13	1.15	1.18	1.20	1.22	1.24	1.27	1.29
90	1.29	1.31	1.33	1.36	1.38	1.40	1.43	1.45	1.47	1.49	1.52
100	1.52	1.54	1.56	1.58	1.61	1.63	1.65	1.68	1.70	1.72	1.74
110	1.74	1.77	1.79	1.81	1.84	1.86	1.88	1.90	1.93	1.95	1.97
120	1.97	2.00	2.02	2.04	2.06	2.09	2.11	2.13	2.16	2.18	2.20
130	2.20	2.23	2.25	2.27	2.29	2.32	2.34	2.36	2.39	2.41	2.43
140	2.43	2.46	2.48	2.50	2.52	2.55	2.57	2.59	2.62	2.64	2.66
150	2.66	2.69	2.71	2.73	2.75	2.78	2.80	2.82	2.85	2.87	2.89
160	2.89	2.92	2.94	2.96	2.98	3.01	3.03	3.05	3.08	3.10	3.12
170	3.12	3.15	3.17	3.19	3.22	3.24	3.26	3.29	3.31	3.33	3.36
180	3.36	3.38	3.40	3.43	3.45	3.47	3.49	3.52	3.54	3.56	3.59
190	3.59	3.61	3.63	3.66	3.68	3.70	3.73	3.75	3.77	3.80	3.82
200	3.82	3.84	3.87	3.89	3.91	3.94	3.96	3.98	4.01	4.03	4.05
210	4.05	4.08	4.10	4.12	4.15	4.17	4.19	4.21	4.24	4.26	4.28
220	4.28	4.31	4.33	4.35	4.38	4.40	4.42	4.44	4.47	4.49	4.51
230	4.51	4.54	4.56	4.58	4.61	4.63	4.65	4.67	4.70	4.72	4.74
240	4.74	4.77	4.79	4.81	4.83	4.86	4.88	4.90	4.92	4.95	4.97
250	4.97	4.99	5.02	5.04	5.06	5.08	5.11	5.13	5.15	5.17	5.20

TABLE 7 PHYSICAL AND THERMAL PROPERTIES FOR VARIOUS SOLIDS, LIQUIDS, AND GASES AT 70°F AND I ATM

The properties listed in the following table are to be considered as representative. It should be kept in mind that the properties listed may vary considerably from the indicated values with composition, pressure, and temperature.

Material	Specific Heat, BTU/lb-°F	Thermal Conductivity, BTU/hr-ft-°F	Coefficient of Thermal Expansion, $°R^{-1} \times 10^6$	Density, lb/ft^3	Electrical Resistivity, ohm-cm	Modulus of Elasticity, psi $\times 10^{-6}$	Yield Point, psi
SOLIDS:							
Alumel	0.125	17.1	6.7	537.0	30.1×10^{-6}	—	—
Aluminum:							
Commercially pure (1060-H-12)	0.21	134.0	12.7	170.0	2.83×10^{-6}	10.0	13,000
Wrought Alloy (6061-T6)	0.22	90.0	12.5	173.0	—	10.6	38,000
Beryllium:							
Commercially pure	0.45	92.0	6.9	114.0	5.0×10^{-6}	37.0	20,000
2%Be, .4%Ni, 97%Cu	—	54.0	9.2	515.0	—	18.0	90,000
Bismuth Telluride	0.13	0.87	7.2	500.0	1.0×10^{-3}	—	1,500
Ceramics:							
Alumina, 96%	0.20	20.4	3.6	223.0	$>10^{14}$	—	200,000
Beryllia, 99%	0.26	133.0	3.3	180.0	$>10^{14}$	—	100,000
Fused quartz	0.19	0.62	0.3	137.0	$>10^{13}$	10.4	160,000
Pyrex	0.20	0.66	1.9	138.0	$>10^{10}$	9.1	100,000
Chromel A	0.11	7.75	7.3	525.0	111.0×10^{-6}	—	—
Chromel P	0.11	11.1	7.6	545.0	72.3×10^{-6}	—	—
Constantan	0.098	13.1	9.4	524.0	49.0×10^{-6}	25.0	—

Copper:							
Electrolytic-hard drawn	0.092	225.0	9.5	556.0	1.77×10^{-6}	17.0	45,000
Admiralty metal (28%Zn-1%Sn)	0.092	70.0	11.2	530.0	—	15.0	20,000
Brass (65%Cu, 35%Zn)	0.082	60.0	10.0	530.0	—	15.0	60,000
Cupro-nickel (70%Cu, 30%Ni)	—	18.0	9.0	560.0	—	22.0	70,000
Aluminum bronze (10%Al)	0.098	45.0	9.2	475.0	15.0×10^{-6}	18.0	25,000
Gold (annealed)	0.031	179.0	7.9	1206.0	2.44×10^{-6}	12.0	—
Insulators:							
Glass Wool	0.16	0.023	—	12.5	—	—	—
Rock Wool	—	0.017	—	8.0	—	—	—
Rubber	0.48	0.087	37.0	58.0	—	—	—
Polyether urethane foam	—	0.01—0.02	—	1.1-2.3	—	—	20-45 (Compression)
ABS Plastics (Heat Resistant)	—	0.17	33.33	66.14	1.6×10^{16}	0.42	6,000
Bakelite	0.38	0.134	12.2	79.5	—	—	—
Fiber insulating board	—	0.028	—	14.8	—	—	—
Silica Aerogel	—	0.013	—	8.5	—	—	—
Nylon (type 6/6)	0.40	0.14	45.0	71.14	1.0×10^{14}	0.42	11,800
Iron:							
Grey cast iron	0.108	31.0	5.8	480.0	20.0×10^{-6}	13.2	15,000
Kovar	0.11	9.55	2.8	522.0	49.0×10^{-6}	19.5	59,500
Low Carbon steel	0.11	28.0	6.4	490.0	—	29.5	39,000
Stainless steel (type 304)	0.11	10.0	9.5	500.0	73.0×10^{-6}	28.0	34,000
Lead (commercially pure):	0.031	20.0	16.3	700.0	22.0×10^{-6}	2.6	800
Magnesium wrought alloy (AZ61A-P)	0.24	35.0	14.4	113.0	4.4×10^{-6}	6.5	31,000
Molybdenum (0.5%Ti, 0.1%Zr)	0.06	85.0	2.7	637.0	7.0×10^{-6}	50.0	130,000
Nickel:							
Commercially pure	0.107	35.0	7.2	555.0	7.5×10^{-6}	30.0	50,000
Monel (67%Ni, 30%Cu)	0.127	14.5	7.8	550.0	43.0×10^{-6}	26.0	35,000
Silver (annealed)	0.056	244.0	10.5	655.0	1.59×10^{-6}	11.0	—
Titanium	0.11	12.0	4.8	273.0	56.0×10^{-6}	15.5	80,000

TABLE 7 (Cont'd.)

PHYSICAL AND THERMAL PROPERTIES FOR VARIOUS SOLIDS, LIQUIDS, AND GASES AT 70°F AND 1 ATM

The properties listed in the following table are to be considered as representative. It should be kept in mind that the properties listed may vary considerably from the indicated values with composition, pressure, and temperature.

Material	Specific Heat, BTU/lb-°F	Thermal Conductivity, BTU/hr-ft-°F	Coefficient of Volume Expansion, $°R^{-1} \times 10^3$	Density, lb/ft^3	Kinematic Viscosity, $ft^2/sec \times 10^5$	Prandtl Number	Latent Heat of Fusion, BTU/lb
LIQUIDS:							
Water	1.0	0.35	0.10	62.5	1.08	7.02	143.0
Nitrogen (-210°F)	0.50	0.041	—	34.5	0.13	1.98	11.0
Ethylene Glycol	0.57	0.14	0.36	69.7	20.64	204.00	78.0
GASES:							
Air	0.24	0.015	1.89	0.074	16.88	0.71	11.4
Nitrogen	0.25	0.015	1.89	0.071	16.82	0.713	11.0
Oxygen	0.22	0.016	1.89	0.081	17.07	0.71	5.95
Carbon Dioxide	0.21	0.01	1.89	0.112	8.96	0.77	81.5
Argon	0.124	0.0092	1.89	0.104	141.0	0.714	12.1
Hydrogen	3.42	0.11	1.89	0.0051	117.9	0.71	25.2

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Notes