THERMOELECTRICS

BORG WARNER®

Borg-Warner Thermoelectrics

BORG-WARNER CORPORATION

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Thermoelectric Cooling

Thermoelectric cooling has much in common with conventional refrigeration methods. 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 above ambient level. The condenser helps discharge the absorbed heat into surrounding ambient.

In thermoelectric refrigeration, 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 direct-current 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. A thermoelectric cooling system refrigerates without the use of mechanical devices, except perhaps in the auxiliary sense, and without refrigerant.

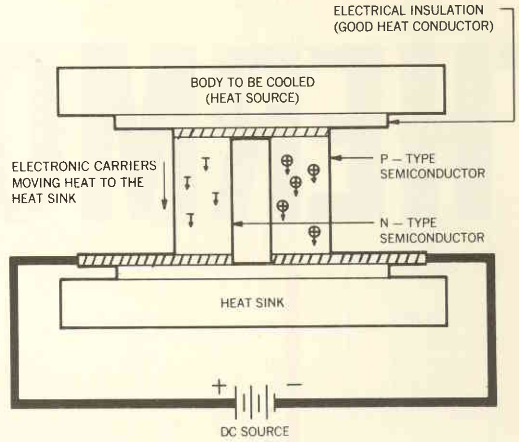


FIGURE 1

ELEMENTS OF THERMOELECTRIC COOLERS

The components of a thermoelectric cooler can be shown best by way of a cross section of a typical unit, as shown in Fig. 1. Thermoelectric coolers such as this are actually small heat pumps which operate on physical principles established over a century ago. In a thermoelectric cooler, semicondutor materials with dissimilar characteristics are connected electrically in series and thermally in parallel so that two junctions are created.

The semiconductor materials are N- and P-type. 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. Only since refinement of semiconductor materials in the early 1950s has thermoelectric refrigeration been considered practical for many applications.

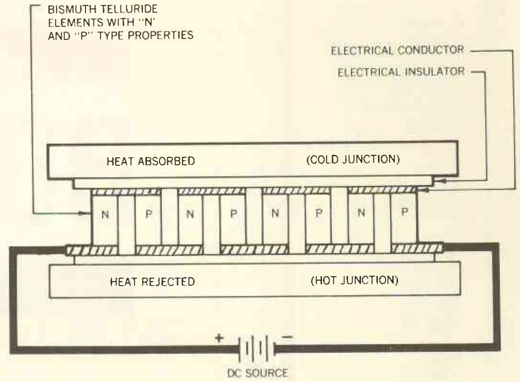


FIGURE 2

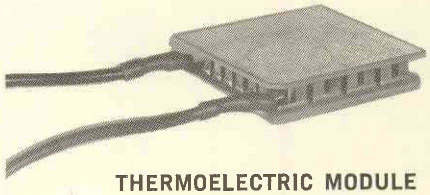
CHARACTERISTICS AND OPERATIVE RANGES

In practical use, couples similar to the single couple shown in Fig. 1 are combined in a module where they are connected in series electrically and parallel thermally, as evident from Fig. 2. Normally, a module is the smallest component available. The user can tailor quantity, size, or capacity of the module to fit exact requirements without procuring more total capacity than actually is needed. Modules are available in a wide variety of sizes, shapes, operating voltages, number of couples, and ranges of heat-pumping levels. The present trend is toward a larger number of couples operating at a low current.

Uses for thermoelectric coolers can be grouped into three categories: (1) electronic components, (2) temperature control units, and (3) medical and laboratory instruments, with numerous examples of use in each category. Thermoelectric coolers are capable of operating from +100°C to −125°C. Special units can be fabricated to withstand temperatures in excess of 150°C. Simple electronic control schemes allow control within a fraction of a degree of desired load temperatures above or below ambient.

Modules normally contain from 2 to 71 couples with ceramic-metal laminate plates (Fig. 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.

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 of the cold junction and the hot junction must be constructed to transfer heat in and out of the module with little difference in temperature. This is accomplished with metal-ceramic laminate plates that give strength and permit good thermal 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.


THERMOELECTRIC MODULE
FIGURE 3

EXTRANEOUS HEAT SOURCES

The load to be cooled should be isolated from other sources of heat to obtain maximum efficiency. Other than the load, there are three losses to consider when applying thermoelectric coolers: (1) conduction losses, (2) convection losses, and (3) radiation losses.

Condution 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 large delta T's, conduction losses increase in importance. Convection losses are greatly reduced when the cold plate is protected from the gaseous enviroment by some form of insulation. 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 Celsius between the cold plate and the ambient [1 mW/cm^2) (°C)]. Radiation losses are approximately equivalent to 50 milliwatts per square centimeter, at cold plate temperatures near −75°C in an ambient of +27°C.

When devices operate in an evacuated enclosure, convection losses are virtually eliminated. If shielding is used, radiation losses are also reduced. To keep convection losses at a low level, a vacuum better than 10^{-3} torr is required.

INTRODUCTION TO THERMOELECTRIC PRODUCTS

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.

HEAT SINKS

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

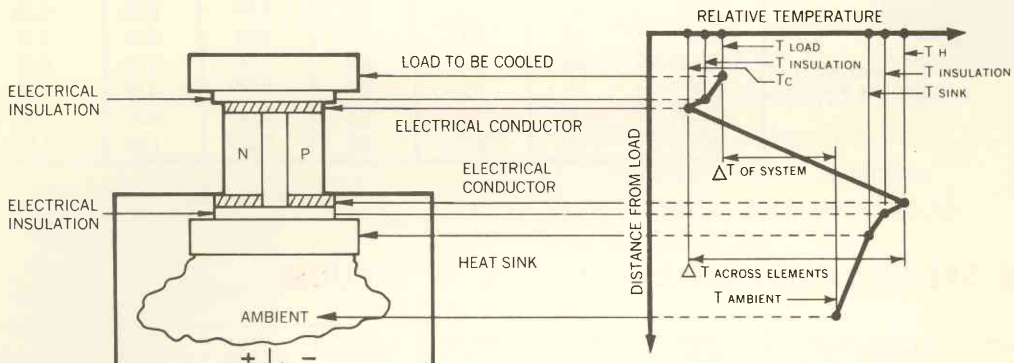
The figure below illustrates the steady-state temperature profile across a typical thermoelectric device from the load side to the ambient.

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_e) + power input (V•I) + heat leakage (Q_1)

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_e and Q_1 may easily be estimated; their total along with the power input gives Q_s, the energy the hot-junction must dissipate.



Typical Temperature Relationship in a Thermoelectric Cooler.

TIME TO COOL OR HEAT VARIOUS MATERIALS

The figure below 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 the Figure at the right is:

$Q\ \Delta t = m\ Cp\ \Delta T$

- ΔT — required temperature change (°F)
- Cp — average specific heat (BTU/lb-°F)
- m — weight of material (lbs)
- Δt — time interval
- 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.

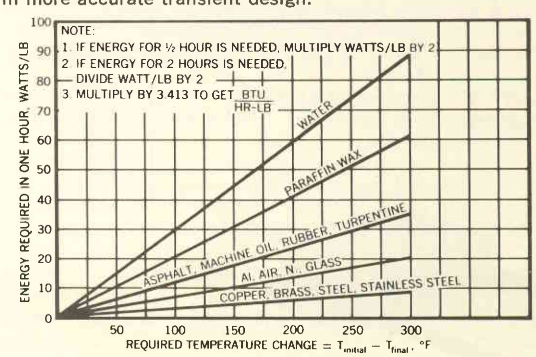
Enter Figure below on the horizontal axis at 50°F. Move vertically to the stainless steel and water curves and read on the vertical axis:

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.

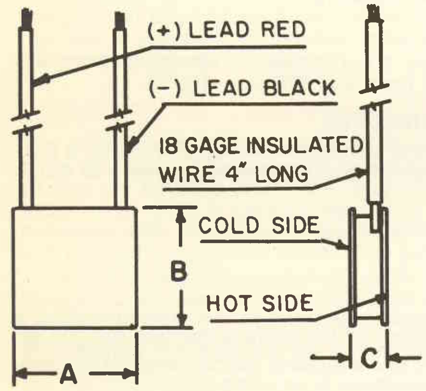
The time provided by this graph is based on a constant heat transfer during the one hour period. Actually, a thermoelectric cooler would not pump heat at a constant level due to change in ΔT and this should be taken into account in a design. An effective heat pumping capacity of a thermoelectric cooler 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.

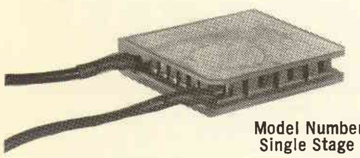


Energy to be Added or Removed Thermoelectrically in One Hour for Various Materials.

THERMOELECTRIC MODULES

SINGLE STAGE MODULE SPECIFICATION CHART — T_H 27°C IN VACUUM

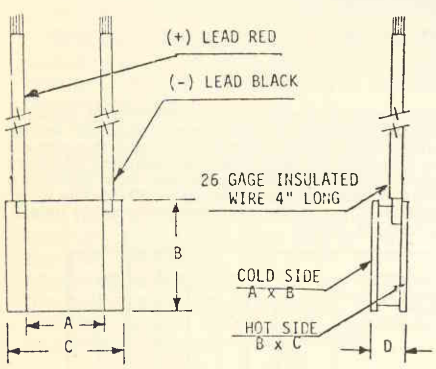




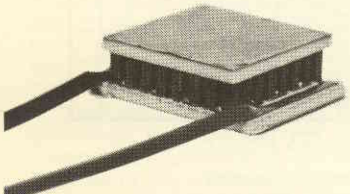
Model Number 920-31
Single Stage Module

MODULE NUMBER	MAX ΔT $Q_C = 0$ ΔT - °C	MAX Q_C ΔT = 0 Q_C - WATTS	MAX CURRENT AMPS	MAX VOLTAGE VOLTS	DIM. A	DIM. B	DIM. C
920-3	66	1.8	8.5	0.34	0.29	0.57	0.22
920-7	66	4.3	8.5	0.80	0.57	0.57	0.22
920-11	66	6.7	8.5	1.24	0.57	0.85	0.22
920-15	66	9.2	8.5	1.70	0.57	1.20	0.22
920-31	66	19.0	8.5	3.50	1.20	1.20	0.22
930-3	66	0.8	3.7	0.36	0.20	0.38	0.21
930-7	66	1.8	3.7	0.84	0.38	0.38	0.21
930-11	66	2.9	3.7	1.30	0.38	0.57	0.21
930-17	66	4.5	3.7	2.00	0.57	0.57	0.21
930-35	66	9.4	3.7	4.20	0.57	1.20	0.21
930-71	66	19.0	3.7	8.50	1.20	1.20	0.21
940-3	66	2.9	14.0	0.34	0.29	0.57	0.18
940-7	66	6.8	14.0	0.80	0.57	0.57	0.18
940-11	66	10.6	14.0	1.24	0.57	0.85	0.18
940-15	66	14.5	14.0	1.70	0.57	1.20	0.18
940-31	66	30.0	14.0	3.50	1.20	1.20	0.18
950-3	66	1.3	6.0	0.36	0.20	0.38	0.17
950-7	66	3.0	6.0	0.84	0.38	0.38	0.17
950-11	66	4.6	6.0	1.30	0.38	0.57	0.17
950-17	66	7.2	6.0	2.00	0.57	0.57	0.17
950-35	66	14.8	6.0	4.20	0.57	1.20	0.17
950-71	66	30.0	6.0	8.50	1.20	1.20	0.17

MINI MODULE SPECIFICATION CHART — T_H 27°C IN VACUUM



MINI MODULE NUMBER	MAX ΔT $Q_C = 0$ ΔT - °C	MAX Q_C ΔT = 0 Q_C - WATTS	MAX CURRENT AMPS	MAX VOLTAGE VOLTS	DIM. A	DIM. B	DIM C	DIM. D
110-4	64	0.24	1.1	0.5	0.08	0.16	0.14	0.13
110-8	64	0.49	1.1	1.0	0.16	0.16	0.22	0.13
110-12	64	0.73	1.1	1.5	0.16	0.24	0.22	0.13
110-18	64	1.10	1.1	2.2	0.24	0.24	0.30	0.13
110-32	64	1.95	1.1	4.0	0.32	0.32	0.38	0.13
120-4	64	0.30	1.4	0.5	0.08	0.16	0.14	0.12
120-8	64	0.61	1.4	1.0	0.16	0.16	0.22	0.12
120-12	64	0.92	1.4	1.5	0.16	0.24	0.22	0.12
120-18	64	1.35	1.4	2.2	0.24	0.24	0.30	0.12
120-32	64	2.40	1.4	4.0	0.32	0.32	0.38	0.12
130-4	64	0.42	1.9	0.5	0.09	0.18	0.15	0.12
130-8	64	0.84	1.9	1.0	0.18	0.18	0.24	0.12
130-12	64	1.25	1.9	1.5	0.18	0.27	0.24	0.12
130-18	64	1.90	1.9	2.2	0.27	0.27	0.33	0.12
130-32	64	3.35	1.9	4.0	0.36	0.36	0.42	0.12



Model Number 110-32
Mini Module

Standard coolers will withstand ambient temperatures of 110°C. Special coolers are available at premium prices that will withstand ambient temperatures of 160°C. For high temperature applications consult the factory.

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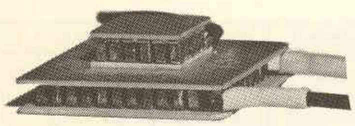
CASCADED THERMOELECTRIC COOLERS



Model Number 932-70-17
Standard Two Stage Cascade

STANDARD

2 - 5 Stages
From T_H 27°C
To T_C 180°K

Over 7000 Optimized Cascade Designs Using Partial Standard Borg-Warner Thermoelectric Modules.

- — Customer Design at Standard Cooler Prices
- — Lowest Price Per Watt of Heat Pumped
- — Quick Delivery, Usually one Week ARO

HIGH PERFORMANCE

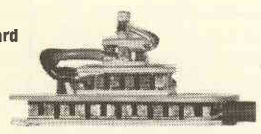
2 - 14 Stages
From T_H 27°C
To T_C 130°K

Individual Computer Aided Cascade Design Using Standard or High Performance Thermoelectronic Materials.

- — Higest Heat Pumping Capability
- — Lowest Temperatures
- — Lowest Power Input

Cascaded Thermoelectric Coolers are available at premium prices that will withstand ambients or bake-out temperatures of 150°C.

Model Number
954-70-16-4-1 Standard
Four Stage Cascade

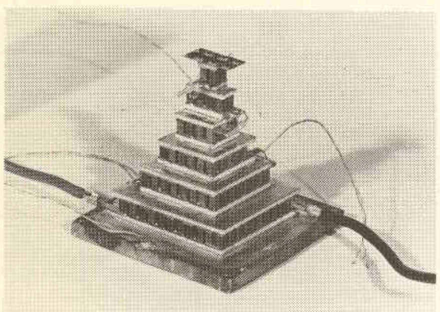


CUSTOM DESIGN

Engineering back-up is available for designs to meet customer specifications.

FOR RAPID QUOTATIONS CALL THE FACTORY

Specify: Q_C — Active Heat Load to be Pumped
T_H — Ambient or Hot Side Temperature
T_C — Cold Side Temperature Required
V — Operating Voltage Desired
P — Maximum Power Available
Environment — Vacuum or Dry Air
Size Requirements



High Performance
Ten Watt 170°K Cascaded Cooler

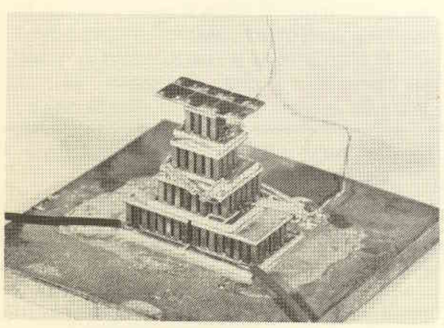
CASCADING

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 delta T'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.

In addition to the heat pumped by any given stage, the next lower stage must also pump the heat resulting from the input power to that upper stage. Consequently, each succeeding stage must be larger — from the top of the cascade downward.

With any given set of heat sink and cold spot temperatures, there exists an optimum heat-pumping capacity or "size" ratio between each adjacent pair or stages. The optimum size ratio increases as the overall delta T increases but decreases as the number of stages (N) increases. It is not necessarily a constant from stage to stage even with delta T and N fixed. Optimization of a cascade design requires accurate temperature-dependent data on the thermoelectric materials in combination with a computerized numerical design theory. Examples of optimized units are shown on this page.

Standard Cascades. Applications requiring low-temperature thermoelectric coolers usually have very strict limitations on available power. Therefore, it is not practical to fabricate and stock numerous different cascades which can be optimized for only one set of conditions. On the other hand, fully optimized prototypes involve engineering and manufacturing costs which may prove uneconomical for some applications. An alternative approach has been developed for responding to such requirements. Standard cascades are fabricated by assembling partials of standard modules. The number of different standard cascades is virtually unlimited due to "free" variables, such as number of stages, couple distribution, and the basic building block module.



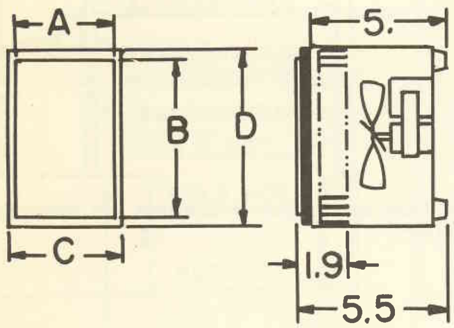
High Performance
Two Watt 193°K Cascaded Cooler

To determine the best standard cascade for a given application the desired hot side temperature, cold side temperature, and thermal load are entered into a computer. The result is a listing of numerous standard coolers which meet these specifications with various combinations of input power and cost. Generally, the lowest input power devices are of higher cost, and vice versa. Thus, cost/performance trade-offs are immediately discernible.

Borg-Warner Thermoelectrics

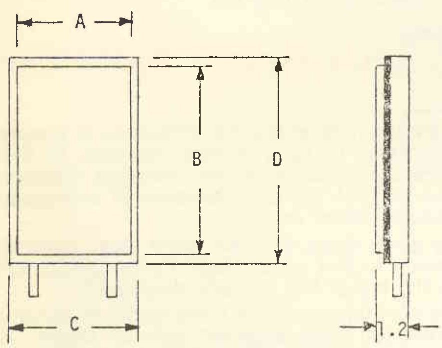
THERMOELECTRIC HEAT PUMPS

HEAT PUMP SPECIFICATION CHART T_H 77°F IN DRY AIR — AIR COOLED HEAT SINK



HEAT PUMP NUMBER	930AHP-1	920AHP-2	920AHP-4	930AHP-6	930AHP-9
MAX HEAT PUMPING WITH COLD PLATE SUPPRESSED TO 77°F AMBIENT (WATTS))	15	30	50	80	120
MIN. COLD PLATE TEMPERATURE OPERATING IN 77°F AMBIENT (°F)	−10	−10	−10	−10	−10
INPUT POWER AMPS	3.6	8.3	7.3	6.4	9.7
INPUT POWER VOLTS	9	7	14	24	24
DIMENSION A	1.5	1.5	3.8	3.8	6.0
DIMENSION B	2.0	3.8	3.8	6.0	6.0
DIMENSION C	4.1	4.1	4.1	4.1	6.6
DIMENSION D	4.1	4.1	4.1	6.6	6.6
POWER SUPPLY REQUIRED	PS-101	PS-102	PS-103	PS-104	PS-104

HEAT PUMP SPECIFICATION CHART T_H 77°F IN DRY AIR — LIQUID COOLED HEAT SINK



HEAT PUMP NUMBER	950LHP-1	940LHP-2	940LHP-4	950LHP-6	950LHP-9
MAX HEAT PUMPING WITH COLD PLATE SUPPRESSED TO 77°F AMBIENT (WATTS))	20	50	90	125	190
MIN. COLD PLATE TEMPERATURE OPERATING IN 77°F AMBIENT (°F)	−20	−20	−20	−20	−20
INPUT POWER AMPS	6	14	12	10	15
INPUT POWER VOLTS	9	7	14	24	24
DIMENSION A	1.5	1.5	3.8	3.8	6.0
DIMENSION B	2.0	3.8	3.8	6.0	6.0
DIMENSION C	4.1	4.1	4.1	4.1	6.6
DIMENSION D	4.1	4.1	4.1	6.6	6.6
POWER SUPPLY REQUIRED	PS-101	PS-102	PS-103	PS-104	PS-104

POWER SUPPLIES

MODEL	VAC	VDC	MAX AMPS
PS 101	115	12.5	7.0
PS 102	115	9.0	20.0
PS 103	115	16.5	12.5
PS 104	115	24.6	24.6

TEMPERATURE CONTROLLERS FOR POWER SUPPLIES

TC-101	Set Point Relay Controlled Accuracy ±3°C	Heat and Cool
TC-102	Set Point Proportional Accuracy ±1°C	Cool only
TC-104	Set Point Proportional Accuracy ±1°C	Heat and Cool

Other Borg-Warner Thermoelectric Heat Pumps are available that will operate with larger or smaller heat pumping capacities, current, and voltage. Power supplies, on/off temperature controllers with set point, and proportional reverse controllers are available to fit these pumps. Please contact factory for further information.

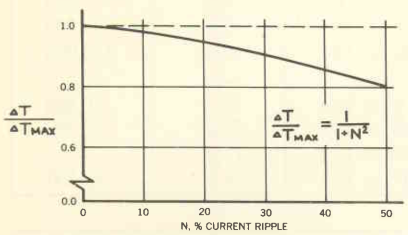
HEAT PUMPS

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 on the preceding page, 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.

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%.

The following graph 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.



Current Ripple Effect on Temperature Differential.

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 control circuit.

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

APPLICATION ASSISTANCE

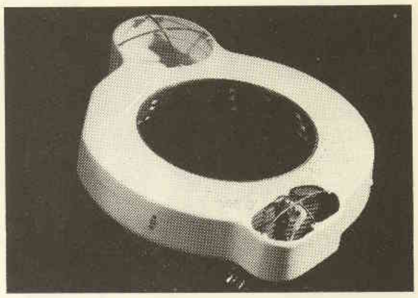
A knowledge of several engineering areas may be necessary to design some thermoelectric systems. Borg-Warner engineers can provide expert application assistance if the problem is properly defined. Borg-Warner engineers will first be interested in knowing as much about the system operation as possible, 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.

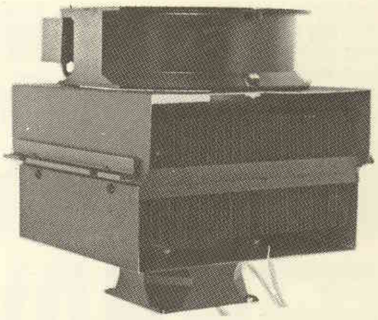
With this information Borg-Warner engineers can rapidly fill your needs and provide the most efficient standard or customized unit tailored to your application.

TRY US!

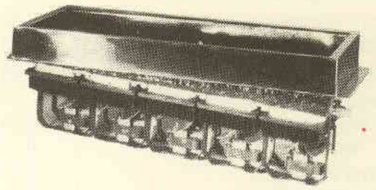
CUSTOM DESIGNS



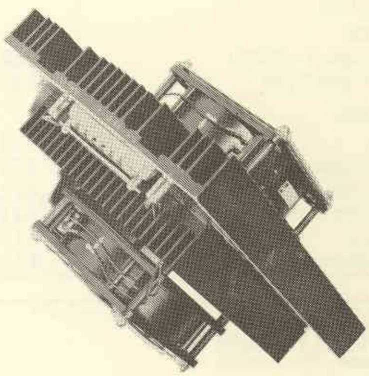
Ring type cooler to stabilize the inertial navigation system at 40°C and pump 280 watts with an input power of 338 watts.



Electronic cabinet cooler pumps 120 watts at 0° ΔT in 27°C ambient drawing 230 watts input power.



This system cools one gallon of chemical solution to 40°F below ambient with 850 watts of input power. Load capability 450 watts at 0° ΔT.



Remote sight cooler. Pumps 160 watts at 0° ΔT in 27°C ambient drawing 300 watts input power.

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 Thermal Expansion, $°R^{-1} \times 10^6$	Density lb/ft³	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

Material	Specific Heat, BTU/lb-°F	Thermal Conductivity, BTU/hr-ft-°F	Coefficient of Volume Expansion, $°R^{-1} \times 10^3$	Density lb/ft³	Kinematic Viscosity, ft²/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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