NORTHERN ALBERTA INSTITUTE OF TECHNOLOGY
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ELECTRONICS DEPARTMENT

SEMICONDUCTOR COOLING - *THEORY and PRACTICE*

1. Fundamentals of Heat Transfer as Applied to Semiconductor Cooling.
2. Temperature Measurement Techniques.
3. Power Measurement Techniques.
4. Air Flow Measurement Techniques.
5. Recommended Rating Procedures.
6. Natural Versus Forced Convection.

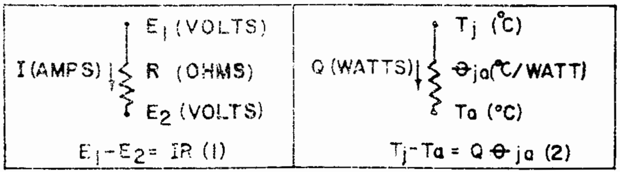
1. Fundamentals of Heat Transfers Applied To Semiconductor Cooling

By conservation of energy it is readily appreciated that the thermal energy conducted away from a semiconductor junction must be equal to the electrical power applied. Therefore, watts become convenient for the expression of heat flow per unit time. If one considers the thermal analogy to Ohm's Law it is seen that thermal resistance may be expressed in terms of degrees C per watt. The unit system outlined above then gives us a complete terminology for the measurement and understanding of heat flow from a semiconductor junction to its ultimate heat sink.

Only one variable in the equation, namely thermal resistance, requires detailed evaluation. The thermal circuits which we will encounter in our study of semiconductor cooling are for the most part series circuits. There are usually a few high impedance thermal paths shunting the circuit under consideration but their effect may usually be considered negligible.

Symbols may be designated for each of the quantities mentioned above. Let us designate temperature as T, heat flow as Q, and thermal resistance as θ. We may then by subfixes designate various points of temperature measurement and various thermal resistance components. For instance, the temperature difference between a semiconductor junction and the hottest point on its case mounting surface may be designated as T_{jc}. The temperature difference between the semiconductor case and the hottest point on the heat sink upon which it is mounted may be designated as T_{cs}. The temperature difference between the sink and ambient air may be designated as T_{sa}. Similarly we may designate θ_{jc}, θ_{cs}, and θ_{sa}. We must of course define a means and the exact locations at which temperature is to be measured. These points will be discussed in paragraph #2.

Let us first consider the analogy between heat flow and electrical current flow as described by Ohm's Law. The two situations are set forth in Fig. 1.



(a) OHMS LAW (b) THERMAL ANALOGY

FIG. I

If T_a of Fig. 1b is the ambient air temperature, θ_{ja} the known thermal resistance between junction and ambient air and Q the watts being dissipated at the junction, then it follows from equation (2) that the junction temperature

$$T_j = T_a + Q\theta_{ja} \quad (3).$$

The total thermal resistance from junction to ambient (θ_{ja}) may be broken into 3 series components as illustrated in Fig. 2.

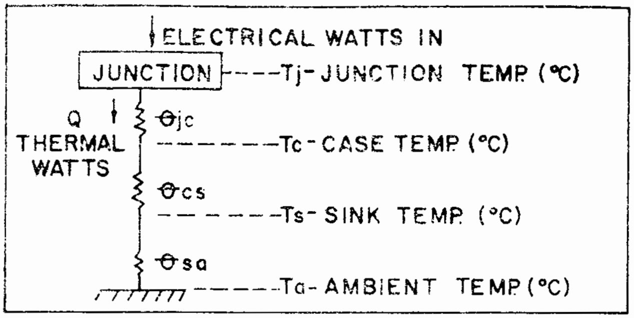


FIG. 2

Rewriting equation (3) for this case we see that the junction temperature is

$$T_j = T_a + Q(\theta_{jc} + \theta_{cs} + \theta_{sa}). \quad (4)$$

The highest permissible heat sink thermal resistance may be expressed as

$$\theta_{sa}\max = \frac{T_j\max - T_a\max}{Q\max} - \theta_{jc} - \theta_{cs} \quad (5)$$

The variables included in equation 5 are:

T_j max (°C)	The maximum junction operating temperature as given by the semiconductor manufacturer.

T_a max (°C)	The maximum anticipated temperature of the air entering the heat sink.
Q Max (watts)	The maximum applied junction power.
θ_{jc} (°C/W)	The thermal resistance from the junction to the semiconductor case as given by the semiconductor manufacturer.
θ_{cs} (°C/W.)	The mounting thermal resistance between the semiconductor case the hottest portion of the heat sink.

θ_{cs} is the most evasive quantity to determine. For the very flattest lapped interfaces it may be as low as .05°C/watt. For a T03 or T06 semiconductor case mounted with silicon grease on an anodized extruded aluminum heat sink, θ_{cs} will usually fall between .15 and .3°C/watt. If the T03 or T06 case is isolated from the heat sink with a mica or anodized aluminum wafer, θ_{cs} will probably range from .5 to 1.0°C/W.

2. Temperature Measurement Techniques

The guiding principles which the author feels are most useful in measuring case and heat sink temperatures are: (1) Always place the temperature sensing element at the hottest point on the device or portion of the device being measured. (2) Make every effort to assure excellent thermal coupling between the temperature sensing element and the surface or volume element, the temperature of which is being measured. (3) Make certain that thermocouple leads or other temperature measuring apparatus does not conduct appreciable amounts of heat energy out of the device under measurement. This last point applies particularly to temperature measurements made on small semiconductor devices which may be dissipating only a fraction of a watt.

As seen from the isothermal lines of Fig. 3, the hottest point on the semiconductor mounting surfaces is at A and the hottest portion of the cooler is at B.

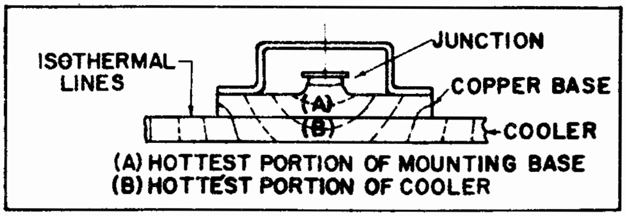


FIG.3

In order to measure these temperatures, sensing elements must be coupled as closely to A and B as practical considerations permit. A scheme utilizing open junction thermocouples permits instrumentation which well approaches the ideal.

An open junction thermocouple is one which utilizes the material under measurement as an electrically conductive element. If a copper-constantan pair is used to measure the temperature of a metallic device, an open junction arrangement can be made by swaging the copper and the constantan leads into separate holes or slots machined close to the point of desired measurement. Point contact junctions are also very reliable and can be made very simply by pressing the ends of the copper and constantan leads against the surface under temperature measurement.

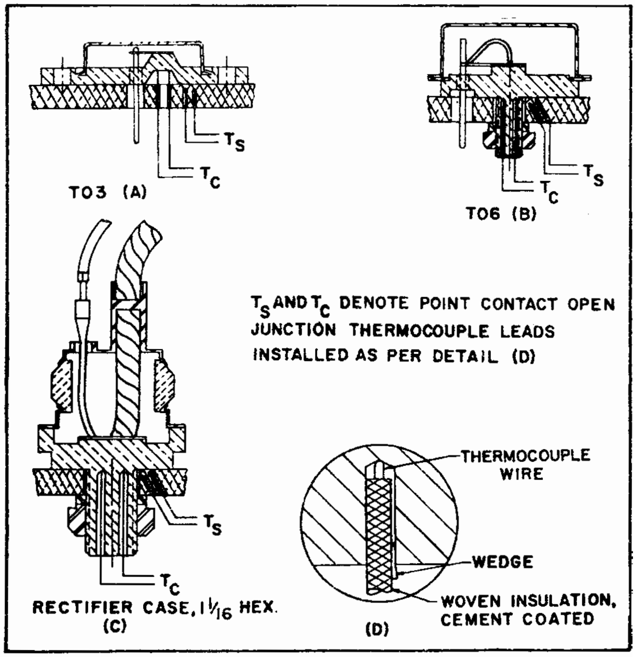


FIG. (4)

THERMOCOUPLE INSTRUMENTATION OF TYPICAL CASE STYLES

Figures 4a, b, and c show various point contact thermocouples applied to semiconductor cases and to the coolers upon which the semiconductors are mounted.

An interesting experiment for verifying the accuracy of a point contact, open junction thermocouple is that of touching the ends of the individual thermocouple leads against a metallic container which contains actively boiling water. The weather bureau may be consulted for the barometric pressure and an altitude correction applied if necessary. (No elevation correction was necessary in our Boston location.) A handbook may then be consulted for the boiling temperature of water at the particular barometric pressure at the time of the experiment. It has been the author's experience that the temperature measured has been accurate to within the readability of the temperature calibrated bridge used, which is $\frac{1}{4}$° C. A container filled with water and crushed ice may also be used for a 0° C calibration. The ice and water should be agitated during the measurement.

Further verification can be obtained by immersing a welded or soldered junction in the boiling water or the crushed ice and water mixture.

If the object under measurement is of the same metal as one of the thermocouple leads, with no major impurities or alloying differences, this lead may be fastened to any part of the object under measurement. The thermal junction will then be at the interface of the object under measurement and the thermocouple lead of differing material. The temperature indicated will be the temperature at this interface.

Concerning the various types of indicators which may be used to convert the thermocouple output potentials to temperature, the following comments are made for your consideration. If your laboratory is equipped with a precision potentiometer and if you have a source of ice and a vacuum bottle, then all that you need in addition, is some thermocouple wire and a conversion chart. If you plan to make extensive measurements you may find it more convenient to purchase a temperature calibrated potentiometer, which does not require usage of ice and which reads-out temperature directly but must however, be nulled for each reading. If you plan production testing or if your budget is generous you may wish to obtain a temperature calibrated potentiometer which is self-nulling and thereby gives direct readout.

Insofar as thermocouple wire is concerned, the author recommends .012″ dia. copper-constantan pair for high power work and .005″ dia. pair for fractional watt applications. For point contact at the bottom of holes, one may use a sliver of wood (a toothpick works well) as a wedge at the top of the hole. The integrity of the woven insulation on the wire may be maintained down to its tip (Fig. 4d) by coating it with a quick-drying cement.

3. Power Measurement Techniques

In order to obtain thermal data on a semiconductor cooler configuration one must be able to measure the electrical power being applied to the cooler. A suitable DC power supply along with appropriate voltage and current metering will be necessary if the power input to a transistor or a zener diode is to be measured. The dynamometer type watt meters are more convenient to use than separate voltage and current meters. The Weston 423 precision wattmeter is one with which we are familiar and is of the type which may be used for either DC or 60 cycle AC power measurement.

In order to simplify circuitry, and provide heat sources which will stand more experimental abuse than semiconductors will, resistive load cells may be constructed for making measurements on cooling devices. The author has designed and constructed loads of two types for simulating the standard TO 6 case style and the standard $1\frac{1}{16}$ hex. stud mounting rectifier cell. In constructing these loads one may either wind nichrome wire on a copper spool lined with mica or insert small ceramic encased heaters into close fitting holes reamed in a copper slug. In either case care must be taken to neck down the load just above the mounting base so that the heat flow will enter the base over an area approximately the same diameters as the silicon or germanium wafer in the semiconductor type being simulated.

The curve of static pressure versus volumetric flow which fan manufacturers customarily furnish with each of their models, is compatible with the approach outlined above. In order to obtain this curve, a typical example of which is given in Fig. 6, the fan under measurement is mounted so that it will discharge air into a large chamber, sometimes referred to as a plenum chamber, which should be sufficiently large that the air within will not be replaced more than five times per minute. This chamber has installed in an opposite wall a place to mount calibrated orifices or nozzles of various diameters. By substituting outlet orifices of various diameters and by measuring for each orifice the corresponding static pressure resulting in the chamber, one may refer to the orifice calibration curves to determine CFM and then immediately plot static pressure versus flow rate in CFM. It should be noted here that the fan inlet and the outlet side of the calibrated orifice are both at atmospheric pressure and that the static pressure rise developed by the fan is equal to the static pressure drop across the orifice and that these pressure differences are, of course, equal to the pressure difference between plenum and atmospheric.

The "Rotameter", a type of flow meter which has gained commercial popularity, utilizes a vertical tapered glass tube with a guided "float" indicating the flow rate. The bottom end of the glass tube is of smaller inside diameter than the top end and the tube is uniformly tapered. The indicating float seeks a level at which the force of gravity upon it is balanced by the fluid pressure differential across it. A flow meter of this type may be used to measure fan characteristics, but usually the pressure drop across the flow meter will be quite high and an auxiliary blower of a high pressure type will be required in series with the flow meter to overcome its flow resistance. If this auxiliary blower employs an AC-DC type motor, a "Variac" may be used to adjust its performance and hence, the system flow rate. It now becomes possible to measure the flow rate for zero static pressure across the fan under measurement. This is done simply by adjusting the speed of the auxiliary blower until the pressure indicator attached to the plenum chamber reads zero pressure differential to atmospheric. CFM may then be read from the flow meter.

The cubic ft. per minute of air being exhausted from an entire cooling system can be measured in exactly the same manner.

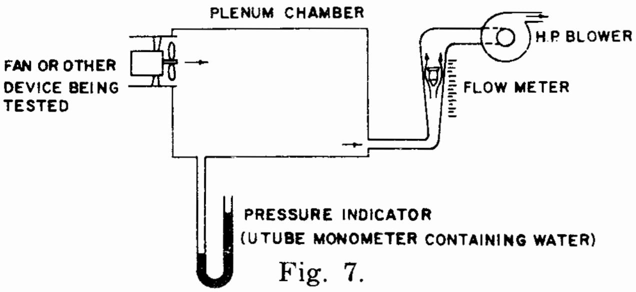


Fig. 7.

Figure 7 is a schematic of the arrangement which has been described above.

If the thermal characteristics of a cooler are to be measured at various air flows, the cooler, installed in a duct, may replace the fan being tested in the setup of Fig. 7. In this case the high pressure auxiliary blowers will remove air from the chamber and the pressure noted therein will be below atmospheric.

For the measurement of very low pressures an aneroid type gauge will be useful since water columns are difficult to read at the very low pressures often encountered in practical cooling systems.

If a fan of known characteristics is coupled to a ducted cooling system of known air flow characteristics, the CFM may be determined by plotting the characteristics of the two devices on one graph of head loss versus CFM. The resulting CFM is at the crossover point as shown in Fig. 8.

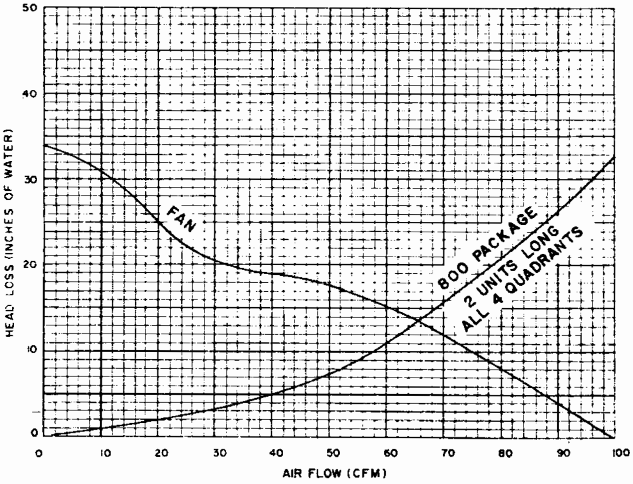


Fig. 8.

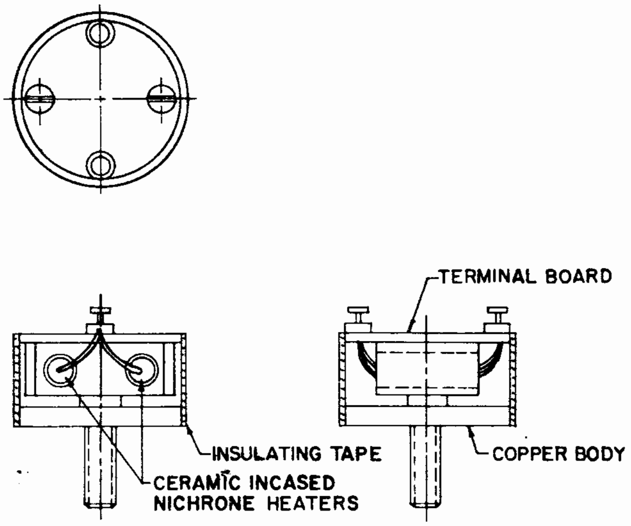


Fig. 5

(See Fig. 5) One or two turns of pressure sensitive tape should be wrapped around the load to thermally insulate it from air current. A plastic terminal board on top of the load will serve to insulate the top surface as well as provide for electrical terminals. Measurements made with these loads have been compared with successive measurements made with semiconductors mounted on the same cooler. Correlation has always been within the readability of the instrumentation. All that is needed to vary and measure the power applied to these loads is a "Variac" and an AC wattmeter.

4. Air Flow Measurement Techniques

To many packaging engineers the problem of measuring air flow in forced convection cooling systems is unfamiliar ground and they tend to shy away. Frequently in designing systems which involve fans, ducting, and forced convection coolers, it is advantageous to make and interpret head loss and volumetric flow measurements. The following is an attempt to clarify this area and to outline instrumentation and procedure. The following does not consider the effects of high altitudes on cooling systems.

The maximum pressures achievable by blowers used in semiconductor cooling are quite low, seldom exceeding 2 inches of water. This permits us to apply the laws governing incompressible fluid flow. Bernoulli's law states that the sum of *velocity head, pressure head* and *elevation head* at one point in a fluid stream will equal the sum of *friction losses* and the same three quantities at a point displaced further along the fluid stream in the direction of flow. We may neglect elevation head since we are working in a buoyant atmospheric environment. Even if we are pumping air to a higher elevation in a hydrogen atmosphere, the density of air is sufficiently low that the elevation head encountered over a 10 ft. rise would be negligible in a practical cooling system. Velocity head is representative of the kinetic energy of the fluid stream and though it is an important quantity to consider, it is difficult to measure in a stream which frequently has a rather large transverse velocity gradient. A further difficulty is that probes intended to indicate velocity are frequently so large that they disturb the original flow conditions. It is very difficult for two experimenters to duplicate one another's velocity data. Therefore, this treatment will not recommend the usage of velocity measurements. We will so arrange our pressure measurements that they will be made in regions of very low velocity. In these regions we will be recording only pressure head and we may then restate Bernoulli's law as simplified for our own special purposes as follows: Static pressure head as measured at a point of negligible air stream velocity equals friction losses plus the static pressure head at another point downstream where the velocity is also negligible.

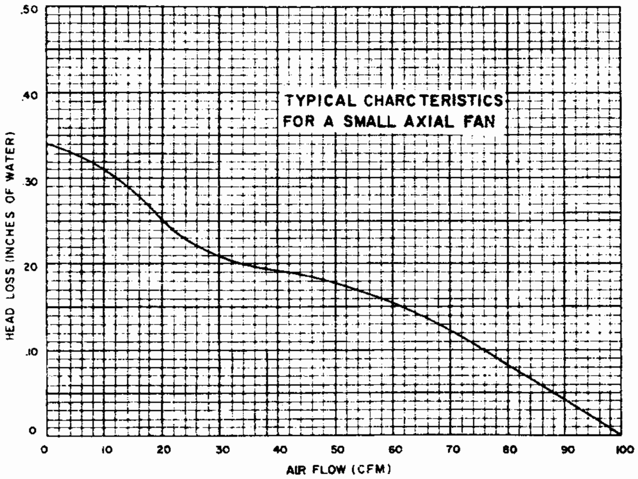


Fig. 6,

A further method for making flow measurements which may be of interest is as follows. If the power input to an air stream is known, then the temperature rise of the air stream can be measured and from consideration of the specific heat of sea level air we may state that:

$$\text{CFM} = \frac{1.76 \times W}{(T_2 - T_1)} \quad (6)$$

where W = power applied to air stream in watts by heat exchangers.
T_1 = temperature in °C of air entering the heat exchangers.
T_2 = Temperature in °C of air exiting from the heat exchangers.

Nichrome heating coils may be strung across the outlet of a cooling system and a known power applied to these coils. Care should be taken to shield thermocouples from radiation and to make certain that enough mixing of the air stream takes place to assure its temperature uniformity. By substituting the measured power and temperatures into equation (6) one may calculate CFM.

5. Recommended Rating Procedure

Three characteristic curves are required to rate semiconductor coolers.

Natural convection coolers require a curve of temperature rise versus power applied. Fig. 9a is illustrative of such a curve for a typical natural convection cooler. (Delta-T Model 423 shown in Fig. 9b.

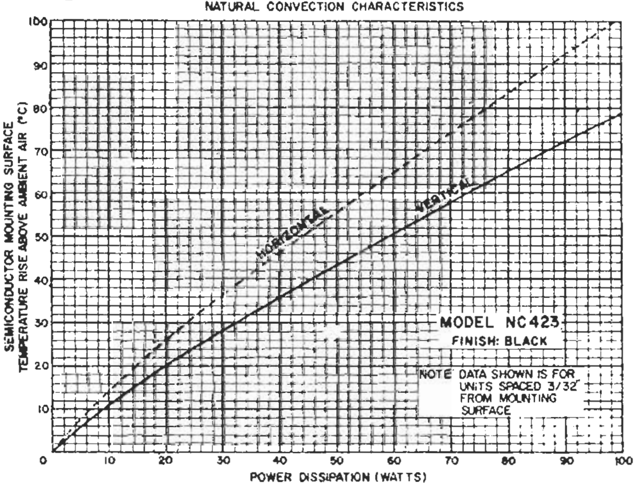


Fig. 9a

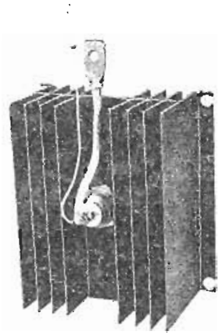


Fig. 9b.

Forced convection coolers require two curves. One shows thermal resistance versus air flow and the other shows static head loss versus air flow. Fig. 10a is a set of curves for a typical forced convection cooler. (Delta-T Model 502 shown in Fig. 10b.)

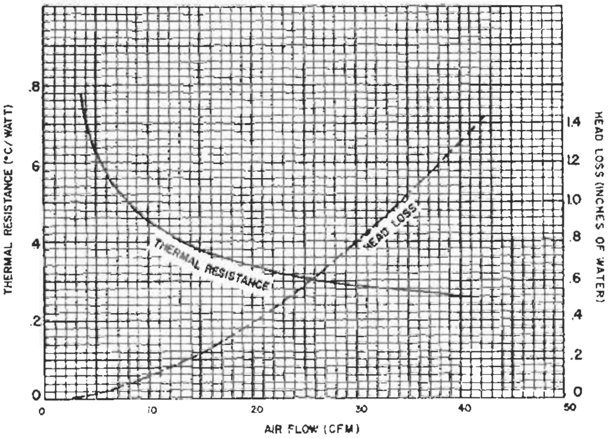


Fig. 10a

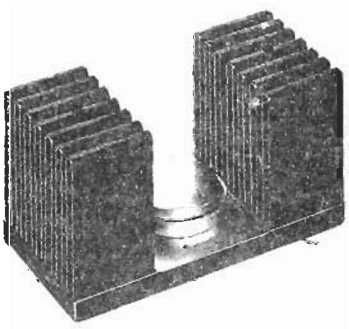


Fig. 10b

In order to rate a modular assembly or group of coolers in conjunction with a fan it is necessary to provide additional rating data. We have chosen as our example of such an assembly the Delta-T Model 800 Package, Fig. 11. This package has coolers arranged in quadrature. The data we have chosen to provide is based on rating each quadrant separately. The number of coolers per quadrant may range from one to six or more. The curves of Fig. 12a show air flow per quadrant versus thermal resistance (θ_{sa}) for the coolers shown in 12b.

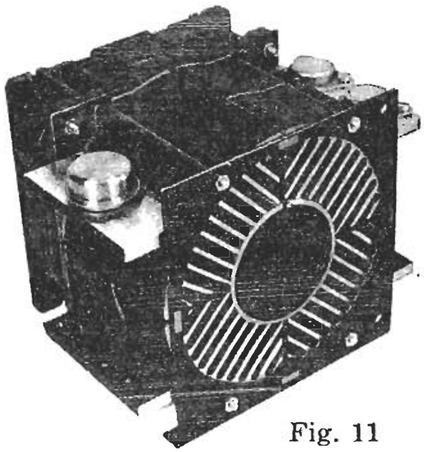
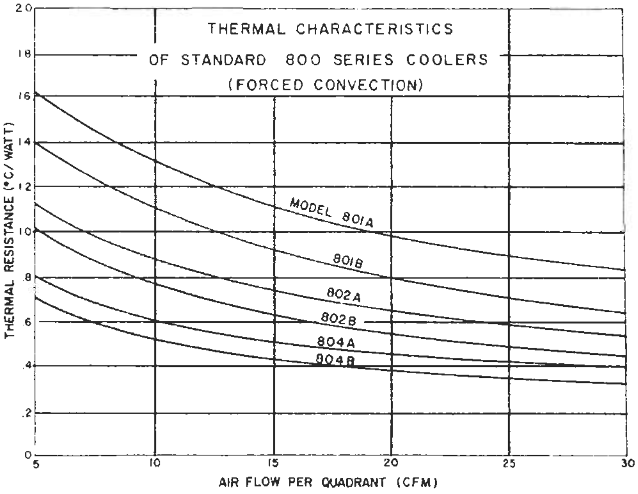
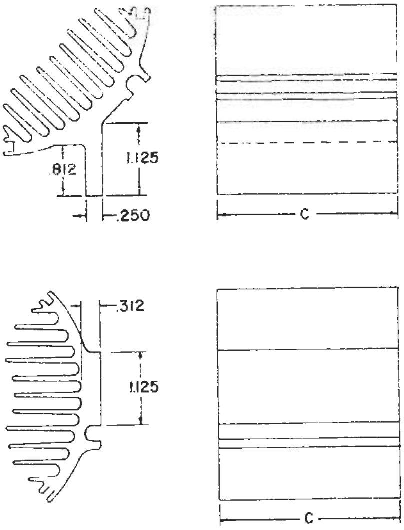


Fig. 11



12a



MODEL NO	DIM. C
801A	1.37
802A	2.81
804A	5.68

MODEL NO	DIM. C
801B	1.37
802B	2.81
804B	5.68

Fig. 12b

In order to determine the air flow per quadrant one may refer to Fig. 13 if the standard fan is used. (Rotron Muffin Fan.) Package length in this curve refers to the number of 801 (Fig. 12b) cooler lengths per quadrant. The 802 cooler is to be considered 2 unit lengths long and the 804 cooler is to be considered 4 unit lengths long.

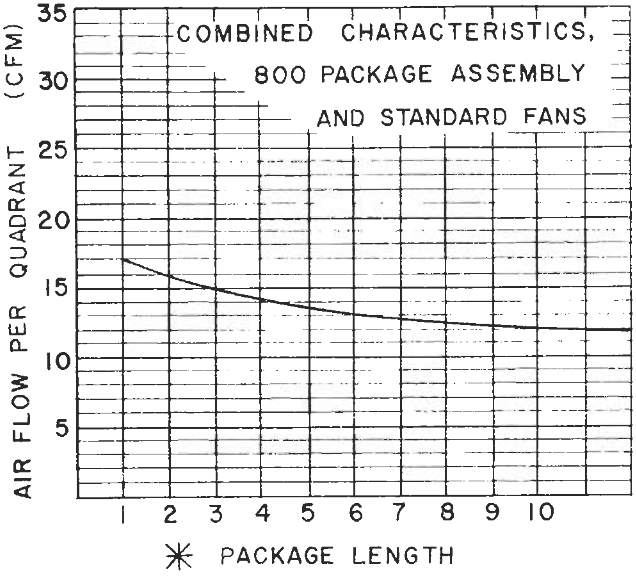


Fig. 13

If a fan other than the standard fan is employed the resulting flow per quadrant may be determined by plotting $\frac{CFM}{4}$ versus head loss of this fan on top of the curves of Fig. 14. The points of intersection will then be at the resulting air flow per quadrant for the various package lengths described by the family of curves.

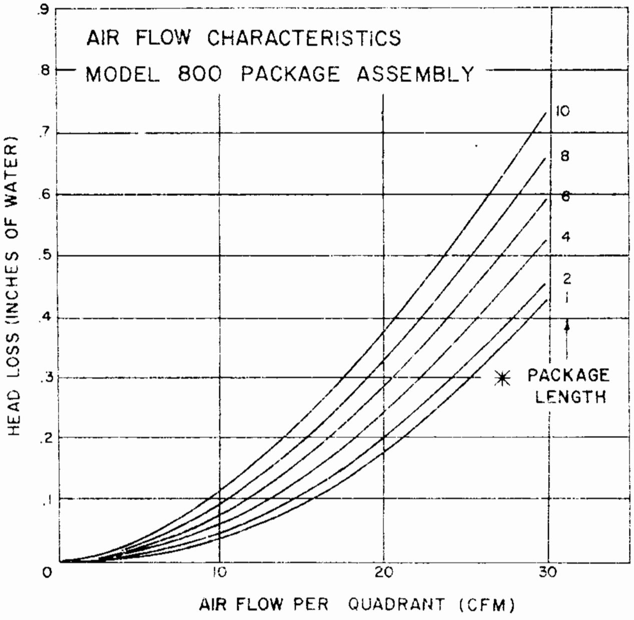


Fig. 14

Natural convection coolers cannot properly be rated in terms of thermal resistance unless the power at which the rating applies is also given. It is readily seen that the curve of Fig. 9a is not a straight line, but that its slope decreases as power increases. This results from the exponential increase of radiation at higher temperatures and from the increasing convection velocities excited by the fins as they increase in temperature.

Another point which should be noted in forced convection cooling systems is that of derating coolers in accordance with upstream power and flow rate. In a series arrangement, the inlet air temperature of a downstream unit will increase by:

$$\Delta T(C^\circ) = \frac{1.76 \times W}{CFM}$$

where W is watts being dissipated upstream. You will note this a rearrangement of equation (6).

The forced convection thermal resistance varies only with air flow. The air flow in this case is provided by a fan rather than the natural convection phenomenon, and is a function of the fan characteristics and the flow resistance caused by the cooler and its associated duct work. For lack of a more reasonable standard we have chosen as a standard duct, one which just encloses the frontal area of the cooler with no clearance. Plastic or other insulatory material should be used to construct the duct. In each case a duct equal to the length of the cooler should be employed.

The mountings provided for the natural convection coolers should be a horizontal surface and a vertical surface. In all cases the cooler should be thermally isolated from its mounting. In rating natural convection coolers the type of finish used should be specified. The author recommends that a black finish be employed.

6. Natural versus Forced Convection

Whenever possible it is preferable to use natural convection coolers for power semiconductors. Not only is the additional cost of a fan eliminated, but also, the fan reliability question does not have to be dealt with. Heat sink thermal resistance as low as 0.5° C/watt can be achieved with natural convection coolers. However, a 0.5° C/W cooler will itself occupy 120 cubic inches of volume and additional space above and below the cooler must be left vacant to provide unrestricted inlet and outlet paths for the air current. A good rule of thumb for estimating the change in natural convection cooler performance as the volume occupied by the cooler varies is as follows:

"To halve thermal resistance one must quadruple the volume the cooler occupies."

The above does not consider the fact that natural convection thermal resistance for any given cooler decreases as the power applied increases.

Vertical stacking of natural convection coolers is not generally admissible because the lower units heat the air stream providing a high effective ambient temperature for the upper units.

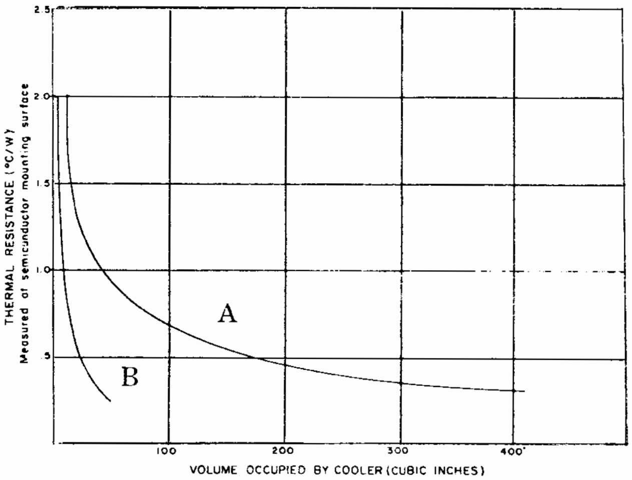


Fig. 15

The curves of Fig. 15 show a comparison between the volume occupied by typical natural (A) and forced (B) convection coolers of varying thermal resistance.

One can see that natural convection coolers become rather cumbersome for thermal resistance below 0.5° C/watt.

The author hopes this booklet will be helpful to engineers dealing with semiconductor cooling. Should you have an unusual problem, he will be pleased to offer his recommendations as to techniques or equipment required to solve it. Please address inquiries to Thomas D. Coe, President, Delta-T Division, Wakefield Engineering, Inc., Wakefield, Mass.