Last month, we concluded with Tables 3 and 4 which were the load line calculations for the driver transistors in the circuit of Fig.1, a straightforward 25 watt amplifier. The next step is to go to your data book and draw the SOAR curves for the BD139/140 transistors. Having done that, plot the load lines from Tables 3 and 4 on to the same graphs. When you have finished, you should find that the curved load lines are fully enclosed by the straight line SOAR graphs. The complete plot was shown in Fig.3 and shows that BD139/140 driver transistors are indeed quite suitable for this application. Last month, we concluded with Tables 3 and 4 which were the load line calculations for the driver transistors in the circuit of Fig.1, a straightforward 25 watt amplifier.

The next step is to go to your data book and draw the SOAR curves for the BD139/140 transistors. Having done that, plot the load lines from Tables 3 and 4 on to the same graphs. When you have finished, you should find that the curved load lines are fully enclosed by the straight line SOAR graphs. The complete plot was shown in Fig.3 and shows that BD139/140 driver transistors are indeed quite suitable for this application. For convenience, we reproduce Fig.3 in this article. *[see earlier article only . . . .ed.]*

With this done, you have finished selecting the output and driver transistors. Now we will move onto calculating the heatsink requirements of the amplifier. This is where, if you made the right choices for transistors, it all comes together.

Selecting the heatsink

The object of selecting a heatsink is to keep the transistor junction temperature below the maximum permissible while still allowing it to dissipate the required power. If the junction temperature rises above the specified maximum, the transistor will probably fail. In any case, it makes good sense to keep the transistor junction as cool as possible. Every 10^0C lower approximately doubles the transistor's life. When considering how a transistor dissipates heat, it is useful to think of Ohm's Law. The heat produced by the transistor chip is analogous to current. The actual temperature at any point is similar to voltage and thermal resistance is like electrical resistance.

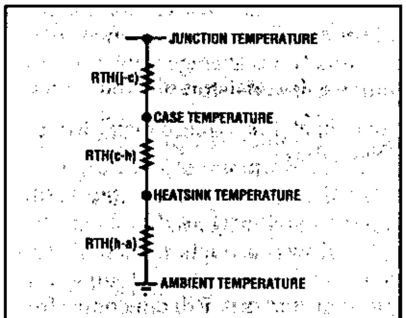

Fig.4: simplified thermal model for a single transistor mounted on a heatsink.

Fig.4 is a simplified thermal model of a single transistor mounted on a heatsink. Notice that there is a resistance between the transistor junction and the transistor case (Rth j-c). This is one resistance you can do nothing about. The method of manufacture and the type of transistor case determine Rth j-c. The other thermal resistances you do have some control over. These include the case to heatsink (Rth c-h) and heatsink to ambient (Rth h-a) resistances. All the components also possess some thermal capacitance. When heat is produced at the transistor junction, the temperature does not rise immediately but climbs more slowly to the peak value. The values of thermal capacitance for the transistor chip, case and washers are small when compared to even a modest heatsink. So for this reason, it is possible to ignore them without significantly affecting the results, in most cases.

There is another thermal path that you should be aware of, even though I won't use it here. It is the heat flow from the case to the surrounding air. The specification is given as either case to ambient (Rth c-a) or junction to ambient (Rth j-a). Either way, it acts as a parallel resistance from the specified point (junction or case). The net effect is to lower the total thermal resistance to ambient. Sometimes there is no value specified or the value is so large that it makes little difference to the final results. Calculating how to keep the transistor junction at a safe temperature is easiest by using the SOAR curves/load lines you have already plotted. You also need to use the temperature derating curves on the data sheets or the formula given later.

At this point, there is no longer any advantage in considering the output stage and driver stage separately. Apply the following steps to both stages.

Derated SOAR curves

On the load line graphs you have to find how far the transistor SOAR curves can be derated while fully enclosing the load line. Draw derated SOAR curves by constructing new power limited and secondary breakdown limited lines parallel to the original lines. The point where the "power limited" line becomes secondary breakdown remains at the same voltage while the current changes. Make sure that part of the SOAR curve just touches the outside of the transistor load lines. Check that the load lines are still fully enclosed by the new SOAR curves.

My new graphs are Fig.5 and Fig.6. Power dissipation is the limiting factor for Fig.5 because the curved load line touches the upper set of sloped lines (which represent the power dissipation limit). In Fig.6, secondary breakdown is the limit because the curved load line touches the lower set of sloped straight lines (which represent the SOAR-limited power dissipation). Look at the power limited section of the new SOAR curves. At a convenient point on the curves, calculate the maximum derated power dissipation. Do this calculation even if secondary breakdown was the limiting factor with your transistor. Note the figures down. Mine are 84 watts for the output transistors (Fig.5) and 5.5 watts for the drivers (Fig.6).

Maximum case temperature

If available, use the temperature derating curve on the data sheet to find the maximum permissible case temperature. Some data sheets have the graph scaled directly in watts while others may use a percentage of the maximum power. The data sheet for the BD139 comes with a temperature derating graph. This graph gives a maximum case temperature of 95^0C. Those data sheets without temperature derating curves can use the following formula to calculate the maximum case temperature:

$$T_{case\ max} = T_{j\ max} - P/P_{max} \times (T_{j\ max} - T_{j\ min})$$

Tj max is the maximum temperature of the transistor junction. At Tj max, the transistor's power handling drops to zero. 200^0C is the most common value for hermetically sealed transistors (metal case) and 150^0C for most non-hermetic (plastic) types. P is the derated power of the transistor from above. Pmax is the maximum power the transistor can dissipate. Tj min is the highest junction temperature at which the transistor can dissipate Pmax. It is usually, but not always, 25^0C and is next to Pmax on the data sheet. For example, Tj mm for the 2N3055 is 25^0C and for the BD139, 70^0C.

For the example of the output stage in my design, the following values are derived from the data sheet: Pmax equals 115 watts; Tj max is 200^0C; and Tj mm is 25^0C. P comes from the derated SOAR curve above and in this example is 84 watts. Poking all the numbers into the formula gives:

$$T_{case\ max} = 200 - 84/115 \times (200 - 25)$$
$$= 200 - 0.73 \times 175 = 72^0C$$

Now is as good a time as any to decide what heatsinking configuration to use. Mathematically, the simplest approach is to mount each transistor on its own heatsink. This has some practical advantages too. With the heatsinks electrically isolated, the insulating washers are superfluous. The lower thermal resistance (Rth c-h) can result in smaller heatsinks or greater reliability. One problem (beside cost) is the greater difficulty in providing the bias current with thermal stabilisation.

A common heatsink

The most common approach is to mount all the transistors with insulating washers on a common heatsink. Check carefully to see if there are any other possibilities that could result in significant benefits. One example would be if you designed an amplifier with only the output transistors connected in common collector mode. Mounting these transistors without insulating washers is possible with an electrically isolated heatsink. This could lead to some savings with either the type of transistor used or size of heatsink.

Fig.7 is a simplified diagram of the thermal paths for my amplifier. I've used the commonest approach and mounted everything on the one heatsink and used insulating washers on all the transistors. The values used for Rth c-h are from Table 5 which is collated from a variety of sources. If you are using a transistor package not listed in Table 5, make an approximation based on the mounting area of one of the listed packages.

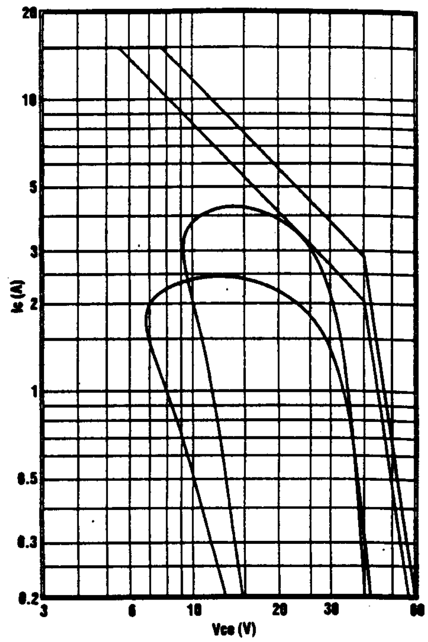

Fig.5: graph showing the derated SOAR curve for the output transistors. This curve is derived by constructing new power limited & secondary breakdown lines parallel to the original lines, so that they just touch the transistor load line.

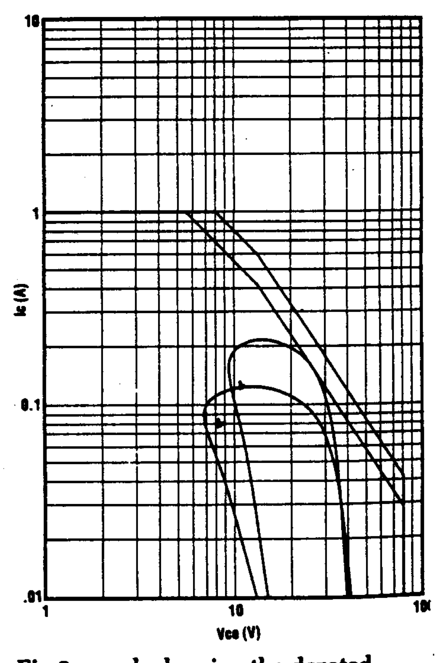

Fig.6: graph showing the derated SOAR curve for the driver transistors. Note that secondary breakdown is the limiting factor here, while power dissipation is the limiting factor for Fig.5.

Table 5: Thermal Resistance (c-h) For Common Packages

	TO-3	TO-66/SOT-93	TO-220	TO-126
Insulating washer No heatsink compound	1.50	4.55	5.68	13.64
Insulating washer Heatsink compound	0.33	1.00	1.25	3.00
No insulating washer No heatsink compound	0.50	1.20	1.50	3.60
No insulating washer Heatsink compound	0.10	0.24	0.30	0.72

Heatsink Compound

Notice that the use of heatsink compound reduces the thermal resistance to one fifth, making it well worth using.

There is one last formula to use before the completing the amplifier design. Truthfully, there is a little more than one but the rest are trivial. You have to calculate the average power dissipated in the transistors while driving the load. The formula is:

Pave diss = [(Vcc - Vripple/2) x ImaxI/*pi* - [Vmax load x Imax load x cos(*T*)]/4

["T" is used in place of Theta, and "pi" = 3.142 etc. . . . . .ed.]

Subtracting half the ripple voltage from Vcc gives a simple approximation for the average voltage supplied to the transistors. Use the values associated with the nominal load impedance for your amplifier. The calculations for my output stage are:

Pave diss = [(27 - 3/2) x 2.5]/*pi* - [20 x 2.5 x cos45^0]/4 = 11.41 watts.

And for the driver transistors:

Pave diss = [(27- 3/2) x 0.125]/pi - [20 x 0.125 x cos45^0]/4 = 0.573 watts.

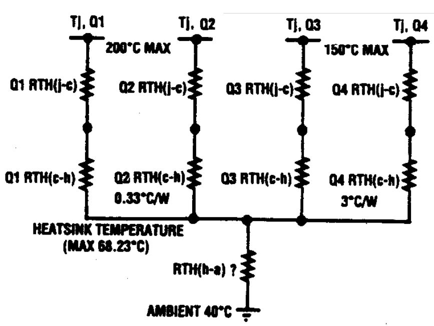

Fig.7: simplified diagram showing all the thermal paths for the amplifier (note: driver & output transistors all mounted on the same heatsink).

This is the average power dissipated by the transistor when producing a continuous full power sinewave into the nominal load. As you would expect, these values are quite a bit lower than the peak values calculated earlier. This is not the worst case figure which is obtained when the output is shorted. Driving the amplifier into clipping also produces higher power dissipation. Both of these conditions are abnormal and can be protected against by the careful selection of fuses or electronic limiting.

Now comes the part that is a little hit and miss, like fitting in the last parts of a puzzle. Exactly how you proceed depends on what you have to fit into place. The object is to find the heatsink size that allows the transistor cases to stay below the maximum temperatures calculated before. For my example, I have all the transistors on one heatsink and I'll proceed as follows.

Heatsink size

First, find the maximum permissible heatsink temperature for both transistor stages. This is simply the maximum transistor case temperature minus the thermal resistance to the heatsink times average power dissipation of the transistor.

Tmax heatsink = Tcase max - Rth c-h x Pave diss

Remember that Pave diss is like current in Ohm's Law. The heat dissipated flows through a thermal resistance and produces a temperature gradient across it. Rth c-h comes from Table 5. For the output stage of my amplifier, the formula becomes:

Tmax heatsink = Tcase max - Rth c-h x Pave diss = 72 - 0.33 x 11.41 = 68.23^{0}C

Similarly, for the driver stage, the maximum heatsink temperature would be 93.28^{0}C. Because in this case all the transistors are mounted on the one heatsink, 68.23^{0}C has to be the maximum allowable temperature. The next step is to find the total heat flow into the heatsink. This is a simple addition of the power dissipation of all the transistors. For my example, there is the power dissipated by the two driver transistors plus the power dissipation of the two output transistors.

This gives a total of 23.97 watts dissipation. Now make an approximation of the maximum ambient temperature inside the amplifier enclosure. 40^{0}C is a commonly used figure. Another item to consider is the use of a mounting bracket for the transistors. The mounting bracket adds further thermal resistance between the transistor and the ambient temperature. In many cases, simply adding 5-10^{0}C to the ambient temperature deals with the problem. But it is better to use the thermal resistance, if you know it. The final value of heatsink thermal resistance is another simple application of Ohm's Law. You know the heat flowing in, the temperature gradient (maximum heatsink temperature - ambient) and you need to find the thermal resistance.

Rth h-a = (Tmax heatsink - T ambient)/Ptotal dissipation
= (68.23 - 40)/23.97
= 1.18^{0}C per watt

That's equivalent to just over 150mm of common fan type heatsink. Unless you need a very sturdy amplifier, such a large heatsink will almost certainly make this design uneconomical.

Smaller heatsinks

Fortunately, the situation of an amplifier delivering its full power on sinewaves for more than a minute is not common. Even the most determined organist is unable to remove every rest from a tune. Music and PA amplifiers produce peak power for only a small percentage of the time. This means you can use a smaller heatsink than shown above because the average power dissipation of the amplifier is much less. The large thermal capacitance of the heatsink will smooth out any high peaks in temperature. How much smaller can you make the heatsinks? There a two widely used rules of thumb that can help to guide you.

The first rule of thumb says that with the worst case signal (rock music from an FM station), the average power dissipation equals 15% of the peak output. For my amplifier above, this would mean the heatsink needs to cope with an average dissipation of 3.6 watts. That works out to a thermal resistance of 7.8^{0}C per watt. A piece of aluminium a bit bigger than normally used as a heatsink mounting bracket will suffice. The amplifier case would also be suitable. This size of heatsink makes the amplifier suitable for

Table 3

ωt-θ	ωt	Vce	Ic	Ppk(W)
0	45	12.858	0.000	0.000
15	60	9.537	0.032	0.309
30	75	7.406	0.063	0.463
45	90	6.611	0.088	0.584
60	105	7.205	0.108	0.780
75	120	9.148	0.121	1.105
90	135	12.308	0.125	1.538
105	150	16.469	0.121	1.988
120	165	21.347	0.108	2.311
135	180	26.611	0.088	2.352
150	195	31.901	0.062	1.994
165	210	36.858	0.032	1.192
180	225	41.142	0.000	0.000

Table 4

ωt-θ	ωt	Vce	Ic	Ppk(W)
0	45	14.781	0.000	0.000
15	60	11.789	0.056	0.659
30	75	9.834	0.108	1.062
45	90	9.048	0.153	1.382
60	105	9.486	0.187	1.774
75	120	11.117	0.209	2.319
90	135	13.831	0.216	2.987
105	150	17.442	0.209	3.639
120	165	21.705	0.187	4.060
135	180	26.328	0.153	4.021
150	195	30.997	0.108	3.348
165	210	35.394	0.056	1.979
180	225	39.219	0.000	0.000

home use or anywhere it will be treated with some respect.

The other rule of thumb is the peak music power figure which says the average power equals the peak power divided by 2.25. This usage has nothing to do with the shameless way some manufacturers use peak music power figures to boost sales. This calculates to an average dissipation of 10.6 watts, requiring a heatsink with a thermal resistance of 2.7^0C per watt. Any of the multipurpose 75mm-long heatsinks will work. This amount of heatsinking gives an amplifier suitable for most professional and semi-professional applications. The choice of a 75mm-long fan type heatsink provides an interesting design. Mounting the transistors through the heatsink directly onto the PC board gives a compact design that will fit inside a "one unit high" rack mounting box. The larger heatsink also means that the amplifier will safely handle quite a bit of sustained thrashing. You beauty!

Fuse selection

One further step is the selection of fuse protection. Fuses are not optional. It is true that the output transistors often blow before the fuse. Don't make the mistake of saying "the transistors often protect the fuse by blowing first. Fuses go open circuit, transistors normally go short circuit. If an output transistor goes short, the speakers are connected directly to your power supply. Without a 50-cent fuse, your expensive speakers can burn out. Should a fire result, you could find yourself being held liable for damages.

Use a normal fast fuse between each supply rail and the output and driver transistors. This placement is preferable to using one fuse in-line with the speakers. If you are using a polyswitch or MOSFET's in the output, you may decide that it's OK to delete these fuses but you will still need the fuse in line with the mains as described later. For the output transistors, the fuse value is selected empirically. A good starting point is to make the fuse equal to Imax load divided by 3.18. This size fuse should allow the amplifier to produce a continuous sinewave output and allows a bit of clipping during music. Gross levels of clipping should blow the fuse. Use a slow blow fuse in line with the mains supply. This provides protection if the power transformer, bridge rectifier or a filter capacitor goes short. Its value should be:

$$\text{Fuse (slow blow)} = \text{Vcc x (Imax load) x } 0.71/240$$

For my amplifier, that comes out to about 200mA. Remember to make allowance for power drawn by other parts of the circuit. For low power amplifiers, it will be difficult to find a slow blow fuse near the value you need. The smallest value you can find will be OK. In any event, the slow blow fuse should only operate in response to catastrophic failures.

That's it, finished. You should now be able to design reliable output stages for your amplifiers. So go to it.