Measurements of a forward SCT thermal module

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1 The Module

Tests were made on a thermal equivalent model of a "Liverpool" module. This module uses single sided silicon detectors glued two on each side of a beryllia spine. There is a beryllia hybrid at the broad end of the wedge and a single point cooling and support contact in between silicon and the hybrid.

The module was assembled in Manchester, following Martin Gibson's prescription for spreading glue over a well-defined area using masks made of wafer protection film. Although fiddly, this was succesful and resulted in a double glue layer thickness which varied from 216 to 243 microns across the module (where we were aiming for 100 microns per glue layer).

The heating of the silicon was simulated by a zig-zag of nichrome wire glued to each side of the modules. The heat load from the chips was simulated by sets of resistor packs glued to the hybrid. The module was mounted on a water cooled support block and enclosed in a $20 \times 15 \times 5$ cm^3 plastic box. Thermocouples monitored the temperature of 8 points on the silicon, 3 points on the hybrid, the support block, the inlet and outlet water pipes, the air at a point about 1 cm from the centre of the module and the enclosing box.

2 Convection coefficient

Given the reported importance of convection in removing heat from a module, we first measured the convection coefficient. This was done by removing the module from its cooling block and supporting it instead on a couple of pieces of insulating foam which touched the module in two small areas. The module was then heated with a uniform power density, ie three times more power into the silicon than into the hybrid because of its three times larger area. The module was initially in a horizontal position with the "air" thermocouple directly above the silicon. Figure 1 section I shows how the temperatures initially rose to an equilibrium with the air temperature about 1.5 degrees below the module temperature when the module power was turned on at 1W. In section II the whole box was then turned on its edge , produlcing a slight drop in module temperature and a sharp drop in the air thermocouple. In section III the box was turned upside-down; the air monitor barely changes but the module warms up slightly. After being put back on its edge again (section IV) the power input was doubled and temperatures rose as shown in section V.

From this series of measurements we conclude that: a) the air temperature inside the box is fairly uniform apart from a stream of warm air which rises from the module. Provided the box is not in the horizontal position the typical air temperature is well represented by the air thermocouple. b) The heat loss by convection is not strongly dependent on the module orientation but is slightly more efficient when the module is vertical (cooling fins are normally vertical). Since the forward modules will always be vertical in Atlas we made all subsequent measurements in the vertical position. The convection coefficient derived from these measurements was 11.5 W K^{-1} m^{-2} with 1 W applied and 11.8 W K^{-1} m^{-2} with 2 W applied.

These numbers seem reasonable but we were concerned that they might not represent the situation where a module is in a much larger volume of gas, such as a module in the SCT. To check this we repeated the measurements with the lid removed from the box so that room temperature air could circulate past the module. In this case we found that the air thermocouple varies rapidly by about 0.5 C due to drafts. Also, the air thermocouple reads on average about 0.5 C above the temperature of the rest of the room, indicating that it is picking up a little heat from the module. In spite of these uncertainties the convection coefficient derived from this measurement was not so different; 10.9 W K^{-1} m^{-2} if we use the air thermocouple temperature or 9.9 W K^{-1} m^{-2} if we use the general room temperature.

Thus we conclude that a single coefficient represents the complex process of heat loss by convection surprisingly well and its value is somewhere around 10 to 12 W K^{-1} m^{-2}.

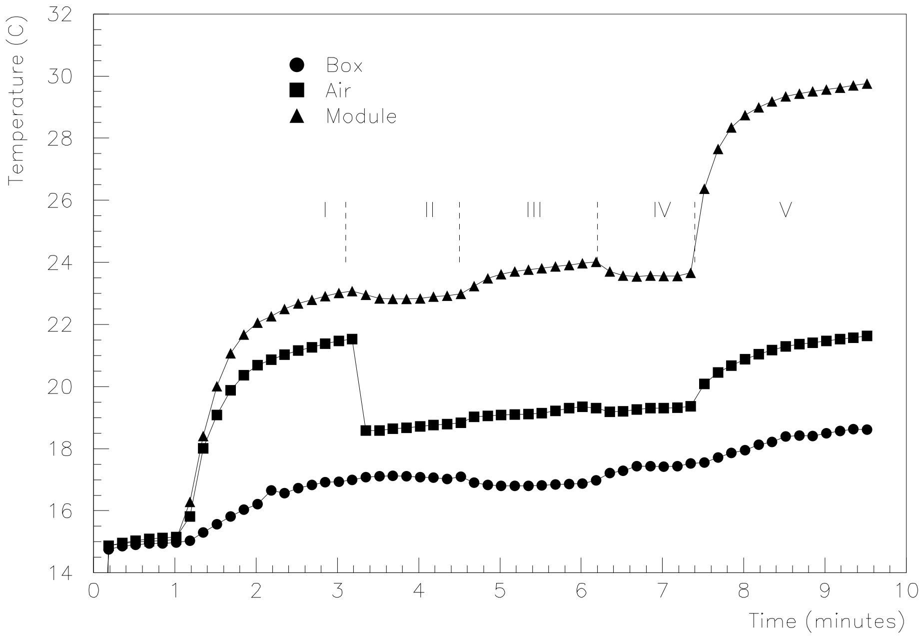


Figure 1: Measurements of the thermal model at various orientations and power densities.

3 Module conduction

3.1 One-dimensional model

In order to understand the module conduction in the presence of convection we need a mathematical model. A simple 1-d model should work quite well because the silicon part of the module is approximately a linear structure with heat applied uniformly along its length and taken out at one end by conduction and taken out at all points by convection. So the equation to solve is ;

$$P + R\frac{d^2T}{dx^2} + S(T_{air} - T) = 0$$

where;

- P is the power input per unit length (1 / 0.12 W m^{-1}).
- R is the cross section of module $\times$ thermal conductivity. Equal to $0.06 \times 0.0006 \times 136$ for the silicon plus $0.02 \times 0.0005 \times 280$ for the beryllia. Total = 0.0077 W m K^{-1}.
- S is the circumference of module (0.12 m) $\times$ convection coefficient.
- T is the temperature .
- x is the distance from the end of the module.

3.2 Measurements

Measurements were made with power applied to the silicon only and with power on both the silicon and the hybrid. The module was in the vertical position for both measurements. Figure 2 shows the measured temperature at three points on the module; near the cooling contact, at the middle and near the tip. The data is compared to the predictions of the 1-d model with various values of the convection coefficient. Agreement between data and model is good when the convection coefficient is given the value 11 W K^{-1} m^{-2} which we measured previously.

This means that the conduction of heat along the module is well represented by the R value used above, showing that the glue joints have little influence and the variable width of the beryllia spine can safely be approximated by an average value.

Figure 3 gives typical measurements of the temperature at several points on the module. The large difference between the coolant and the cooling block temperature is because we did not take care of this part of the design; it could certainly be reduced. The difference between the cooling block and the closest part of the silicon is almost acceptable and it may be improved by increasing the area of the diamond-shaped contact area. At first sight the temperature variation within the silicon looks very good but as explained above this is due to a large heat flow from the silicon by convection which can not be used within the Atlas environment. The hybrid temperature is less influenced by convection because of its smaller surface area.

3.3 Extrapolations

Given that the model seems to work, we can now use it to simulate the temperature distribution along a module when it is in equilibrium with the air around it. The result is shown in figure 4 where it is compared with a simulation having no convection. The air reaches equilibrim with the silicon when its temperature is 4.66 C.

4 Improvements

Clearly this module with a single cooling point, when in equilibrium with the surrounding air, does not meet the specification that the temperature variation within the silicon must be less than 4 C to avoid thermal runaway. However it may be improved by either cooling the air to a tempereature a little below the cool end of the module or by adding another cooling connection at the tip of the module.

4.1 Cooling through the wheel skin

We have investigated the possibility that the carbon-fibre skin of the wheel may be cooled sufficiently by the existing cooling block to provide a second cooling point at the tip of the module wiithout adding extra pipework.

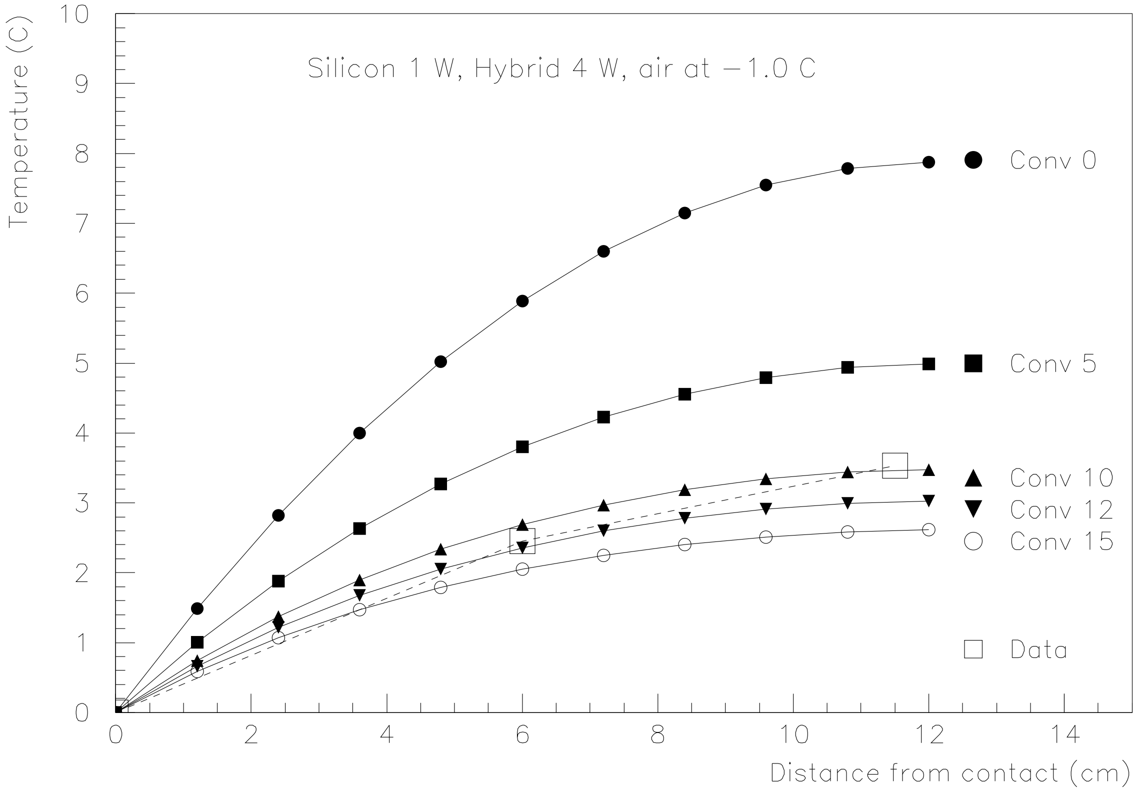
We mounted the module on a 6×12 cm^2 piece of carbon fibre honeycomb and connected the tip to the carbon fibre with an aliuminium block. The resulting temperature distribution along the module is shown in figure 5 where it is compared with the simulation described earlier which assumed no heat flow from the tip of the module. This shows that the module tip has been cooled slightly by making a thermal connection between it and the carbon fibre plate but this is not sufficient to bring it within spec. We find that the simulation can reproduce this data if a heat flow of about 0.1 W from the tip of the module is included and the simulation shows that this needs to be increased to more than 0.3 W to bring the module within spec.

4.2 A second cooling pipe

The previous section shows that a cooling connection between the module tip and a nearby pipe will probably bring the module within spec. We made such a connection with a lightweight aluminium clip having a cross section of approximately 10×1 mm ^{2} and length of 8 mm. One end was bolted onto the beryllia extention at the tip of the module and the other end clipped onto a circular cooling pipe. The resulting temperature distribution along the silicon when it is heated with 1 W is shown in figure 6. In order to match the temperatures at the tip and the base of the silicon we found it necessary to assume a heat flow of 0.24 W from the tip, the simulation then predicts the temperature distribution shown by the black circles and it predicts that 0.27 W is being conducted from the base of the module and the remainder (0.49 W) is lost by convection. From these figures we can then calculate the thermal resistance between the two ends of the module and the coolant, which leads to the prediction that when the silicon is in equilibrium with the air its temperature distribution will be as shown by the squares in figure 6.

5 Conclusion

- A single point cooling contact is not enough for this module but two point cooling brings the ΔT_{Si} value down to 2.2 C which should be low enough to prevent thermal runaway. The second contact may be lightweight compared to the main one which cools the hybrid.
- Convection has an important effect on module temperature and seems to be well described by a single coefficient of 11 W m^{-2} K^{-1}.
- Given the importance of convection it seems possible that a significant vertical temperature gradient may build up when several modules are enclosed in the same gas volume. This needs more investigation.



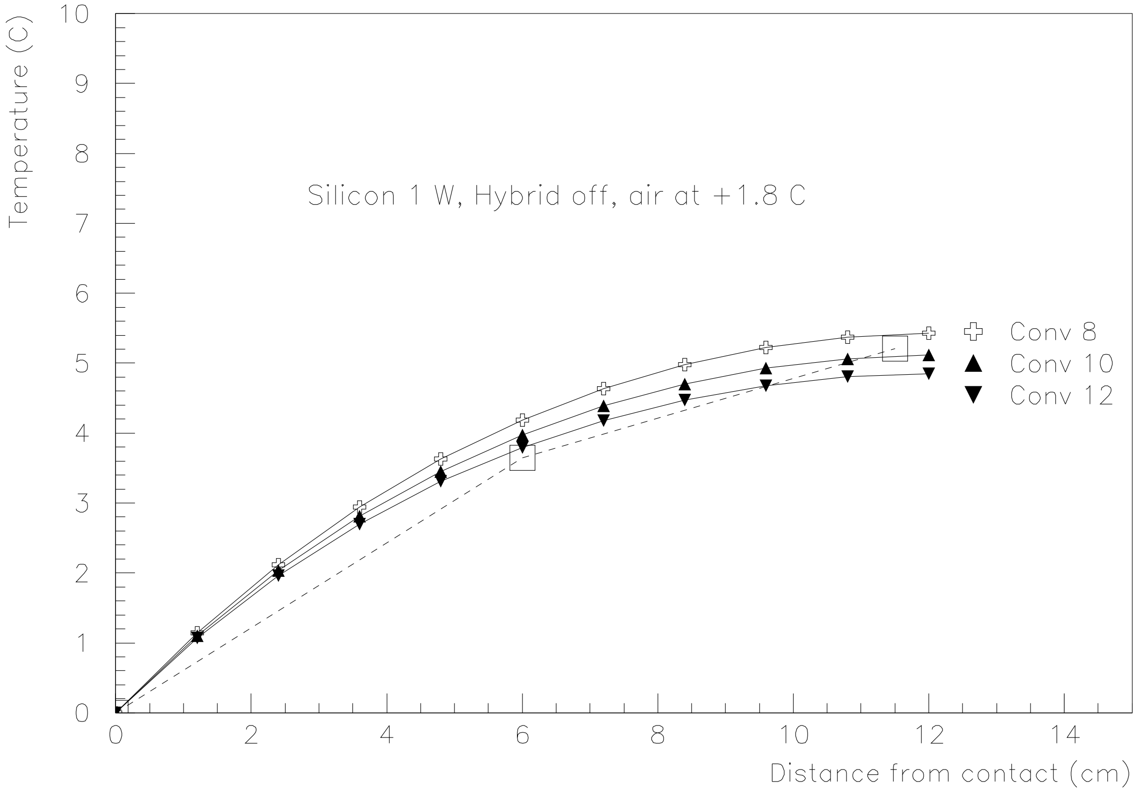


Figure 2: Measurements of the thermal model in two different conditions are compared with the results of a simple 1-d model which has just one free parameter; the convection coefficient. Data agrees with the model when the coefficient is about 10 W K^{-1} m^{-2}

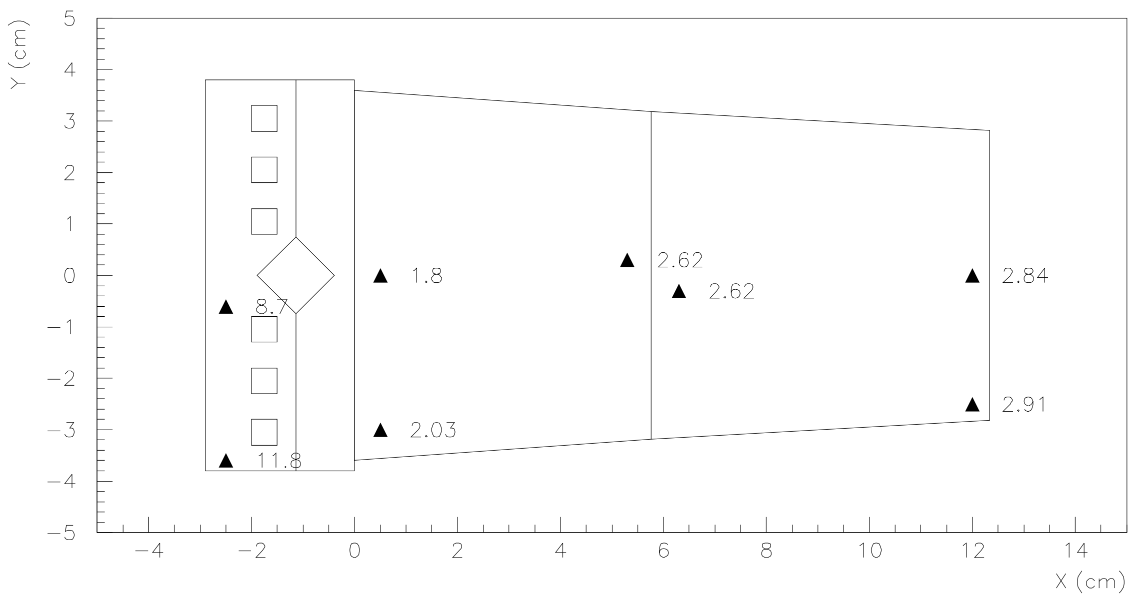


Figure 3: Measurements of the thermal model with 1 W supplied to the silicon and 4 W on the hybrid. The air was at -4 and the coolant was at -5.9 degrees. All temperatures are measured relative to the cooling block.

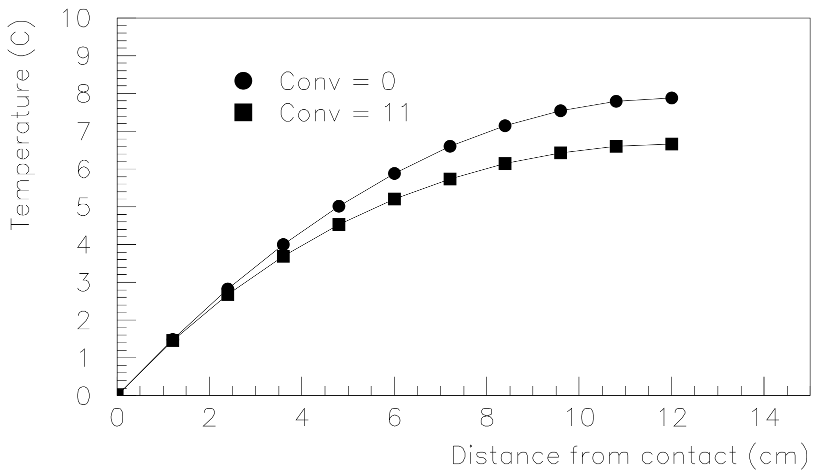


Figure 4: Simulation of temperature distribution along the silicon when it is in equilibrium with the air.

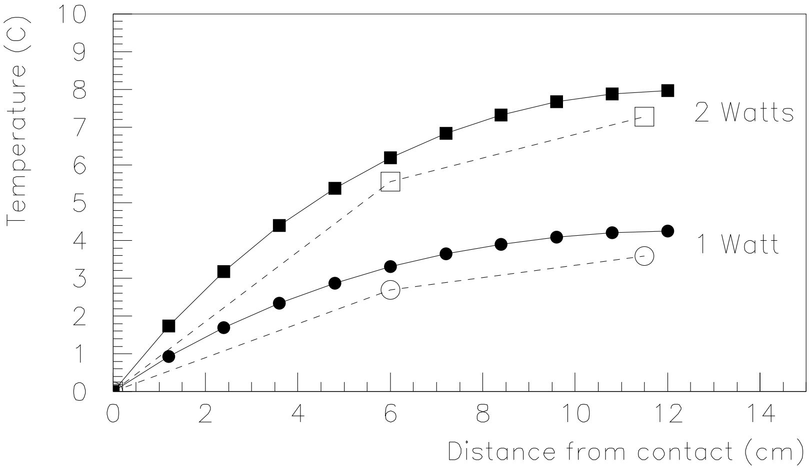


Figure 5: Measurement of temperature distribution along the silicon when the point at 12 cm was thermally connected to the c/f support. Simulation does not take into account this thermal connection. The air temperature was 0.63 C in the 1 Watt case and 0.36 C in the 2 Watt case.

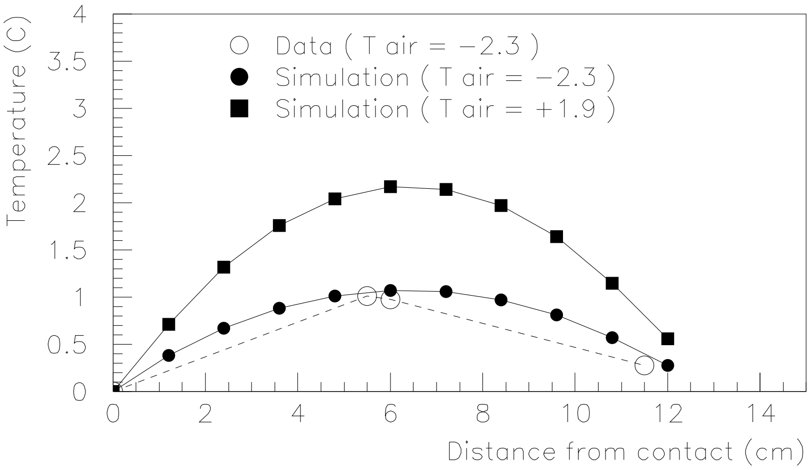


Figure 6: Measurement of temperature distribution along the silicon when the point at 12 cm was thermally connected to a second cooling pipe. This is compared with a simulation which matches the data and a second simulation in which the air is in equilibrium with the silicon. The power input to the silicon was 1 W in all cases.