HEAT LOADS AT HIGH TEMPERATURE PROTECTION DIODES FOR A MERCURY MISSION

Reul, S.[1]; Zimmermann, W.[2]; Strobl, G.F.X.[2]; La Roche, G.[2]; Baur, C.[3]

[1]PRETECH Predictive Design Technologies GmbH, Hamburg, Germany: sreul@pretech.de

[2]AZUR SPACE Solar Power GmbH, Heilbronn, Germany: walter.zimmermann@azurspace.com, gerhard.strobl@azurspace.com, g.laroche@t-online.de

[3]European Space Agency - ESTEC, Noordwijk, The Netherlands: carsten.baur@esa.int

ABSTRACT

In the frame of the BepiColombo project (see Fig. 1) the solar generators have to withstand the environment near Mercury. Thus all components must withstand an solar irradiation of 10 solar constants or 13.67 kW/m². Due to manoeuvres it can happen, that e.g. solar cells will be shadowed or all cell interconnections can fail. To prevent the solar cells from operating in reverse a high temperature protection shunt diode is foreseen for each GaInP/GaInAs/Ge solar cell. This paper reports about first computations of the temperature distributions for different load cases with useful assumptions for the generator structure, sizes/shapes, etc.

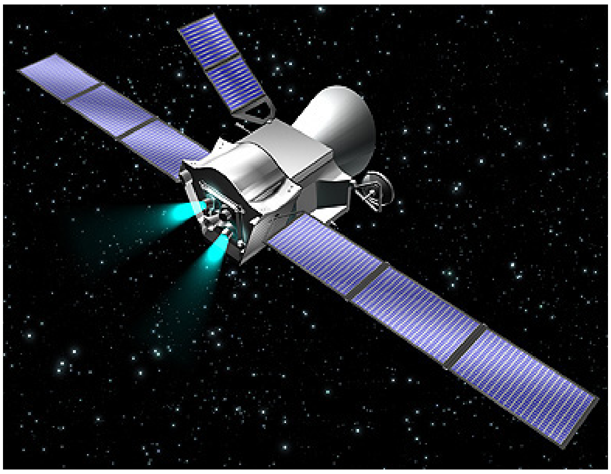

Figure 1: BepiColombo Spacecraft

Also the main temperature influencing parameter and some useful consequences for a high temperature design of a solar generator and Si-diodes will be discussed.

The work is part of the ESA contract 19739/06/NL/JD. The Si-diode layout is proposed by AZUR SPACE solar power, Heilbronn.

1. GENERAL REQUIREMENTS

Near Mercury the following general requirements should be met (will be changed in future development work):

- Solar irradiation intensity: 10 solar constants, thus 13.67 kW/m²
- Max. irradiation angle: 45° (max. sun intensity 70.7 % or 9.666 kW/m²)
- Max. temperature: <300 °C
- Max. solar cell current: 3.0 A.

The diode temperatures (p/n-junction) may be higher than 300 °C, but the laydown and cover glass adhesives as well as other components must be below 300 °C.

Structural requirements are not considered in this investigation.

2. GENERAL LOAD CASES

During the mission e.g. the following load cases or failure modes will be considered:

- All solar cells see the full solar irradiation ('normal operation', case lc1):
  - absorbed solar irradiation
  - electrical power at 3.0 A
- A solar cell in a string is totally shadowed (case lc2):
  - no solar irradiation at this solar cell and thus, no power input (no solar irradiation)
  - electrical power on all other cells at 3.0 A
  - neighbor diode generates maximum power at 3.0 A
- All interconnectors are totally broken at one solar cell (case lc3):
  - neighbor diode generates maximum power at 3.0 A
  - affected solar cell 'sees' full solar irradiation.

3. CONSIDERED GENERATOR COMPONENTS

The computation model includes the following generator components/parts as geometric volumes or areal shells (with considered thicknesses):

- Generator substrate (will be changed in future development work):
  - Carbon fibre skins (2x) each 0.40 mm
  - Honeycomb core 18.00 mm
  - Kapton plus resin 0.05 mm
  - Total thickness structure 18.85 mm.
- Solar cell assembly SCA (preliminary values):
  - CMX cover glass 0.100 mm
  - Cover glass adhesive 0.025 mm
  - GaInP/GaInAs cell layer 0.008 mm
  - Ge cell substrate 0.140 mm
  - Ag read side contact (shell) 0.005 mm
  - Cell laydown adhesive 0.100 mm
  - Total thickness SCA 0.378 mm.

Proc. of the '8th European Space Power Conference', Constance, Germany, 14–19 September 2008 (ESA SP-661, September 2008)

- Diode assembly DA (preliminary values)
  - CMX cover glass 0.100 mm
  - Ag-reflector (shell) 0.0005 mm
  - Cover glass adhesive 0.025 mm
  - Ag top layer (shell) 0.005 mm
  - Si substrate 0.140 mm
  - Ag read side contact (shell) 0.005 mm
  - Diode laydown adhesive 0.100 mm
  - Total thickness DA 0.3755 mm.
- Cell and diode laydown adhesive size
  - Usually the adhesive size is different from the cell or diode size; thus, in the calculation model a not-covered border of about 4 mm is integrated for the cells; this is a worst case situation and will result in maximum temperatures
  - The same is assumed for the diodes; here a border of about 1 mm is considered.
- Diode and solar cell interconnectors (used only in the 'core' region of the calculation model; will be changed in future development work):
  - Each connecting region uses 4 fingers (see Fig. 3)
  - Finger width 1.25 mm
  - Interconnector thickness 0.02 mm.

The GaInP/GaInAs/Ge solar cells are from ASUR SPACE of the type 3G ID2*/150-8040 (size 80 x 40 mm). The Si-diode has a triangular shape of 10.8 x 10.8 mm.

4. CALCULATION METHOD AND SOFTWARE

Modeling of such a complex geometry is best done with the Finite Element Method. In this case the software CFdesign from Blue Ridge Numerics is used [1]. Here - using the native geometry of a CAD code - the boundary conditions (e.g. temperatures, heat loads, initial conditions, etc.), the element definitions (element sizes; generation of the elements is performed fully automatic), the materials (fluids, solids, special elements, etc.) and settings are defined. After computation the results will be displayed graphically.

In this investigation only radiation and heat conduction is considered.

The geometry is generated in the CAD system Pro/ENGINEER from Parametric Technology [2]. This makes it quite simple to change the dimensions of the geometry and exchange parts.

5. GENERATOR GEOMETRY MODEL

As stated above the solar generator components are very thin and have a big areal extension. If the geometry is modeled in the original size and then meshed automatically the number of elements will be too big.

Thus, a very helpful trick is to model all components thicker than in reality. In this investigation the thicknesses are scaled between 1- (original thickness of the honeycomb core) and 500-times (GaInP/GaInAs layer on top of the solar cell).

For compensation of these wrong thicknesses the thermal conductivities are multiplied or divided by the thickness factor: the perpendicular thermal conductivity is increased and the inplane conductivity is lowered appropriate. Thus, all material data are defined orthotropic. If transient analyses are performed the thermal capacities must be lowered as well. This results in correct temperature fields.

Basis of the calculations is a 3D-CAD model of a generator cut-out with 9 x 6 SCA's (see Fig. 2 and Fig. 3).

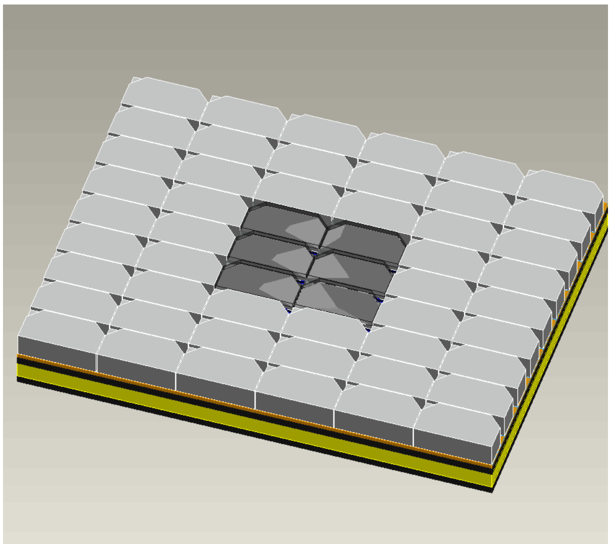

Figure 2: Solar generator with scaled thicknesses

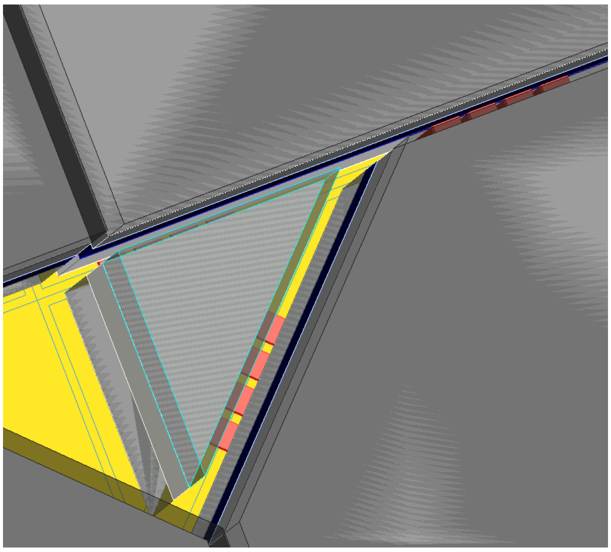

Figure 3: Si-diode and interconnectors

Outside of the core region (the darker grey 2 x 3 solar cells) dummy cells and diodes are modeled (only one layer with appropriate material data).

6. GENERATOR CALCULATION MODEL

All in chap. 3 presented parts/components are incorporated in the calculation model. Some details are reported hereafter.

6.1 Boundary conditions

Main boundary conditions are the heat loads and radiation properties of the top and bottom surfaces of the generator.

In Fig. 4 a detail is shown in the core region. Here the cover glasses and cover adhesive layers are hidden. So a view can be seen to the heat absorbing GaInP/GaInAs layers on top of the solar cells (blue stripes). In the upper left area the diode cover glass is seen with a magenta stripe, which represents the emissivity to free space.

It can be seen also, that the interconnections are also modeled, so that the ohmic losses and the heat fluxes can be considered, too. The green surfaces represent the Kapton layer in the cell gaps.

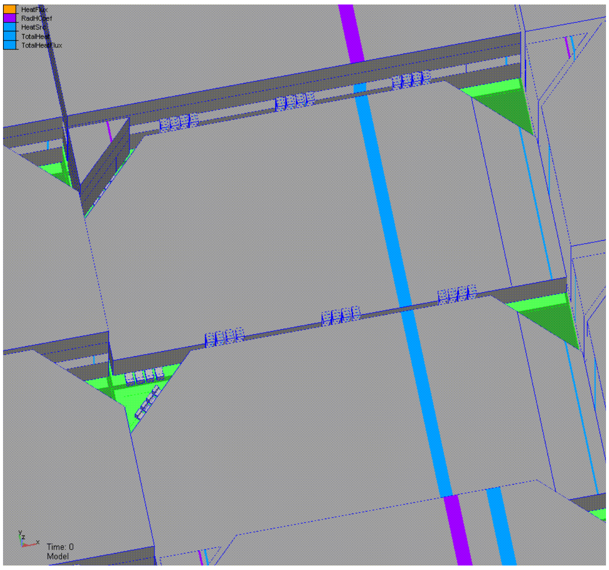

Figure 4: Thermal model with boundary conditions (colored stripes), detail with cells, interconnectors and Kapton layer (green)

Heat loads are considered according to the above mentioned irradiation intensities (9.666 kW/m^2), the absorption coefficients and - for the solar cells only - the electrical power (lowers the absorption according to the - at a given temperature - generated electrical power). The diode heat load in lc2 and lc3 is also defined temperature dependent. At 300 °C a Si-diode can generate a power loss of 1.716 W.

6.2 Material data

As stated above all material data are defined orthotropic to consider the greater thicknesses in the calculation model.

Additionally - if known - all data are defined temperature dependent. For the adhesive layers it is also incorporated, that transfer resistances are given at the interfaces to the cells/diodes, cover glasses and Kapton layer. They lower the conductivity on thin films only.

The interconnectors have no orthotropic conductivities, because only the cross-section and length of an interconnector finger is of interest.

All material data are defined with the lowest known values to get worst case conditions. A typical material definition is documented in Fig. 5.

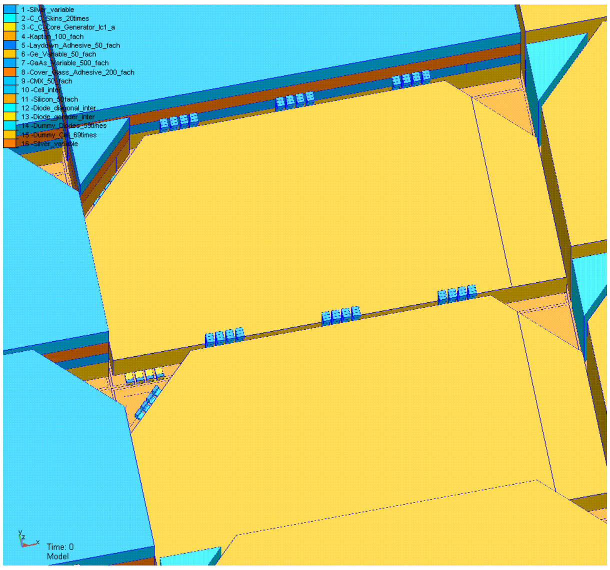

Figure 5: Material definition in the core region

6.3 Model size

In the element size settings it is considered, that in nearly all areal components a minimum of 3 element layer are generated. This is helpful to get very precise temperature gradients inside the model.

The model has the following characteristic data:

- Solid elements (tetrahedrons): 2,590,722
- Shell elements (triangles): 22,754
- Element nodes: 483,232.

6.4 Computation settings and computer resources

Due to the strong nonlinearity of the calculation model an iterative solver will be used. A stationary solution is performed with CFdesign 9.0 [1].

The first computation run needed 84 iterations. All other load cases are calculated using the first run, but with changes in the boundary conditions. The additional computations last 30 iterations.

Typical computation resources for 84 iterations are:

- RAM allocation: 2,730 MB
- Output capacity (archive file): 679 MB
- Computer: 2 QuadCore (2.7 GHz, 64-bit)
- Computation elapsed time: 17,106 sec.

7. RESULTS

In the following chapters the results of the computations will be discussed. Particular attention is given to the comparison of the calculated temperatures. All temperature views are scaled between 250 °C and 300 °C.

7.1 Temperatures for load case lc1

In the following the temperature results of the stationary analysis for load case lc1 (all cells at 3.0 A, no diode active -> normal operation) will be presented. These results are the basis for the comparisons with the failure cases lc2 and lc3.

Temperature pictures are shown in Fig. 6 to Fig. 9:

- Fig. 6: Total view over the model:
  - the maximum temperature of about 294 °C can be found at a corners of one of the inner 6 solar cells, because the cells are not glued at these borders to the generator structure
  - this could not be seen at dummy cells
  - the temperature shows - as expected - nearly no decrease from the left to the right
  - the diodes are a bit cooler due to the cover glasses with an Ag reflector
  - the biggest difference of about 44 K perpendicular to the structure is caused by the honeycomb core.

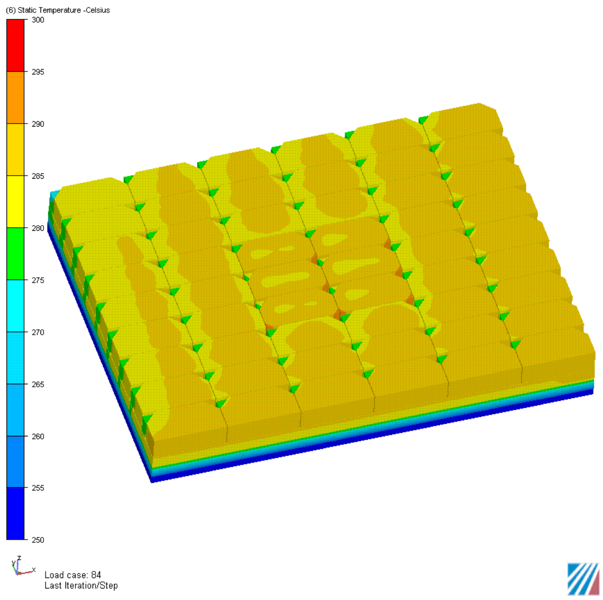

Figure 6: Load case lc1: temperature, overview

- Fig. 7: Partial view over the core region (cover glasses and adhesives hidden):
  - temperature on the GaInP/GaInAs solar cell layers
  - the maximum temperatures on cell level can be found here
  - the diodes are cooler due to the cover glasses with an Ag reflector.

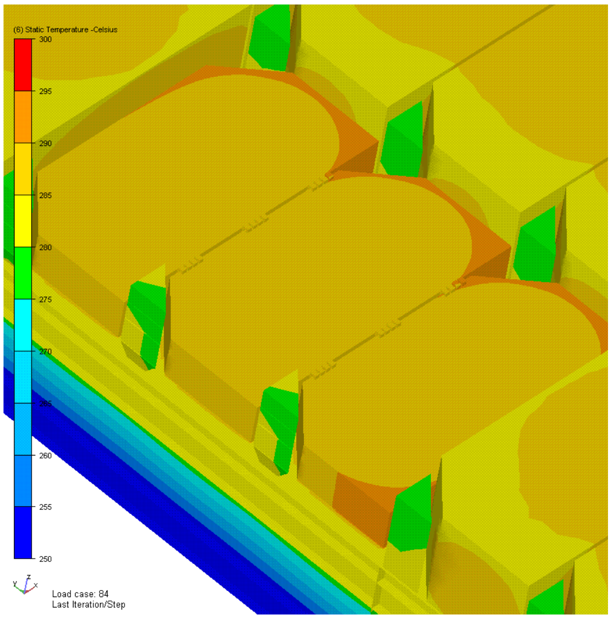

Figure 7: Load case lc1: temperature, cut-out for solar cells and diodes

- Fig. 8: Temperature plot through the solar cell assembly and the structure near the cell edge:
  - the maximum temperatures can be found inside the cell (absorption region)
  - the maximum temperature reaches at this position about 288 °C
  - bigger gradients are found inside the adhesives (cover glass and laydown adhesives)
  - the biggest gradient is through the honeycomb core
  - the minimum temperature is found at the generator rearside with about 252 °C.

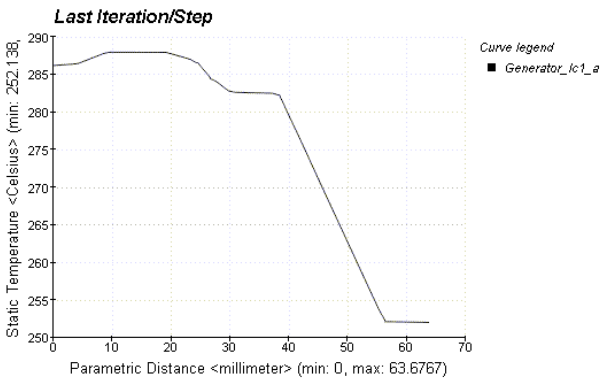

Figure 8: Load case lc1: temperature plot through solar cell assembly and generator structure

- Fig. 9: Temperature plot through the diode assembly and the structure:
  - the diode cover glass is about 2 K cooler than the Si-diode and the generator structure -> less solar absorption

- the biggest gradient is through the honeycomb core
- the maximum temperature reaches at this position about 282 °C
- the minimum temperature is found at the generator rearside with about 252 °C.

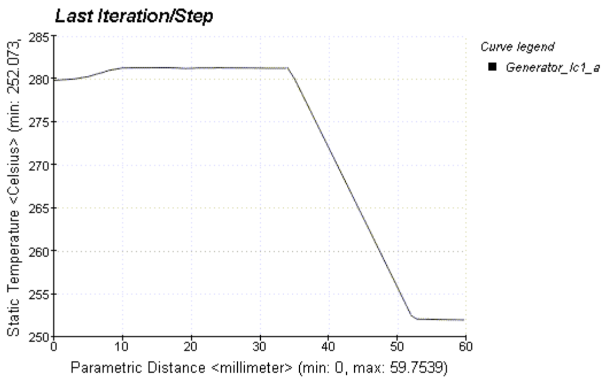

Figure 9: Load case lc1: temperature plot through diode assembly and structure

In total the following general results are found for lc1:

- Average diode temperature: 281 °C
- Average solar cell temperature: 288 °C
- Maximum solar cell temperature: 294 °C
- Average generator temperature: 279 °C
- Minimum generator temperature: 250 °C
- Average temperature difference diode/cell: -7 K
- Maximum generator temperature difference: 44 K
- Total power (heat loads = power loss): 1,308 W.

Thus, this generator design fulfills the above mentioned general requirements at nominal operation.

7.2 Temperatures for load case lc2

In this chapter the results of the thermal analysis for load case lc2 (one cell totally shadowed, all other cells at 3.0 A, one active diode) will be presented.

Temperature pictures are shown in Fig. 10 to Fig. 12:

- Fig. 10: Partial view over the core region (cover glasses and adhesives hidden):
  - the maximum temperature of about 311 °C can be found inside the active Si-diode
  - the affected (inactive) solar cell shows in average a temperature of 244 °C; thus this cell cools the surrounding area and partially also the active diode
  - all other temperatures around the affected region behave as seen in lc1.
- Fig. 11: Temperature plot through the affected solar cell assembly and the structure near the cell edge:
  - the maximum temperatures can be found inside the structure skins (about 255 °C)
  - the minimum temperature is on the generator rear side with about 236 °C
  - the solar cell cover glass shows in this plot a minimum of about 249 °C.

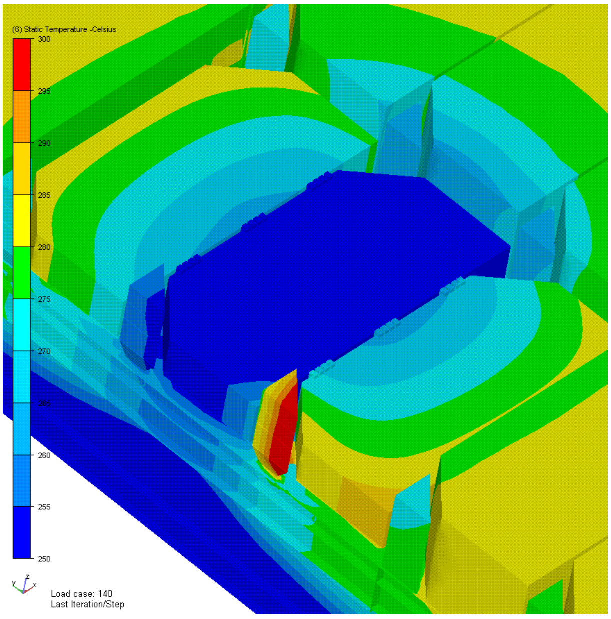

Figure 10: Load case lc2: temperature, cut-out for solar cells and diodes

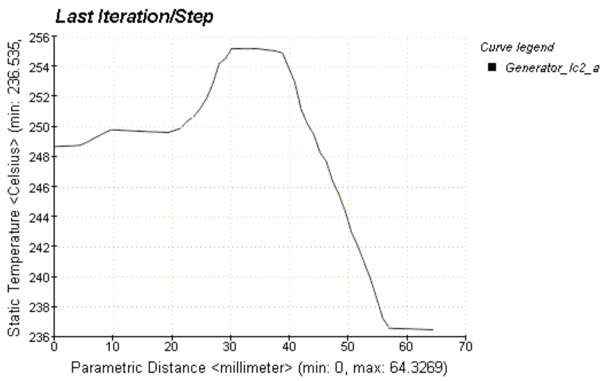

Figure 11: Load case lc2: temperature plot through solar cell assembly and generator structure

- Fig. 12: Temperature plot through the active Si-diode assembly and the structure near the diode edge:
  - now the maximum temperatures can be found inside the Si-diode with about 294 °C (please note that this position is near the 'cooling' solar cell and doesn't represent the max. temperature of the diode of 311 °C)
  - the generator skin temperature is at about 268 °C; thus, about 26 K lower than the diode; this indicates a strong heat flux from the diode to the generator structure through the laydown adhesive; if the thermal conductivity of this adhesive can be increased the Si-diodes can be held below 300 °C
  - there is also a temperature gradient in the interconnector fingers; this means that a part of the gener-

ated heat is conducted away by the Ag-interconnectors (about 10 to 20 %).

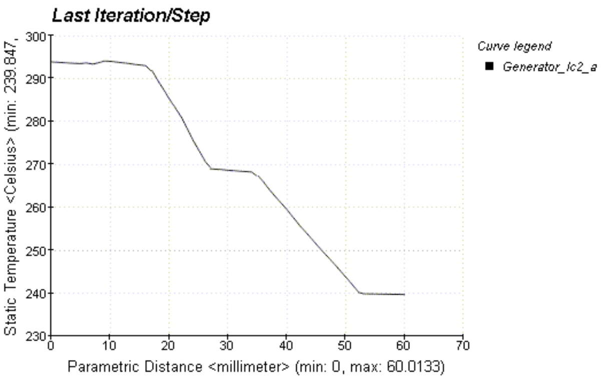

Figure 12: Load case lc2: temperature plot through diode assembly and structure

In total the following general results are found for lc2:

- Average loaded diode temperature: 294 °C
- Maximum loaded diode temperature: 311 °C
- Average affected solar cell temperature: 244 °C
- Average generator temperature: 274 °C
- Minimum generator temperature: 229 °C
- Average temperature difference loaded diode / affected cell: 51 K
- Maximum generator temperature difference: 83 K
- Total power (heat loads = power loss): 1,287 W.

From these results it can be stated:

- The Si-diode is much warmer than the cell, but is 'cooled' by the shadowed cell
- Thus, the maximum diode temperature is about 30 K higher than the inactive diodes
- But the active diode doesn't met the 300 °C criterion.

7.3 Temperatures for load case lc3

In this chapter the results of the thermal analysis for load case lc3 (one cell with totally broken interconnectors, all other cells at 3.0 A, one active diode) will be presented.

Temperature pictures are shown in Fig. 13 and Fig. 14:

- Fig. 13: Partial view over the core region (cover glasses and adhesives hidden):
  - the maximum temperature can be found at the right corner of the active Si-diode with about 329 °C
  - the failing solar cell is warmer than all other cells and thus heats up the active diode
  - all other temperatures around the affected region behave as seen in lc1.
- Fig. 14: Temperature plot through the active Si-diode assembly and the structure near the diode edge:
  - the maximum temperature can be found inside the Si-diode with about 318 °C (please note that this position is near the solar cell and doesn't represent the max. temperature of 329 °C)

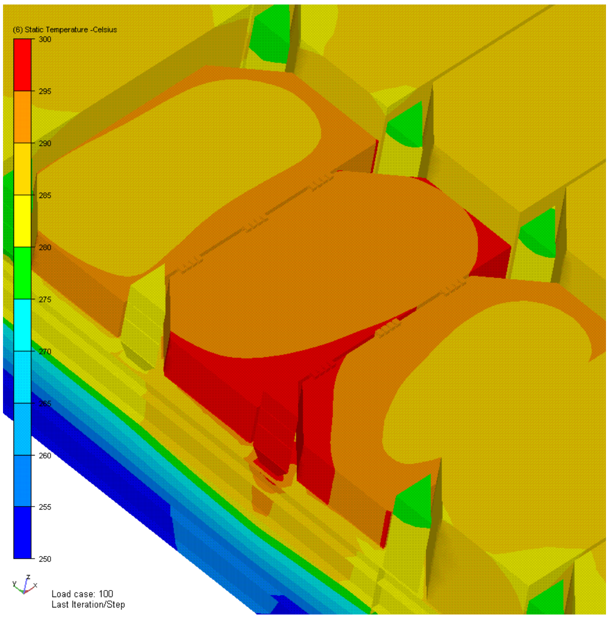

Figure 13: Load case lc3: temperature, cut-out for solar cells and diodes

  - the generator skin temperature is about 292 °C; thus, once more about 26 K lower than the Si-diode (-> heat flux from the diode to the generator structure through the laydown adhesive).

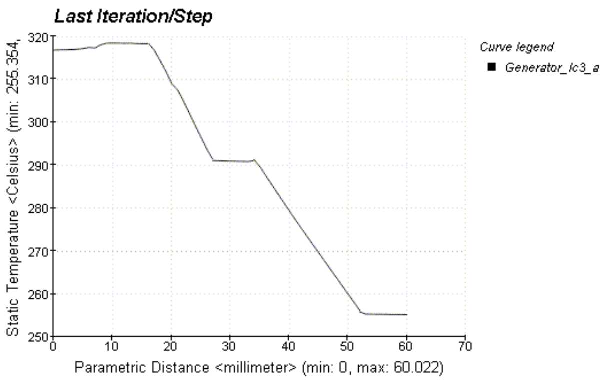

Figure 14: Load case lc3: temperature plot through diode assembly and structure

In total the following general results are found for lc3:

- Average loaded diode temperature: 318 °C
- Maximum loaded diode temperature: 329 °C
- Average affected solar cell temperature: 294 °C
- Maximum affected solar cell temperature: 306 °C
- Average generator temperature: 280 °C
- Minimum generator temperature: 250 °C
- Average temperature difference loaded diode / affected cell: 25 K
- Maximum generator temperature difference: 79 K
- Total power (heat loads = power loss): 1,308 W.

From these results it can be stated:

- The Si-diode is warmer than the cell and is also heated by the cell
- Thus, the maximum Si-diode temperature is about 46 K higher than the inactive diodes
- Now not only the active diode but also the affected solar cell misses the 300 °C requirement.

8. CONCLUSIONS

Main results for the FEM calculations are:

- Using the proposed/assumed generator structure the Si-diodes and all other generator components - if the standard conditions 10 SC and an angle of 45° are kept - doesn't exceed a temperature of about 294 °C; thus, the temperature requirement is met.
- Considering the above mentioned failure modes (lc2 and lc3) the maximum Si-diode and solar cell temperatures found are 329 °C and 306 °C, respectively; thus, the temperature requirements are not met.

Further observations during this investigation loop:

- Regions below the solar cells or diodes without adhesive will increase the temperatures
- A high thermal out of plane conductivity of the structure honeycomb core is one key for as low temperatures as possible
- The in-plane thermal conductivity of the generator structure skins has a strong influence to the surrounding parts if a failure mode occurs in a solar cell or diode
- The interconnectors increase the heat flux, if failure modes are present (some times to lower, some times to increase the Si-diode temperatures)
- The current flow through the diode interconnectors has nearly no influence to the temperatures (the current densities are too small)

It can be stated also that the geometric modeling of a generator cut-out is useful in investigation of many details on a generator structure; in future investigations it might be beneficial to consider additionally e.g. the generator borders with the power lines, the albedo radiation of Mercury, the welding spots, etc.

The generator design and the discussion of the requirements are still in progress; thus, these investigation results are preliminary in nature. The quantitative and qualitative results will help to improve the design and find an optimum between parameters such as temperature, irradiation angle, mass, electrical output, size, etc.

9. ACKNOWLEDGEMENT

The authors want to thank the colleagues from EADS Astrium, Ottobrunn, for the useful tips to the thermal behavior of the proposed initial generator structure and the interconnector design.

10. REFERENCES

1. See *http://www.cfdesign.com*
2. See *http://www.ptc.com*