Thermal Model Predictions of Advanced Stirling Radioisotope Generator Performance

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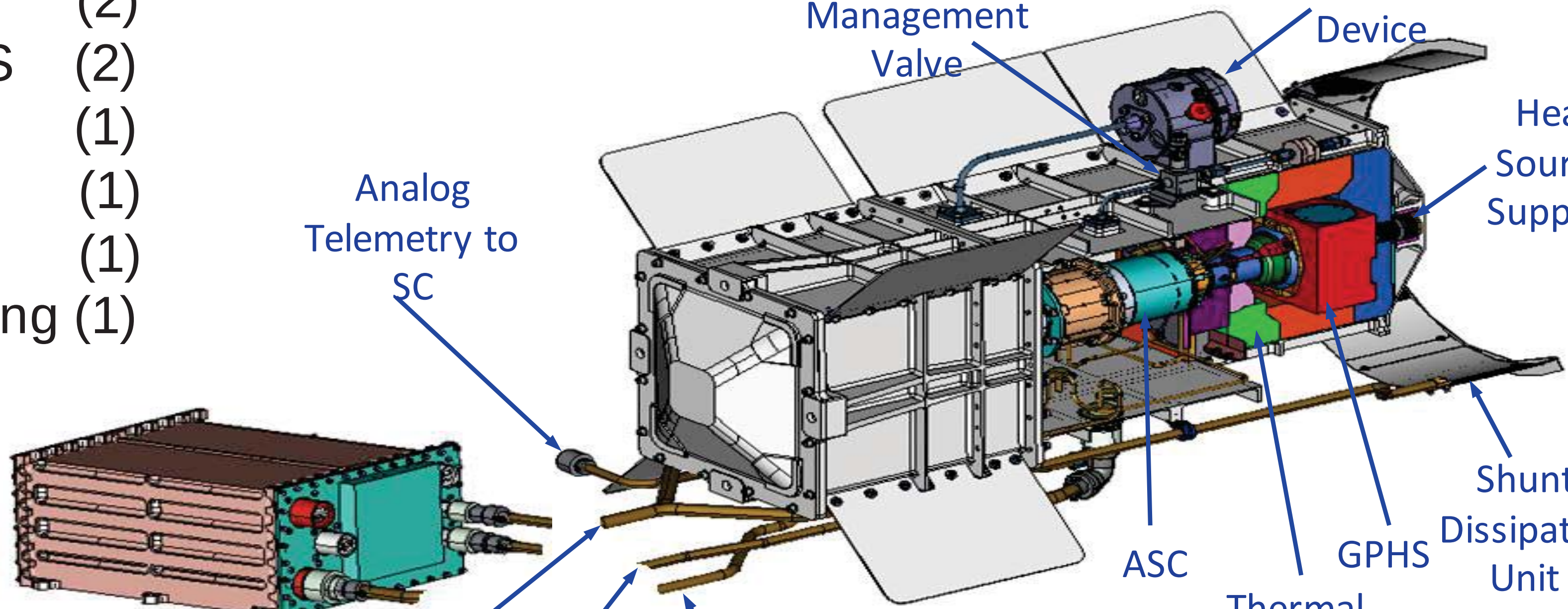
Outlines

- Background of ASRG
- Description of the 3D ASRG thermal power model
- Model predictions results of
  - Auxiliary cooling system (ACS) performance
    - nominal conditions
    - Venus flyby scenario
  - Venus flyby transient analysis with a representative trajectory
    - ASRG alone
    - ASRG with a Cassini-like spacecraft and sunshade
  - ASRG performance with one ASC Failure
- Summary

Background of ASRG

- ASRG was developed for multi mission applications
- ASRG has high efficiency(28%-32%)Reduce the required amount of Pu-238 by a factor of 4 compared with radioisotope thermoelectric generators (RTG)

ASC (2)
GPHS (2)
GMV (1)
PRD (1)
ACU (1)
Housing (1)



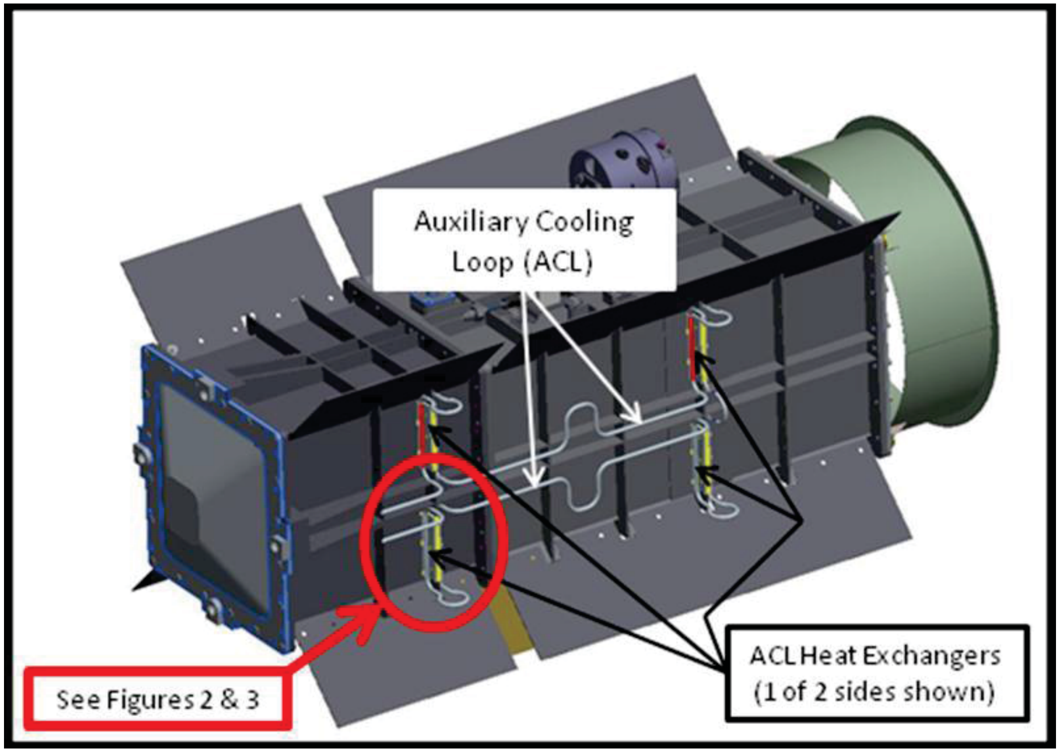
Overview of ASRG components

Outline- thermal power model

- 3D ASRG thermal model in Thermal Desktop/SINDA-FLUINT
  - Finite Element/Finite Difference Mesh for the geometries
  - Radiation/conduction/convection heat transfer and orbit heating
  - Both steady-state and transient analysis
  - Auxiliary cooling system (ACS) is included
  - Advanced Stirling Convertor (ASC) control strategy:
    - Fix the T_h (hot end temperature of ASC)
    - Fix the A_p (piston amplitude of ASC)
  - Model correlated with test data for ASRG Engineering unit (EU)
  - Model correlated with LM model-predicted results for ASRG flight unit
- Use Matlab to integrate 1D/3D ASRG thermal-power models, Sage model for ASC, and control strategy of ASC.

Auxiliary Cooling System (ACS)

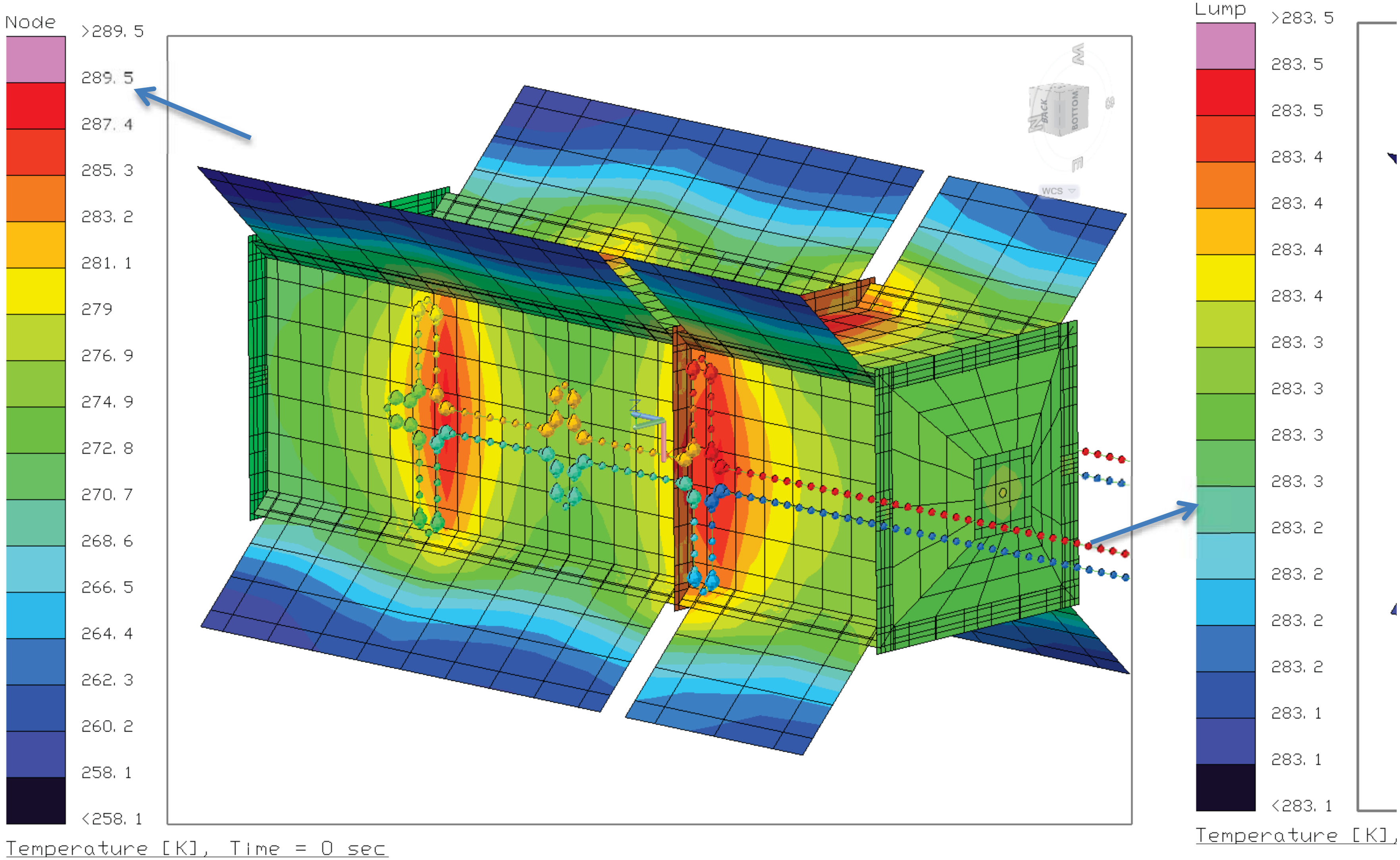
- ***Concept:*** Remove waste heat from ASRG for use in heating spacecraft components.
- Baseline design is a pumped fluid loop going through two sides of the ASRG housing attached to the housing near CSAF by block heat exchangers



Model Results of ACS

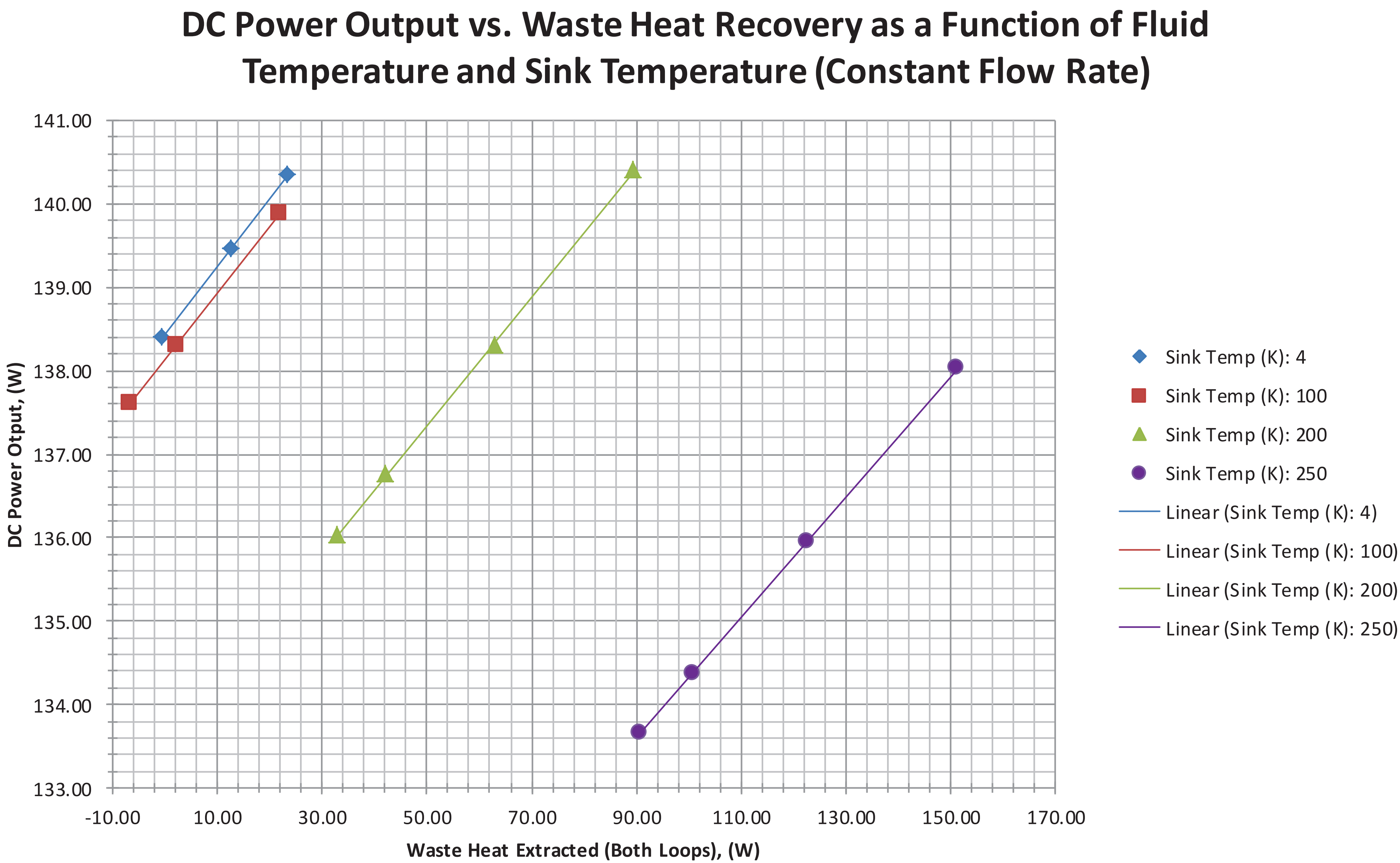
Housing T range

Fluid T range

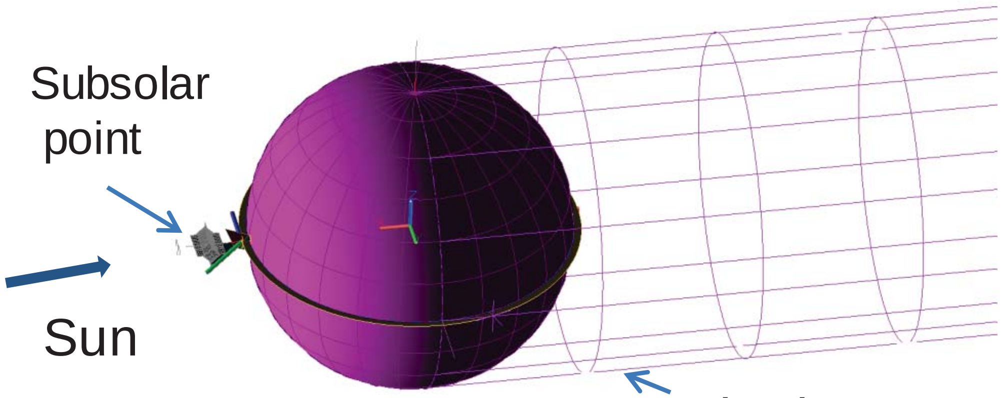


T_h = 760 C, 4 K sink T, 5" fin, 23.3 W total waste heat is removed.

T_h = 760 C, BOM, 4K sink T, 5” fin (baseline)

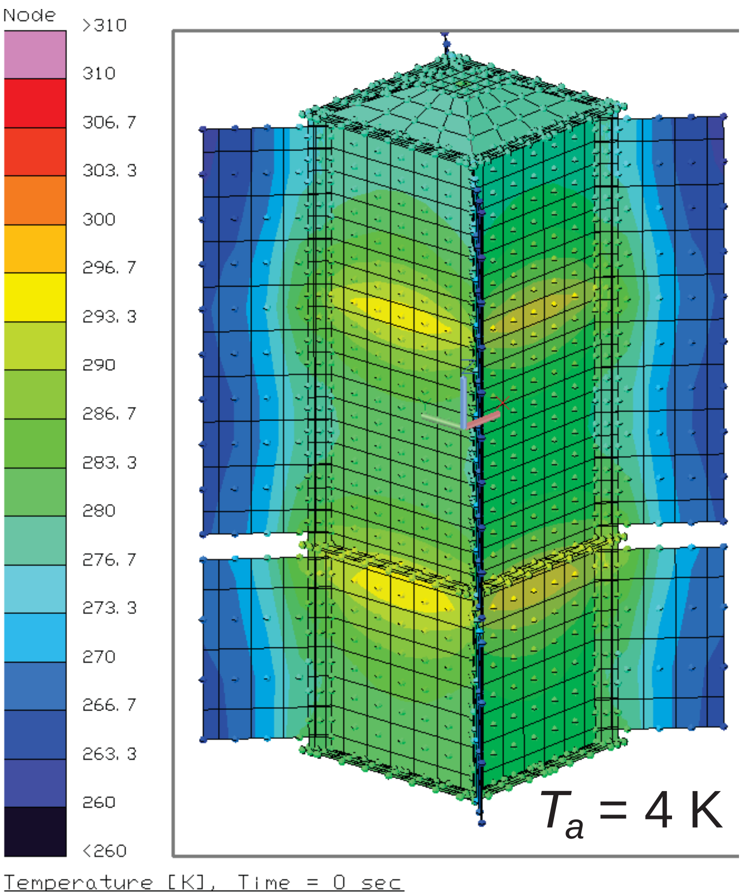


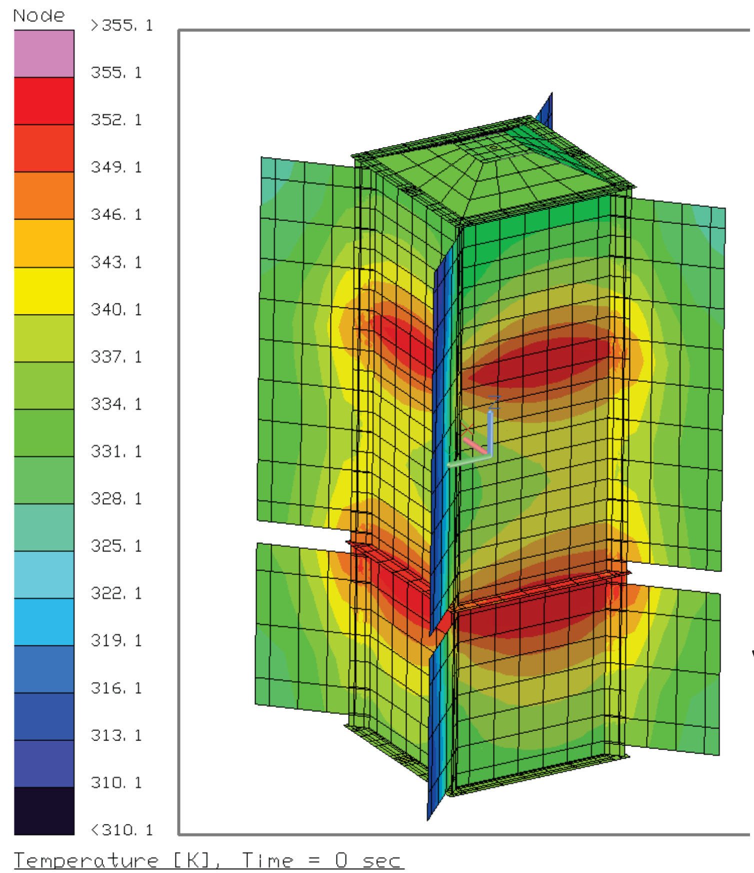
ASRG Venus Flyby



- During the flyby the spacecraft can come as close as 300 km from the surface (~LEO orbit altitudes)
- During this period of time:
  - Direct solar radiation (orbit of 0.7 AU) ~ 2588 w/m^2
  - Reflected solar energy from Venus (albedo = 0.72) ~1900 w/m^2
  - IR energy radiated energy from Venus (Venus as thermal source)~ 120 w/m^2
- Steady-state analysis for the worst case
  - Flyby transient ~ 2 hours

Temperature of the ASRG housing (T_h = 760 C, BOM)





Venus flyby

ACS off
T_h = 1033 K
T_c = 313 K
Q_{in} = 206.4 W
W_{alt} = 81.2 W

ACS on
23.3 W heat removal
T_c = 304.7 K.
W_{alt} = 82.1 W

ACS off:
T_h = 1033 K
T_c = 373 K
Q_{in} = 207.9 W
W_{alt} = 71.4 W

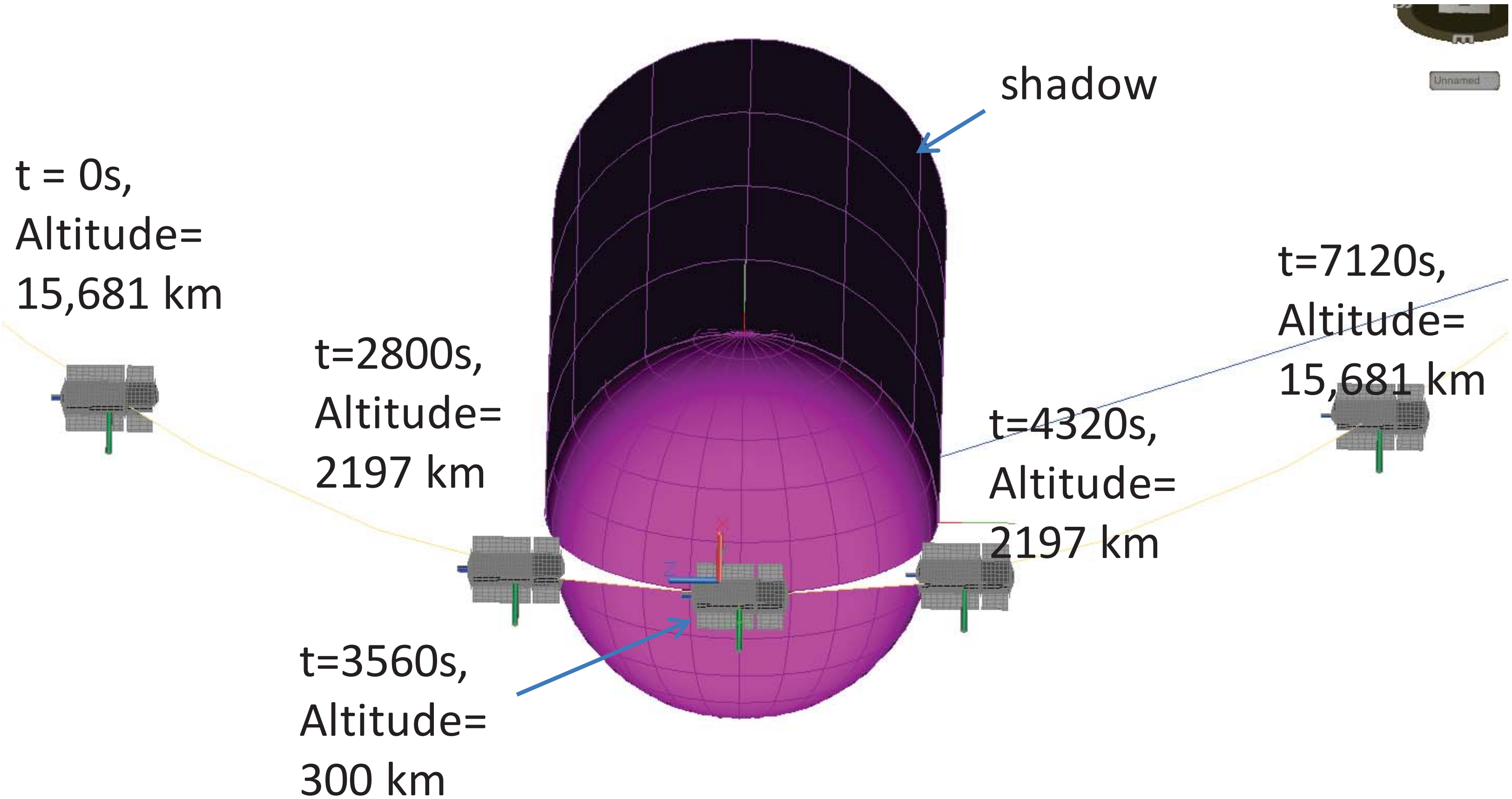
ACS on
189.4 W heat removal
T_c = 330.4 K
W_{alt} = 78.4 W

Transient Analysis of ASRG Venus flyby

From the steady-state thermal model, modifications are made for the transient thermal model:

- Update the thermal mass and specific heat for each component based on the data from LM report
- ASC represented by SAGE map is updated at every time step
- ASRG control strategy is to maintain a constant piston amplitude instead of constant T_h.
- Use the transient solver in Thermal Desktop/SINDA-FLUINT

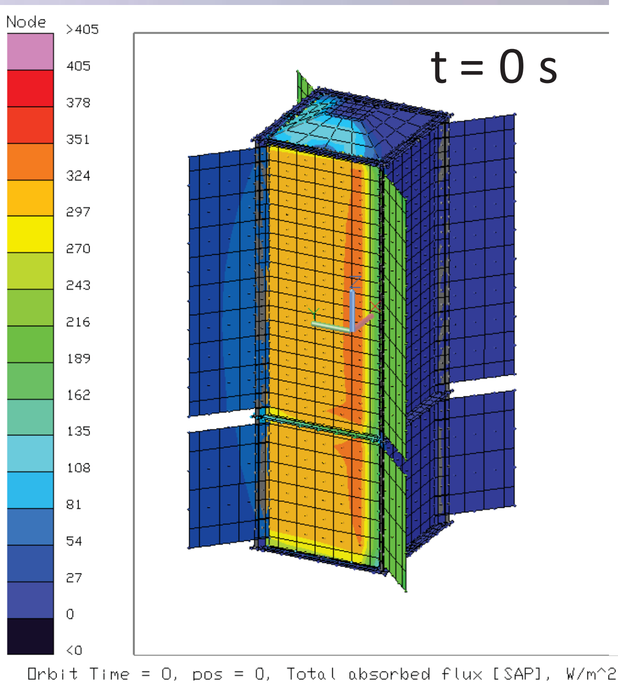
Venus flyby trajectory

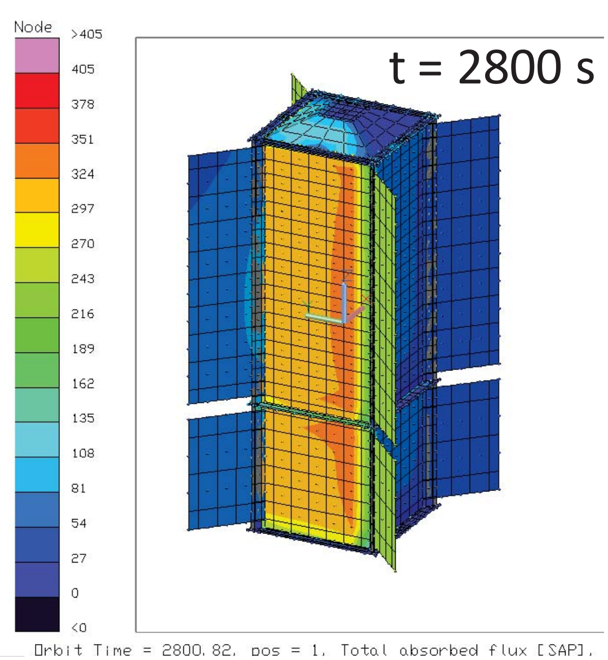


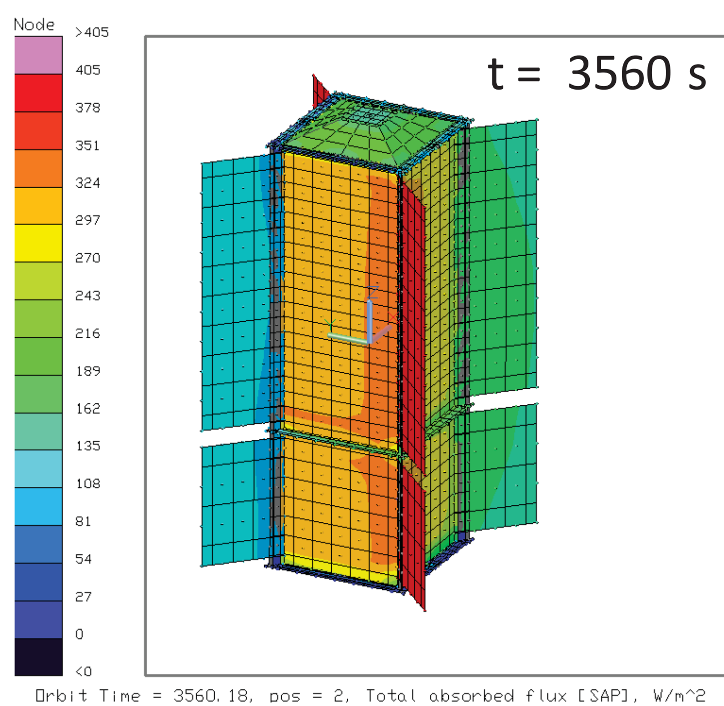
2-hr flyby trajectory showing time and altitude at 5 positions (View from the Sun).

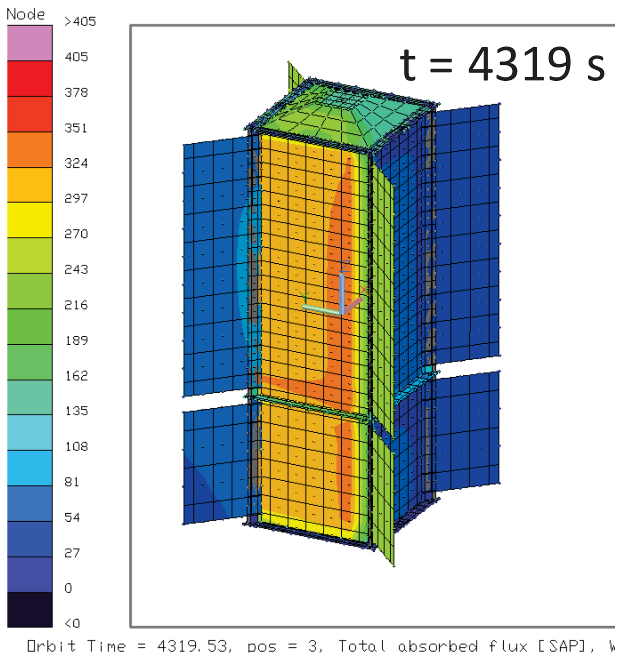
Total absorbed flux from the environment at the five positions on the trajectory

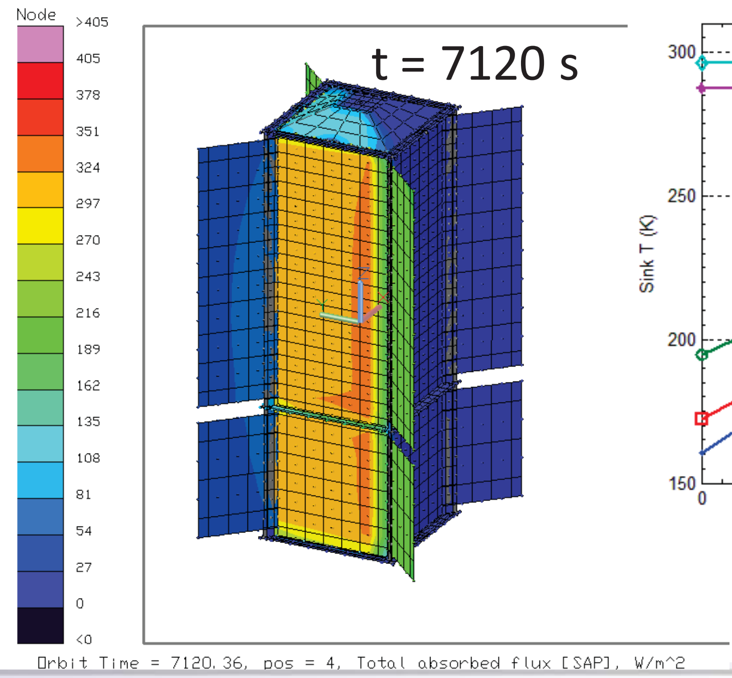
RPS

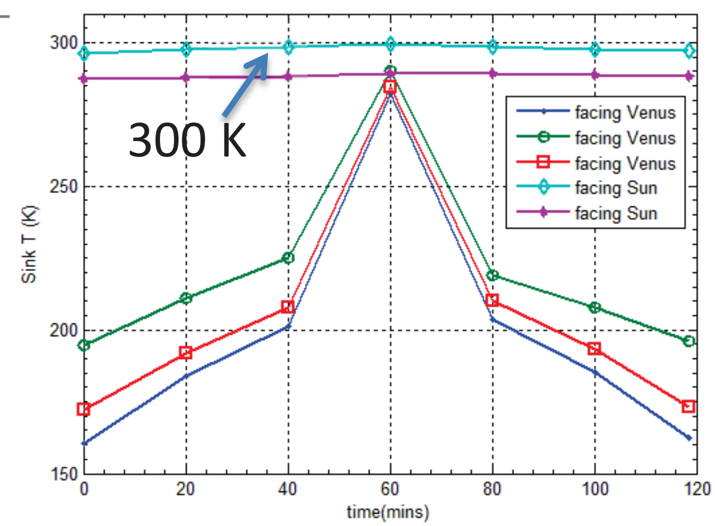








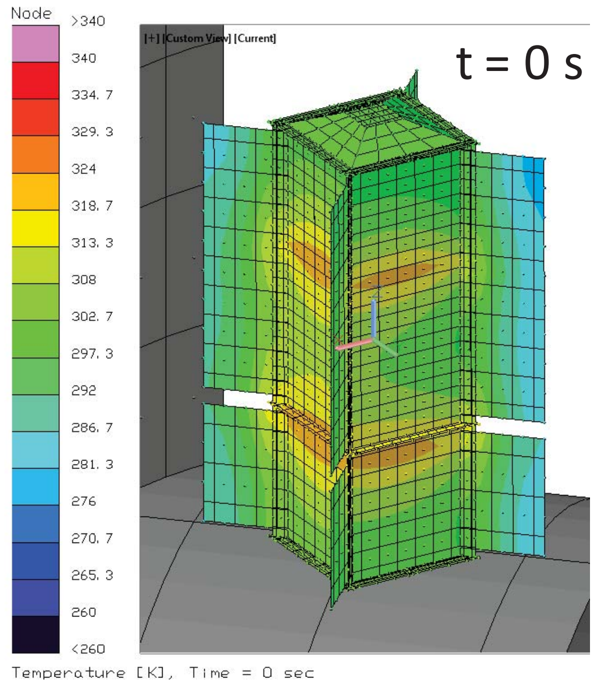


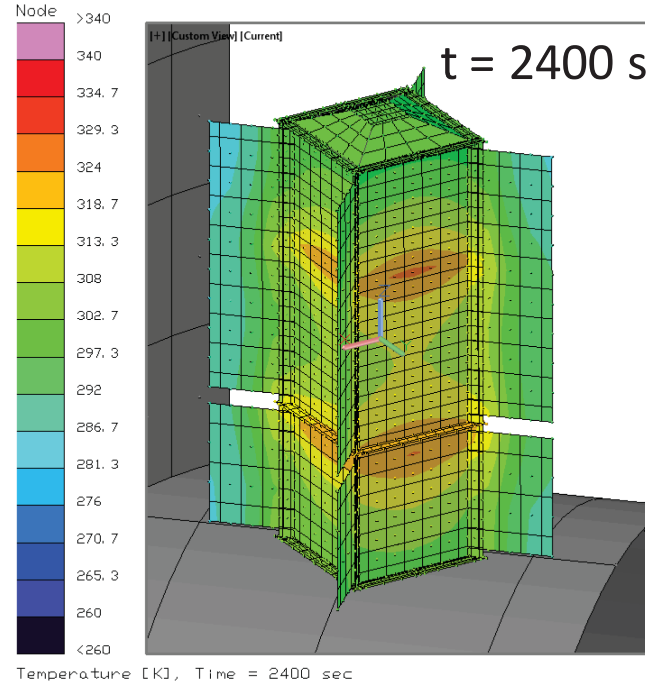


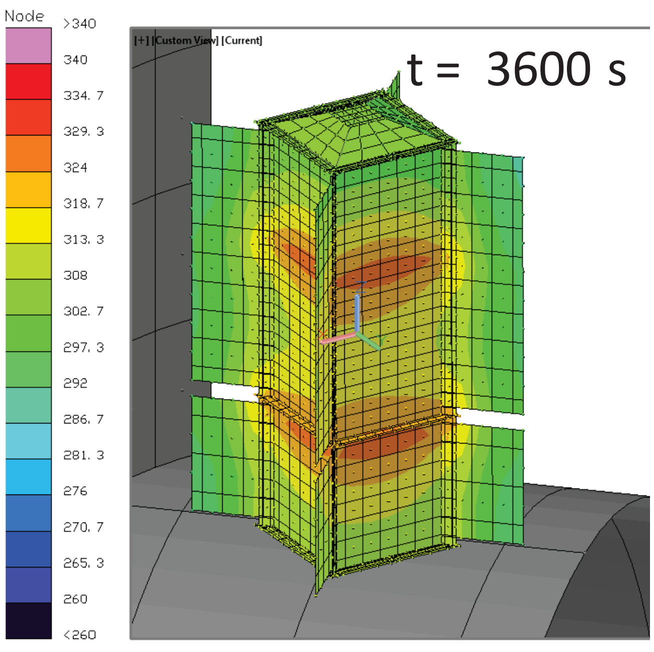
Equivalent sink T on the ASRG housing (located along the housing length)

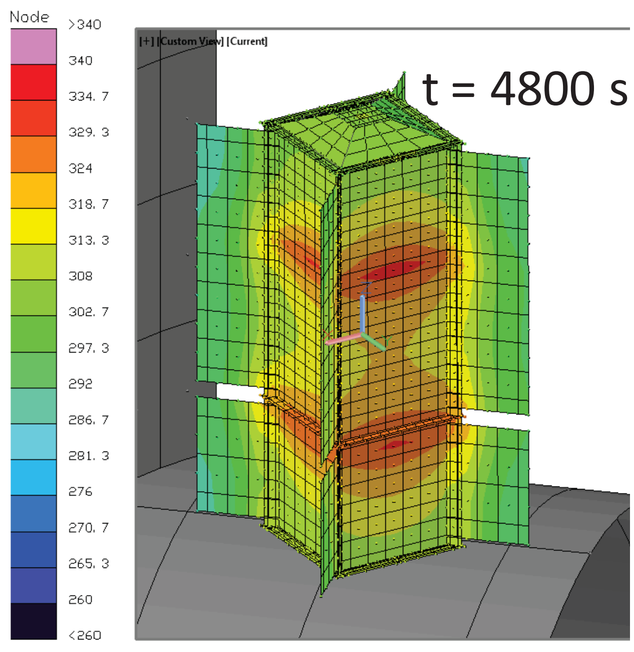
TD model results at different time on the trajectory

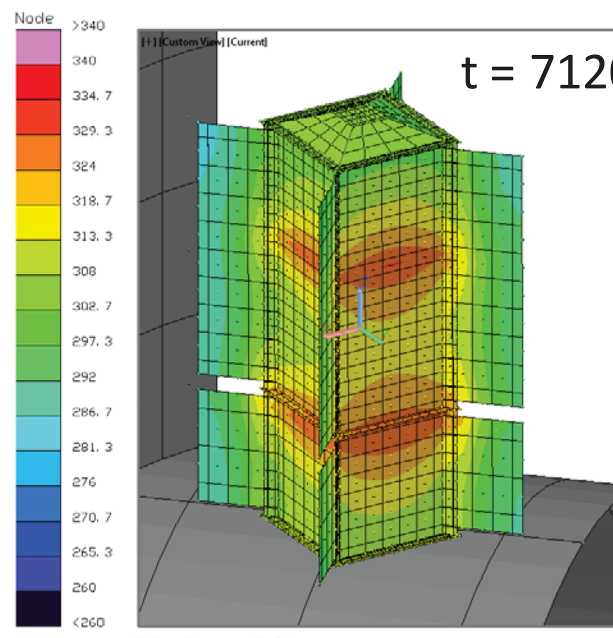
- The initial condition of the transient analysis is defined using the steady-state solution at the starting position on the trajectory, which is identical to the steady-state solution when ASRG is on the Sun orbit of 0.72 AU.



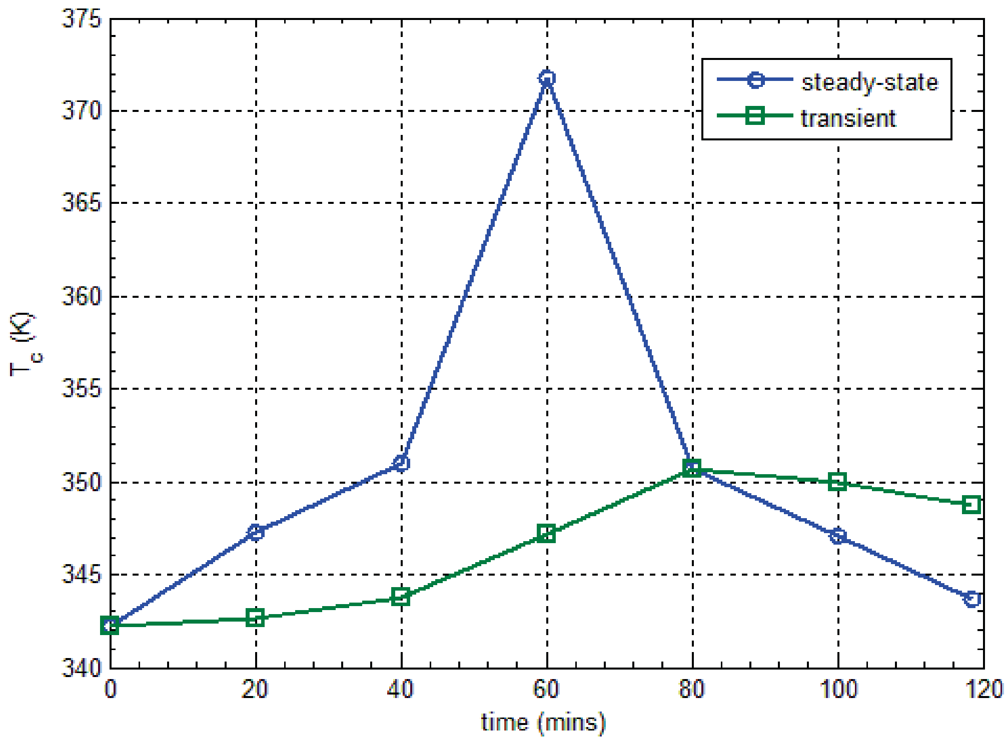








- For both steady-state and transient analysis, a constant piston amplitude is used.
- For 4K vacuum condition, steady-state results show T_h = 742.3 C, T_c = 40 C, DC power is 84.3 W for one ASC.
- Since the alternator temperature (= T_c+10 C) limit is the concern, here the T_c is plotted along with the prediction from the steady-state solution.
- Steady-state results show T_c is increased by 30 C, while transient results show 10 C increase.



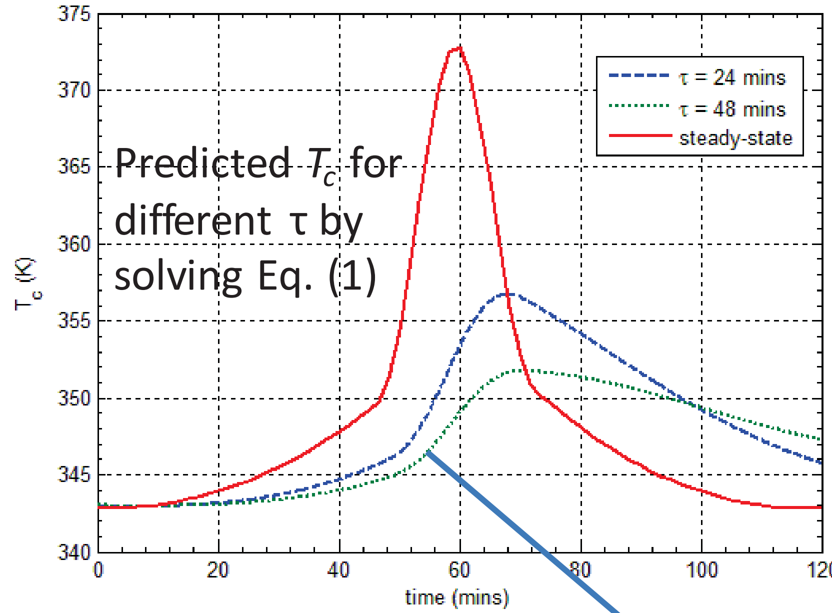
TD model results of T_c as function of time (steady-state and transient results).

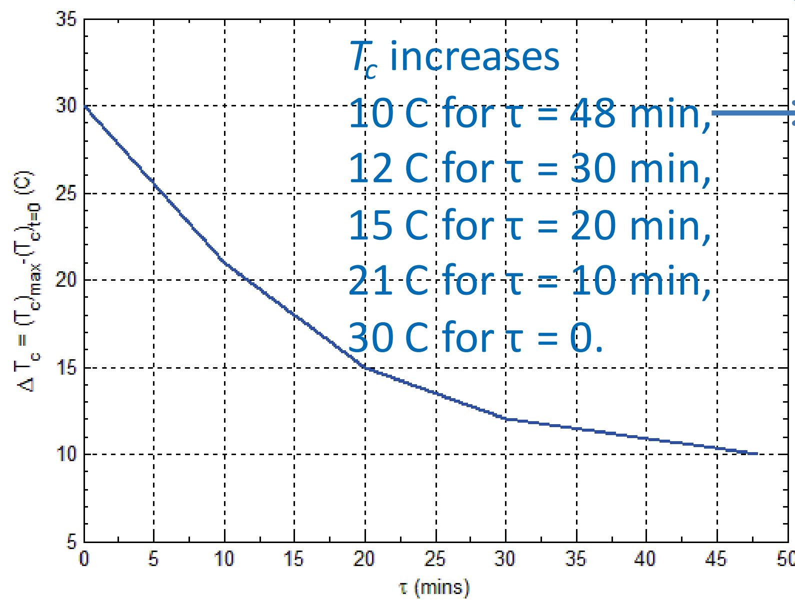
T_c increases versus ASRG response time (τ) to the environment temperature changes

- Based on LM data of T_c versus time when the environment changes to 4 K vacuum from the launch pad condition, the estimated τ is roughly 48 mins for the cold end.
- Using Eq. (1), the sensitivity study of how T_c changes for different τ is performed.

$$\frac{dT_c}{dt} = \frac{(T_c)_{steady} - T_c}{\tau} \qquad (1)$$

$$\Delta T_c = (T_c)_{max} - (T_c)_{t=0} \qquad (2)$$



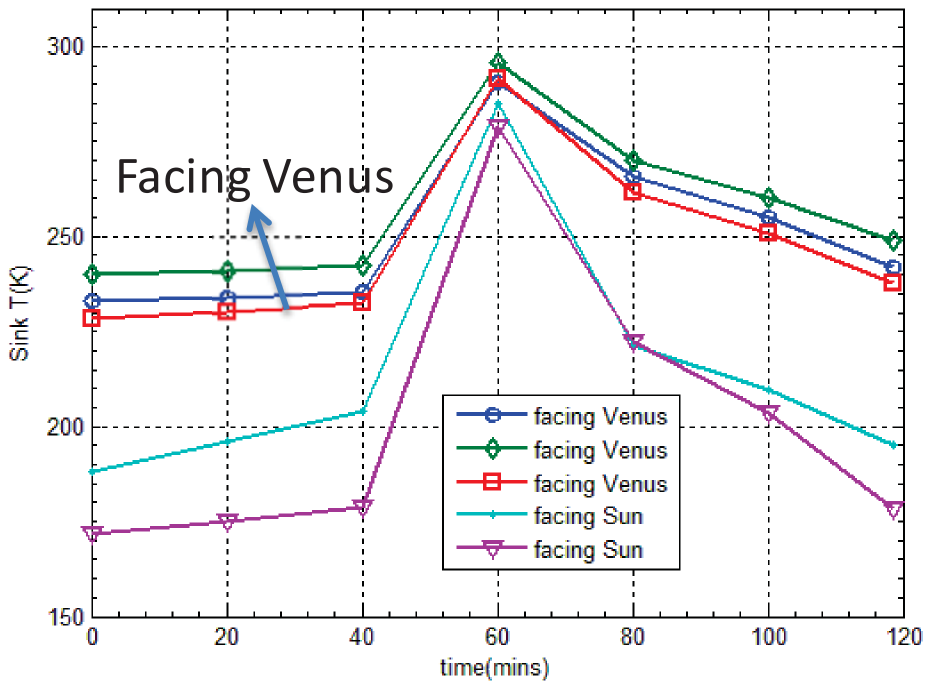


Agree with transient model results (~10 C increase)

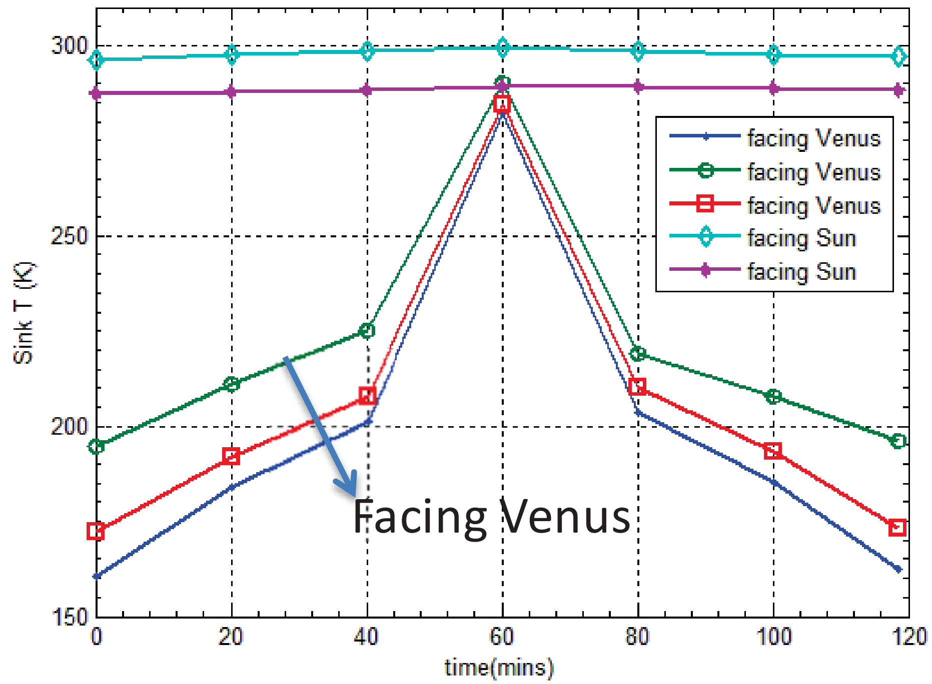
ASRG Venus flyby with sunshade on spacecraft

- Spacecraft (SC): a Cassini-like, 2 m diameter and 2 m height.
- Sunshade:
  - facing Sun side: epsilon = 0.88, alpha = 0.1
  - Facing Venus side: epsilon = 0.04, alpha = 0.3, k_{eff} = 0.0004 (assume MLI blanket insulation)
- ASRG performance for the nominal conditions (4K vacuum):
  - T_h = 738.1 C, T_c = 44.7 C, DC power is 83.4 W for one ASC.
  - T_h = 742.3 C, T_c = 40.0 C, DC power is 84.3 W for one ASC (no SC and sunshade).

Equivalent sink T on the ASRG housing



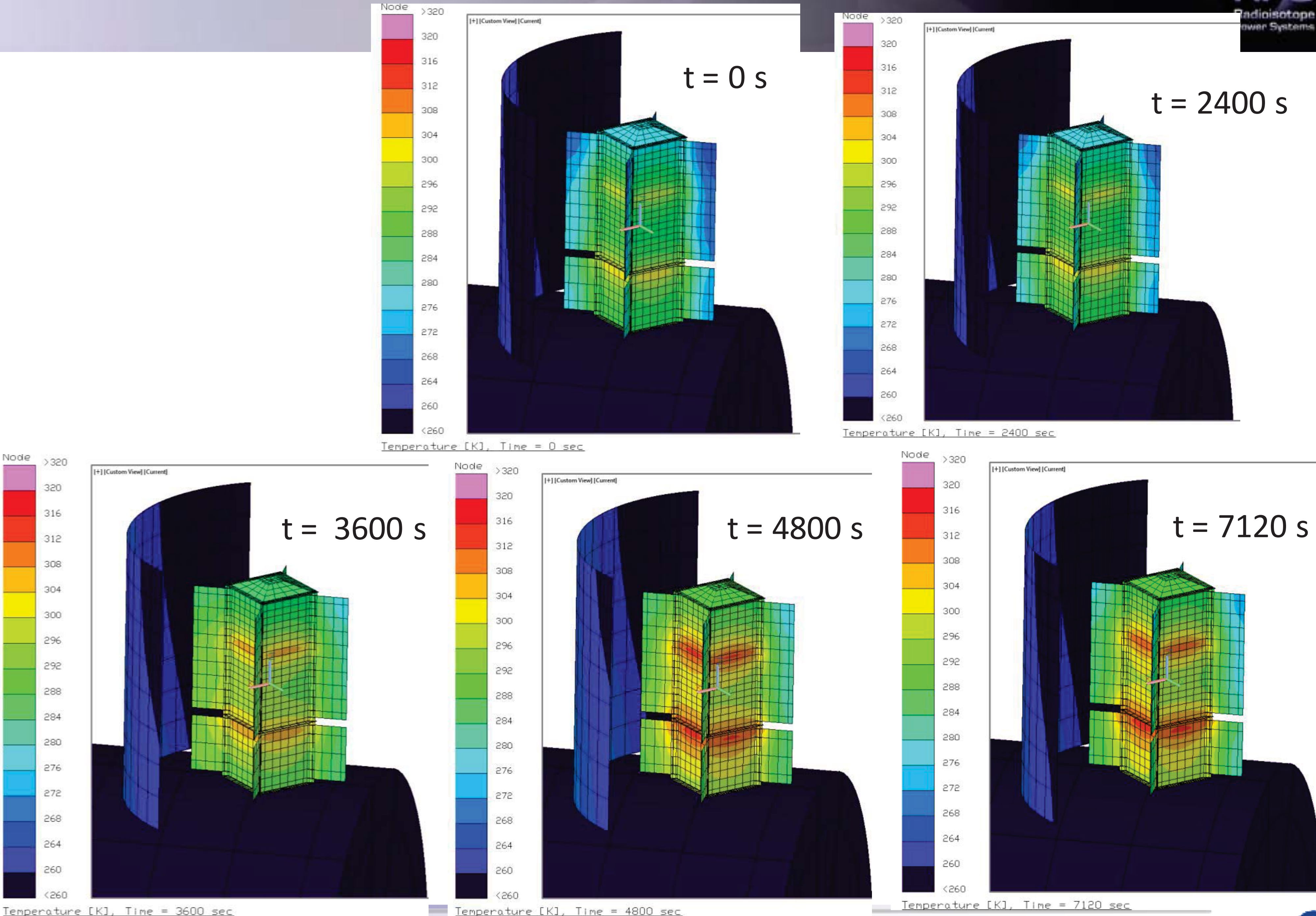
(a) With sunshade



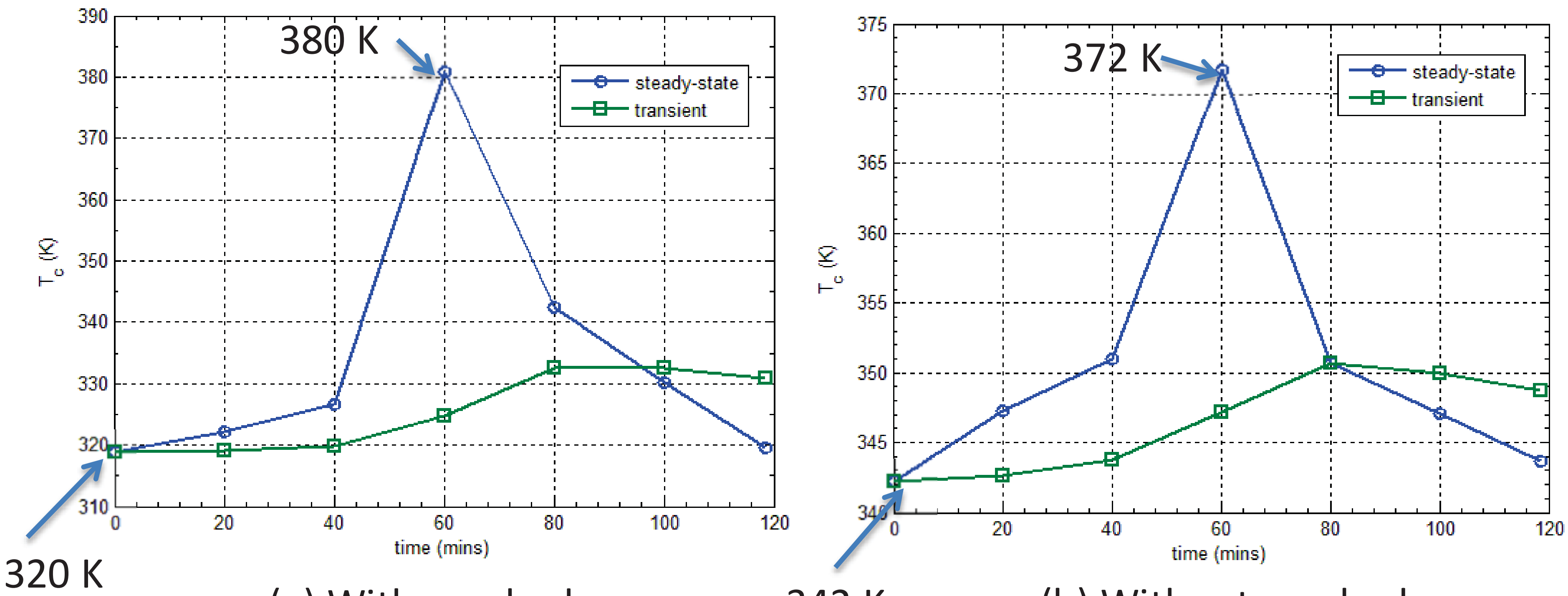
(b) Without sunshade

It can be seen that the housing facing the Sun gets much cooler with sunshade. The housing facing the Venus gets warmer due to the spacecraft and sunshade. At the minimum altitude (t = 60 mins), the equivalent sink temperature is similar with or without sunshade.

TD model results at different times on the trajectory (with SC/sunshade)



TD model results of T_c as function of time



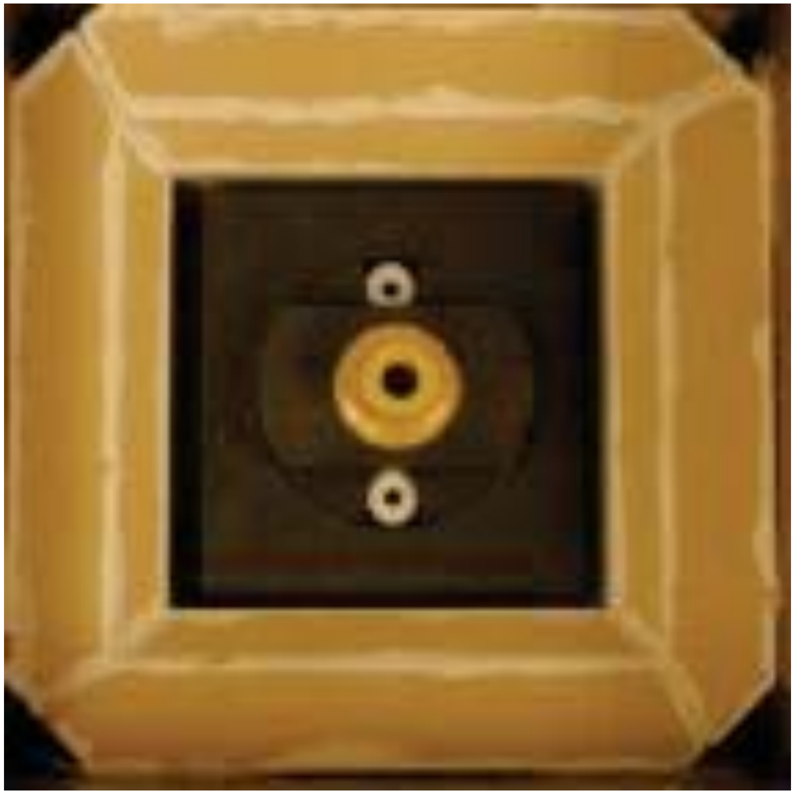
(a) With sunshade (b) Without sunshade

The transient analysis results show that sunshade can lower ASRG T_c by approximately 22 C at the starting position of the trajectory. The maximum T_c increase is 15 C with sunshade.

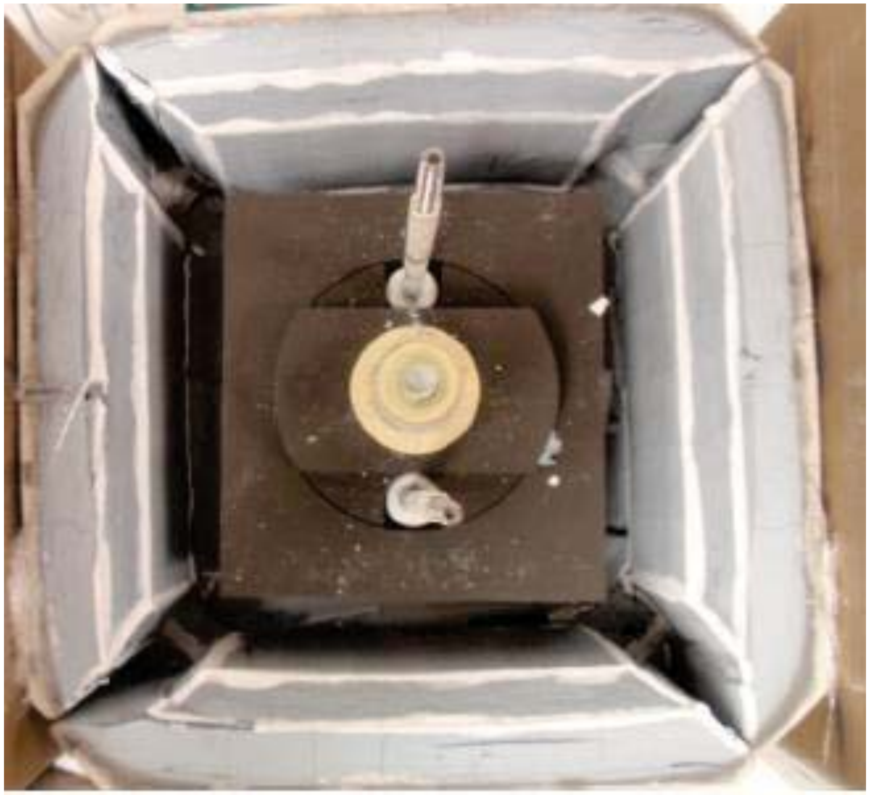
The steady-state analysis results show that, at the minimum altitude of 300 km, due to albedo and IR are increased so much, sunshade can not really lower T_c instead of getting higher due to the heat transfer between spacecraft, sunshade and ASRG.

Post ASC Failure/Heat Dump Simulation

View of insulation



(a) Normal operation; Pre heat-dump



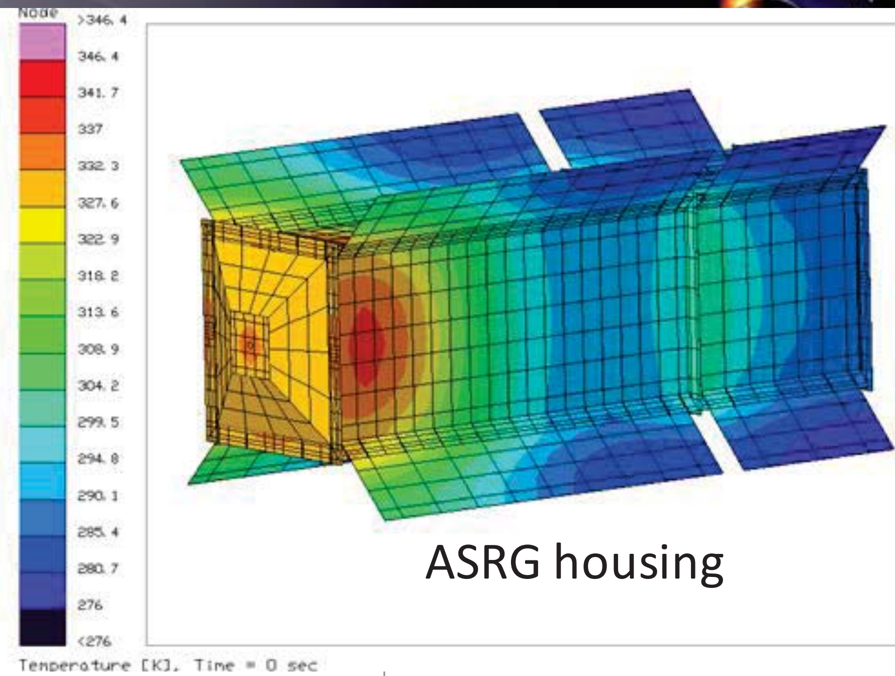
(b) Failed ASC; Post heat dump

- The cavity around EHS shape changed; (radiation heat transfer will be different)
- The insulation material deformed and shrunk; (thermal conductivity changes)
- Nuclear clad temperature under limit and Heat will leak through insulation & stud;

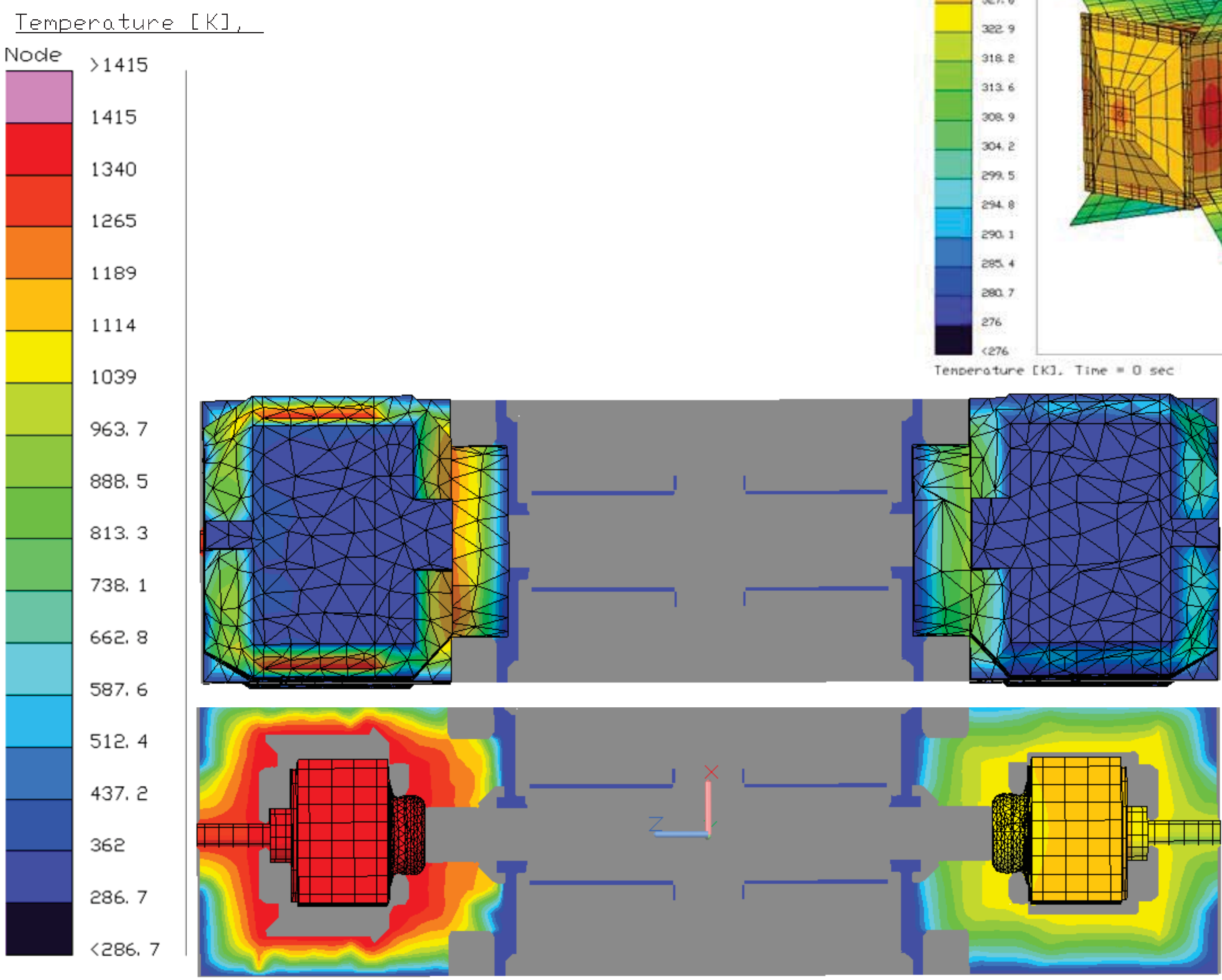
Flight Insulation – Post Heat-Dump

- Geometry Modification
  - Side pieces thickness reduced from 1.52” to 1.02” (0.5” reduction measured by Lockheed).
  - Gaps between sides pieces modified by hand to match (eyeball) photographs taken of post heat-dump insulation by Lockheed.
  - Geometry for Front and End insulation pieces were not modified, however, contact was deleted from areas where it could be expected to be lost due to the shrinkage seen in the test.
- IR emissivity/absorptivity for the shrunken insulation was modified based on the test data.

Model Results for One failed ASC



ASRG housing



Exterior surface of insulation block

Inside the cavity (a cut plane)

Outboard A

Inboard B

Results summary

- Lockheed Martin reported that a post heat-dump steady state temp for the EHS was 1142°C.
- Outboard (A) insulation:
  - Microtherm HT anisotropic thermal conductivity was modified in all three dimensions with a common multiplier.
  - After successive runs, a multiplier value of 2.18 yielded an EHS temperature of 1140°C (based on Lockheed results)
  - In line with estimates shown in LM document.
- Inboard (B) side engine continues to operate normally, the total heat going to ASC is 205 w.

Summary

- The performance of Auxiliary cooling system of ASRG was reported for nominal conditions and Venus flyby scenario.
- Transient results of Venus flyby have been presented for a representative flyby trajectory.
  - The analysis results show that the alternator temperature increase around 10 C.
  - The analysis results show that sunshade on spacecraft can lower ASRG T_c by approximately 20 C for the Venus flyby.
  - For the nominal condition (4K vacuum), ASRG is slightly warmer with sunshade.
- ASRG thermal model simulates the scenario when one ASC is failed. The results are correlated with the test data to determine the thermal property of the shrunk insulation material.

Acknowledgments

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