

# Thermal Model Predictions of Advanced Stirling Radioisotope Generator Performance

Xiao-Yen Wang  
William Fabanich  
Paul Schmitz  
NASA Glenn Research Center  
07/28/2014

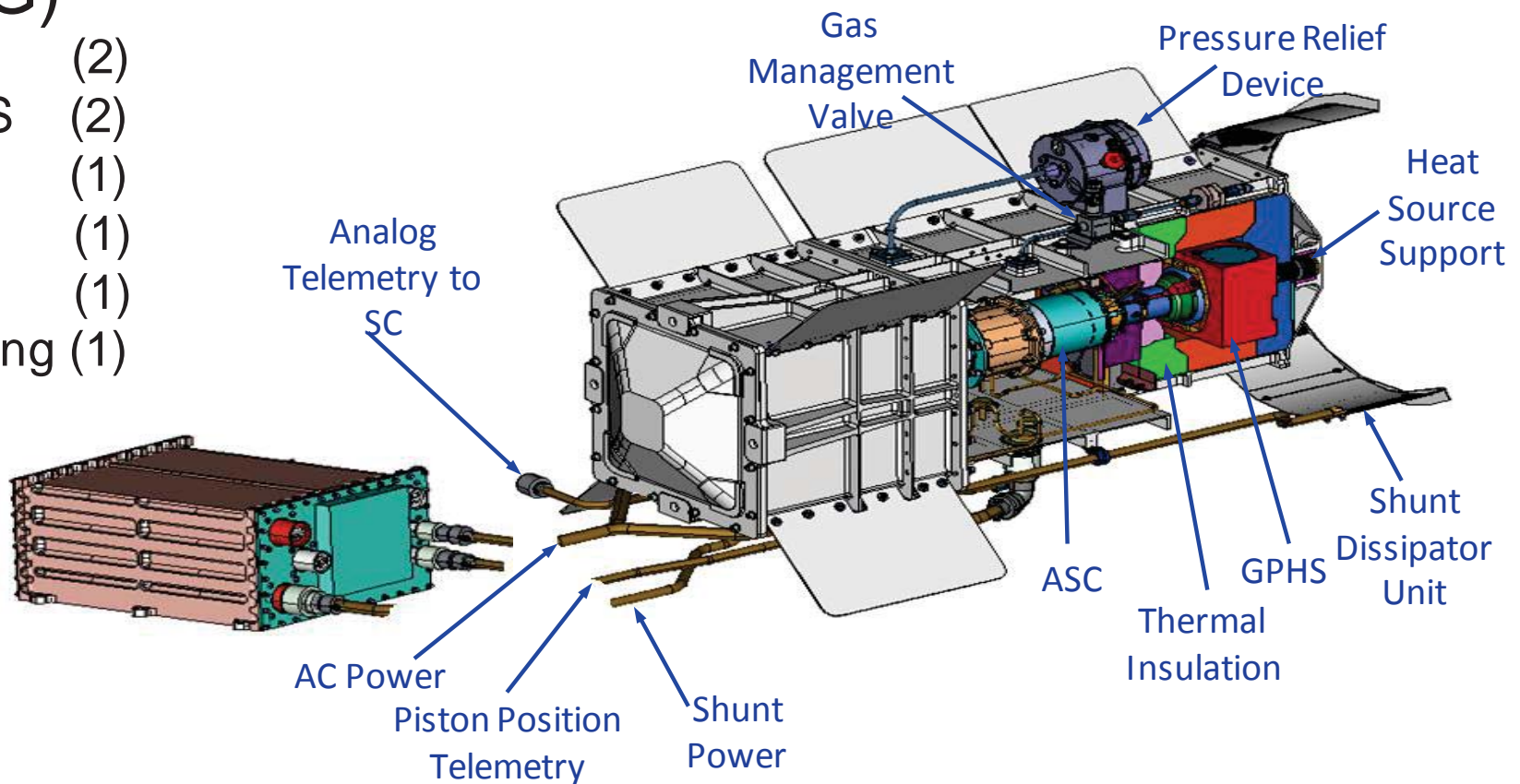
AIAA Propulsion and Energy Forum 2014

- 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)

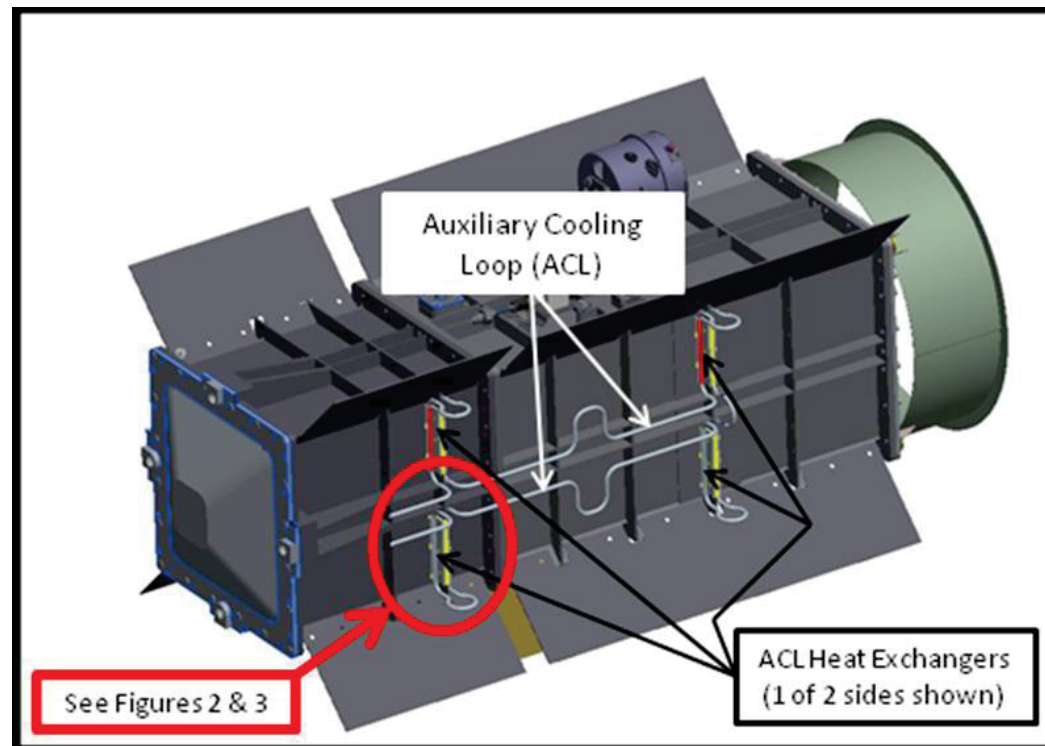


Overview of ASRG components

- 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 Converter (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.

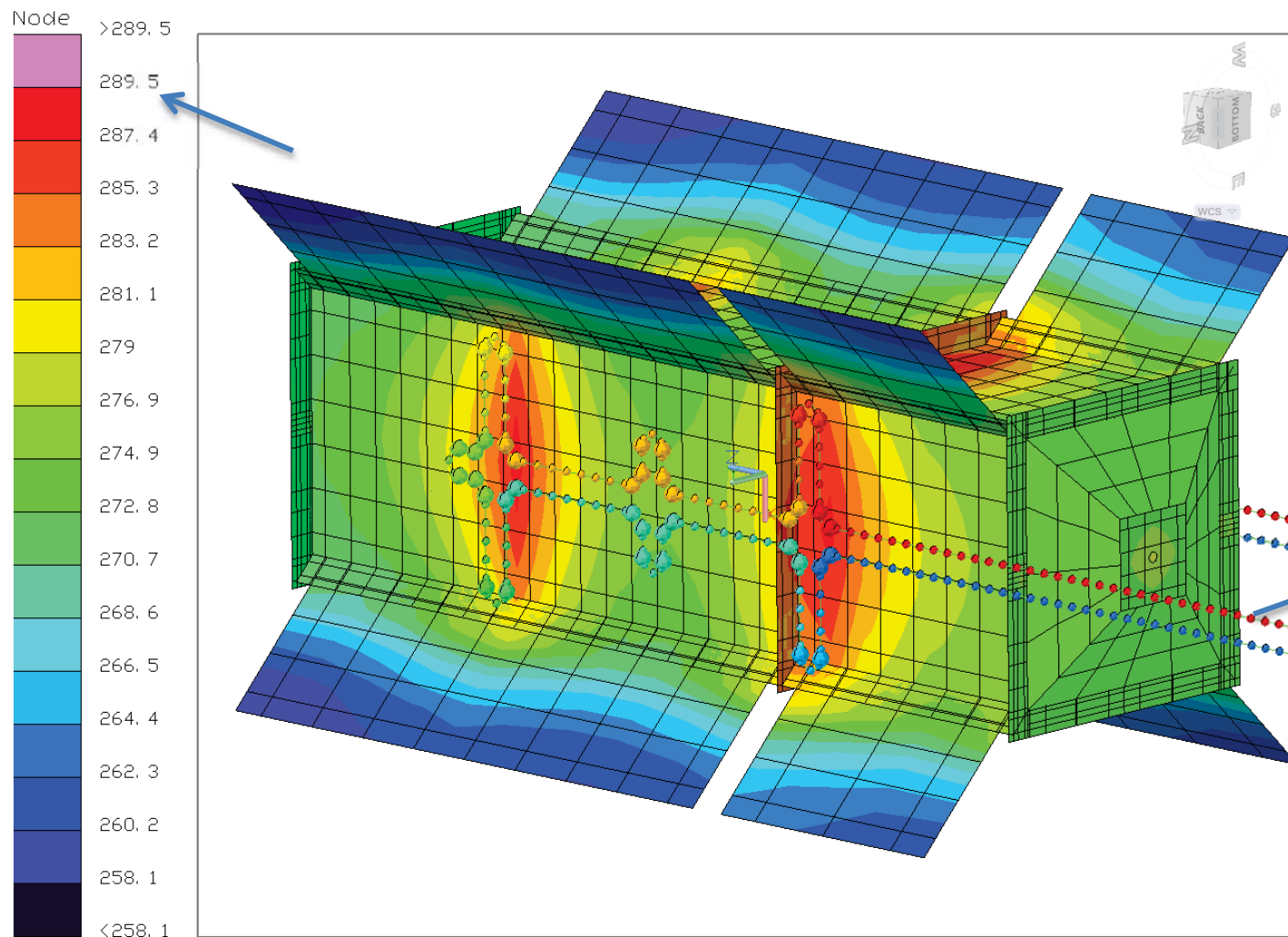
# Auxiliary Cooling System (ACS)

- **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



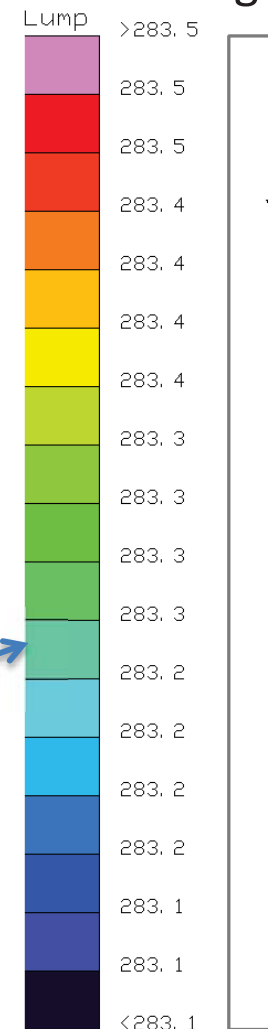
# Model Results of ACS

## Housing T range



Temperature [K], Time = 0 sec

## Fluid T range

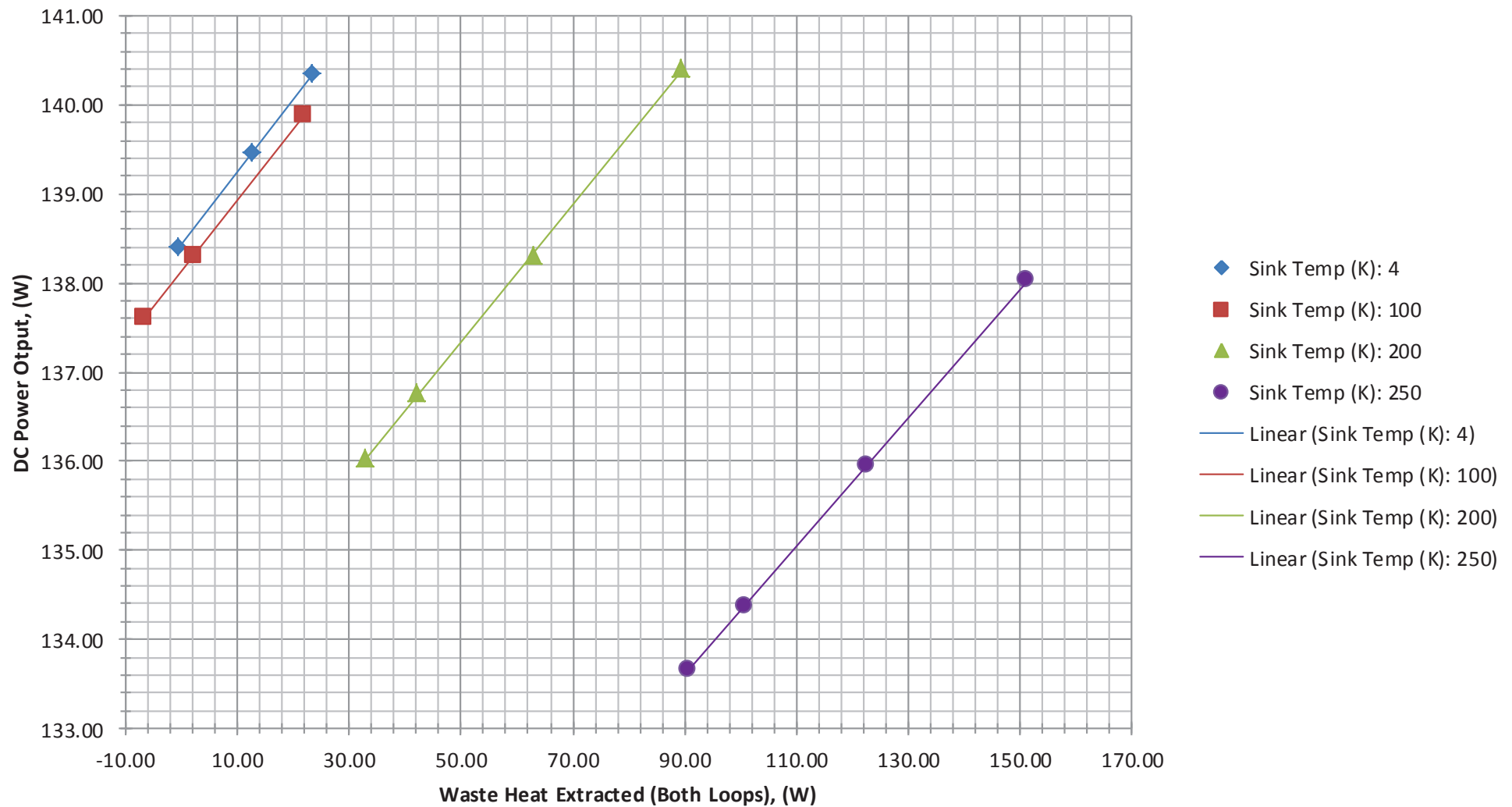


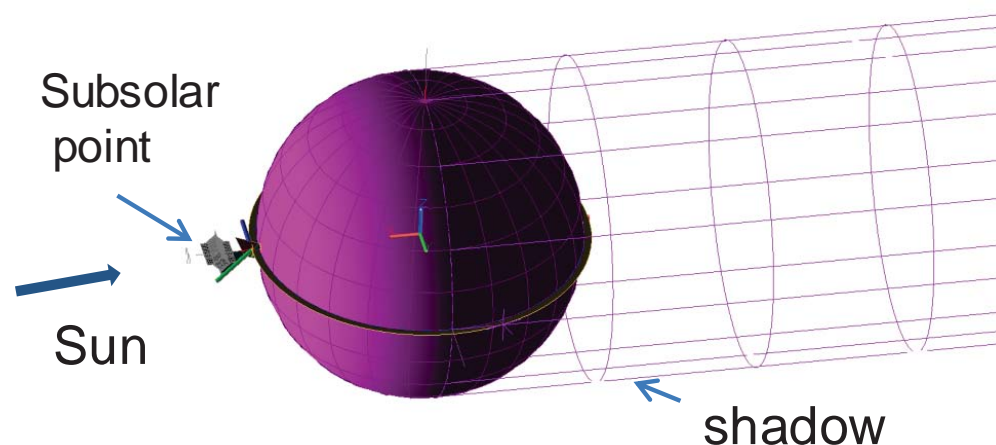
Temperature [K]

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

# $T_h = 760\text{ C, BOM, 4K sink T, 5'' fin (baseline)}$

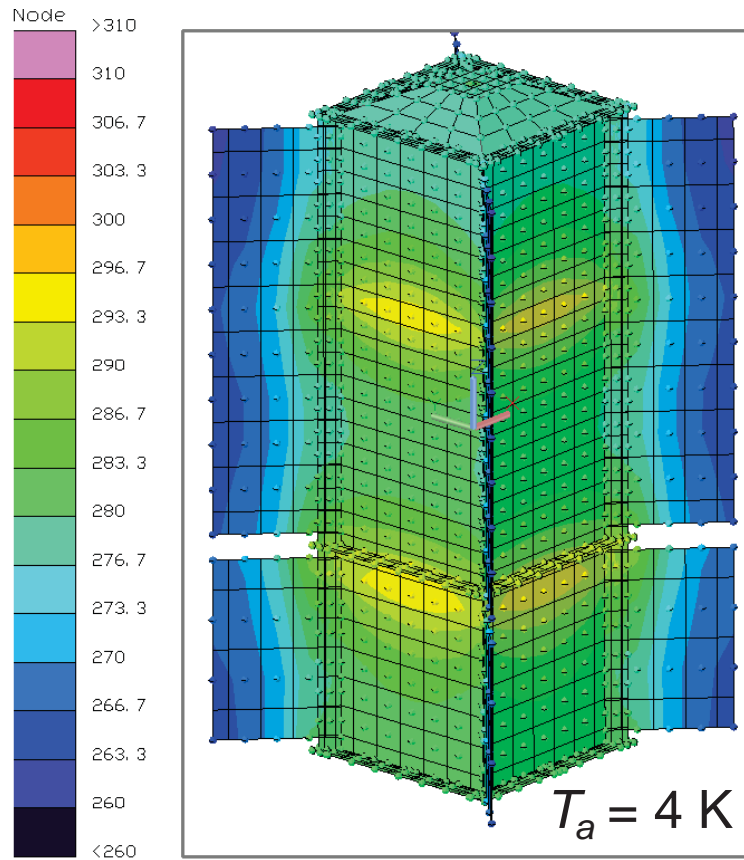
## DC Power Output vs. Waste Heat Recovery as a Function of Fluid Temperature and Sink Temperature (Constant Flow Rate)



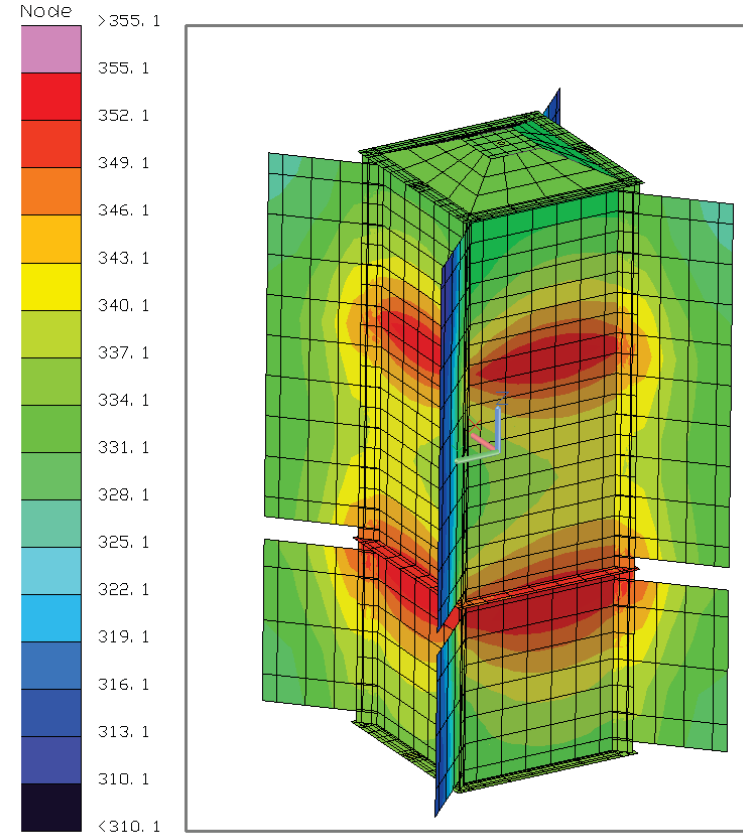


- During the flyby the spacecraft can come as close as 300 km from the surface (~LEO orbit altitudes)
- During this period of time:
  - Direct solar radiation (orbit of 0.7 AU)  $\sim 2588 \text{ w/m}^2$
  - Reflected solar energy from Venus (albedo = 0.72)  $\sim 1900 \text{ w/m}^2$
  - IR energy radiated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

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



Temperature [K], Time = 0 sec



Temperature [K], Time = 0 sec

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

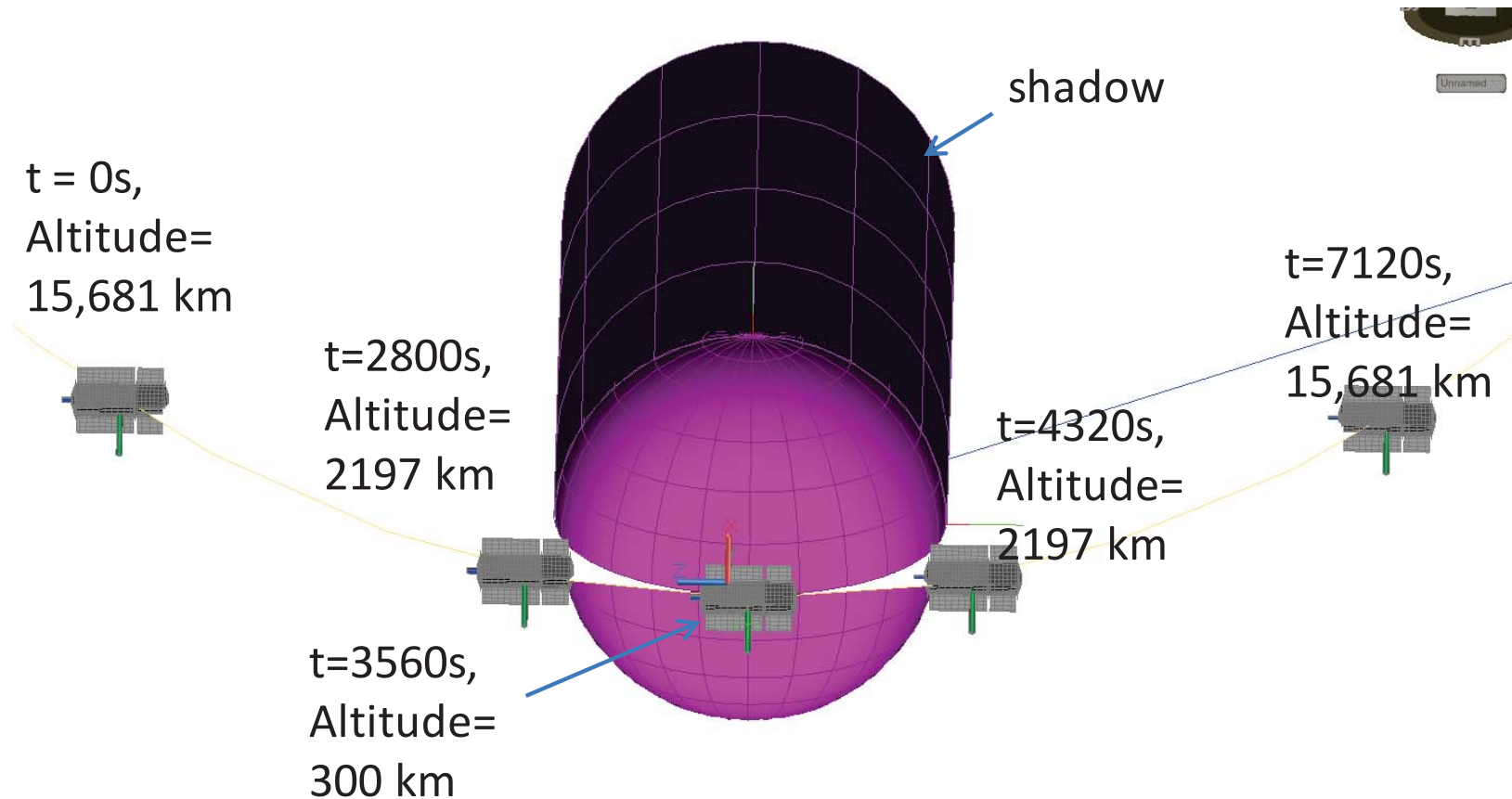
$T_c = 330.4$  K

$W_{alt} = 78.4$  W

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

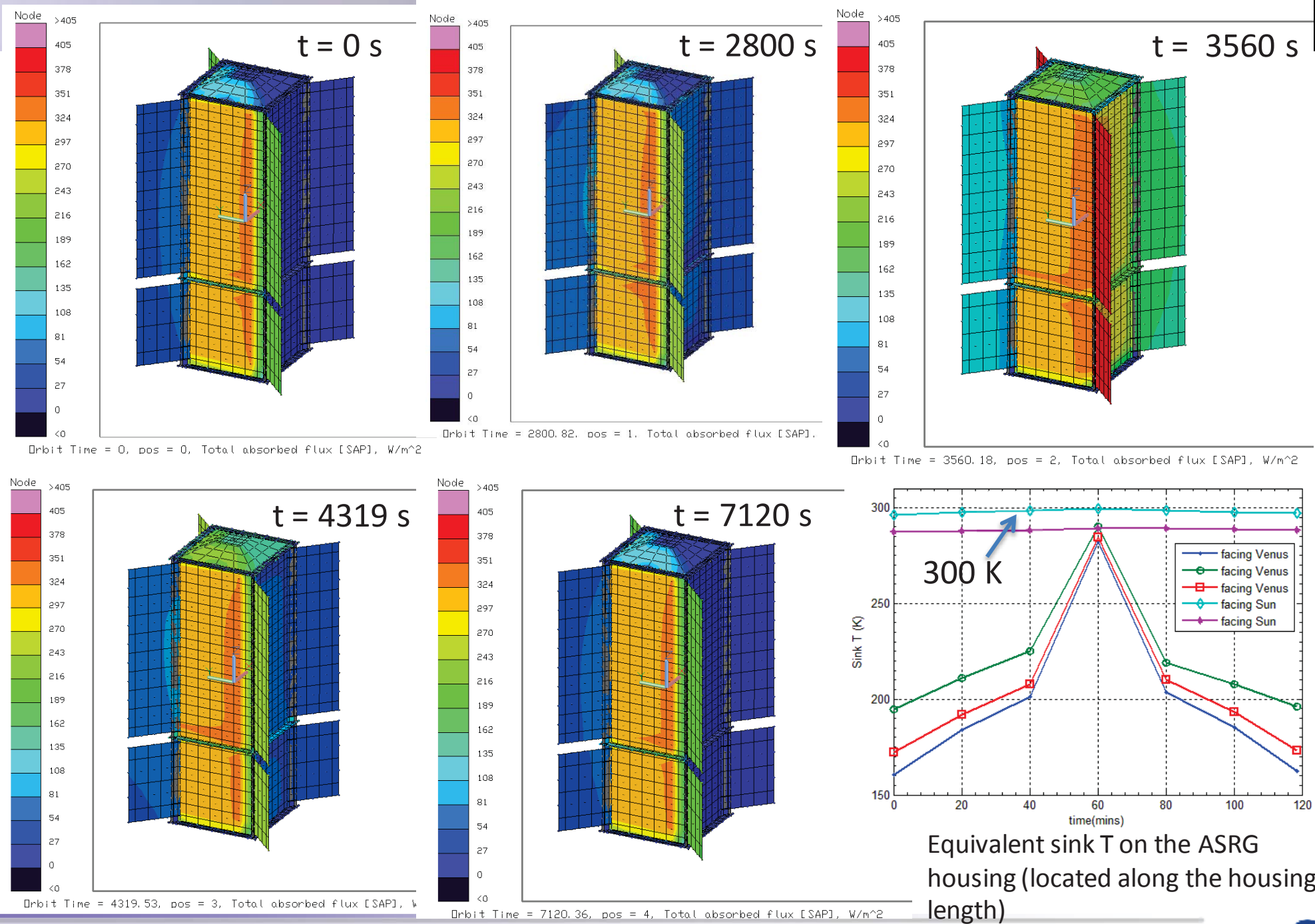
- Update the thermal mass and specific heat for each component based on the data from LM report
- ASC represented by SAGE map is updated at every time step
- ASRG control strategy is to maintain a constant piston amplitude instead of constant  $T_h$ .
- Use the transient solver in Thermal Desktop/SINDA-FLUINT

# Venus flyby trajectory



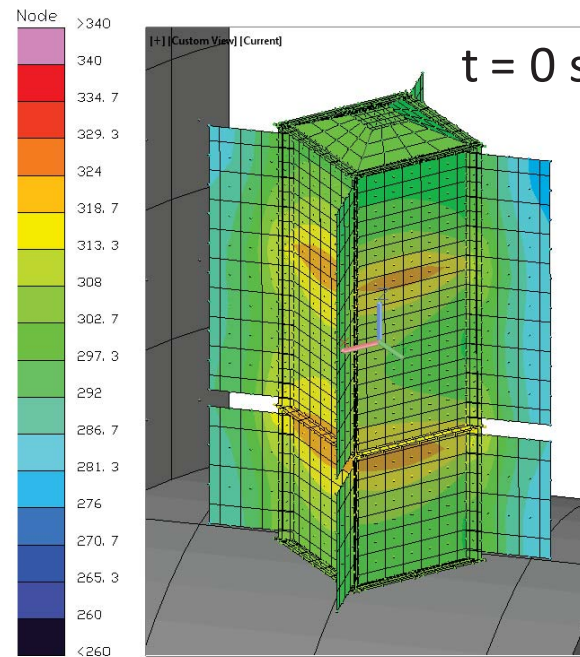
2-hr flyby trajectory showing time and altitude at 5 positions  
(View from the Sun).

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

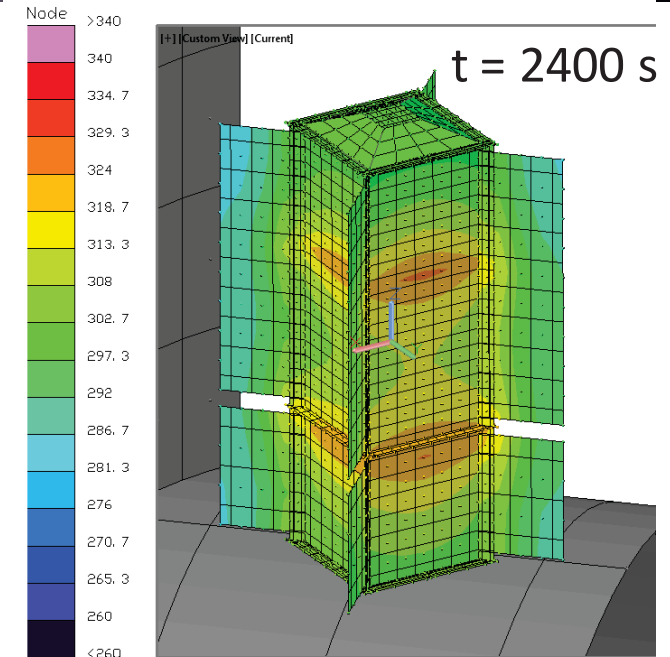


# TD model results at different time on the trajectory

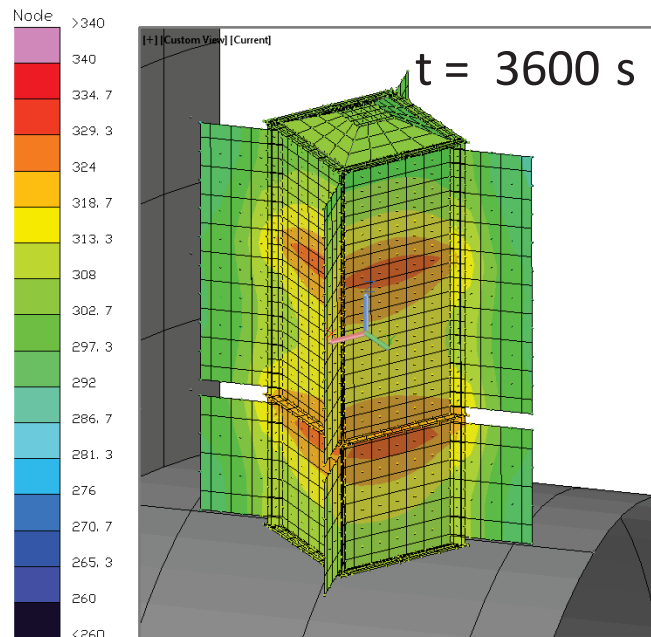
- The initial condition of the transient analysis is defined using the steady-state solution at the starting position on the trajectory, which is identical to the steady-state solution when ASRG is on the Sun orbit of 0.72 AU.



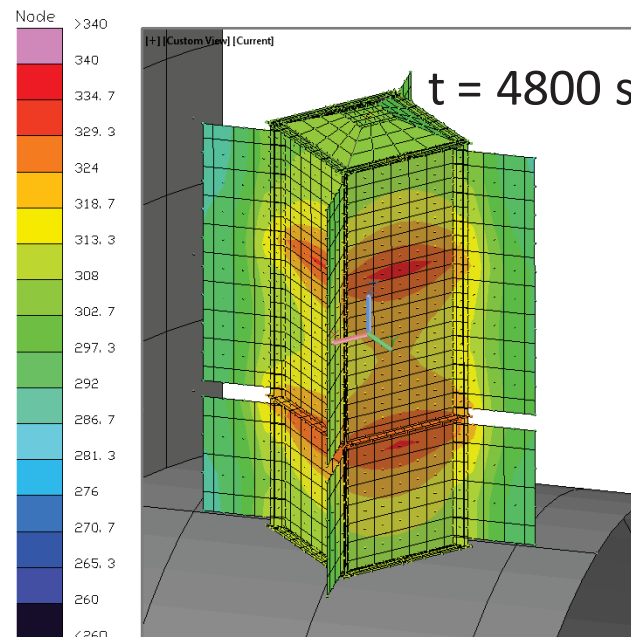
Temperature [K], Time = 0 sec



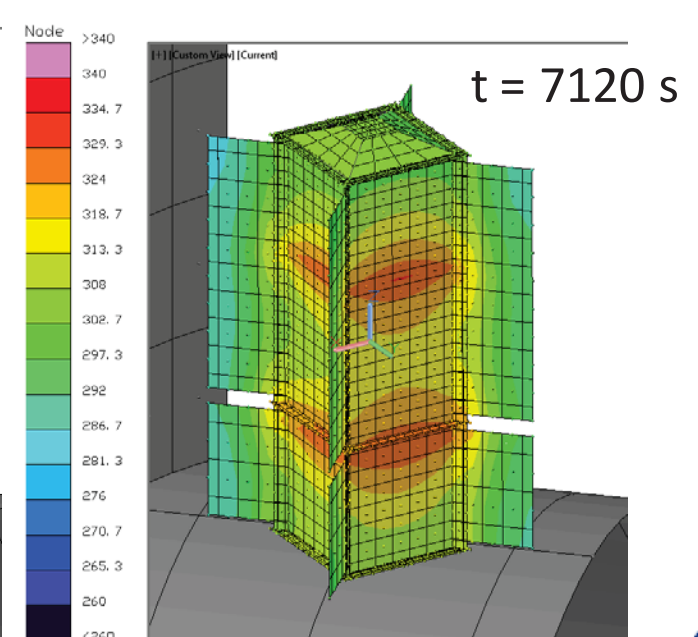
Temperature [K], Time = 2400 sec



Temperature [K], Time = 3600 sec

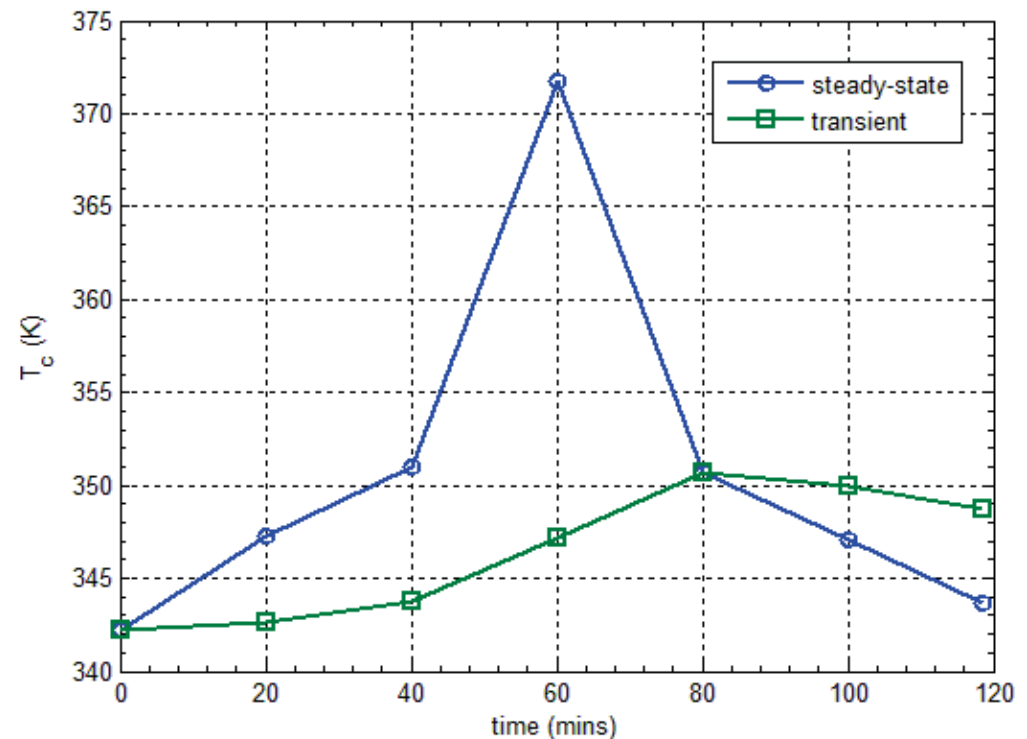


Temperature [K], Time = 4800 sec



Temperature [K], Time = 7120 sec

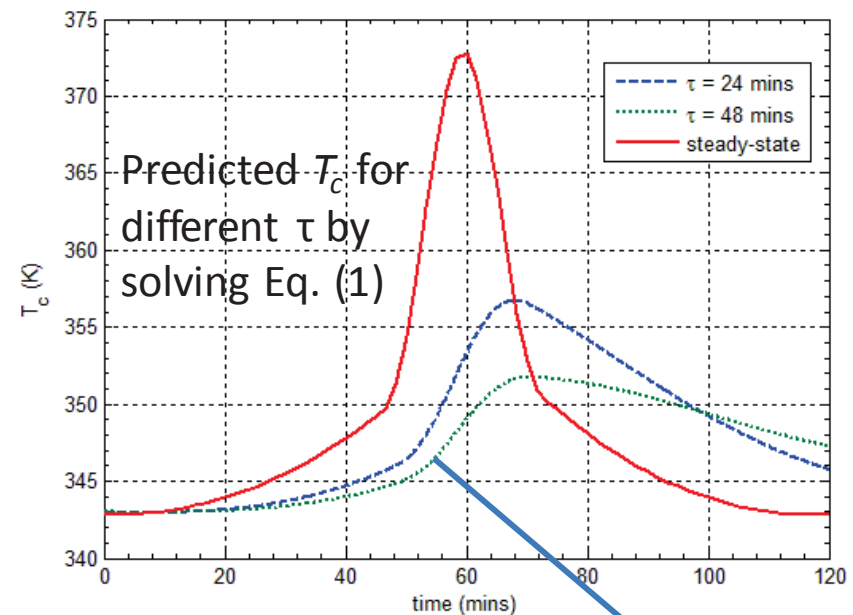
- For both steady-state and transient analysis, a constant piston amplitude is used.
- For 4K vacuum condition, steady-state results show  $T_h = 742.3$  C,  $T_c = 40$  C, DC power is 84.3 W for one ASC.
- Since the alternator temperature ( $= T_c + 10$  C) limit is the concern, here the  $T_c$  is 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).

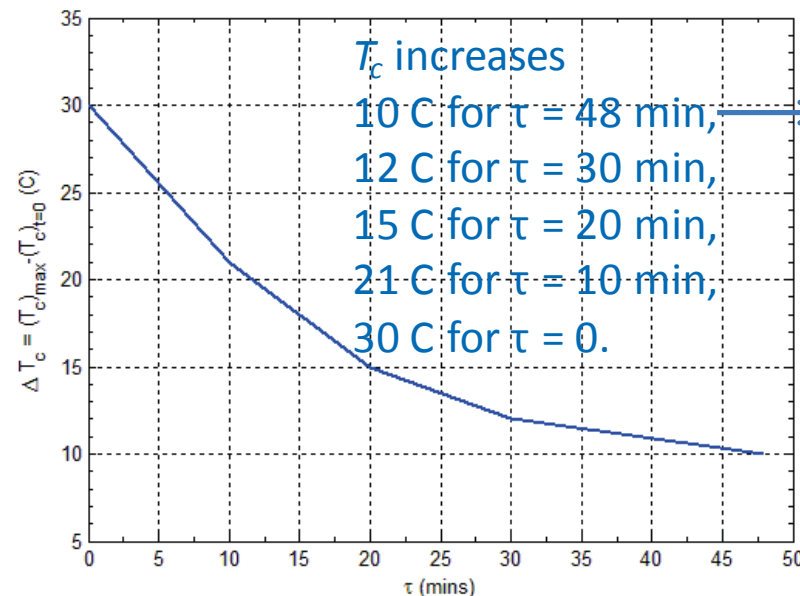
# $T_c$ increases versus ASRG response time ( $\tau$ ) to the environment temperature changes

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



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

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

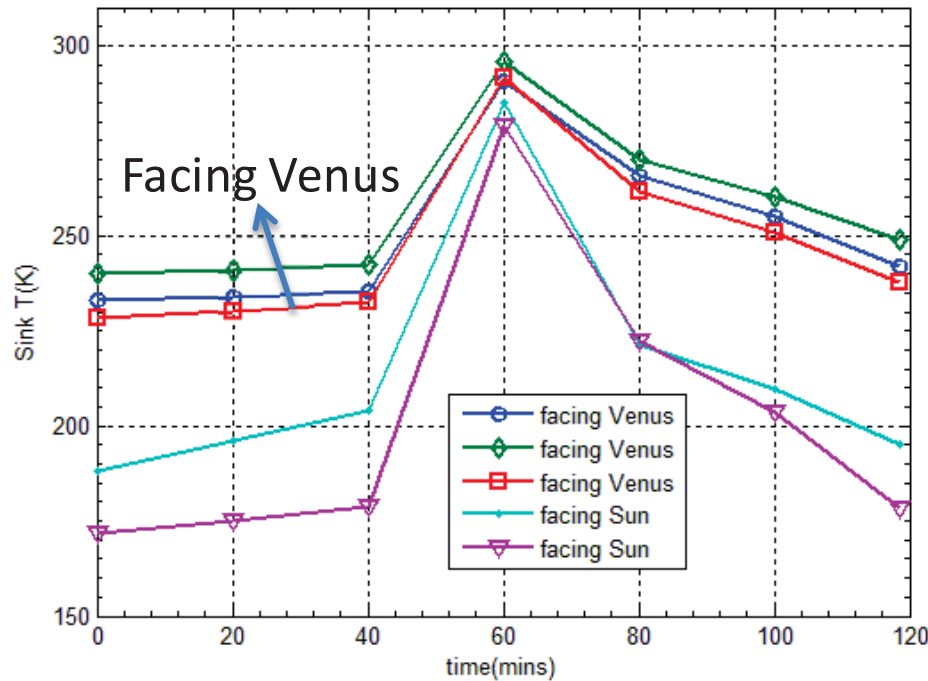


Agree with transient model results (~10 C increase)

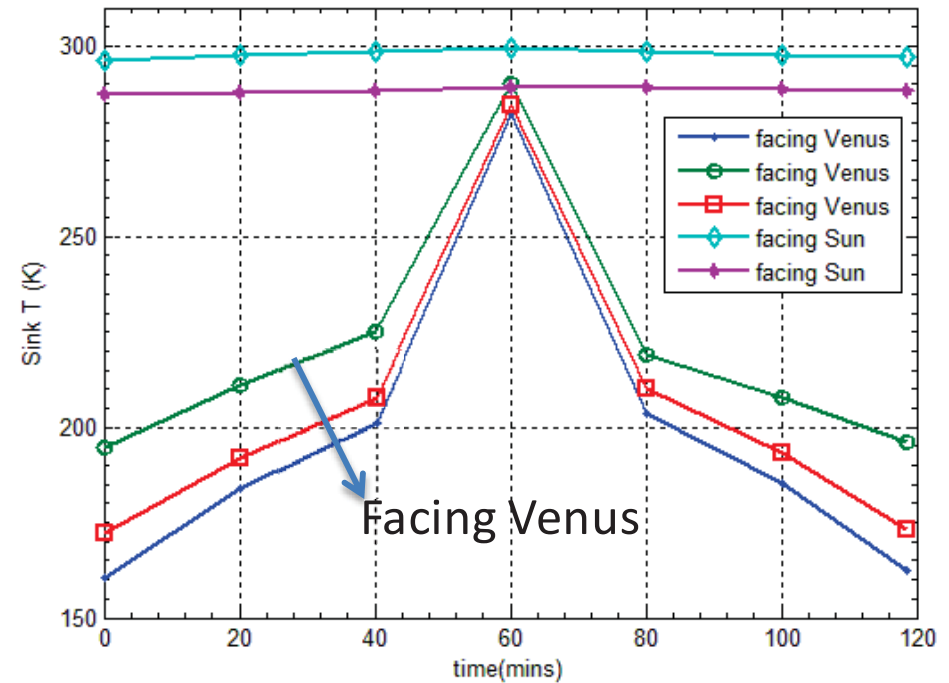
# ASRG Venus flyby with sunshade on spacecraft

- 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:  $\epsilon = 0.04$ ,  $\alpha = 0.3$ ,  $k_{\text{eff}} = 0.0004$   
(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



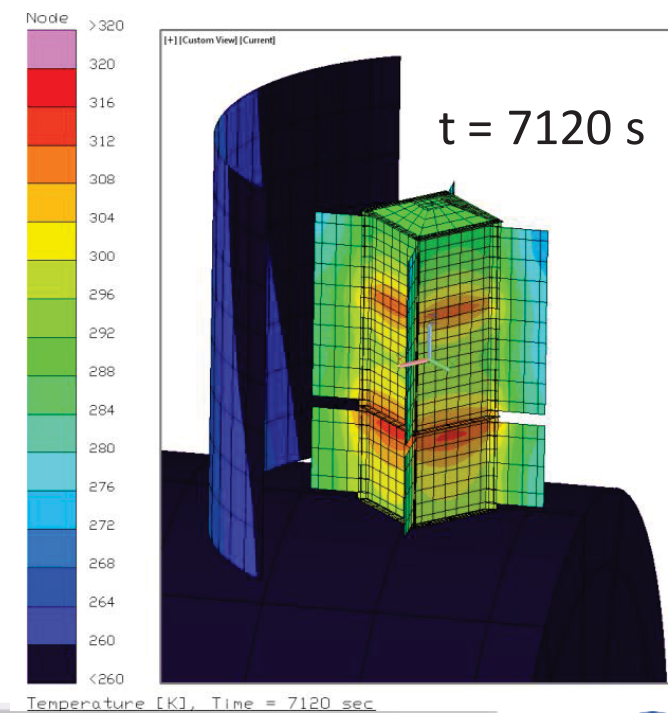
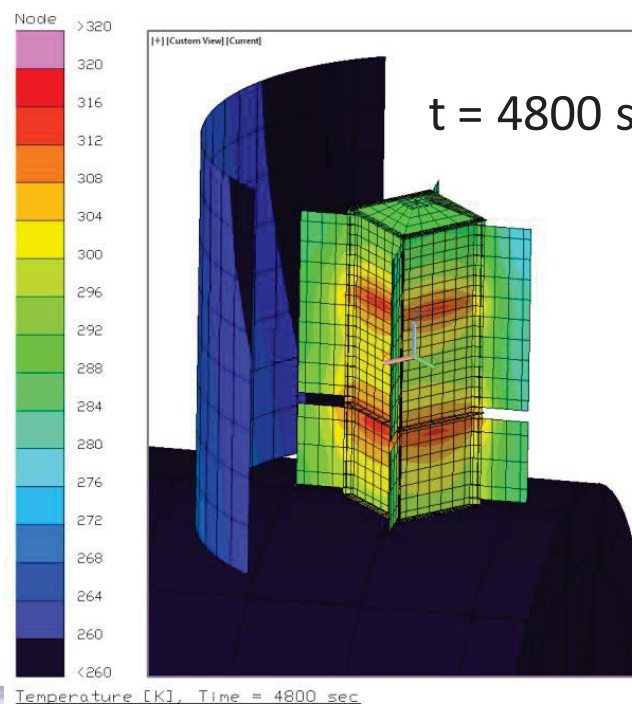
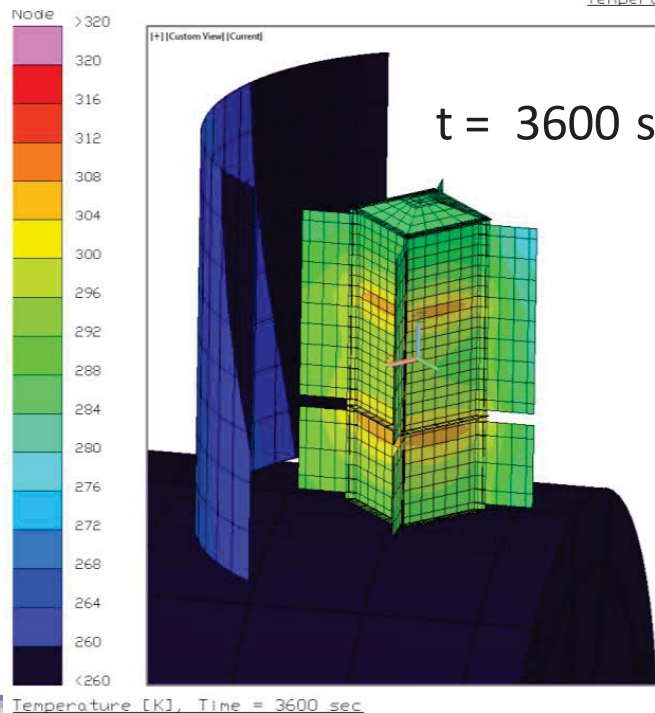
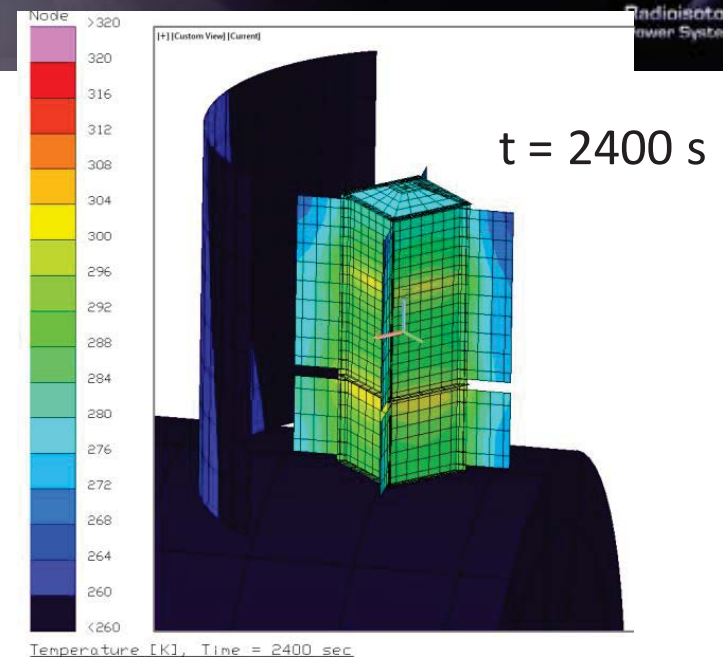
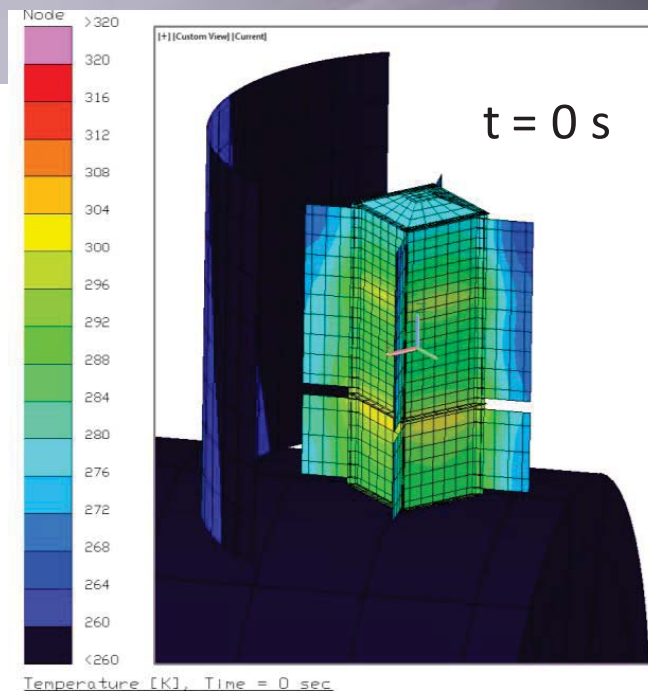
(a) With sunshade



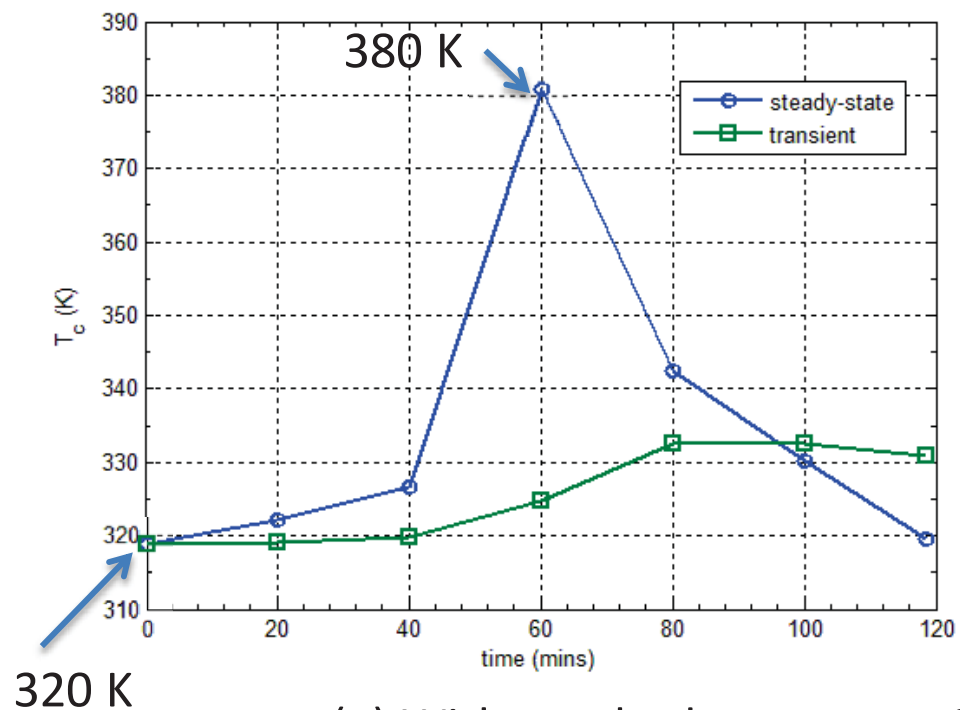
(b) Without sunshade

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.

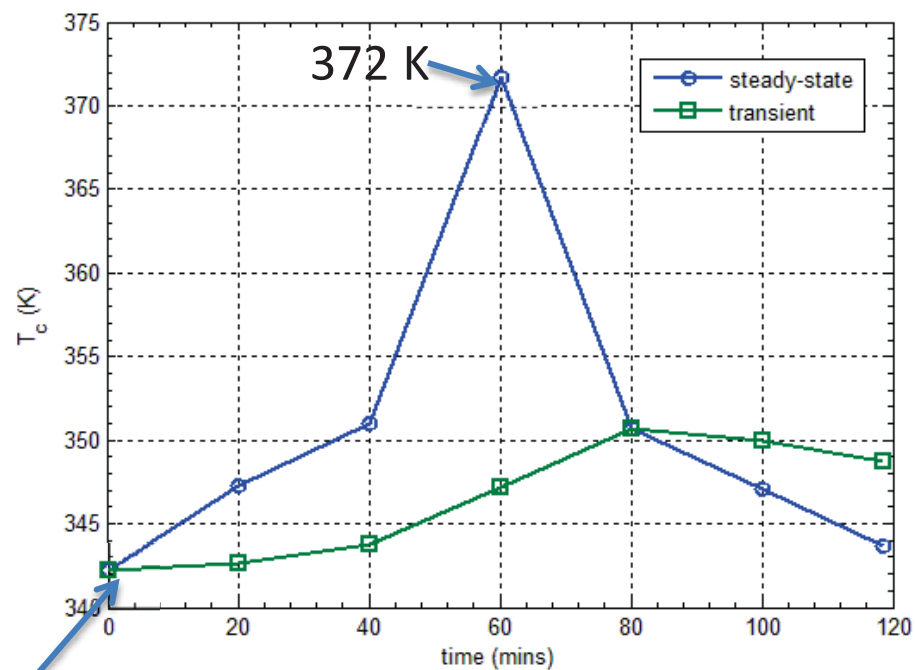
# TD model results at different times on the trajectory (with SC/sunshade)



# TD model results of $T_c$ as function of time



(a) With sunshade



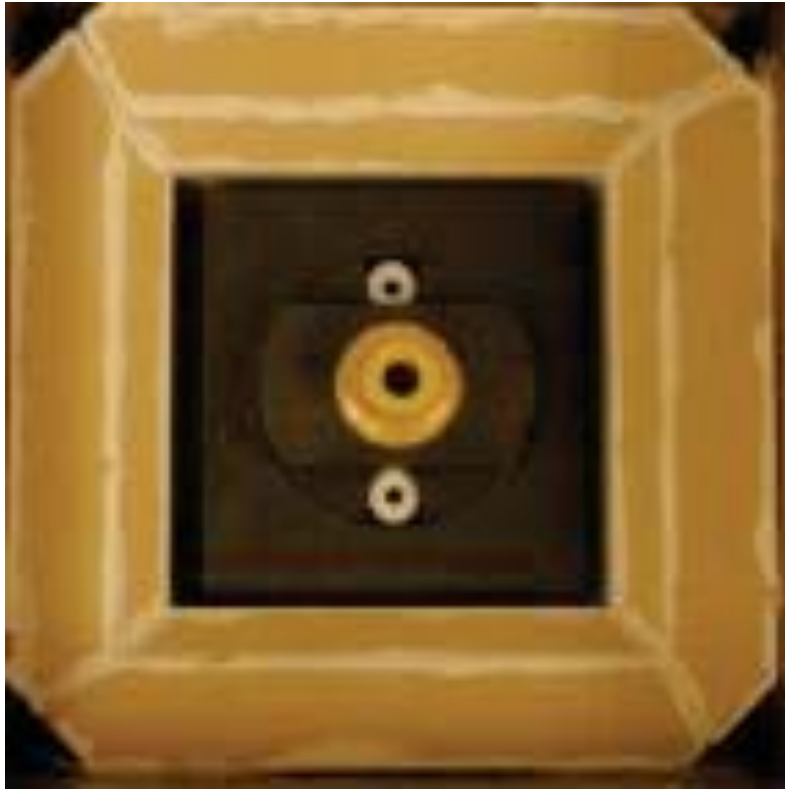
(b) Without sunshade

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



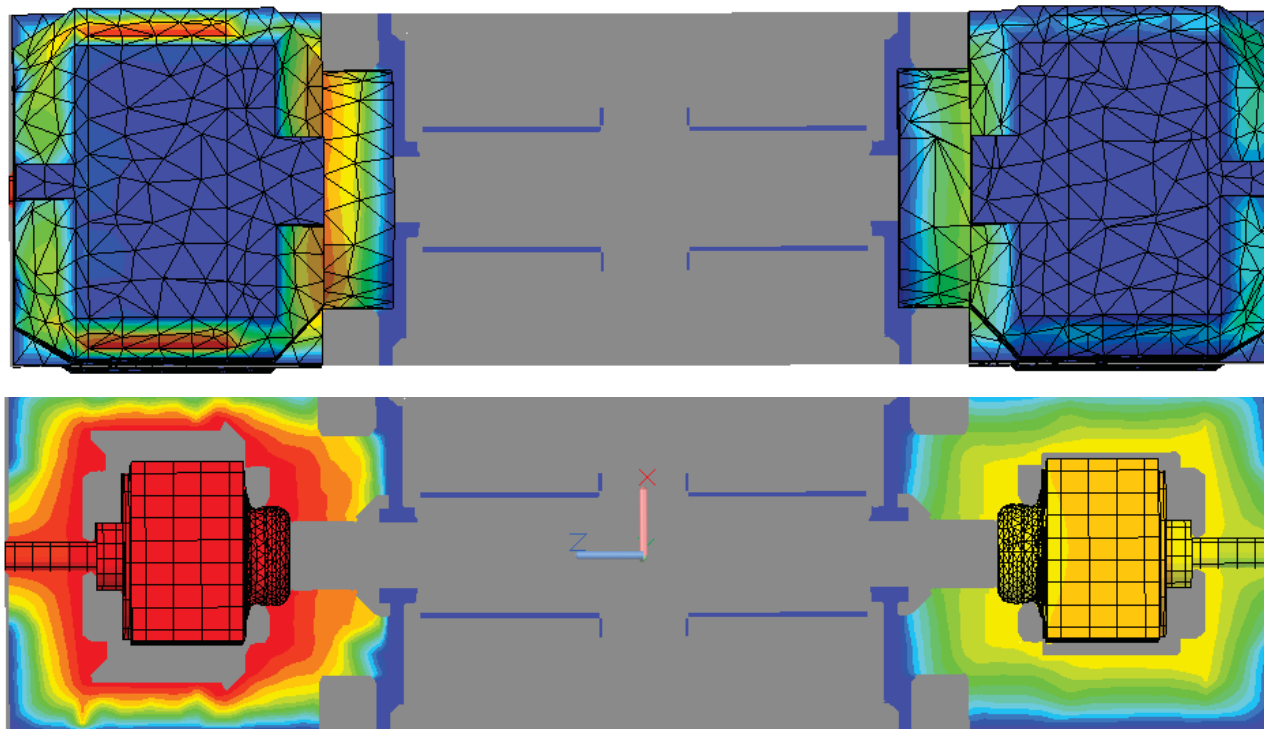
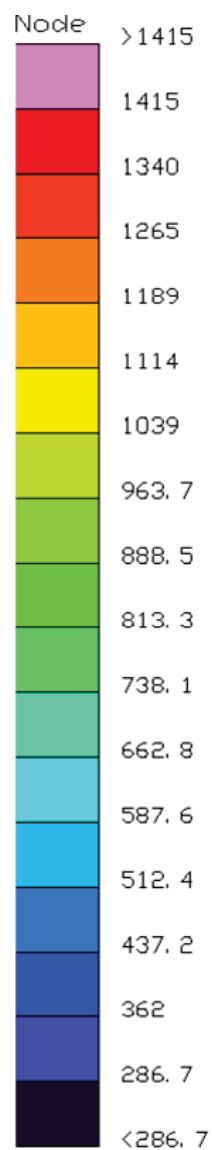
(b) Failed ASC; Post heat dump

- 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;

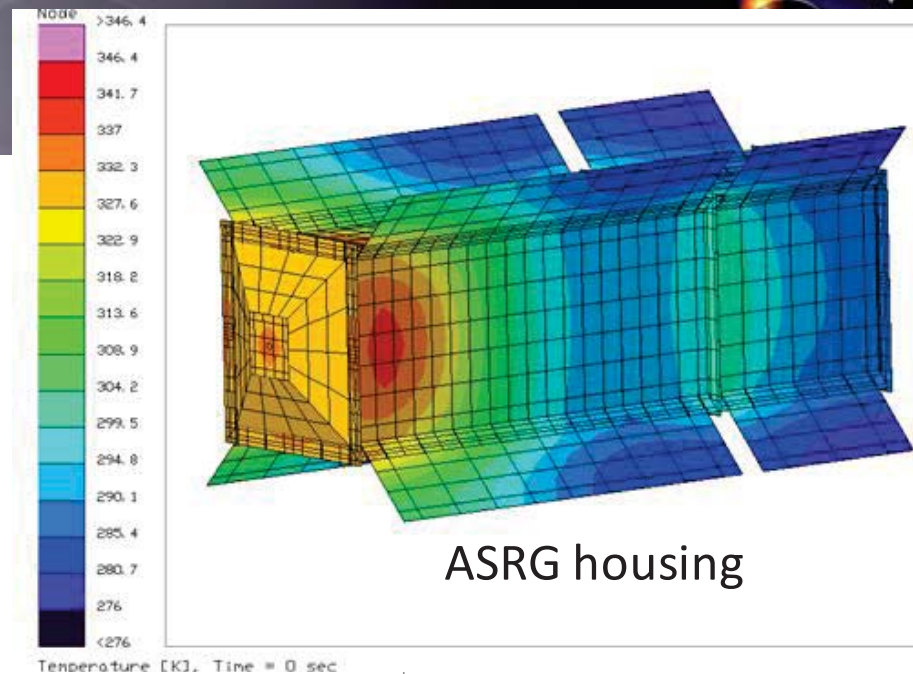
- Geometry Modification
  - Side pieces thickness reduced from 1.52” to 1.02” (0.5” reduction measured by Lockheed).
  - Gaps between sides pieces modified by hand to match (eyeball) photographs taken of post heat-dump insulation by Lockheed.
  - Geometry for Front and End insulation pieces were not 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

Temperature [K],



Outboard A



ASRG housing

Exterior surface of  
insulation block

Inside the cavity  
(a cut plane)

- 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

The authors thank **June Zakrajsek** and **Lee Mason** at NASA Glenn Research Center (GRC) for supporting this effort under the Radioisotope Power System Program, **Duane Beach** at GRC for his advice and support to this modeling work.