Paper 101

Transient Thermal Analysis of a Nano-Satellite in Low Earth Orbit

V. Chandrasekaran and Subramanian E.R.
Department of Mechanical and Manufacturing Engineering
Manipal Institute of Technology, India

Abstract

In this paper, a MATLab code is written to obtain the fluctuation of heat flux as a function of time on a nano satellite and these values are input into ANSYS where the analysis is performed on the primary structure and panels. The various flux and temperature values are obtained from a transient thermal analysis and validated to see if the structure can take the thermal stress induced and check if the working temperature of the internal components is maintained. Use of multi layer insulation (MLI) blankets and paints are suggested to maintain the same.

Keywords: transient, thermal, ANSYS, MATLab, multi layer insulation, nano-satellite.

1   Introduction

Nano satellites are satellites that weigh between 1 and 10 Kgs. A Nano satellite has high importance when it is launched as a secondary payload or as a piggyback, as opposed to primary payloads. The main challenge in designing a nano satellite is in designing the subsystems within dimensional and weight constrains with no compromise on its performance. There are various components like printed circuit boards (PCBs), global positioning system (GPS) receiver, integrated circuits, batteries, magnetorquer which have a very specific temperature range of working, outside which their functional capabilities will not be achieved. Hence, the thermal analysis of the module requires us to understand the thermal loading and provide passive or active protection to maintain the operating temperatures of the interior components.

2   Structural Aspects

The satellite used in this analysis is based upon the 2U cube-sat where the dimensions are 227 mm X 100 mm X 100 mm. The entire primary structure is manufactured from Aluminium 6061-T6 with the ends of the rods anodized to prevent cold welding and for comfortable deployment of the satellite from the deployer. There are four aluminium shear panels of dimensions 207mm X 83mm X 2mm placed on the axial sides and two 100mm X 100mm panels on the lateral sides. There are four solar panels placed on the +Y Panel and –X Panel and four on the +Z and –Z panel each. Each solar panel is of 40mm X 70mm in area with a crop length of 5mm. [1]
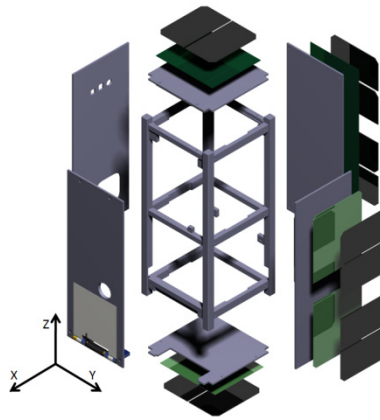

Figure 1: The exploded view of the primary structure with only the solar panels and PCB (without interior configuration) is as shown.

+X Panel	Nadir (earth facing)
-X Panel	Zenith
+Y Panel	Sun facing
-Y Panel	Anti sun facing
+Z Panel	Leading face
-Z Panel	Lagging face

Table 1: The nomenclature of various faces

3   Thermal Loads

The satellite is constantly under the influence of a phenomenon known as thermal cycling, wherein it keeps moving between the sunward side and eclipsed side. The major heat load is due to the heat flux from the sun incident on the various faces of the module. The second type of heat load is the Albedo radiation which is the intensity of heat incident on the satellite due to the reflection from a planet. In case of earth, it is not a constant and varies depending on the surface topography,

continents, ocean cover, snow caps, etc. The third load is the earth emitted infra red radiation. The earth is considered to be a huge mass emitting radiations at a temperature of -18˚C. We cannot neglect this because unlike the sun's radiation, the wavelength is very long and could severely affect the effective radiation of satellites and thus the heat balance in low earth orbit (LEO). The last type of heat load is the heat generation due to heat dissipation of the internal components. All the loads are not static and keep changing with respect to the satellite orientation on the orbital plane. Hence it requires us to perform a transient analysis on the system. [2]

3.1 Calculation of flux due to the sun

This is considered on the faces facing the sun. At a given point of time a maximum of three faces the sun. This is expressed as a direct function of time. Thus the inputs are heat flux values incident on 5 aluminum panels (-Y Side does not receive any flux), 4 PCBs, and 12 solar panels.

The faces of the module that are facing the sun keep changing according to the position of the satellite in its orbit. The changing flux is directly a function of the position of the satellite. Assuming a certain position for time t=0, the absolute position of the satellite can be described as a function of time. Considering time steps of 60 seconds, the flux values on different faces and the temperature are calculated accordingly.

The sun is considered a point source emitting heat in all directions. When this flux is incident on the face of the satellite only the component of the heat flux perpendicular to the surface causes any change in temperature, while the component tangential to the surface is neglected. To ensure that only perpendicular components of the incident flux are included in the calculations a dot product of the incident radiation on the surface.

3.1.1 Axis system

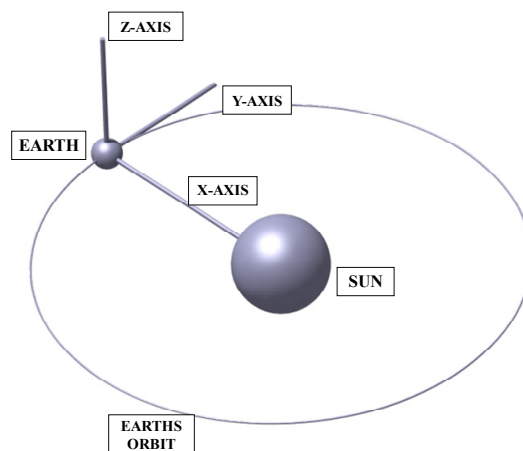The axis system used for the analysis is as shown in figure (2)

Figure 2: Axis system

3

3.1.2 Orbital Elements

The satellite orbit is assumed to be circular, with the earth as its centre. It is possible to completely specify a satellite's circular orbit at any time by a set of parameters. [1]

- **D:** The semi-major axis gives the length from the centre of the ellipse to the farthest point on the ellipse. It is considered to be a value of 1340Km, giving us a radius of 670Km.
- **i:** It is the angle of the orbit plane compared to the fixed equatorial reference plane. The inclination is an angle from 0 to π and the value used is 98 Degrees. Refer figure (3).
- **Ω (RAAN) :** The longitude of the ascending node is an angle that takes values from 0 to 2π. It is the angle between the X-axis of inertial frame and the ascending intersection of the reference and orbital plane. Value used is 66 Degrees. Refer Figure (3)
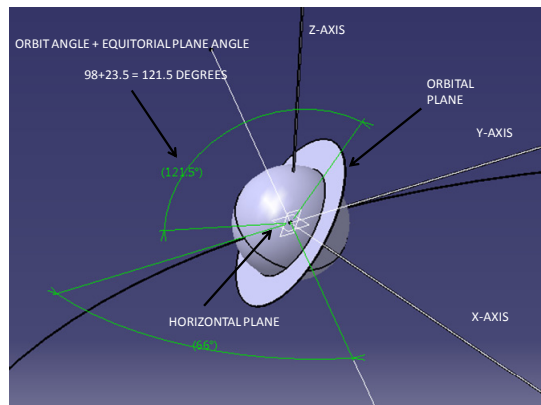

Figure 3: Orbital elements

3.1.3 Calculations

$$r_x = \vec{r}\sin(\emptyset)\cos(\omega)\,\hat{\imath} + \vec{r}\sin(\emptyset)\cos(\varphi)\,\hat{\jmath} + \vec{r}\cos(\emptyset)\hat{k} \qquad (1)$$
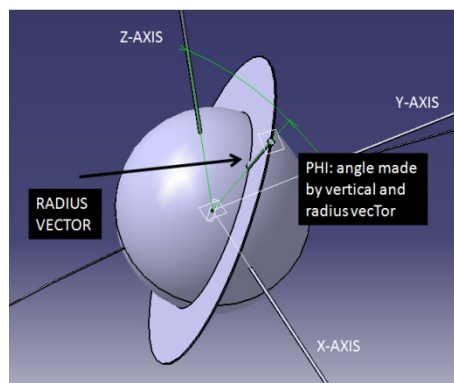
Figure 4: Angle $\emptyset$
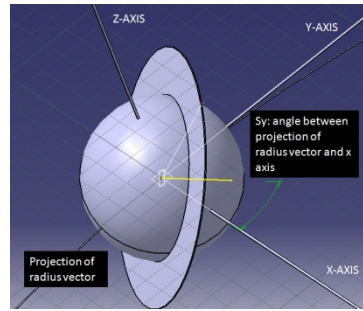
Figure 5: Angle ω

$$r_y = \vec{r}\sin(\emptyset + 90)\cos(\omega)\,\hat{\imath} + \vec{r}\sin(\emptyset + 90)\sin(\omega)\,\hat{\jmath} + \vec{r}\cos(\emptyset + 90)\hat{k} \quad (2)$$

$$r_z = \vec{r}(\cos(90 - \omega t)\cos(\Omega - 180) + \cos(\omega t)\cos(i + 22.5)\cos(\Omega - 180)\,)\,\hat{\imath} \\ + \vec{r}\sin(\emptyset + 90)\sin(\omega)\,\hat{\jmath} + \vec{r}\cos(\emptyset + 90)\hat{k} \quad (3)$$

By vector addition refer Figure (6)

$$\vec{ss} = \vec{d} + \vec{r} \quad (4)$$

$$\hat{ss} = \frac{(\vec{d} + \vec{r})}{(\vec{d})(\vec{r})} \quad (5)$$

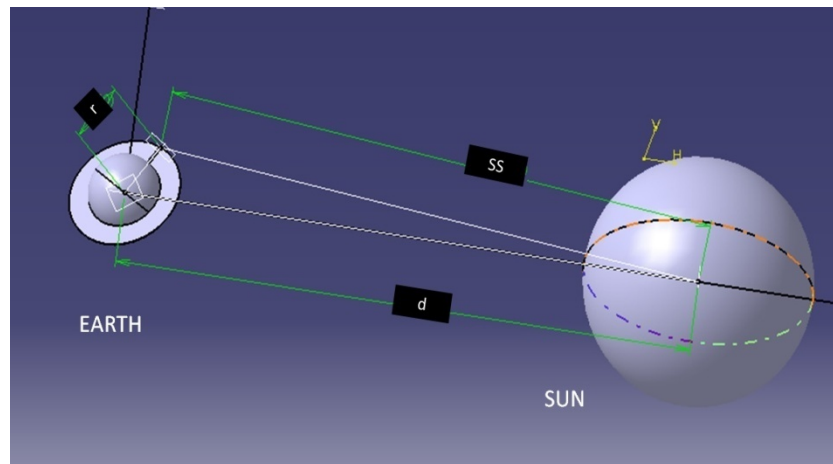$$H = SC\ X\ (\hat{ss}\,.\,\hat{r}) \quad (6)$$

This is used to give us the heat flux in the X, Y and Z directions.
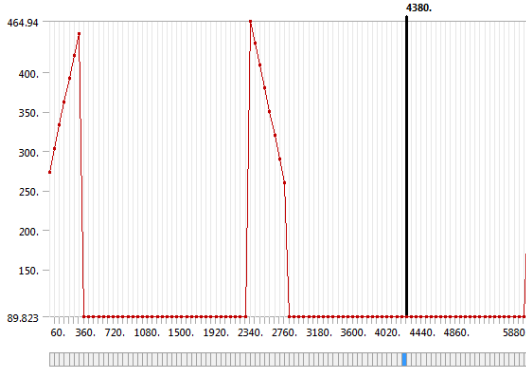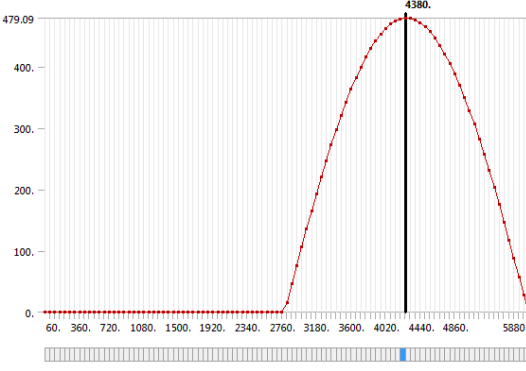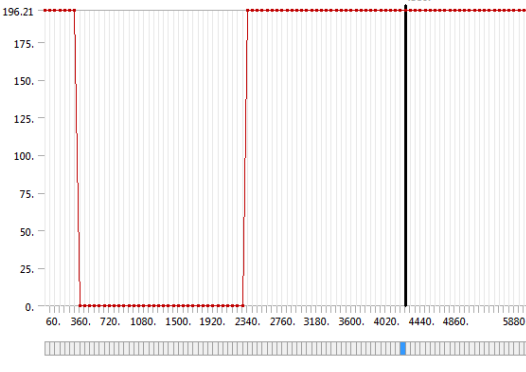

Figure 6: Vector addition

Face	Heat Flux
+X	
-X	
+Y	
+Z	

Table 2: Loading on different faces of the module
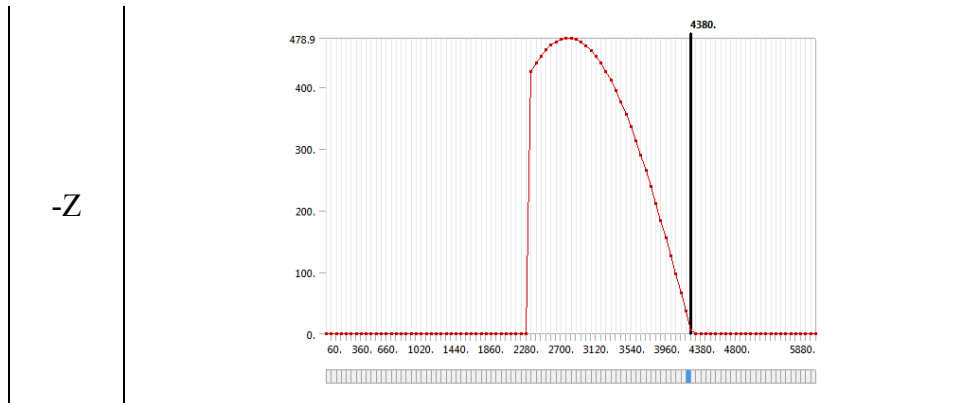
-Z	

Table 2: (continued) Loading on different faces of the module

3.2 Heat flux due to albedo

This is an added flux considered on the +X face. When the +X face faces the earth, there is an added flux due to emitted infra red radiation and albedo by the earth's surface. This on an average is considered to be a fixed value of 0.3 times the incident flux. [2]

4 Heat Transfer

4.1 Conduction

The conductive heat transfer between any two bodies is given by:

$$Q = -KA \frac{dT}{dx} \qquad (7)$$

Where K: Thermal conductivity, A is the area of cross-section resisting the heat flow and dT/dx is the temperature gradient. Conduction takes place between the solar panel and PCB and the PCB and aluminium.

4.2 Radiation

The Stefan's Boltzmann equation for radiation is given by

$$Q = \sigma \varepsilon A (T_1{}^4 - T_2{}^4) \qquad (8)$$

Where σ is the Stefan Boltzmann's constant = 5.678×10^{-8} W/m²K⁴ and ε is the emissivity of the surface. Radiation occurs between deep space and aluminium on

five faces and the sixth face facing earth radiates to the earth. Radiation also occurs between solar panels and deep space.

4.3 Wien's displacement law

Wien's displacement law states that the wavelength distribution of thermal radiation from a black body at any temperature has essentially the same shape as the distribution at any other temperature, except that each wavelength is displaced on the graph. [3]

5 Analysis

5.1 Assumptions

A few of the assumptions used in our analysis are as follows.
- At such high altitudes the atmospheric pressure is so low that the heat transfer between 2 bodies is purely through radiation and conduction when there is a contact. Convective heat transfer is negligible.
- The albedo constant for the satellite based on the above orbit is 0.3 averaging it over the entire earth surface for that particular trajectory.
- The heat flux incident on a particular surface is multiplied by the absorptivity value to account for the absorbed and reflected radiation before putting into ANSYS.
- The MATLAB code neglects minor variations in the orientation of the three axis stabilized satellite.
- Direct solar radiation intensity falling on the satellite is 1367 W/m²
- The earth, which emits radiation between 8 and 15μm, is treated as a body of temperature 251.15K which follows from Wein's displacement law.
- The deep space temperature to which the faces are exposed to, is considered to be 3.15K
- Effects due to molecular heating and atomic oxygen, though prominent in LEO, are neglected.
- Internal heat generation has been neglected in the analysis to simplify the problem.

As a preliminary step, a steady state analysis of a hot case condition, corresponding to maximum heat flux incident on the surface and cold case, for minimum heat flux incidence are done to get the expected range of temperature. It is important to note that these temperatures need not dictate the actual temperatures achieved in the orbit corresponding to these flux values. As mentioned above, it's a preliminary step before setting up the analysis. Using the basic heat balance equation, we have
$$\text{HeatInput} = \text{HeatOutput} \tag{3}$$

5.2 Thermal Protection

Following the basic analysis, the designer can chose between passive and active thermal control procedures. Active thermal control involves the employment of heaters, louvers, phase change materials, pumped fluid loops. All the above require external current which will cause a huge requirement of power from the electrical power. The use of surface finishes, multi-layer insulations, paints come under the passive thermal control. They can be used as a sole protection system only for short term small missions because prolonged exposure could degrade their performance. Here, we consider the use of passive control on the satellites, for the use of active methods will increase the power budget. [2]

5.2.1 Paint

Paints are used for surface finishes on the satellite. The main purpose of applying a surface coating on the exteriors is to reflect off most of the incident energy and thereby reduce the induced inside temperatures. The α/ε is maintained minimum through which the incident energy is reduced considerably and most of the possessed energy is emitted. Z-93 is a surface paint manufactured by AZ Technologies. It is a white paint with absorptance 0.15 and emittance 0.91, thus reducing the effective α/ε value. [4]

5.2.2 Multi layer insulation

Multi-layer insulation, or MLI, is thermal insulation composed of multiple layers of thin sheets that is often used on spacecraft. It is one of the main items of the spacecraft thermal design, primarily intended to reduce heat loss by thermal radiation.

The principle behind MLI is that of radiation shields; to reduce the overall heat transfer coefficient between two radiating surfaces material which are highly reflective. It is introduced between the heat exchanging surfaces. The radiation shield reduces the radiation heat transfer by effectively increasing the surface resistances without actually removing any heat from the overall system. [5]

When two bodies at different temperatures are kept at a certain distance of d from each other, there are three resistances that come into play [5]

- Surface resistance of body 1 given in Equation

$$r_{Surface} = \frac{1-\epsilon}{A\epsilon} \qquad (10)$$

ϵ is the emissivity of the object. A is area of radiating surface.
- Space resistance due to the space in between the two bodies.

$$r_{Space} = \frac{1}{A_1 F_{1-2}} \qquad (11)$$

- Space resistance of body 2

When there is a radiation shield that is introduced in between these two surfaces it cause an increase in resistance by increasing the surface resistance due to introduction of two extra surfaces as well as a conductive resistance.
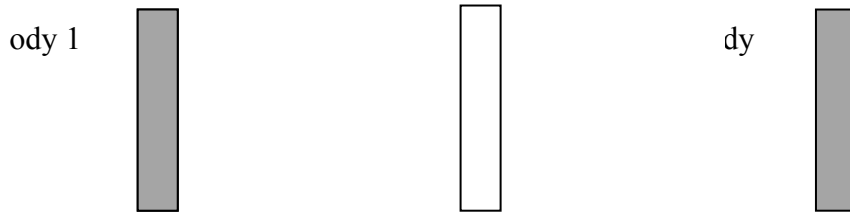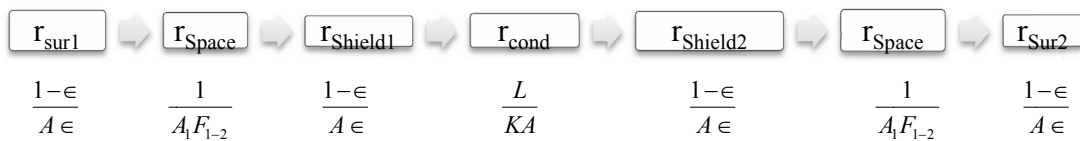

Figure 7: Radiation shield between two bodies

$$r_{sur1} \Rightarrow r_{Space} \Rightarrow r_{Shield1} \Rightarrow r_{cond} \Rightarrow r_{Shield2} \Rightarrow r_{Space} \Rightarrow r_{Sur2}$$

$$\frac{1-\epsilon}{A\epsilon} \qquad \frac{1}{A_1 F_{1-2}} \qquad \frac{1-\epsilon}{A\epsilon} \qquad \frac{L}{KA} \qquad \frac{1-\epsilon}{A\epsilon} \qquad \frac{1}{A_1 F_{1-2}} \qquad \frac{1-\epsilon}{A\epsilon}$$

Figure 8: Resistances when a shield is introduced

Hence adding of shields adds to the resistance thus decreasing the heat transfer.

5.3 Material Properties

Components	Material	Sp. heat (J/kg°C)	Thermal Conductivity (W/m-K)		Density (kg/m³)	Young's Modulus (Pa)	Poisson's ratio
H Brackets	Aluminium 6061 T-6	875	-100°C	114	2700	5.2 X 10⁹	0.35
			0°C	144			
			100°C	165			
			200°C	175			
Solar Panels	Germanium	310	58		5323	1.026 X 10¹¹	0.278
PCB	FR4	1150	0.29		1820	1.6 X 10⁹	0.143

Table 3: Material Properties

Material	Absorptivity	Emissivity
Aluminium 6061 T6	0.379	0.08
Germanium	0.92	0.85
FR4	0.6	0.7
MLI	0.2	0.8
Z93	0.17	0.82

Table 4: Surface properties

In this analysis we observe that the thermal conductivity of Aluminium, which is a material property, is not a constant and depends on temperature, resulting in a non-linear analysis and thus requiring an iterative procedure to solve.

5.4 Geometry

The CATIA Assembly file is converted into a .stp file and imported into ANSYS Workbench. The body is placed along the same co-ordinate axis as shown and the model was checked for any discrepancies. Contact regions are specified by bonded connections which are introduced between the solar panel and PCB interface. The PCB is bonded on the solar panel.

5.5 Element Descriptions

5.5.1 SOLID90

SOLID90 is a 3-D thermal element with conduction capability. The element has 20 nodes with a single degree of freedom, which is temperature, at each node. The element is applicable to a 3-D, steady-state or transient thermal analysis. A prism-shaped element, a tetrahedral-shaped element, and a pyramid-shaped element may also be formed to map the geometry of the body. The applied heat flux is positive into the element and a free surface of the element that is not adjacent to another element and not subjected to a boundary constraint is assumed to be adiabatic
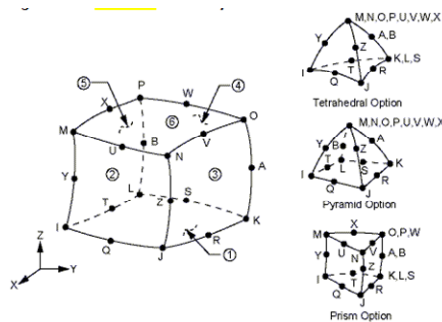

Figure 9: SOLID90

5.5.2 SURF152

SURF152 is used for various load and surface effect applications. It may be overlaid onto an area face of any 3-D thermal element. Hence it adheres to the constraints of the SOLID90 element. The element is defined by four to ten nodes and material properties. An extra node (away from the base element) is used for modeling convection or radiation effects.

The finite element is then formed using these two elements. The relevance centre was set was fine, smoothing- medium and minimum edge length as 0.5mm with 125732 nodes and 55819 elements. The model is as shown in Figure (11)
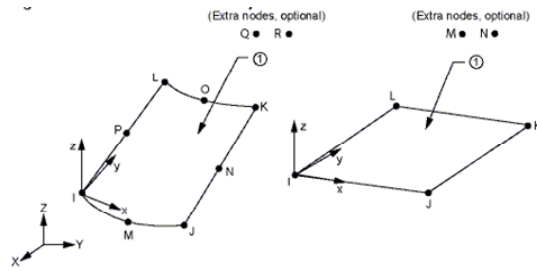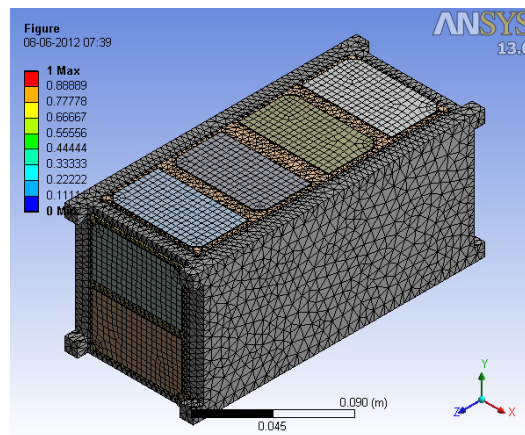
11

Figure 10: SURF152

Figure 11: Finite element model

5.6 Analysis Settings

5.6.1 Time steps

Since the entire orbit is divided into 98 minutes, we take the time step to be 1 minute. Since the computation involved is too much, higher sub time steps are given. With auto time stepping on, the initial time step is 5 seconds, the minimum time step is 4 seconds and maximum is 20 seconds. The flux convergence is 0.0001 with maximum iterations being 1000. The heat flux, being a surface load is applied on each face.

5.6.2 Loading

The generated values from MATLab are imported into this and provided against the corresponding time step. Thus heat flux values incident on 5 aluminium panels (-Y Side does not receive any flux), 4 PCBs, and 12 solar panels are input. +X face faces the earth and hence the earth emitted infrared radiation and albedo are incorporated in the +X flux values.

5.6.3 Boundary Conditions:

The radiation boundary condition incorporates two things- temperature and emissivity. All aluminum panels, solar cells and PCBs, except the +X Panel radiate heat to deep space which is considered as a heat sink with a temperature of 3K and the +X Panel radiates to earth whose temperature has been calculated as 251K from Wien's displacement law.

6   Results

6.1   Analysis with pure Aluminium 6061 T6 without any external components

Initially the analysis is done with pure aluminium without solar panels and PCB on the exterior just to check the temperatures Aluminium 6061 T6 will attain.
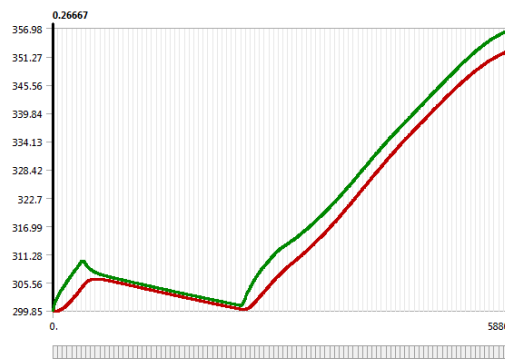

Figure 12: Temperature variation of aluminium about the entire time period

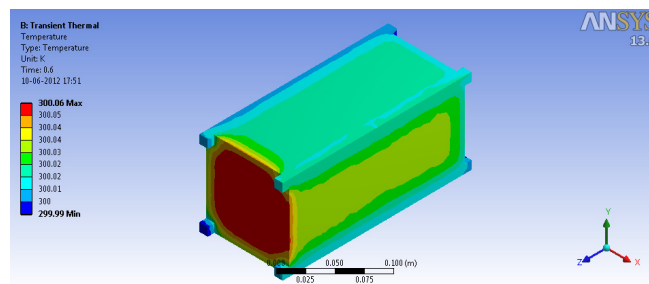| Criterion	Temperature
Minimum Temperature	299.85 K
Maximum temperature	356.98 K

Table 5: Temperature range

Figure 13: Contour plot of temperature ranges at 0.6 seconds

6.2   Analysis with solar panels and PCBs

This analysis incorporates Aluminium with solar panels and PCB without any thermal protection.
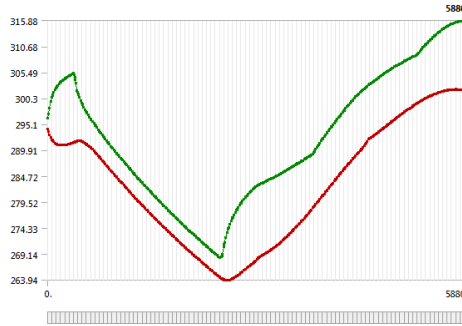

Figure 14: Temperature Variation with PCB and solar panel

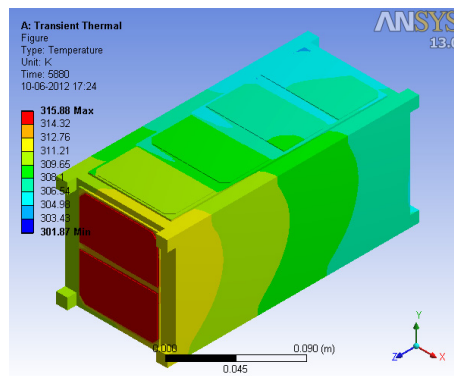| Criterion	Temperature
Minimum Temperature	263.94 K
Maximum temperature	315.88 K

Table 6: Temperature range

Figure 15: Contour plot of temperature distribution during the last time step

6.3   Analysis with paint Z 93

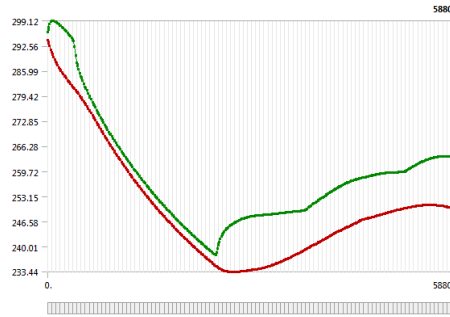This analysis incorporates paint Z 93 with solar panels and PCB.

Figure 16: Temperature Variation with paint Z 93

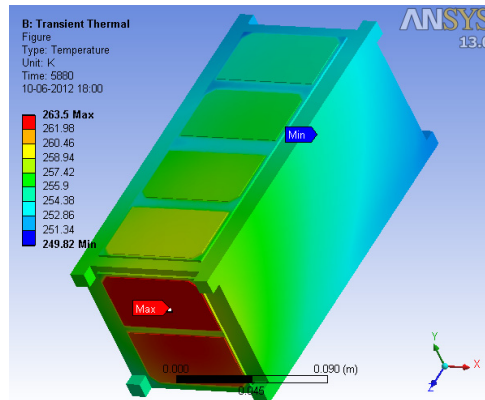| Criterion	Temperature
Minimum Temperature	233.44 K
Maximum temperature	299.12 K

Table 7: Temperature range

Figure 17: Contour plot of temperature variation with paint Z 93

The upper limit of temperature dropped by 16.76 K resulting in 299.12K which is because of the low value of the α (0.17). However the low limit temperature achieved is 233.44K which means that the emissivity of the paint is so high that most of the heat possessed by the body is radiated to deep space.

6.4 Analysis with MLI

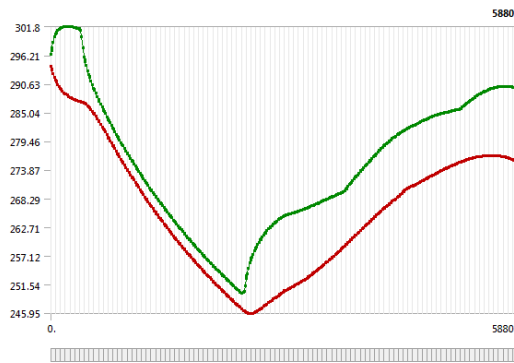MLI of thickness 0.2mm was used throughout the structure.

Figure 18: Temperature plot with MLI of 0.2mm thickness.

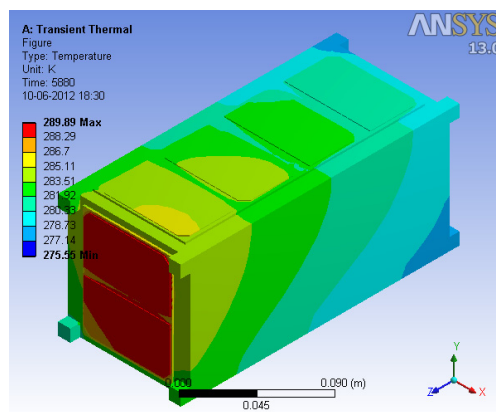| Criterion	Temperature
Minimum Temperature	245.95 K
Maximum temperature	301.8 K

Table 8: Temperature range

Figure 19: Contour plot with a layer of MLI

By using the MLI, the lower limit of temperature increased by 10K and the maximum temperature has recorded a rise of 2.68 degrees which is acceptable.

6.5 Static structural analysis

A coupled static structural analysis is done where the body temperature is imported.
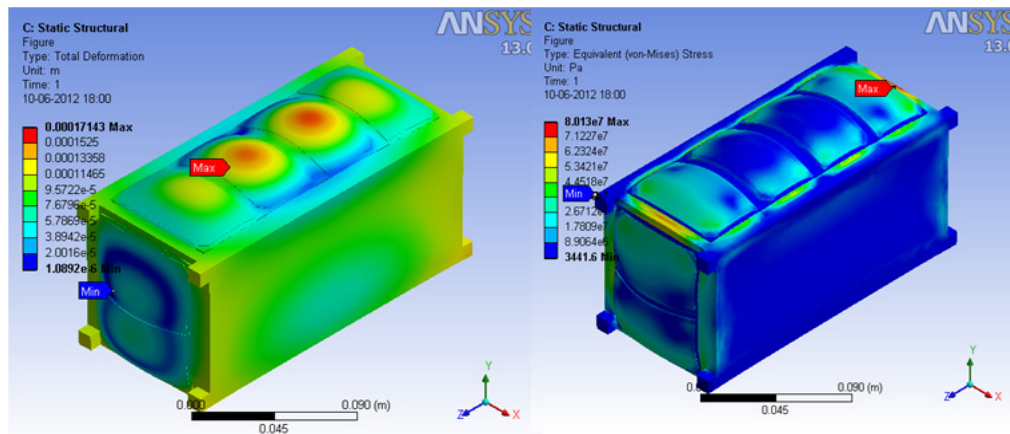
Figure 20: Deformation and stress contours

Maximum Deflection	0.17143	mm
Maximum Stress	80.13	MPA

Table 9: Stress and deflection values

7   Conclusion

Condition	Minimum Temperature (K)	Maximum Temperature (K)
Only Aluminium	299.85	356.98
Aluminium with solar panel & PCBs	263.94	315.88
Application of Z-93	233.4	299.12
Addition of MLI	245.95	301.8

From the above table, it is very clear that the satellite will be thermally stable when MLI of thickness 0.2 mm is wrapped around out. The graph also shows that the lower temperature period is less for the MLI model.

References

[1]   V. Chandrasekaran, K. Sinha, "Parikshit Structures Thermal & Mechanism Report", January 2012
[2]   D.G. Gilmore, "Spacecraft Thermal Control Handbook Volume 1: Fundamental technologies 2002", The Aerospace Corporation, 2002
[3]   F.P. Incropera, D.P. Dewitt, "Fundamentals of Heat and Mass Transfer" Fifth Edition, January 2008
[4]   http://www.aztechnology.com/materials-coatings-AZ-93.html
[5]   R. K. Rajput, "Heat and Mass transfer",2011

Appendix A

MATLab code used for calculation of heat flux

```
clc
r = (6378.16+670)*10^3;
sc = 1353;
pal = 66;
d = 1.495*10^11;
v = 7.5*10^3;
T = 5880;
w = 2*pi/T;
for t= 0:60:T
theta = 90 - (w*t*180/pi);
vx = v*(sind(theta)*cosd(pal)-cosd(theta)*cosd(98+22.5)*cosd(pal+90));
vy = v*(sind(theta)*sind(pal)-cosd(theta)*cosd(98+22.5)*sind(pal+90));
vz = v*(-1*cosd(theta)*sind(98+22.5));
ivz = (v/(-1*w*180/pi))*((-1)*sind(theta)*sind(98+22.5));
ivy                =                (v/(-1*w*180/pi))*((-1)*cosd(theta)*sind(pal)-
sind(theta)*sind(pal+90)*cosd(98+22.5));
hm = 140000*(sind(98+22.5)*sind(90-(w*T*180/(pi*4))));
phi = acosd((hm-ivz)/r);
phi0 = acosd(hm/r);
lmin = r*sind(phi0)*sind(90-pal);
sy = asind(((lmin+ivy))/(r*sind(phi)));
rxx = r*(sind(phi)*cosd(sy));
ryx = (sind(phi)*sind(sy));
rzx = (cosd(phi));
ssx = (d-rxx)/((d^2+(rxx)^2)^0.5);
ssy = ryx;
ssz = rzx;
hfx = sc*(((rxx*ssx)/r)+ryx*ssy+rzx*ssz);
rxy = sind(90+phi)*cosd(sy);
ryy = sind(90+phi)*sind(sy);
rzy = cosd(90+phi);
hfy = sc*(rxy*ssx+ryy*ssy+rzy*ssz);
rxz = (vx/v);
ryz = (vy/v);
rzz = (vz/v);
display (hfy);
hfz = sc*(rxz*ssx+ryz*ssy+rzz*ssz);
end
```