EXCEL Based Tool for Spacecraft Thermal Design

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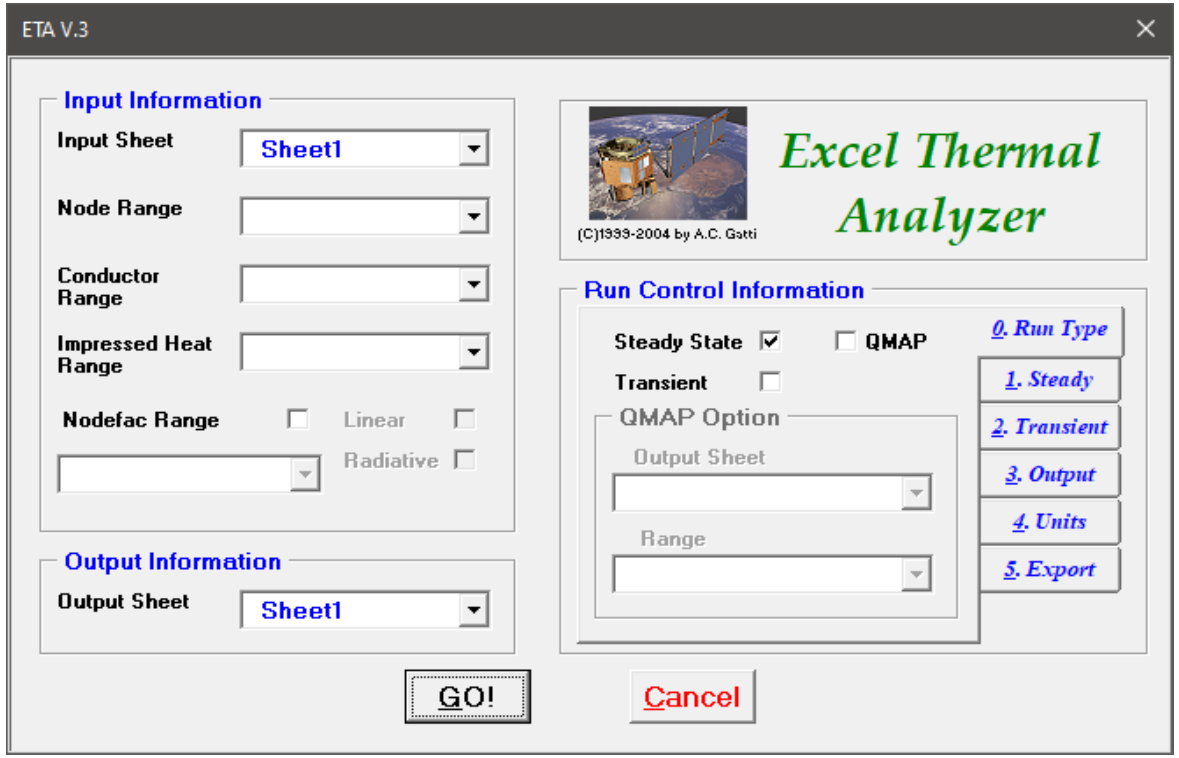
Abstract

- This paper presents an EXCEL based thermal analysis tool aptly named the ETA (EXCEL Thermal Analyzer)
- The ETA tool is a self-contained thermal analysis tool which can be used by engineers with knowledge of EXCEL
- The ETA tool takes advantage of mature spacecraft designs and models to quickly determine temperatures as a function of payload options and is especially effective and useful in an interdisciplinary team environment, whereby design iterations can be exercise quickly
- This paper presents the methodology of the ETA tool followed by a validation case study of an archived spacecraft thermal design
- The ETA tool can handle thermal models with sizes on the order of 1X10^6 conductors and 1X10^5 of nodes solving radiation and linear heat transfer simualtaneously

Introduction

- The tool maximizes the ability to input and output information in Excel, which is traditionally a thermal engineer's primary tool for data gathering and data summary
- The ETA tool's Graphic User Interface is shown below



Methodology

- The computational methodology for the ETA took described herein is based upon the framework of SINDA laid out by Ishimoto and Fink (1971), Mockenhaput (1971)
- The steady state heat balance equation at the ith node may be written as follows in terms of a coefficient matrix, a_{ij} for linear conductors and a coefficient matrix b_{ij} for non-linear conductors

$$q_i + \sum_{j=1}^{p} a_{ij}\left(T_j - T_i\right) + \sum_{j=1}^{p} \sigma\left(T_j^4 - T_i^4\right) = 0; i = 1,2,\cdots,N, T_j = constant, N < j \leq p$$

- The heat balance equation embodies a set of non-linear algebraic equations to be solved simultaneously
- The steady state solver solves temperature of nodes specified as diffusion by the “block” iteration method and temperatures of nodes specified as arithmetic (no capacitance) by the “successive point” iteration method

Methodology

- The use of a pseudo-compute sequence is a method to store data efficiently
- A long pseudo-compute sequence (LPCS) identifies the position and value of all off-diagonal elements of the coefficient matrix, a_{ij} (linear conductors) and b_{ij} (non-linear conductors)
- This is done by operating on adjoining node numbers which have been assigned relative node numbers by the preprocessor
- Since nodal temperatures are computed sequentially in ascending numerical order, the conductor and adjoining node number are searched until node one is found with the conductor number and the other adjoining node number stored in a single core location

Methodology

- Diffusion nodes use the following block iteration algorithm per Ishimoto and Fink (1971)

$$T_{i,k+1} = DD * T_{i,k} + DN * \left(q_{i,k} + \sum_{j=1}^{p} G_{ij,k} T_{j,k} \right) \Big/ \sum_{j=1}^{p} G_{ij,k}$$

$$G_{ij,k} = a_{ij,k} + \sigma b_{ij,k} \left(T_{j,k}^2 + T_{i,k}^2 \right) \left(T_{j,k} + T_{i,k} \right)$$

i=1,2, …., NND (number of diffusion nodes),

$T_{j,k} = constant,$

$(NND + NNA) < j \leq p$

(NNA is the number of arithmetic nodes and p is the total number of nodes)

$DN = DAMPD$ (diffusion node damping factor) with $DD = 1 - DN$.

Methodology

- Arithmetic nodes employ the following successive point iteration algorithm per Ishimoto and Fink (1971)

$$T_{i,k+1} = AD * T_{i,k} + AN * \left(q_{i,k} + \sum_{j=1}^{i} G_{ij,k} T_{j,k+1} + \sum_{j=i+1}^{p} G_{ij,k} T_{j,k} \right) \Big/ \sum_{j=1}^{p} G_{ij,k}$$

$$G_{ij,k} = a_{ij,k} + \sigma b_{ij,k} \left(T_{j,l}^2 + T_{i,k}^2 \right), l = k \; if \; j \geq i \; \& \; l = k + 1 \; if \; j < i$$

i=(NND+1), (NND+2),…, (NND+NNA),

$$T_{j,k} = constant,$$

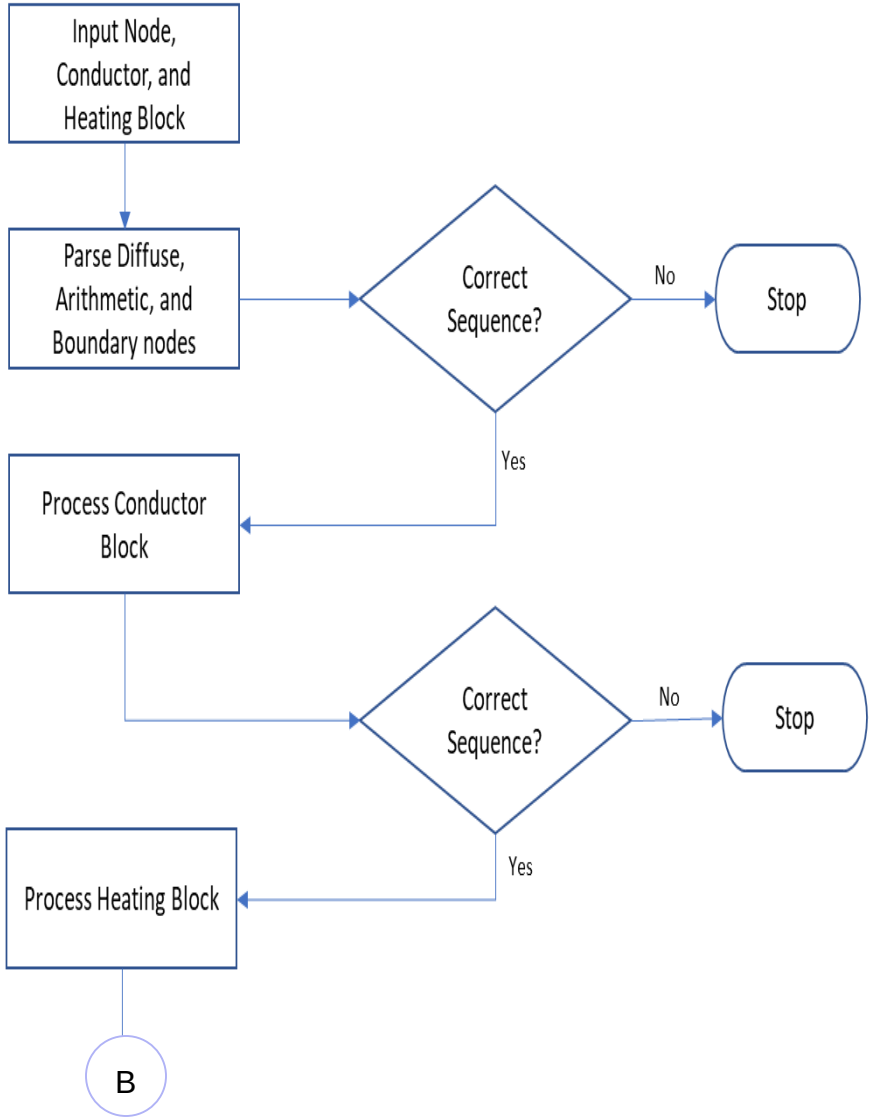
$$(NND + NNA) < j \leq p$$

(NNA is the number of arithmetic nodes and p is the total number of nodes)

$AN = DAMPA$ (arithmetic node damping factor) with $AD = 1 - AN$.

Methodology

FLOWCHART OF ETA STEADY STATE SOLVER



Nodal sequence must be:

1. Diffuse
2. Arithmetic
3. Boundary

Node Block must consist of three columns in following order:

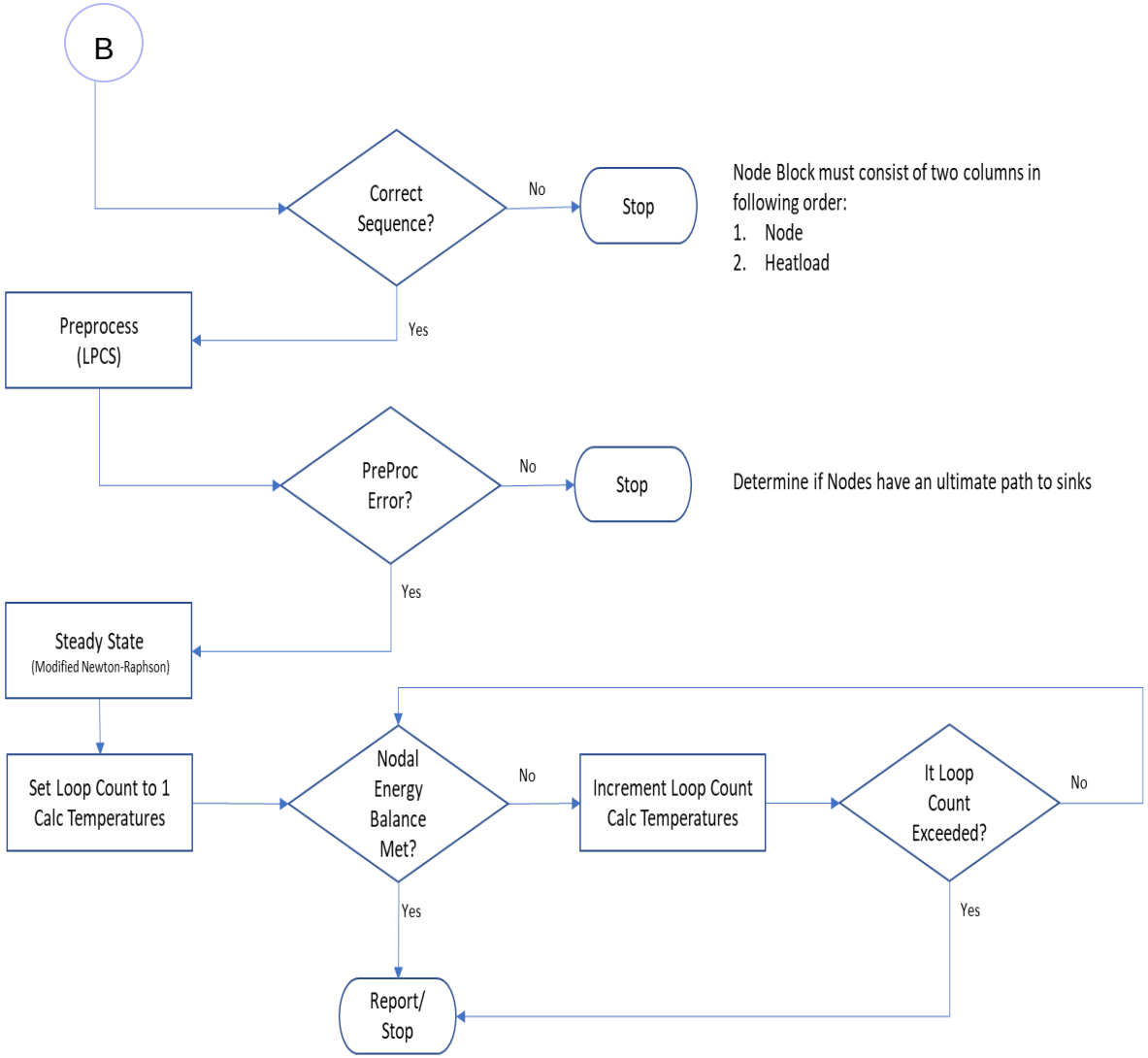
1. Node number
2. Temperature (Initial)
3. Capacitance

Conductor sequence must be:

1. Linear
2. Radiation

Node Block must consist of four columns in following order:

1. Conductor number (negative for Radition)
2. Node 1
3. Node 2
4. Conducatance



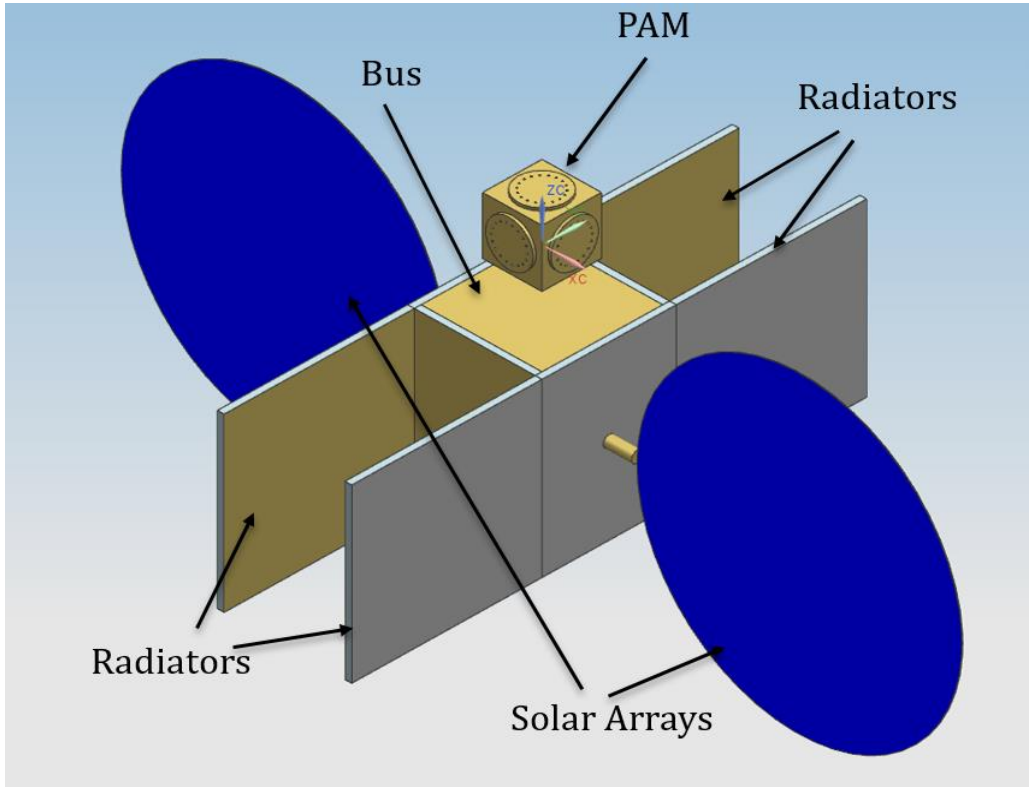
Node Block must consist of two columns in following order:

1. Node
2. Heatload

Determine if Nodes have an ultimate path to sinks

Validation Case

- The ETA tool discussed herein was validated using the study of Anderson et al. (2014) for the case study of Thermal Design and Analysis of a High Usability Host (HUH) Spacecraft (S/C)
- The HUH S/C model is shown below

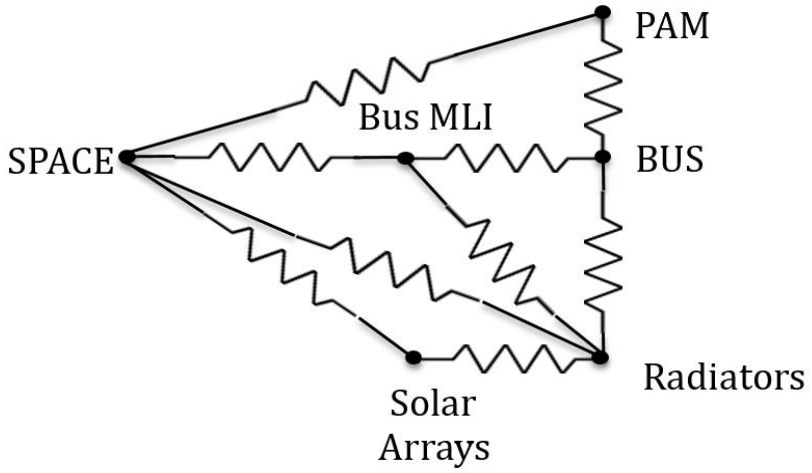


Validation Case

- A Payload Accommodations Mount (PAM) would be used to maintain the science components within their operating temperature limits
  - Each payload would have its own internal thermal subsystem
  - The PAM would strive to give the instruments the best chance at meeting their objectives
  - The PAM would serve as the interface to future payloads and provide features to enhance the compatibility between science objectives and the flight system.
- The proposed work was to design the thermal subsystem of the flight system, which is the combination of the bus and the payload
  - The bus would consist of the attitude control subsystem (ACS), power subsystem (PWR), command and data handling (C&DH), telecommunications (TELECOM), guidance and navigation control (G&NC), and the thermal subsystem (THERM)
- The dimensions of the design are as follows: PAM – 0.5m x 0.5m x 0.5m, BUS – 1m x 1m x 1, Deployable Radiators – 1m x 1m, Solar Arrays (Not Shown) – 1m diameter. Other details of the S/C can be found in Anderson et al. (2014)

Validation Case

- ETA Thermal model of HUH S/C



NODE #	Location
11	+Z PAM
22	-Y PAM
33	+X PAM
44	+Y PAM
55	-X PAM
66	-Z PAM
100	+Z Bus
200	-Y Bus
300	+X Bus (Radiator)
400	+Y Bus
500	-X Bus (Radiator)
600	-Z Bus

NODE #	Location
1310	+X+Y Depl. Radiator
1320	+X-Y Depl. Radiator
1510	-X+Y Depl. Radiator
1520	-X-Y Depl. Radiator
2001	+X Solar Array
2002	-X Solar Array
777100	+Z Bus MLI
777200	+Z-Y Bus MLI
777400	+Z+Y Bus MLI
777600	-Z Bus MLI
-99999	Space (Boundary)

LINEAR CONDUCTORS

COND #	NODE i	NODE j	G (W/K⁴)	Description
-2007	300	99999	9.6E-09	Rad to Space
-2008	1310	99999	3.4E-08	Rad to Space
-2009	1320	99999	3.4E-08	Rad to Space
-2010	500	99999	9.6E-09	Rad to Space
-2011	1510	99999	3.4E-08	Rad to Space
-2012	1520	99999	3.4E-08	Rad to Space

COND #	NODE i	NODE j	G (W/K⁴)	Description
-2013	777100	99999	2.3E-08	Bus MLI to Space
-2014	777200	99999	1.8E-08	Bus MLI to Space
-2015	777400	99999	1.8E-08	Bus MLI to Space
-2016	777600	99999	4.5E-08	Bus MLI to Space

COND #	NODE i	NODE j	G (W/K⁴)	Description
-2018	777200	1320	1.4E-08	Bus MLI to Rad
-2019	777200	1520	1.4E-08	Bus MLI to Rad
-2020	777400	1310	1.4E-08	Bus MLI to Rad
-2021	777400	1510	1.4E-08	Bus MLI to Rad

COND #	NODE i	NODE j	G (W/K⁴)	Description
-2000	11	99999	1.2E-08	PAM to Space
-2001	22	99999	1.2E-08	PAM to Space
-2002	33	99999	1.2E-08	PAM to Space
-2003	44	99999	1.2E-08	PAM to Space
-2004	55	99999	1.2E-08	PAM to Space

COND #	NODE i	NODE j	G (W/K⁴)	Description
-2037	300	2001	3.9E-08	Rad to Solar Arrays
-2038	1310	2001	1.4E-08	Rad to Solar Arrays
-2039	1320	2001	1.4E-08	Rad to Solar Arrays
-2040	500	2002	3.9E-08	Rad to Solar Arrays
-2041	1510	2002	1.4E-08	Rad to Solar Arrays
-2042	1520	2002	1.4E-08	Rad to Solar Arrays

COND #	NODE i	NODE j	G (W/K⁴)	Description
-2045	2001	99999	2.5E-08	Solar Array to Space
-2050	2002	99999	2.5E-08	Solar Array to Space

RADIATION CONDUCTORS

COND #	NODE i	NODE j	G (W/°C)	Description
10	100	200	8.40	Within Bus
20	100	300	8.40	Within Bus
30	100	400	8.40	Within Bus
40	100	500	8.40	Within Bus
50	200	300	8.40	Within Bus
60	200	500	8.40	Within Bus
70	200	600	8.40	Within Bus
80	300	400	8.40	Within Bus
90	300	600	8.40	Within Bus
100	400	500	8.40	Within Bus
110	400	600	8.40	Within Bus
120	500	600	8.40	Within Bus

COND #	NODE i	NODE j	G (W/°C)	Description
410	66	100	482	Thru Aluminum Therm Doubler

COND #	NODE i	NODE j	G (W/°C)	Description
510	300	1310	8.40	+X Rad to +X+Y
520	300	1320	8.40	+X Rad to +X-Y
530	500	1510	8.40	-X Rad to -X+Y
540	500	1520	8.40	-X Rad to -X-Y

COND #	NODE i	NODE j	G (W/°C)	Description
210	11	22	8.40	Within PAM
220	11	33	8.40	Within PAM
230	11	44	8.40	Within PAM
240	11	55	8.40	Within PAM
250	22	33	8.40	Within PAM
260	22	55	8.40	Within PAM
270	22	66	8.40	Within PAM
280	33	44	8.40	Within PAM
290	33	66	8.40	Within PAM
300	44	55	8.40	Within PAM
310	44	66	8.40	Within PAM
320	55	66	8.40	Within PAM

COND #	NODE i	NODE j	G (W/°C)	Description
710	100	777100	0.5	+Z Bus to MLI
720	200	777200	0.5	+Z-Y Bus to MLI
730	400	777400	0.5	+Z+Y Bus to MLI
740	600	777600	0.5	+Z Bus to MLI

COND #	NODE i	NODE j	G (W/°C)	Description
750	300	2001	0.5	Rad to Solar Array
760	500	2002	0.5	Rad to Solar Array

Methodology

- Environmental loads were implemented into the ETA model using the environmental loading equations via Kirkpatrick (1999)
- The table below includes the environmental as well as heat dissipation assumptions for both worst-case hot and cold scenarios
  - The cold case includes heat dissipation from the bus, survival heaters, and minimal environmental heating
  - The hot case includes dissipation from the bus and payload as well as maximum heat load from the environment

Location	*Cold Case*	*Hot Case*
+Z PAM	60	311
-Y PAM	55	250
+X PAM	56	278
+Y PAM	55	250
-X PAM	56	278
-Z PAM	55	0
+Z Bus (MLI)	17	170
-Z Bus (MLI)	18	141
+Z Bus	116	80
-Y Bus	116	80
+X Bus (Rad)	95	140
+Y Bus	116	80
-X Bus (Rad)	95	140
-Z Bus	116	80
+X+Y Depl Rad	34	60
+X-Y Depl Rad	34	60
-X+Y Depl Rad	34	60
-X-Y Depl Rad	34	60
Total	**1165**	**2517**

Results

- Results from the current ETA toolkit study were found to be in qualitative and quantitative agreement with the previous study of Anderson et al. (2014)

COLD CASE RESULTS

NODE #	*°C*	*Location*
11	**-10.9**	+Z PAM
22	**-11.0**	-Y PAM
33	**-11.0**	+X PAM
44	**-11.0**	+Y PAM
55	**-11.0**	-X PAM
66	**-11.0**	-Z PAM
100	**-11.1**	+Z Bus
200	**-12.3**	-Y Bus
300	**-18.4**	+X Bus (Radiator)
400	**-12.3**	+Y Bus
500	**-18.4**	-X Bus (Radiator)
600	**-13.0**	-Z Bus
1310	**-30.6**	+X+Y Depl. Radiator
1320	**-30.6**	+X-Y Depl. Radiator
1510	**-30.6**	-X+Y Depl. Radiator
1520	**-30.6**	-X-Y Depl. Radiator
2001	**-39.7**	+X Solar Array
2002	**-39.7**	-X Solar Array
777100	**-63.9**	+Z Bus MLI
777200	**-49.8**	+Z-Y Bus MLI
777400	**-49.8**	+Z+Y Bus MLI
777600	**-86.6**	-Z Bus MLI
-99999	**-273**	Space

HOT CASE RESULTS

NODE #	*°C*	*Location*
11	**70.3**	+Z PAM
22	**65.8**	-Y PAM
33	**66.3**	+X PAM
44	**65.8**	+Y PAM
55	**66.3**	-X PAM
66	**49.3**	-Z PAM
100	**48.1**	+Z Bus
200	**33.8**	-Y Bus
300	**25.0**	+X Bus (Radiator)
400	**33.8**	+Y Bus
500	**25.0**	-X Bus (Radiator)
600	**31.0**	-Z Bus
1310	**4.4**	+X+Y Depl. Radiator
1320	**4.4**	+X-Y Depl. Radiator
1510	**4.4**	-X+Y Depl. Radiator
1520	**4.4**	-X-Y Depl. Radiator
2001	**-3.0**	+X Solar Array
2002	**-3.0**	-X Solar Array
777100	**26.0**	+Z Bus MLI
777200	**-19.4**	+Z-Y Bus MLI
777400	**-19.4**	+Z+Y Bus MLI
777600	**-25.7**	-Z Bus MLI
-99999	**-273**	Space

Conclusions

- The ETA tool discussed herein has proven to be useful as a thermal analyzer over the years for quick back-of-the-envelope calculations and for sophisticated networks, as well.
- The ETA tool employs the Long Pseudo Compute Sequence, or LPCS, at its heart.
  - The LPCS provides an accessible and proven data structure that allows a quick solution from simple to complex thermal networks
- A basic requirement of a versatile thermal analyzer, such as ETA, is that it be applicable to both steady-state and transient problems involving any of the three heat transfer modes: conduction, convection, and radiation.
  - ETA can handle any combination of these three heat transfer modes
  - At present, only steady-state solution is available with the tool, a transient capability is in the works for the near future
- Herein, the accuracy of the ETA tool has been confirmed and verified against an archived benchmark case

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