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.

NOMENCLATURE

A	Area
ACS	Attitude Control Subsystem
a_{ij}	Linear Conductance Coefficient Matrix
b_{ij}	Nonlinear Conductance Coefficient Matrix
C&DH	Command and Data Handling
ETA	EXCEL Thermal Analyzer
F	View Factor
G	Conductance
G&NC	Guidance and Navigation Control
HUH S/C	High Usability Host Spacecraft
i	Node Number
j	Node Number
k	Thermal Conductivity, Iteration Level

LPCS	Long Pseudo Compute Sequence
MLI	Multi Layer Insulation
PAM	Payload Accommodations Mount
PWR	Power Subsystem
p	Total Number of Nodes
q	Heat Load
TELECOM	Telecommunications
THERM	Thermal Subsystem
T	Temperature
ε	Emissivity
σ	Stefan-Boltzmann Constant

INTRODUCTION

The unique aspect of this work is that is that the EXCEL tool is based completely around and within the framework of EXCEL and VBA. 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. 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 tool's Graphic User Interface is shown in **Figure 1**.

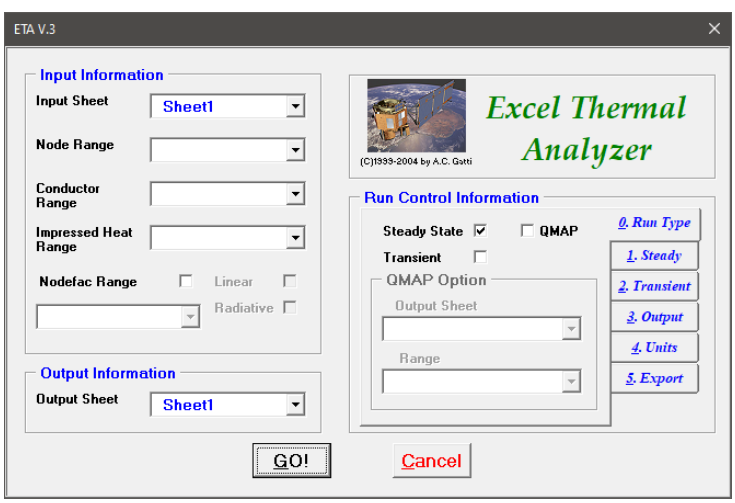

Figure 1 – ETA Graphical User Interface

METHODOLOGY

The computational methodology for the ETA took described herein is based upon the framework of SINDA laid out by Ishimoto and Fink (1971) and 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 per Ishimoto and Fink (1971)

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

where p = total number of nodes, T_i is the temperature of node i, and q_i is the heat load at node i. As cast, Equation (1) embodies a set of non-linear algebraic equations to be solved simultaneously. Since 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, two successive approximation algorithms are used.

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.

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

$$T_{i,k+1} = DD * T_{i,k} + DN * \left(q_{i,k} + \sum_{j=1}^{p} G_{ij,k} T_{j,k}\right) / \sum_{j=1}^{p} G_{ij,k} \quad (2)$$

with G_{ij} denoting the conductor between node i and node j, and k being the *k* = kth iteration, *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)

$$G_{ij,k} = a_{ij,k} + \sigma b_{ij,k}\left(T_{j,k}^2 + T_{i,k}^2\right)\left(T_{j,k} + T_{i,k}\right) \quad (3)$$

where *DN = DAMPD* (diffusion node damping factor) with *DD = 1 – DN.*

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

$$T_{i,k+1} = AD * T_{i,k} + AN * \left(q_{i,k} + \sum_{j=1}^{i} G_{ij,k} T_{j,k+1} + \sum_{j=i+1}^{p} G_{ij,k} T_{j,k}\right) / \sum_{j=1}^{p} G_{ij,k} \quad (4)$$

where k = kth iteration, 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)

$$G_{ij,k} = a_{ij,k} + \sigma b_{ij,k}\left(T_{j,l}^2 + T_{i,k}^2\right), l = k \; if \; j \geq i \; \& \; l = k + 1 \; if \; j < i \tag{5}$$

where *AN = DAMPA* (arithmetic node damping factor) with A*D = 1 – AN.*

A flowchart of the steady state solver used within ETA is shown in **Figure 2**.

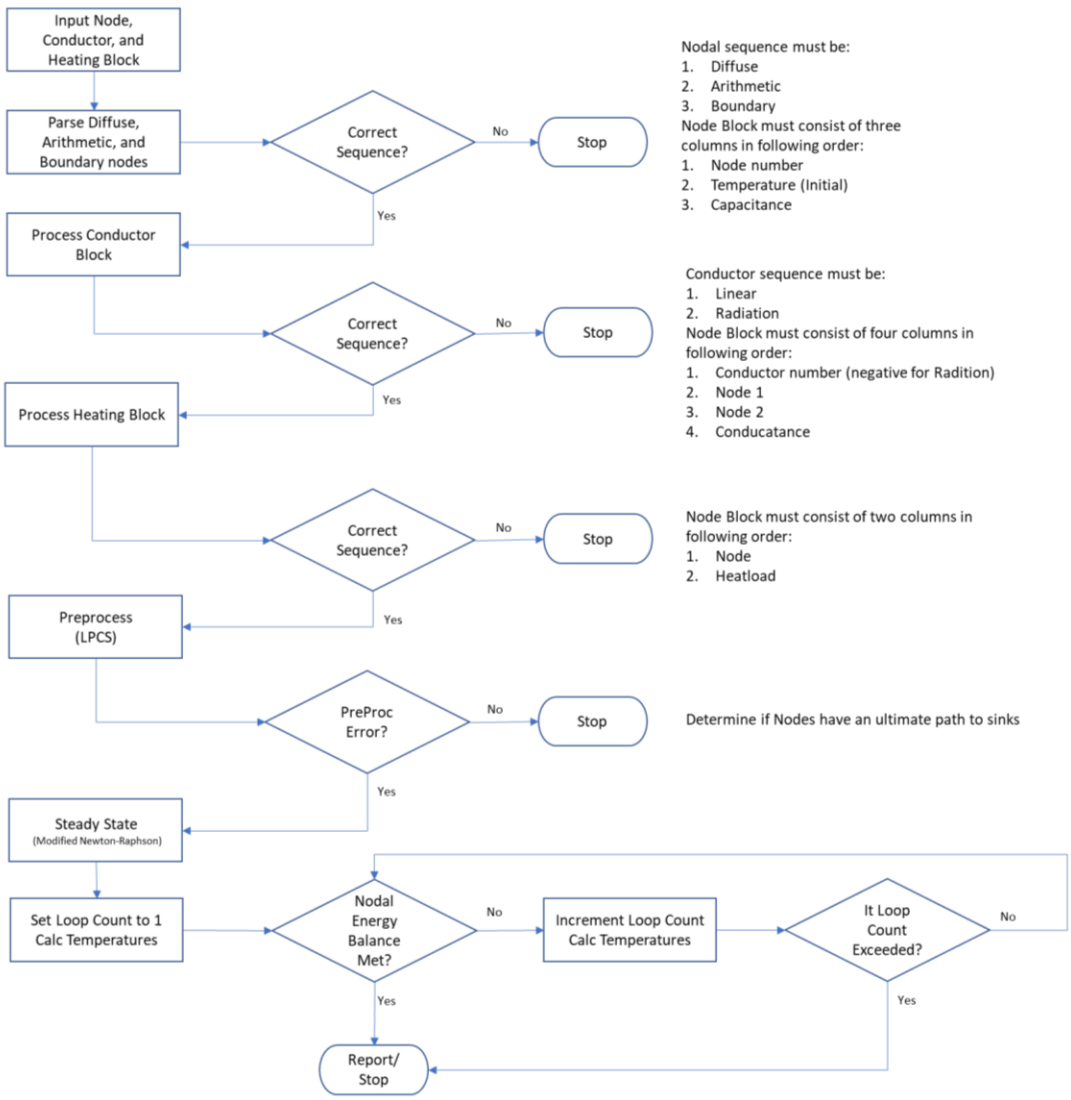

Figure 2 - ETA flowchart

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 in Figure 3.

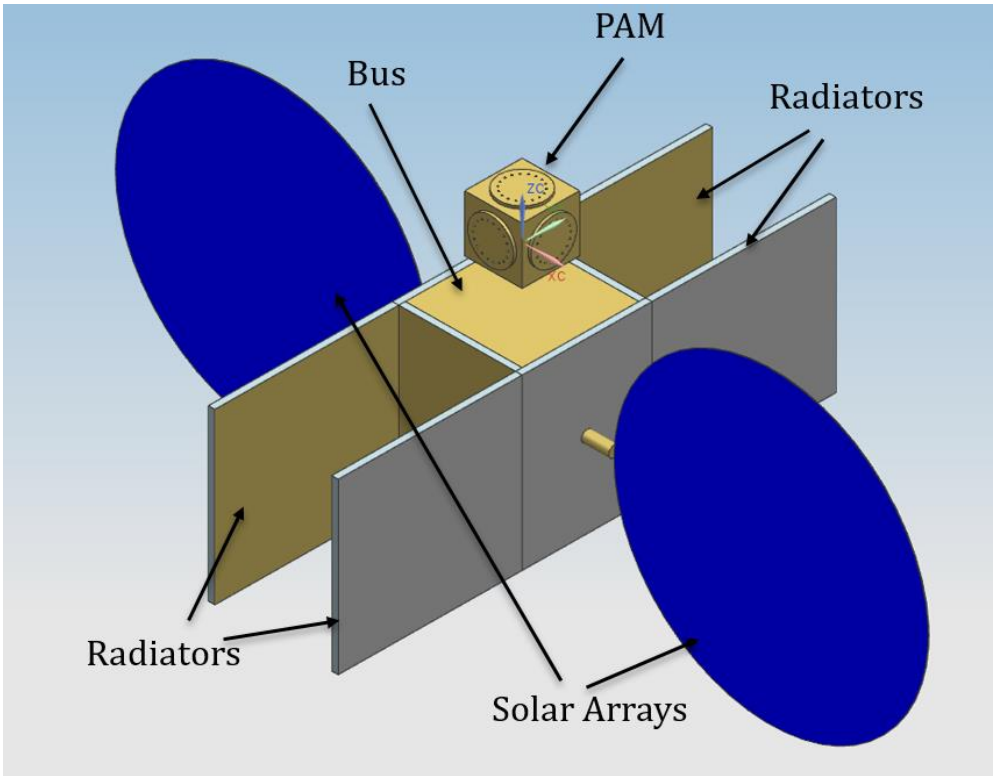

Figure 3 - ETA validation case study HUH S/C thermal model.

As detailed in Anderson et al. (2014), the HUH S/C would serve as a plug-and-play platform carrying a variety of payloads of given size and power dissipation. The design would consider the use of both active and passive thermal control components to keep the bus and the payloads at acceptable temperature limits. For the design, the payloads were not specified. Rather, 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. As detailed in Anderson et al. (2014) 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). These subsystems are necessary to carry out the mission of the payloads. The thermal control subsystem design to protect the payload to carry out its mission was the scope of this project.

The thermal network of the HUH S/C is shown in Figure 4. The XYZ locations used in the following conductor descriptions is taken from the XYZ coordinate system shown on the HUH S/C model of Figure 2. 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)

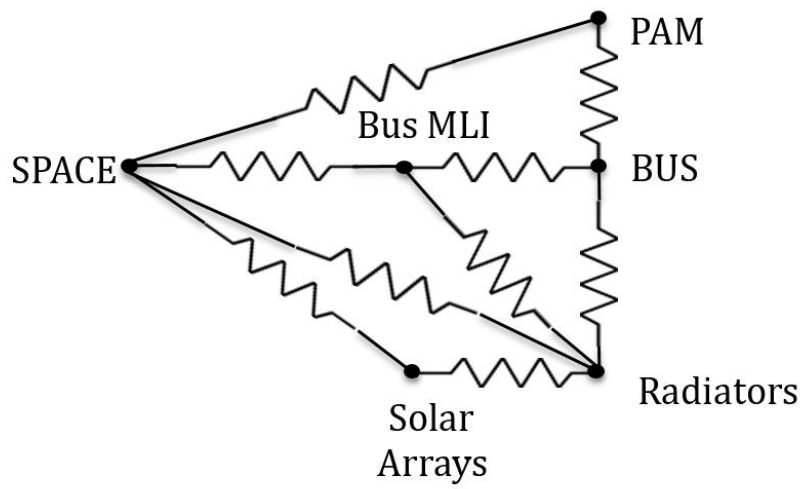

Figure 4 - ETA Validation case study HUH S/C thermal network

A network of conductors were created to tie the entire model together. These conductors represent both conduction (represented by positive conductor values) and radiation (represented by negative conductor values). For conduction, these values are $G = k A / L$, in units of W/K, where k is the effective thermal conductivity of the material, A is the cross-sectional area, and L is the length. For radiation, these values are $G_{rad} = \sigma \varepsilon A_s F$, in units of W/K^4, where $\sigma = 5.67\times10^{-8}$ $W/m^2/K^4$, ε is emissivity, A_s is the surface area, and F is the view factor. The nodes and conductors of the HUH S/C are listed in Table 1 and Table 2, respectively.

Table 1- ETA Validation Case Study HUH S/C Thermal Model Nodes

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)

Table 2- ETA Validation Case Study HUH S/C Thermal Model Conductors

Linear Conductors

COND #	NODE i	NODE j	G (W/K^4)	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/K^4)	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/K^4)	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/K^4)	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/K^4)	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/K^4)	Description
-2045	2001	99999	2.5E-08	Solar Array to Space
-2050	2002	99999	2.5E-08	Solar Array to Space

Table 2- ETA Validation Case Study HUH S/C Thermal Model Conductors (continued)

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

COND #	NODE i	NODE j	G (W/K^4)	Description
-2022	100	200	3.4E-10	Internal Radiation
-2023	100	300	3.4E-10	Internal Radiation
-2024	100	400	3.4E-10	Internal Radiation
-2025	100	500	3.4E-10	Internal Radiation
-2026	100	600	3.4E-10	Internal Radiation
-2027	200	300	3.4E-10	Internal Radiation
-2028	200	400	3.4E-10	Internal Radiation
-2029	200	500	3.4E-10	Internal Radiation
-2030	200	600	3.4E-10	Internal Radiation
-2031	300	400	3.4E-10	Internal Radiation
-2032	300	500	3.4E-10	Internal Radiation
-2033	300	600	3.4E-10	Internal Radiation
-2034	400	500	3.4E-10	Internal Radiation
-2035	400	600	3.4E-10	Internal Radiation
-2036	500	600	3.4E-10	Internal Radiation

COND #	NODE i	NODE j	G (W/K^4)	Description
-2055	11	22	8.5E-11	Internal Radiation
-2056	11	33	8.5E-11	Internal Radiation
-2057	11	44	8.5E-11	Internal Radiation
-2058	11	55	8.5E-11	Internal Radiation
-2059	11	66	8.5E-11	Internal Radiation
-2060	22	33	8.5E-11	Internal Radiation
-2061	22	44	8.5E-11	Internal Radiation
-2062	22	55	8.5E-11	Internal Radiation
-2063	22	66	8.5E-11	Internal Radiation
-2064	33	44	8.5E-11	Internal Radiation
-2065	33	55	8.5E-11	Internal Radiation
-2066	33	66	8.5E-11	Internal Radiation
-2067	44	55	8.5E-11	Internal Radiation
-2068	44	66	8.5E-11	Internal Radiation
-2069	55	66	8.5E-11	Internal Radiation

Heat was applied strategically to simulate the maximum and minimum environmental loads as well as the dissipated heat from the electronics on the PAM. Environmental loads and heat dissipated from the electronics represent the independent variables of the system. Table 3 shows the heat loads modeled in ETA.

Table 3 - Dissipations in ETA Validation Model

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**

Environmental loads were implemented into the ETA model using the environmental loading equations via Kirkpatrick (1999). Table 3 includes the environmental as well as heat dissipation assumptions for both worst-case hot and cold scenarios. Note that 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.

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). Table 4 lists the results for the cold case. Table 5 lists the results for the hot case.

Table 4 - ETA Validation Model 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

Table 5 - ETA Validation Model 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. It 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. The ETA toolkit is an indispensable part of many a thermal engineer's tool chest.

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