Creating a Voyager Thermal Model 39 Years Into the Flight Mission, Along With Model Correlation and Application

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After 39 years of continuous operation in space, the output of the Voyager 1 & 2 spacecraft RTG power systems has decreased to the point where managing the power margin and maintaining thermal control has become increasingly difficult. As the total power dissipation in the bus has decreased, propellant line temperatures and margin above minimum AFTs have decreased, creating risk of the hydrazine freezing (at 1.6°C). This is further complicated by the lack of existing thermal models that can be used to assess propellant tank and line temperatures. In 2014, an effort was begun to create a Voyager spacecraft thermal model for that purpose.A steady-state Thermal Desktop model has been created from scratch over the past two years. The initial thermal model development was started by Applied Sciences Laboratory (ASL) under contract to JPL. The effort relied primarily on archived manufacturing drawings, limited documentation, interviews of senior engineers who worked on the Voyager design and implementation, and the experience of the Voyager Flight Operations team.Data from the Voyager System Thermal Vacuum tests is no longer available, making it necessary to correlate the model to more recent flight data and small in-flight tests. Correlation was achieved to within ±5°C for a hot case and a cold case (both data sets from 2014). However, the flight system has very few temperature sensors directly on propellant lines. So the task remains to determine how best to use the model, in conjunction with flight data, to make sure the Voyagers can continue to fly successfully. How does one go about creating a thermal model for a spacecraft that is already launched, has limited existing mechanical description files, no thermal model in order to do a maneuver that was never planned when the spacecraft was designed?

Nomenclature

ASL	Applied Sciences Laboratory
°C	Degrees Celsius
DTR	Digital Tape Recorder
JPL	Jet Propulsion Laboratory
IPU	Injection Propulsion Unit
KSC	Kennedy Space Center
MJS 77	Mariner Jupiter Saturn 1977
PDF	Portable Document Format
PWS	Plasma Wave Subsystem
RHU	Radioisotope Heater Unit
RTG	Radioisotope Thermal-Electric Generator
STV	system thermal vacuum test
TBus S/P	Bus shear plate temperature
TCAPU	Trajectory Correction/Attitude Propulsion Unit (TCAPU
T/VA	Thruster/Valve Assembly
W	Watts

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I. Introduction[1]

THE Voyagers were launched in 1977 to explore the outer planets of the solar system. Originally designated as "Mariner Jupiter Saturn" or "MJS 77", the twin spacecraft have survived long past their original design, as they celebrate their 40th anniversary in space this year.

A. Voyager Science

Only five investigator teams are still supported, though data are collected for two additional instruments. With the exception of the Voyager 1 PLS instrument, all of the above are working well and are capable of continuing operations in the expected environment. In addition, data are collected from the Planetary Radio Astronomy (PRA) instrument and Voyager 1's Ultraviolet Spectrometer (UVS). The Flight Data Subsystem (FDS) and a single 8-track digital tape recorder (DTR) provide the data handling functions. The FDS configures each instrument and controls instrument operations. It also collects engineering and science data and formats the data for transmission. The DTR is used to record high-rate PWS data. Data are played back every six months.

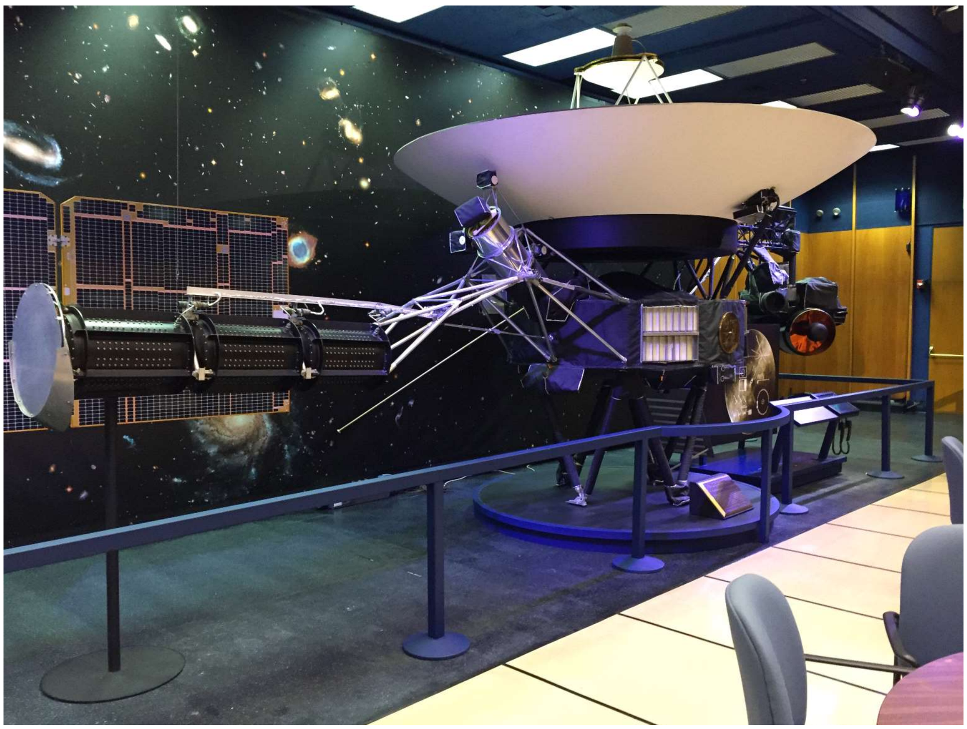

Figure 1. Voyager Spacecraft (Full Size Model in von Karman) ***(Citation: needed)***

B. Spacecraft Description

The identical Voyager spacecraft are three-axis stabilized systems that use celestial or gyro referenced attitude control to maintain pointing of the high-gain antennas toward Earth. The prime mission science payload consisted of 10 instruments (11 investigations including radio science).

At launch, the flight system included the Spacecraft Assembly, the Injection Propulsion Module (IPU) and a Centaur upper stage. The Centaur stage was jettisoned shortly after launch. The IPU's used on-board hydrazine fuel to achieve proper trajectory insertion for the multiple planetary-flyby journeys to be taken by each spacecraft. Pyro devices were fired to isolate the IPU's from the Propulsion Subsystem and separate them from the remaining spacecraft.

For Voyager 1, this meant encounters with Jupiter and Saturn prior with the final gravity-assist directing the spacecraft out of the ecliptic plane with sufficient velocity to reach the edge of the solar system and beyond. Voyager 2's trajectory enabled fly-by's of Uranus and Neptune before heading for interstellar space.

The basic structure of the spacecraft is called the "bus," which carries the various engineering subsystems and scientific instruments. It is like a large ten-sided box, which can be seen in the Voyager diagram. The centerline of the bus is called the z-axis (and thus the High Gain Antenna) points to Earth. The spacecraft is designed to roll about this axis by firing small thrusters attached to the bus.

Each of the ten sides of the bus contains a compartment (a bay) that houses various electronic assemblies. Bay 1, for example, contains the radio transmitters. The bay are numbered 1 to 10 (numbered clockwise as seen from Earth).

The Attitude and Articulation Control Subsystem (AACS) controls spacecraft orientation, maintains the pointing of the high gain antenna towards Earth, controls attitude maneuvers, and positions the scan platform.

Uplink communications is via S-band (16-bits/sec command rate) while an X-band transmitter provides downlink telemetry at 160 bits/sec normally and 1.4 kbps for playback of high-rate plasma wave data. All data are transmitted from and received at the spacecraft via the 3.7-meter high-gain antenna (HGA).

Electrical power is supplied by three Radioisotope Thermoelectric Generators (RTGs). The current power levels are about 315 watts for each spacecraft. As the electrical power decreases, power loads on the spacecraft must be turned off in order to avoid having demand exceed supply. As loads are turned off, some spacecraft capabilities are eliminated.

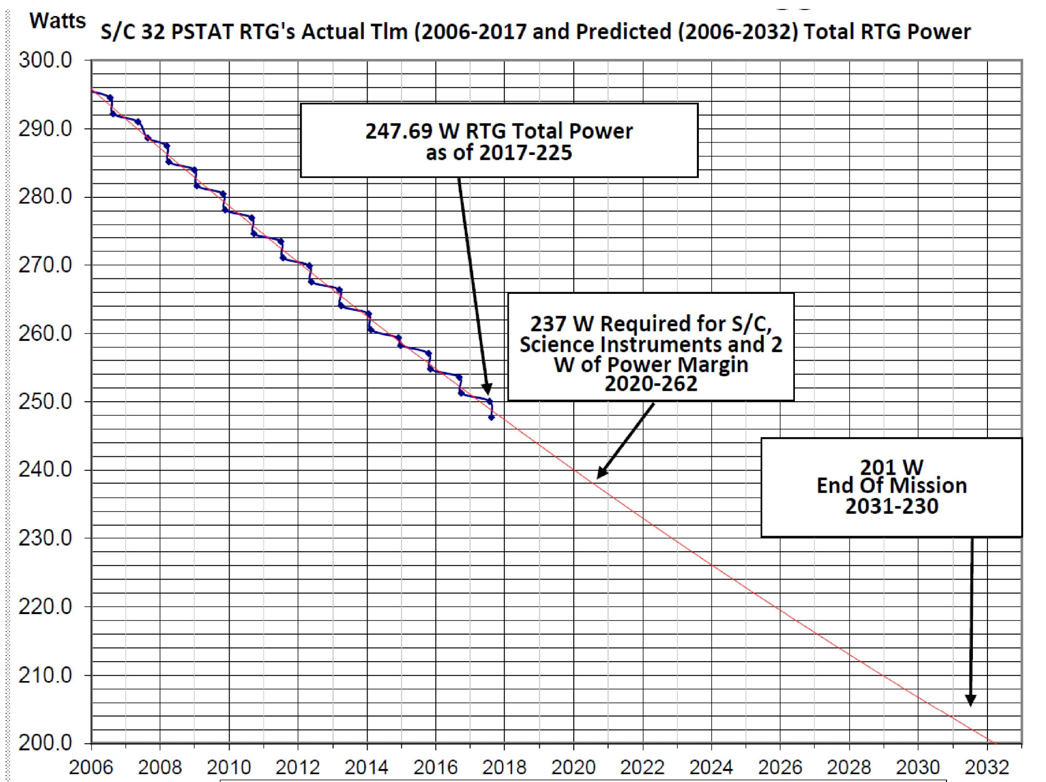

Figure 2. S/C 32 Total RTG Power At RTG Toggle Points ***(Citation: report by E. Medina)***

To date, the entire Voyager 2 scan platform, including all of the platform instruments, has been powered down. All platform instruments on Voyager 1, except the UVS, have been powered down. The Voyager 1 scan platform was scheduled to be powered down in late 2000, but has been left on at the request of the UVS investigator (with the concurrence of the Science Steering Group) to investigate an unexpected excess in UV from the upwind direction. The PLS experiment on Voyager 1 is currently turned off to accommodate UVS observations. *[Citation: Voyager Outreach Website.]*

To achieve this longevity, the Flight Operations Team has had to deal with hardware failures, telecommunication challenges as the distance from Earth increases and the slow but steadily decreasing power output of the Radioisotope Thermoelectric Generators (RTGs). This decreased power, combined with the distance from the sun and planets has caused the propulsion subsystem to cool to the point where freezing of the hydrazine monopropellant has become a serious risk that must be assessed whenever the spacecraft power state changes.

Table 1. Voyager Mission Timeline & Milestones[4]

DATE	Voyager 1 Milestone	Voyager 2 Milestone
1977 Aug. 20	Launched from KSC	
1977 Sept. 5		Launched from Kennedy Space Flight Center. Returns first spacecraft photo of Earth and Moon
1979 Mar. 5	Closest approach to Jupiter	
1979 July 9		Closest approach to Jupiter
1980 Nov. 12	Saturn Fly-by and trajectory to leave the Solar System	
1981 Aug. 25		Saturn Fly-by
1986 Jan. 24		Uranus Fly-by
1987		Voyager 2 "observes" Supernova 1987A
1988		Voyager 2 returns first color images of Neptune
1989 Aug. 25		Neptune Fly-by begins its trip out of the Solar System, below the ecliptic plane
1990 Jan. 1	Voyager Interstellar Mission begins	
1990 Feb. 14	Last Voyager Images - Portrait of the Solar System	
1998 Feb. 17	Passes Pioneer 10 to become the most distant human-made object in space	
2004 Dec. 16	Crosses Termination Shock	
2007 Aug. 30		Crosses Termination Shock
2012 Aug. 25	Enters Interstellar Space	

II. Creating a Voyager Thermal Model

A. Hydrazine Freezing Issue

In May of 2014, the Voyager Flight Operations Team contacted Gary Kinsella, supervisor of the Spacecraft Thermal Engineering and Flight Operations (STEFO) group in Section 353 regarding their concerns about gradual cooling of the spacecraft due to steadily decreasing power output from the RTGs. Specifically, propellant line temperatures were approaching the freezing point of the hydrazine fuel, which could result in mission ending thruster failures.

Gary and I met with the Voyager team to discuss how to assess the thermal state of the two spacecraft, given limited temperature telemetry. Earlier in the mission, thermal assessments were made using a SINDA model and documented in IOMs.

B. Choosing an Option for Thermal Modeling

Five months later, after searching for Voyager thermal documentation, and interviewing former Voyager thermal engineers, Ledeboer, Lee (ASL) and Kinsella presented the Status of Voyager Thermal Model to the project. Three options were proposed to create a thermal model for predicting propellant line temperatures.

1. *Correlate existing SINDA thermal model to flight data.*

This model would be used to predict "Ballpark propellant line temperature" inferred from predicted average bus shear plate temperature (since one node per panel in model). This option was deemed to be high risk, but the least expensive and fastest.

Unfortunately, the SINDA model no longer exists in an electronic, machine-readable form. A copy of a model listing from 1985 was found in documents received from former Voyager thermal engineer, Art Avila. The difficulty of re-creating the old model, which pre-dated the correlation to Voyager STV data contributed to the high risk assessment for Option 1.

2. *Build coarse Thermal Desktop model and correlate to flight data.*

Again, to "ballpark propellant line temperature" inferred from predicted local bus shear plate temperature, $T_{Bus\ S/P}$. This option was also deemed to be a high risk though less expensive, but not as fast.

3. *Similar to option 2, but explicitly model the propellant lines so that the local gradients are visible.*

This option reduced risk, but was much more expensive and time consuming. It had the significant advantage of having higher certainty on propellant line temperatures than options 1 and 2.

Thermal engineers recommended Option 3, since it was only medium risk and propellant line temperatures are inherently difficult to predict due to large thermal sensitivity (~5°C/W typical) due to their small dimensions and thermal properties of stainless steel. Part of the estimated risk was due to uncertainty about how well the model could be correlated to either system thermal vacuum (STV) test or flight data.

One week after the presentation, Suzy Dodd, Voyager Project Manager, emailed the thermal engineers stating that the Flight Operations team approved option 3 as the desired approach. What follows is the story of how we created the new Voyager Thermal Desktop model.

C. Gathering and Reviewing Drawings

The Voyager project gave us the mandate to approve a maneuver with potential thermal implications—particularly freezing of the hydrazine lines—and there was no extant thermal model. So how does one go about creating a thermal model for a spacecraft that is already launched, has limited existing mechanical description files, no thermal model in order to do a maneuver that was never planned when the spacecraft was designed? How would any thermal model then be correlated without test data, using only the limited telemetry points available?

Development began with a search for data on which to base the new model. Voyager project files were searched, as well as the JPL Library, Photo Lab, Vellum Files, the full-sized, in the Von Karman museum at JPL, and personnel who had worked on the Voyager team during its development, testing, launch and operations were contacted.

Construction of the Thermal Desktop model began November 1, 2014 under contract with the Applied Sciences Laboratory (ASL). The work order called for the model to be created by Larry Chan of ASL under the guidance of the author and his supervisor, Gary Kinsella, with the final model, correlated to flight data to be delivered to the Voyager Project. The model was constructed with the goal of calculating steady-state temperatures within ±5°C of flight data. Prediction of propellant line temperatures would also be cold-biased, due to the criticality of preventing hydrazine freezing in the range 0.1°C – 1.6°C[5].

The Voyager model was constructed in Thermal Desktop utilizing data from engineering drawings, reports and data provided by the Flight Operations team and the thermal engineers (Ledeboer/Kinsella/Avila). Most of the detailed modeling was of the spacecraft bus and the Trajectory Correction/Attitude Propulsion Unit (TCAPU) since this was the primary focus of the investigation. The TCAPU included geometric modeling of all of the propellant lines from the outlet of the fuel tank through the fan-out to the 16 Thruster/Valve Assemblies (T/VA's). Other subsystems are included to provide appropriate representation of the interfaces and boundary conditions.

1. *Voyager Drawings.*

JPL Vellum Files (Danielle Medina) has archived the Voyager drawings created as the spacecraft were designed and built. The drawing tree starts with the Spacecraft System drawing and calls out (TBS) additional drawings. A total of 237 drawings were retrieved from Vellum Files and converted to PDFs.

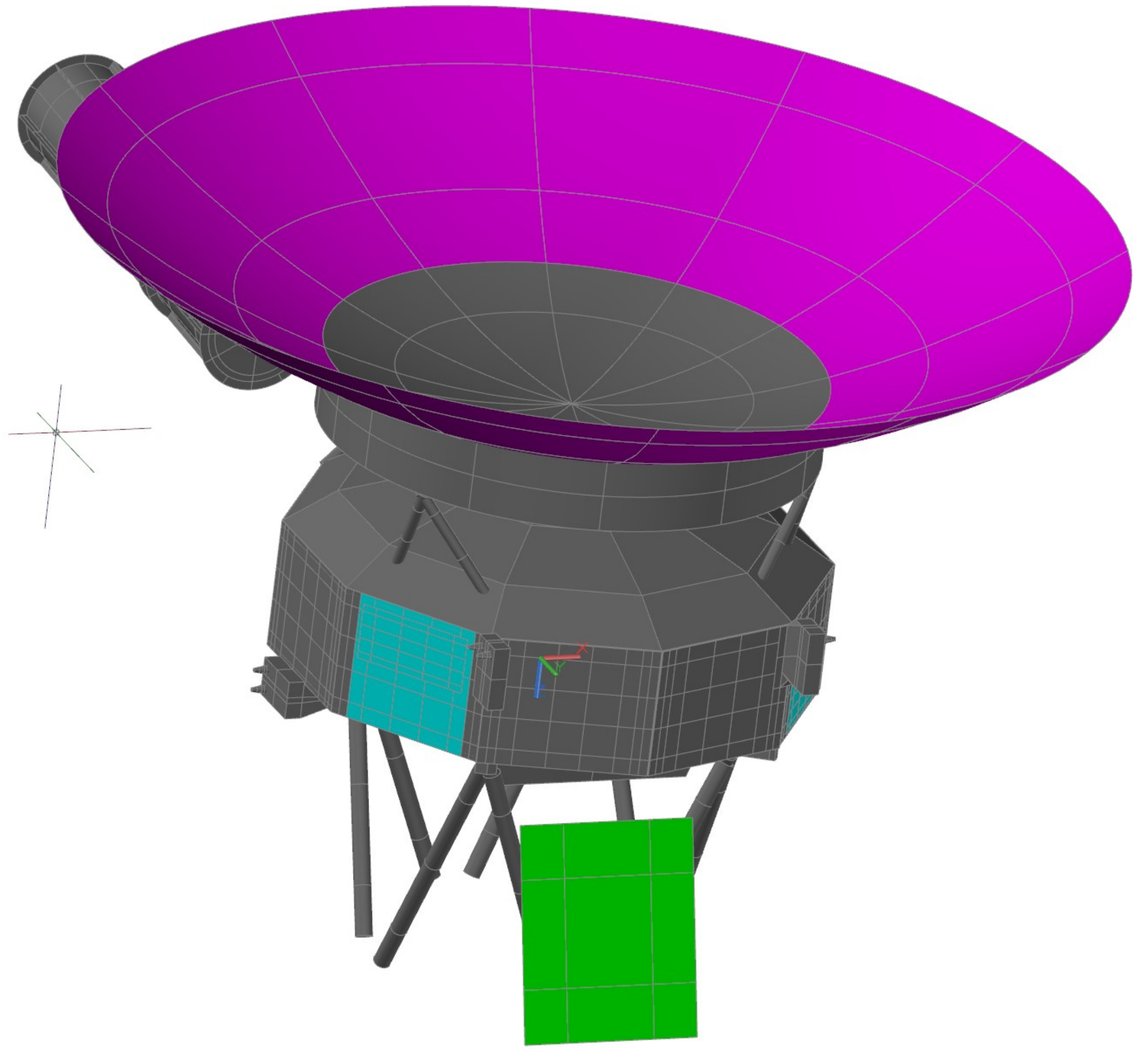

Figure 4 - Image of the Thermal Desktop Model with the TCAPU and T/VA's

2. The Drawing Tree.

The MJS77 Drawing Tree is a two-sheet roadmap showing the relationships between the component, assembly and installation drawings. The top level drawing is titled "Spacecraft System" which depicts the system as the "Spacecraft Assembly" and 10 drawings defining how the outboard subsystems are installed.

3. Material Specifications and Properties.

Material specifications were obtained from drawing Part List call-outs and corresponding properties retrieved from standard references and databases. *[Citation(s) needed]*

D. TMM Overview

Each Voyager spacecraft system is defined as a spacecraft assembly and a set of installation drawings for hardware that was added to the spacecraft as it was built. Table 2 shows the entire Spacecraft System from the drawing tree, and what components were modeled geometrically. The components of the Spacecraft Assembly (which is a subset of the Spacecraft System) include:

Table 2 - Voyager Spacecraft subsystems included in the thermal model

SUBSYSTEM	Included in the TMM?	RATIONALE
ENVIRONMENTAL BAFFLE	NO	Once the RTG is deployed, this is no longer significant in the interface to the spacecraft. Used to shield the spacecraft and science instruments launch to deployment.
MAGNETOMETER	NO	No geometry, modeled as a conductive heat leak from the bus.
S/C ADAPTER	NO	Separated from the IPU. The interface is modelled thermally, but the adapter is not included.
SCIENCE BOOM	NO	No geometry, modeled as a conductive heat leak from the bus.
THERMAL CONTROL	YES	
SCIENCE BOOM PLATFORM	NO	No geometry, modeled as a conductive heat leak from the bus. (An extension of the Science Boom.)
RTG	YES	Radiative interface seen by the bus, MLI on that side of the spacecraft, and louvers. Just outside geometry of the RTG as a heat source. Temperature telemetry of the surface of the RTG used as a boundary condition.
ANTENNA	YES	
PYROTECHNIC	NO	Fine detail not required for the model.
Spacecraft Assembly	YES	

1. Model Size and Boundary Conditions

The basic boundary condition is deep space, the sun is not significant source of heat, and there are no planets/moons in either Voyager's vicinity. Model statistics: 4563 nodes, 1177 elements & surfaces, 598 linear conductors, >205,364 exterior and 63,526 interior radiation conductors, and 86 heat loads.

E. Detailed Modeling of Propellant Lines

The propellant lines of voyager were the crux of the thermal modeling task and concern of the project. Understanding the material and cross section of the prop lines were uniform through the Voyager system. Filled with Hydrazine from the Fuel Tank to the thruster inlets, and they were made of Stainless steel lines with an aluminum block for heat spreading. Mounted to the aluminum blocks were spot heaters, located directly on propellant lines, and pad heaters mounted directly to aluminum blocks used as structural support for propellant lines. The total dissipation of the spot and pad heaters 3.06 Watts and controlled by a single computer controlled switch. The heaters were either all-on, or off. So all heaters, unlike modern systems, were turned on at once or off together with no zones. There was something like 55 heaters wired together into a single heater circuit. There is an A and B switch. There are only two temperature sensors on the propellant lines. This makes the model correlation extremely difficult, but was the driving reason for the need for a detailed thermal model to inform the Voyager team decisions.

The Spot heaters are solid power resistors and the pad heaters were Kapton film heaters.

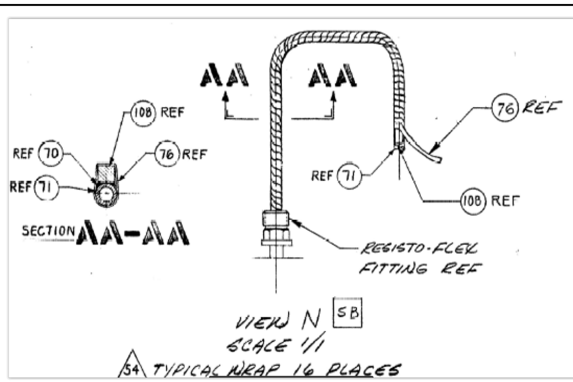

Figure 5 - Cross Section of "Enhanced Conduction" segments of propellant lines, typically near thruster inlets. Illustrates the aluminum bar to increase the thermal conductance along the Stainless Steel prop lines.

F. Other Propulsion Subsystem Components

Fuel Tank consists of a single Titanium tank, mono-propellant (Hydrazine) with an elastomeric diaphragm pressurized with Helium gas. As of the writing of this paper, both Voyager 1 and 2 have a positive Helium pressure. There are two film heaters on the tank. There are two temperature sensors, one on the Helium side and one of the fuel side of the tank. These temperature sensors tend to be at the same temperature (throughout the mission). There is a transition to a stainless steel tube from the Titanium tank.

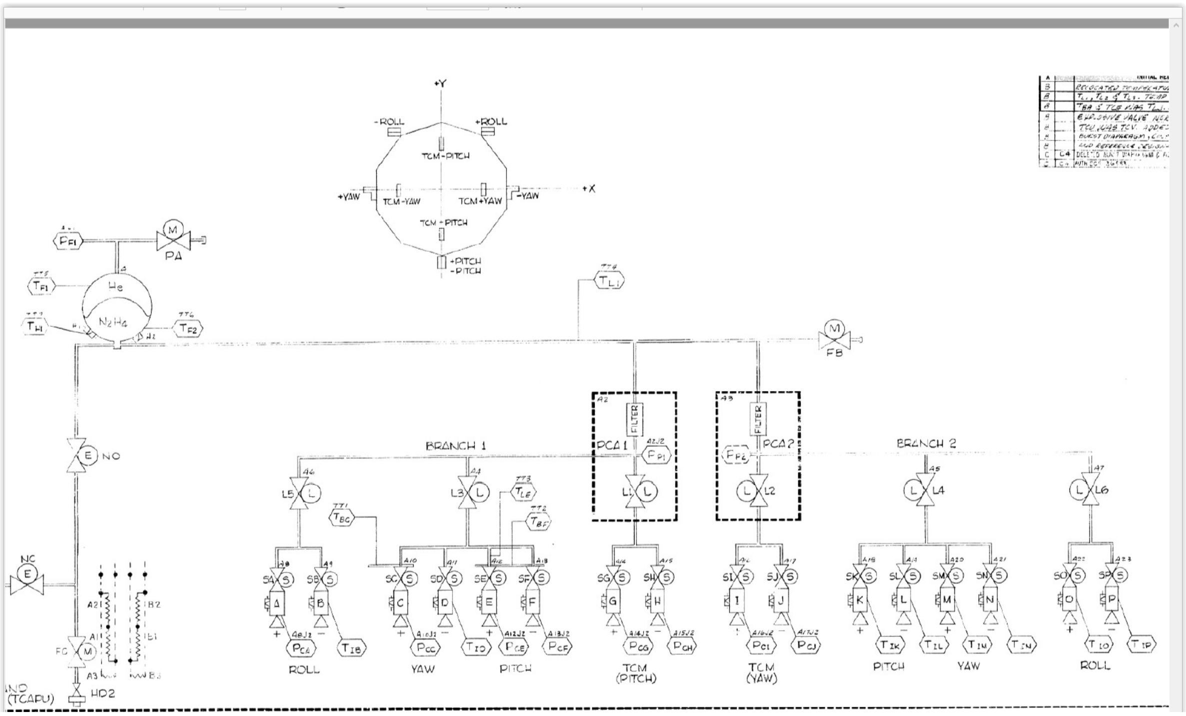

Figure 6 Propulsion Subsystem Functional Block Diagram

The Propellant Valve Package and Line Brackets have another two PRTs. Most of the latch valves and filters are mounted to a magnesium plate referred to as the propellant valve package and located under the tank between the bay 5 and bay 6 (TBC) of the spacecraft. Refer to Figure 6.

Further complicating the thermal challenge and modelling the Thruster/Valve Assemblies were initially modelled as 6-sided boxes, but later realized that there was a significant contribution from the high temperatures of the Cat-Beds inside of the thrusters when turned on to the rest of the model as only the tip of the thrusters are exposed outside of black blanket. The thrusters do have internal blanketing, but this is not modelled. The correct size cat beds and geometry, and with the applied power the model correlates with the local temperatures. We used thermal data from a 1974 cold qualification test for the thruster valves to further correlate the model.

G. Temperature Control Subsystem Components

Heaters—there are supplemental and replacement heaters (part of the bus thermal design). The supplemental heater is used when the component in the local bay is on, but not sufficient to maintain minimum AFTs. If the DTR is turned off (17-W), the replacement heaters would replace the power (10 W). The three types of heaters as previously mentioned are the cat bed heaters (C-shaped, ceramic with a Nichrome wire wound heater to heat the catalyst to ignite the cold hydrazine as it enters the thruster), spot heaters and the pad heaters.

RHU. There are a number of RHUs used as part of the thermal design throughout Voyager, the only ones used here are for this thermal model were the ones that are installed on the pitch thruster support (a total of 4 RHUs). After 40-years, it is believed that the output is about 3 W total (0.75 W each)

Louvers—There are four sets of louvers; two full sets on bays 1 and 7, and two half sets on bays 2 and 5. Based on current telemetry. Bay 1 is partly open.

MLI. Documentation discussed inner and outer blankets without further description. The blanket going around the outside of the S/C was the outer blanket. There was an upper and lower blanket on the S/C. There was no inner blanket on the drawings. In a discussion with retired engineer Ray Becker, while looking at the Voyager model in Von Karman, he remembered that they failed the cold case in the Voyager STV, so they quickly planned to redo the STV, and our blanket engineer made a second blanket to go around the outside of the bus. The blanket solved the problem. The solution to this mysterious inner/outer blanket is that there are literally two external blankets surrounding both spacecraft! One ten layer blanket with a second ten-layer blanket right on top of that blanket, hastily made and installed. In the thermal model, this is represented as a single blanket with a single effective emittance.

H. Discovery of TCAPU S/N 3

On 3/17/15, Andrea Angrum (Voyager Project Administrator) received e-mail from David Klein (JPL Assets/Storage) –

"The below image is of an old container that is in storage and has been there for about 30 years. It is in your name? We are desperately trying to find space for new projects, so we are trying to excess large items that have no future use. We would like to get rid of it. Do you know of any reason it cannot be excessed?"

Figure 7 - Voyager Flight Spare TCAPU (in shipping/storage container)

On 4/27/15, a trip was arranged to the storage facility to open the container and inspect its contents. It turned out to be an assemblu of Voyager TCAPU flight spare hardware (S/N3).

Figure 8 - Voyager TCAPU Flight Spare

III. Correlation of TMM to Flight Data & Peer Review

A. Thermal Telemetry

Table 3 lists the Voyager temperature telemetry channels used for model correlation, validation and predictions.

B. Selection of Hot and Cold Cases

Without STV data to use for model correlation, it was necessary to find flight power and temperature telemetry to use for that purpose. It was initially hoped that 3-5 data sets, representing steady-state conditions and covering a range of power states could be found. But as the spacecraft operations have become more and more constrained by the decreasing power from the RTG's, the difference between power states was found to be smaller than desired in terms of total dissipation in the bus bays (hot case power = ~110% of cold case power).

Two fairly recent data sets were chosen for the model correlation: Hot Case (2014-343) and Cold Case (2014-247).

C. Discovery of Inconsistent Flight Data

Another data set from earlier in the mission (2000-139) was also examined, but the power and temperature telemetry could not be reconciled. The total heat loss via all thermal paths was calculated to be higher than the total steady-state power being dissipated in the bus at that time. The unexplained "conservation of energy violation" implied by these data meant they could not be used to correlate or validate the thermal model.

D. Correlation Methodology (Parameters, Criteria and Results)

Addition of small, local heat loads as necessary to achieve matching temperatures at 16 temperature telemetry locations. 10 of the measurements were at the center of the outboard shear plates on the bus. The 6 measurements on the TCAPU include 2 on the fuel tank, 2 on thruster supports and 2 directly on propellant lines.

E. Correlation Results

Only two heat loads were required to achieve the correlation goal of matching the flight data to within 5°C. One was applied on the propellant line near the inlet to the Branch 1 –Yaw T/VA and the other was applied near the inlet to the Branch 2 – Pitch T/VA. Table 3 shows the results, comparing the hot and cold case steady-state model predictions with corresponding flight telemetry.

			2014-343	2014-247					
			XB-LO, GYON	XB-HI, GYOFF					
			HOT CASE	COLD CASE	HOT CASE	COLD CASE	HOT CASE	COLD CASE	
VGR 2 CHNL #	VGR 2 CHNL LABEL	Description	Flight Data [°C]	Flight Data [°C]	Predictions [°C]	Predictions [°C]	Delta [°C] TMM-Flt	Delta [°C] TMM-Flt	TD Model Node Number
E-0000	BAY_1T	Bay 1 Temp	25.8	23.7	24.2	22.6	-1.6	-1.1	AVG (BAY1_RFS.17,19,27,29)
E-0001	BAY_2T	Bay 2 Temp	17.6	14.1	19.0	17.3	1.4	3.2	BAY2_DSS.79
E-0002	BAY_3T	Bay 3 Temp	15.4	11.9	18.8	16.9	3.4	5.0	BAY3_CCS.84
E-0003	BAY_4T	Bay 4 Temp	13.3	9.7	15.8	13.6	2.5	3.9	BAY4_FDS.23
E-0004	BAY_5T	Bay 5 Temp	23.4	18.5	22.9	20.7	-0.5	2.2	BAY5_HYPACE.42
E-0005	BAY_6T	Bay 6 Temp	25.4	16.9	24.1	15.9	-1.3	-1.0	BAY6_DRIRU.32
E-0006	BAY_7T	Bay 7 Temp	20.3	20.3	19.8	19.0	-0.5	-1.3	AVG (BAY7_PWR.26,28,34,36)
E-0007	BAY_8T	Bay 8 Temp	13.8	10.3	14.9	11.9	1.1	1.6	BAY8_PSU.24
E-0008	BAY_9T	Bay 9 Temp	18.0	13.8	18.6	14.5	0.6	0.7	BAY9_RFS.23
E-0009	BAY_10T	Bay 10 Temp	21.1	19.0	21.8	19.0	0.7	0.0	BAY10_MAG_MDS.43
E-0292	SURF_T1	TCAPU Surface Temp 1	20.5	14.9	18.6	18.7	-1.9	3.9	PROP_LINE1.14
E-0293	SURF_T2	TCAPU Surface Temp 2	25.0	20.1	25.6	24.6	0.6	4.5	PROP_LINE1.145
E-0294	TANK_T1	TCAPU Tank Temp 1	15.4	12.6	12.2	9.0	-3.2	-3.6	AVG (FUEL_TANK.1, 8)
E-0295	TANK_T2	TCAPU Tank Temp 2	14.8	12.7	11.0	8.0	-3.8	-4.6	AVG (FUEL_TANK.50 47)
E-0296	FEED_T1	TCAPU Feed System Temp 1	12.0	8.5	11.1	9.6	-0.9	1.1	PROP_LINE.20
E-0297	FEED_T2	TCAPU Feed System Temp 2	22.0	17.8	17.9	17.0	-4.1	-0.8	PROP_LINE1.268

Table – 3 Comparison of Correlated Model Predictions and Flight Data

F. Informal Peer Review

An informal peer review of the model was held on 7/6/16. Reviewers were Gordy Cucullu, Mike Pauken and Josh Kempenaar. Reviewers were supplied with a) 5 page hand-out from thermal support kick-off meeting held 5/20/14 b) Current version of Voyager Thermal Desktop model c) Thermal Model and Analyses of Voyager *[Citation needed: ASL Final Report]* and d) READ_ME text file documenting revisions to model since ASL delivery.

Josh was asked to independently run the model, using latest release of Thermal Desktop software, post-process the output files and provide comments and suggestions. Discussion during the review focused on a) Evaluating modeling of: MLI, louvers, thrusters, propellant lines b) Verifying system-level energy balance (i.e. did calculated temperatures represent steady-state condition) and c) Reviewing any warnings or error messages from Thermal Desktop.

Action items from the review were worked and closed as indicated in Table 4.

Table 4. Informal Peer Review Action Items

Action Item	Closure
Review the Voyager model against generic Thermal Desktop checklist (supplied by Josh).	Completed.
Review outputs from Voyager model Hot & Cold correlation cases against criteria in checklist.	Completed.
Check warnings of incomplete contact. Suggested use of Thermal Desktop edge contactors where possible.	Completed
Generate system-level heat maps and validate with independent calculations.	Completed

IV. Application of TMM to Voyager Flight Operations

A. Model Validation

Once the correlated model was complete, it was used to make predictions for several validation cases. These were cases where complete, uncorrupted telemetry existed for a past power state which persisted long enough for temperatures to reach steady-state.

B. MAGROL Maneuvers & Thermal Tests

Voyager 2 power margin has decreased to the point where it is unable to turn on the gyros (for conditioning or maneuvers (check this with Enrique. Maneuvers meaning MAGROLs etc.) without turning off the Bay 1 Heater to make the needed power available.

C. DTR Analysis

A possible option for boosting Voyager 2 power margin was investigated, involving turning the DTR OFF (17.4 W in Bay 2) and turning the DTR Replacement Heater ON (10.2 W in Bay 2). The combination of recent temperature telemetry and change in steady-state temperatures for this power state change indicated that minimum propellant line temperatures would be expected to reach the hydrazine freezing point. On the basis of this analysis, the project did not approve this change to the Voyager 2 baseline power configuration.

III. Conclusion

Creating a thermal model of an active spacecraft after 39 years of continuous operation in space, long after its primary, secondary, and tertiary extend missions was a challenge. The output of the Voyager 1 & 2 spacecraft RTG power systems has decreased to the point where managing the power margin and maintaining thermal control has become increasingly difficult. As the total power dissipation in the bus has decreased, propellant line temperatures and margin above minimum AFTs have decreased, creating risk of the hydrazine freezing (at 1.6°C).

A new, steady-state Thermal Desktop model was created from scratch. The initial thermal model development was started by Applied Sciences Laboratory (ASL) under contract to JPL. The effort relied primarily on archived manufacturing drawings, limited documentation, interviews of senior engineers who worked on the Voyager design and implementation, and the experience of the Voyager Flight Operations team.

In the absence of data from the Voyager System Thermal Vacuum tests, the new model was correlated to more recent flight data. Correlation was achieved to within ±5°C for a hot case and a cold case (both data sets from 2014).

Recently, the model has been used to predict whether or not the spacecraft can safely change power state without causing any freezing of propellant. Based on these predictions, both Voyager 1 and 2 have executed Magnetometer Roll [MAGROL) calibration maneuvers as well as thermal tests up to 7 hours duration demonstrating no sign of freezing or propellant starting to turn "slushy".

The model has also been used to recommend against making a change to the Voyager 2 baseline power state that is predicted to cool propellant lines near Bay 2 to the hydrazine freezing point.

Acknowledgments

The creation of the Voyager Thermal Desktop model was performed primarily by Larry Chan of Applied Sciences Laboratory with additional updates by the author. Supervision and guidance were supplied by Gary Kinsella of JPL and Dr. Siu-Chun Lee of ASL. Fernando Peralta and Enrique Medina helped procure drawings from JPL Vellum Files as well as numerous other documents. The Thermal Desktop Model Checklist was provided by Josh Kempenaar of JPL.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1]Voyager website, (https://www.voyager.jpl.nasa.gov)

[2]Citation for photo of Voyager model in von Karman Auditorium.

[3]Citation for Figure 2 (Medina, E. "Total RTG Power").

[4]Voyager website, (https://www.vodyager.jpl.nasa.gov)

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[6]Citation for Thermal Desktop software