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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 Radioisotope Thermoelectric Generator (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 Allowable Flight Temperature (AFT) 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. Applied Sciences Laboratory (ASL) started the initial thermal model development under contract to Jet Propulsion Laboratory (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 (STV) 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. Therefore, 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.

Nomenclature

ASL	=	Applied Sciences Laboratory
AFT	=	Allowable Flight Temperature
CEO	=	Chief Executive Officer
°C	=	Degrees Celsius
DTR	=	Digital Tape Recorder
IOM	=	Interoffice Memorandum
IPU	=	Injection Propulsion Unit
JPL	=	Jet Propulsion Laboratory
KSC	=	Kennedy Space Center
LCSSE	=	Low-Cost Standardized Spacecraft Equipment
MAGROL	=	Magnetometer Roll
MJS 77	=	Mariner Jupiter Saturn 1977
PDF	=	Portable Document Format
PMS	=	Propulsion Module Subsystem
PRT	=	Platinum Resistance Thermometers
PWS	=	Plasma Wave Subsystem
RHU	=	Radioisotope Heater Unit
RTG	=	Radioisotope Thermoelectric Generator
SINDA	=	Systems Improved Numerical Differencing Analyzer
STEFO	=	Spacecraft Thermal Engineering and Flight Operations

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STV	=	System Thermal Vacuum
$T_{Bus\ S/P}$	=	Bus Shear Plate Temperature
TCAPU	=	Trajectory Correction/Attitude Propulsion Unit (TCAPU)
TMM	=	Thermal Math Model
T/VA	=	Thruster/Valve Assembly
USC	=	Unidentified Shipping Container
VIM	=	Voyager Interstellar Mission
W	=	Watts

I. Introduction[1]

FORTY-ONE years ago, two Voyager spacecraft (see Figure 1) were launched on trajectories to explore the outer planets Jupiter and Saturn. After successful encounters with their primary targets, Voyager 1 was targeted toward the edge of the Solar System, while Voyager 2 was navigated to encounters with the other gas giants, Uranus (1986) and Neptune (1989) before heading for interstellar space.

The Voyager website (Ref. 1) contains more details about the Voyager Interstellar Mission (VIM), the spacecraft and their status.

A. Voyager Science

Each spacecraft carries 10 science instruments (Figure 2). 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.

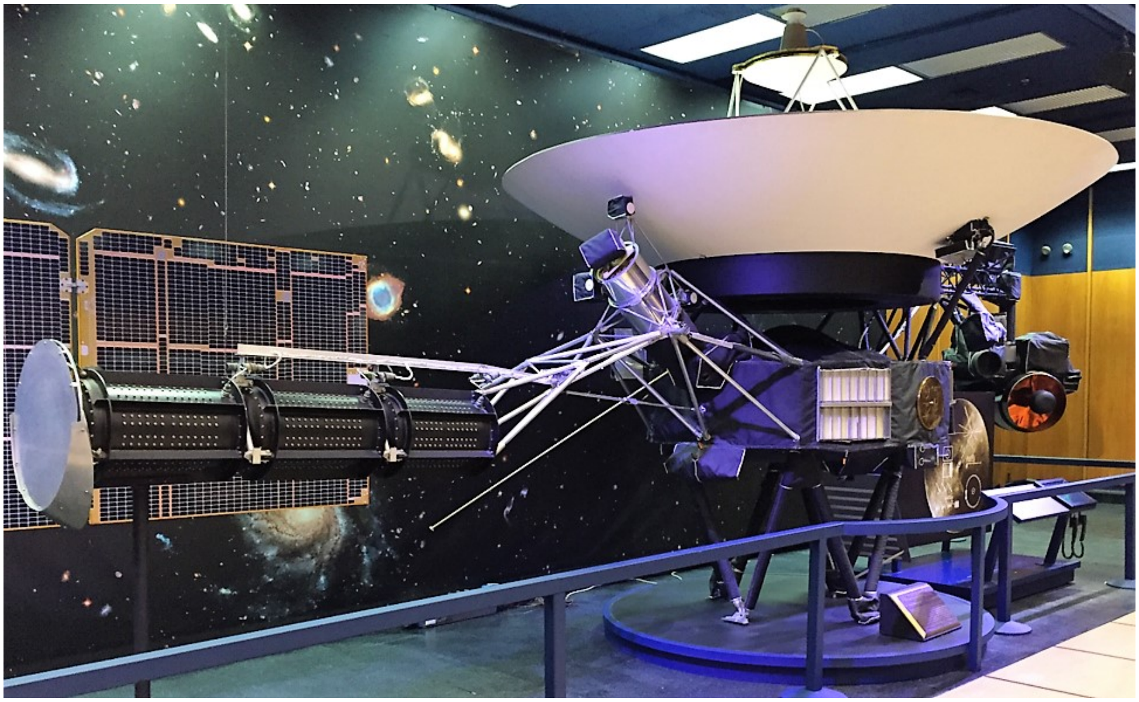
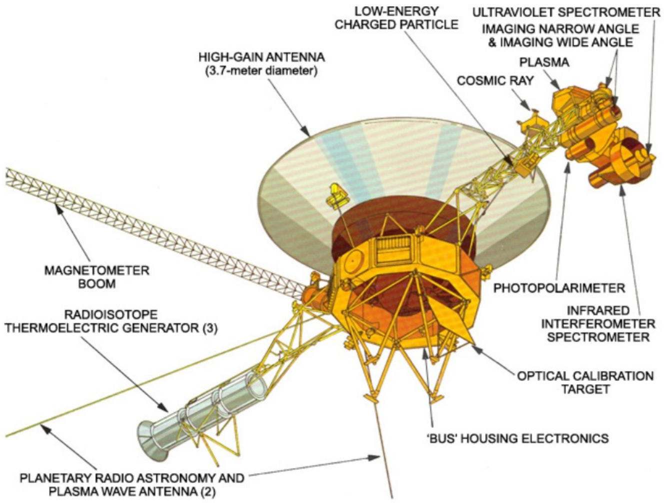


Figure 1. Full Size Model of Voyager Spacecraft in von Karman Auditorium at JPL. *(Photo by author)*



Instrument List

- 'BUS' Housing Electronics
- Cosmic Ray Subsystem (CRS)
- High-Gain Antenna
- Imaging Science Subsystem (ISS)
- Infrared Interferometer Spectrometer and Radiometer (IRIS)
- Low-Energy Charged Particles (LECP)
- Magnetometer (MAG)
- Optical Calibration Target
- Photopolarimeter Subsystem (PPS)
- Planetary Radio Astronomy (PRA)
- Plasma Science (PLS)
- Plasma Wave Subsystem (PWS)
- Radioisotope Thermoelectric Generators (RTG)
- Ultraviolet Spectrometer (UVS)

Figure 2. Voyager Science Instruments.

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).

Figure 3 shows the downward trending of available power for Voyager 2. The current power levels, as of 2018-120, are about 245 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 have been turned off, some spacecraft capabilities are no longer available (e.g. imaging instruments).

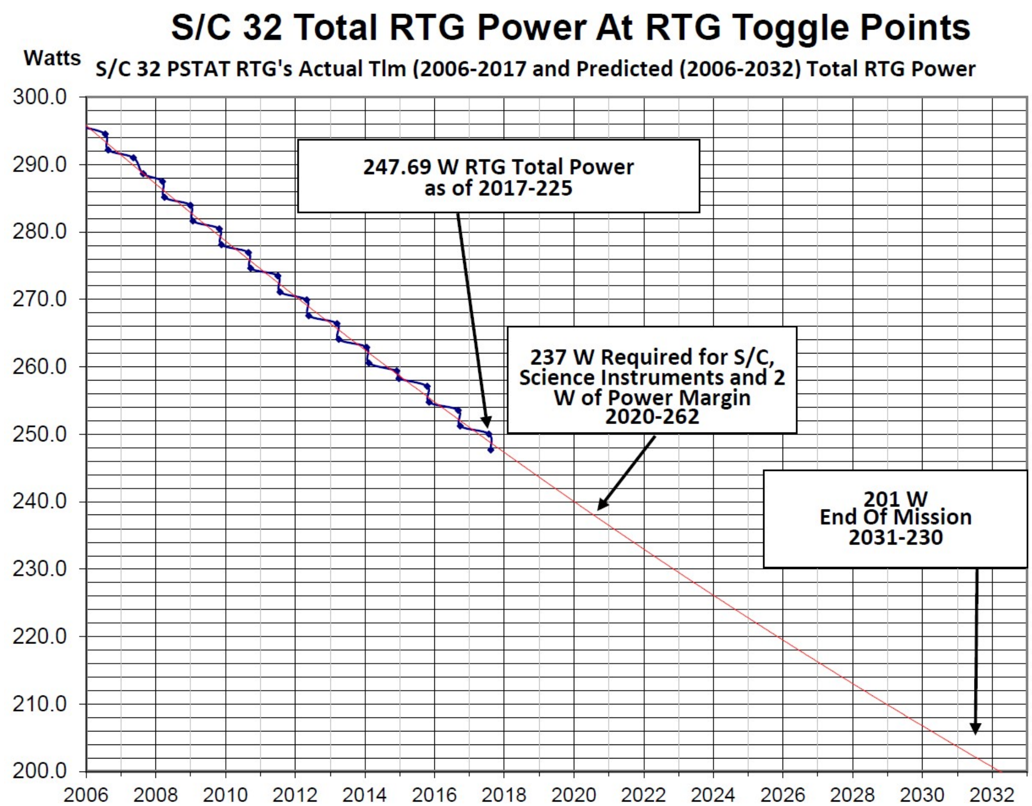


Figure 3. S/C 32 Total RTG Power at RTG Toggle Points (Ref. 2).

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.

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.

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	
2004 Dec. 16	Crosses Termination Shock	
2007 Aug. 30		Crosses Termination Shock
2012 Aug. 25	Enters Interstellar Space	
???		Enters Interstellar Space

II. Creating a Voyager Thermal Model

A. Hydrazine Freezing Issue

In May of 2014, the Voyager Flight Operations Team contacted the Spacecraft Thermal Engineering and Flight Operations (STEFO) group 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 (in the range 0.1°C – 1.6°C[3]), which could result in mission ending thruster failures.

The Voyager team held a kick-off meeting 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 thermal model formatted for use with the Systems Improved Numerical Differencing Analyzer (SINDA) program and documented in interoffice memorandums (IOMs).

B. Choosing an Option for Thermal Modeling

Five months later, after searching for Voyager thermal documentation, and interviewing former Voyager thermal engineers, the STEFO engineers (and ASL) presented the project with three options for creating a new thermal model[4].

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 a former Voyager thermal engineer (Ref. 5). 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[6] 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. Reviewing Drawings, Documents and Photographs

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 existent 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 and Vellum Files. Personnel who had worked on Voyager during its development, testing, launch and operations were contacted. The full-sized model, in the Von Karman museum at JPL, was used as a guide to understanding the current spacecraft configuration and correctly interpret the drawings.

Construction of the Thermal Desktop model began on 1 November 2014. The work order called for the model to be created by ASL under the guidance of the author and his supervisor. 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.

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.

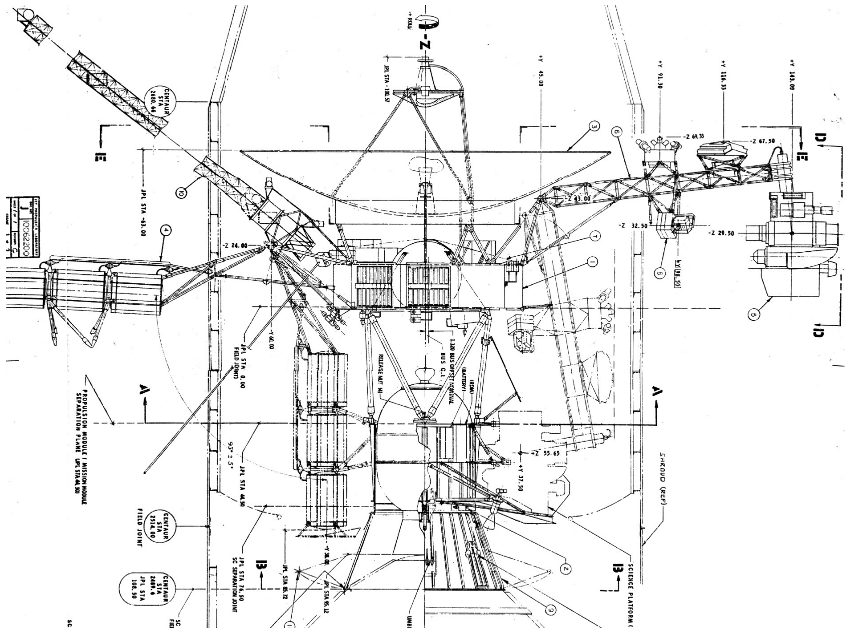


Figure 4. Voyager Spacecraft System (-X View from Ref. 7).

1. Voyager Drawings.

JPL Vellum Files has archived the Voyager drawings created as the spacecraft were designed and built. The drawing tree starts with the Spacecraft System drawing. 237 drawings were retrieved from Vellum Files and used in building the thermal model.

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” (see Figure 4) 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 Parts List call-outs and corresponding properties retrieved from standard references and databases[8,9].

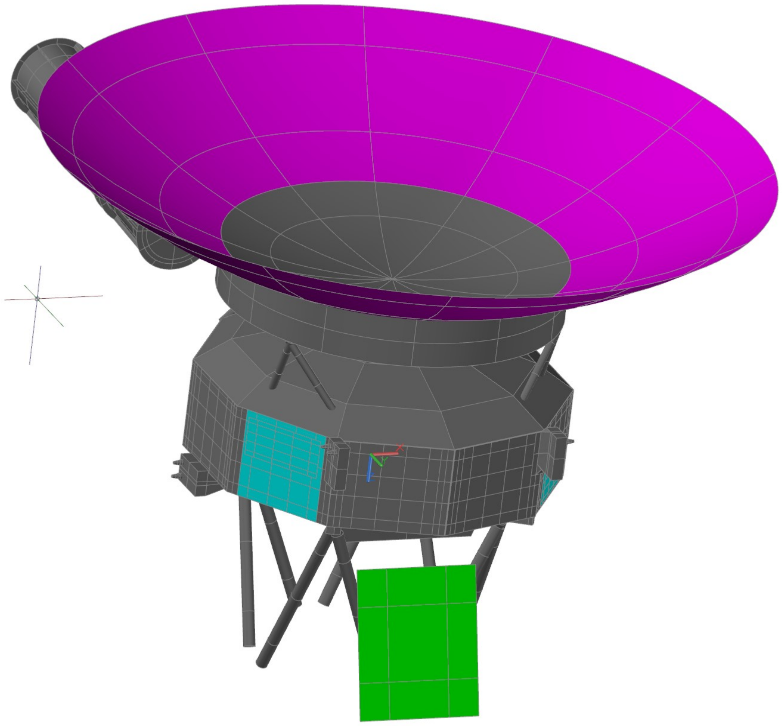


Figure 5. Overview of the Thermal Desktop Model.

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 contains the Spacecraft System drawing Parts List, indicating which parts were modeled geometrically in the Thermal Desktop model (see Figure 5).

Table 2. Voyager Spacecraft System Drawing Parts List[7].

Description	In TMM?	Rationale
ENVIRONMENTAL BAFFLE INSTALLATION	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 INSTALLATION	NO	No geometry, modeled as a conductive heat leak from the bus.
S/C ADAPTER INSTALLATION	NO	Separated from the IPU. The interface is modelled thermally, but the adapter is not included.
SCIENCE BOOM SCIENCE INSTALLATION	NO	No geometry, modeled as a conductive heat leak from the bus.

Description	In TMM?	Rationale
THERMAL CONTROL INSTALLATION	YES	Includes all louvers, MLI blankets, RHUs, shields and shades on the spacecraft.
SCIENCE BOOM PLATFORM INSTALLATION	NO	No geometry, modeled as a conductive heat leak from the bus. (An extension of the Science Boom.)
RTG INSTALLATION	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 INSTALLATION	YES	Also required for accurate radiative and conductive interface.
PYROTECHNIC INSTALLATION	NO	Fine detail not required for the model.
SPACECRAFT ASSEMBLY	YES	Includes Bus and hardware attached to bus, plus TCAPU and truss.

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 (Referred to as "cladding". See Figure 6 from Ref. 10). 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. There are 59 "spot" heaters and 6 "pad" heaters. The total dissipation of the spot and pad heaters is 3.06 Watts and controlled mainly by a single computer controlled switch (a second switch controls 4 of the spot heaters and a third handles 2 of the pad heaters. Therefore, the heaters are either all-on, or off. 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.

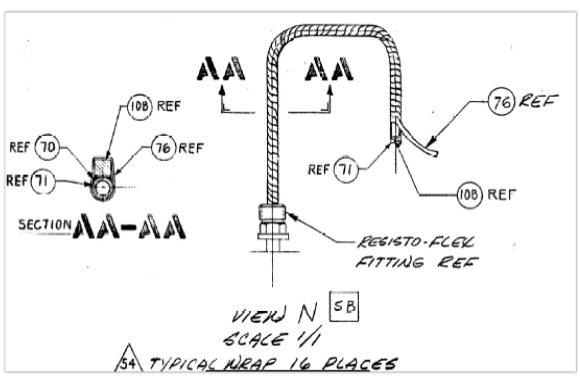


Figure 6. Cross Section of "Enhanced Conduction" segments of propellant lines, typically near thruster inlets. Illustrates the aluminum bar to increase the thermal conductance along the Stainless Steel prop lines (from TCAPU Installation drawing[10]).

F. Other Propulsion Subsystem Components

Figure 7 is the TCAPU portion of the Propulsion Module Subsystem (PMS). Fuel Tank consists of a single Titanium tank, monopropellant (Hydrazine) with an elastomeric diaphragm pressurized with Helium gas. 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.

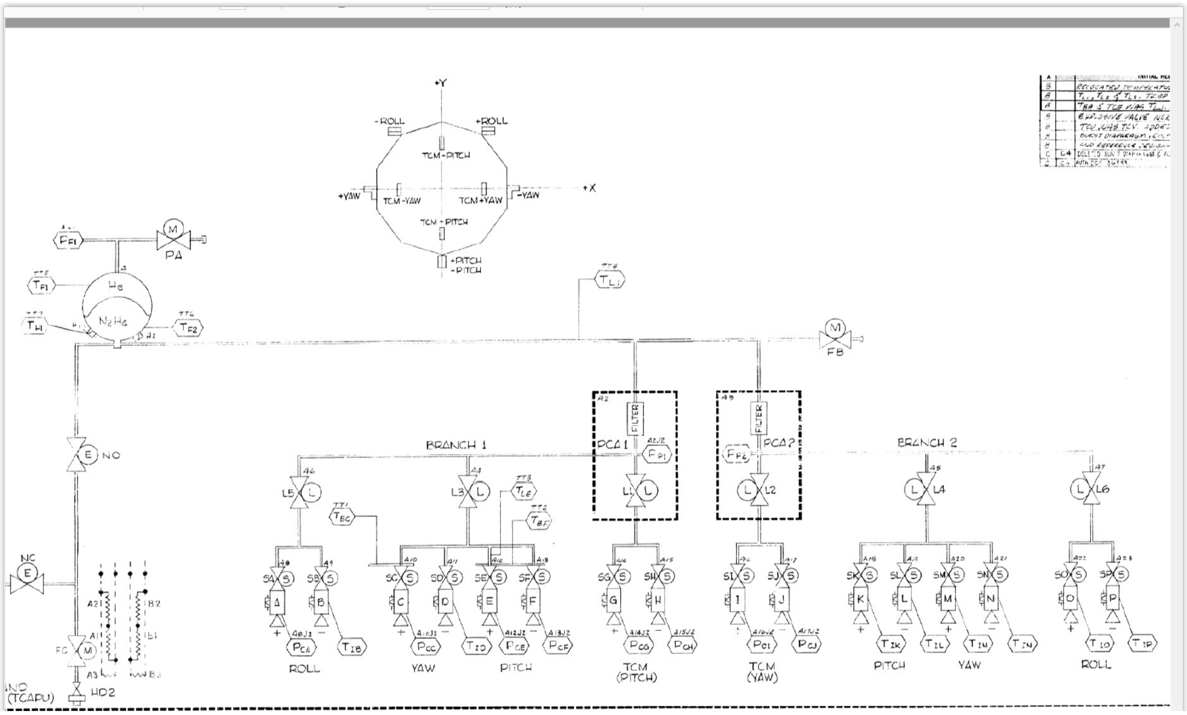


Figure 7. Propulsion Subsystem Functional Block Diagram (from Ref. 11).

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 of the spacecraft.

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[12].

G. Temperature Control Subsystem Components

Supplemental and replacement heaters were used in the bus thermal design. Supplemental heaters are 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[12]), spot heaters and the pad heaters.

RHUs are used in several places on the Voyager spacecraft. The only ones simulated in the thermal model were the ones installed on the pitch thruster support (4 RHUs). After 40-years, it is estimated that the output is about 3 W total (0.75 W each)

Four sets of louvers are mounted on bus outboard shearplates; 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.

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 *two* external blankets surrounding both spacecraft. One ten layer blanket with a second ten-layer blanket installed over the first. In the thermal model, this is represented as a single blanket with a single effective emittance.

Figure 8. Unidentified Shipping Container (USC).

H. Discovery of TCAPU S/N 3

On 17 March 2015, the Voyager Project Administrator received e-mail stating, "This image is of an old container that is in storage and has been there for about 30 years" (See Figure 8). A trip was arranged to the storage facility to open the container and inspect its contents. It turned out to be an assembly of Voyager TCAPU flight spare hardware (See Figure 9).

Figure 9. 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[14].

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 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. These abstractions did not capture nuances of the heat sources—and much of the heat distribution is not known with a high degree of certainty. However, this decision did maintain the overall energy balance. The heat loads were added to compensate for the complexity of the odd shapes and bolted interfaces that contributed to the conductive coupling through the thruster brackets.

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. The final placement of these heat sources was the result of multiple correlation runs until the 5°C criteria was met, and was within the bounds of maintaining the overall energy budget. The heat loads that were added were in terms of milli-Watts, so did not disrupt the energy balance in any significant way.

Table 3. Comparison of Correlated Model Predictions and Flight Data.

			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

F.Informal Peer Review

An informal peer review of the model was held on 6 July 2016. Reviewers were asked to independently run the model, using latest release of Thermal Desktop software, post-process the output files and provide comments and suggestions.

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 (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[15]. Based on 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 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 (STV) 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 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.

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