Magnetospheric Multiscale (MMS) Propellant Tank Thermal Capacitance Model

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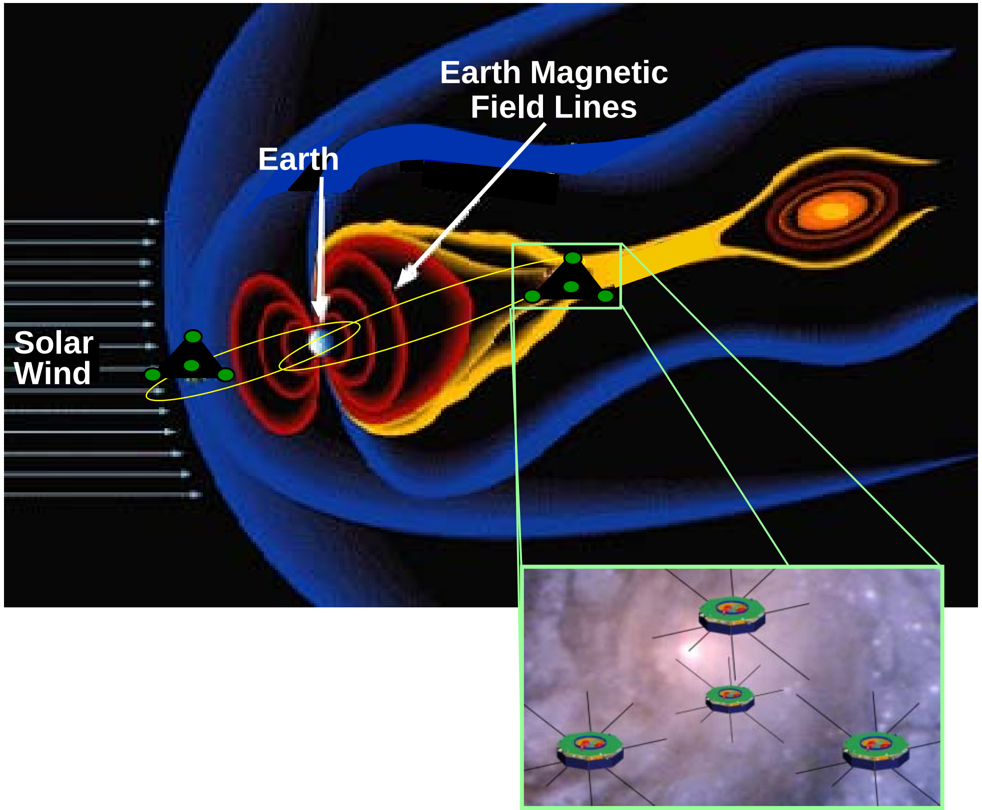
Agenda

- Magnetospheric Multiscale (MMS) mission overview
- Model approach and overview
- Propellant Gauging Method and ANSY Model
- Test Cases and Model Validation
- Results
- Model Refinements
- Conclusions & Continuing Work

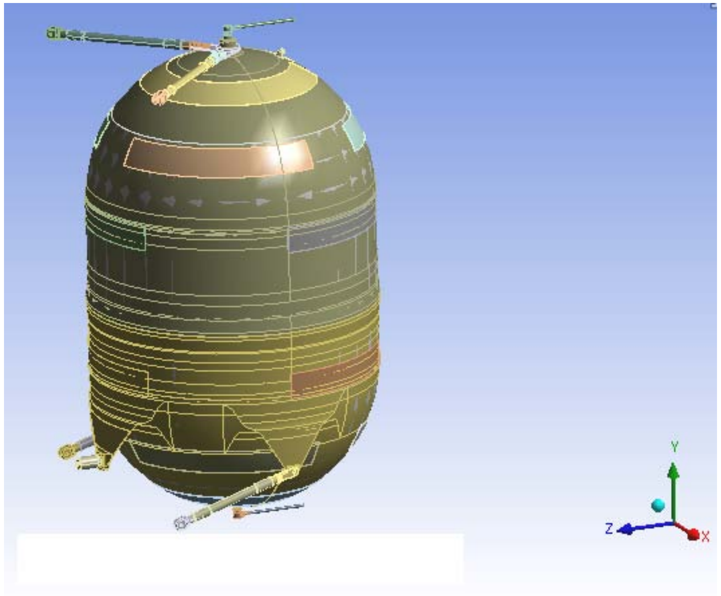
Magnetospheric Multiscale (MMS) Mission Overview

- **Science Objectives**
  - Discover the fundamental plasma physics process of reconnection in Earth's magnetosphere
- **Mission Description**
  - 4 identical satellites
  - Formation-flying in a tetrahedron
  - 2 year operational mission
- **Propulsion System**
  - Identical on each satellite
  - Each contains
    - 4 Tanks
    - 8 Radial thrusters (18 N)
    - 4 Axial thrusters (5 N)
    - 4 Latch valves
    - 4 Filters
    - 8 Pressure transducers



Model Objective & Approach

- **Objective**
  - Develop a tool to predict propellant mass using tank temperature data
- **Approach**
  - Develop a thermal model of the MMS propellant tank using a Finite Element Model (ANSYS)
  - Validate thermal model with existing tank Thermal Desktop model and during future thermal balance testing



Propellant Gauging Systems

- **Typically three common Propellant Gauging Systems (PGS) used**
  - 1) Bookkeeping
  - 2) Pressure-Volume-Temperature (PVT)
  - 3) Thermal Capacitance

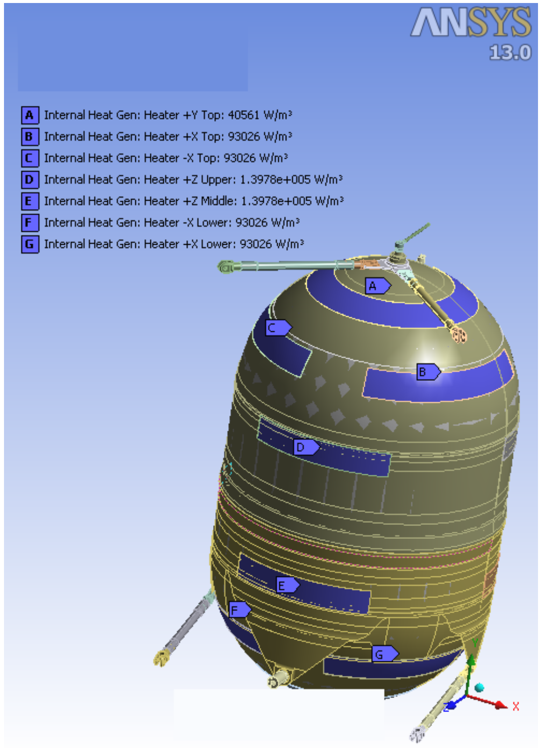
- **Thermal Capacitance**
  - Inaccurate at BOL (little variation of tank surface temperature due to large volume of propellant)
  - Accurate at EOL (large variation of tank surface temperature due to less volume of propellant)
  - Requires a detailed thermal model of propellant tank and typically of surrounding spacecraft

- **How do you estimate propellant load using tank temperature data?**
  - 1) Develop a thermal model of the tank
  - 2) Apply boundary conditions to tank
  - 3) Generate temperature vs. time curves for different propellant loads in tank
  - 4) On spacecraft, heat tank using heaters and record temperature telemetry
  - 5) Compare temperature telemetry to temperature vs. time curves generated in model.

Assumptions & Boundary Conditions

- **Assumptions**
  - Convection neglected
  - Fluid shapes do not change due to temperature effects
  - The tank diaphragm was not modeled, but its mass was considered
  - Tank blanket and tape were not physically modeled.
  - Heater power based on constant bus voltage
  - Boundary conditions were based upon the average temperature of the tank/spacecraft interface location and were assumed constant over time*
  - A “perfect” bonded contact existed between all touching parts in the model

- **Boundary Conditions**
  - Heaters have total heat input of 29.87W
  - Struts, inlet & outlet tubes, and axial pin set to 23°C
  - Radiation applied to tank surface using blanket effective emissivity



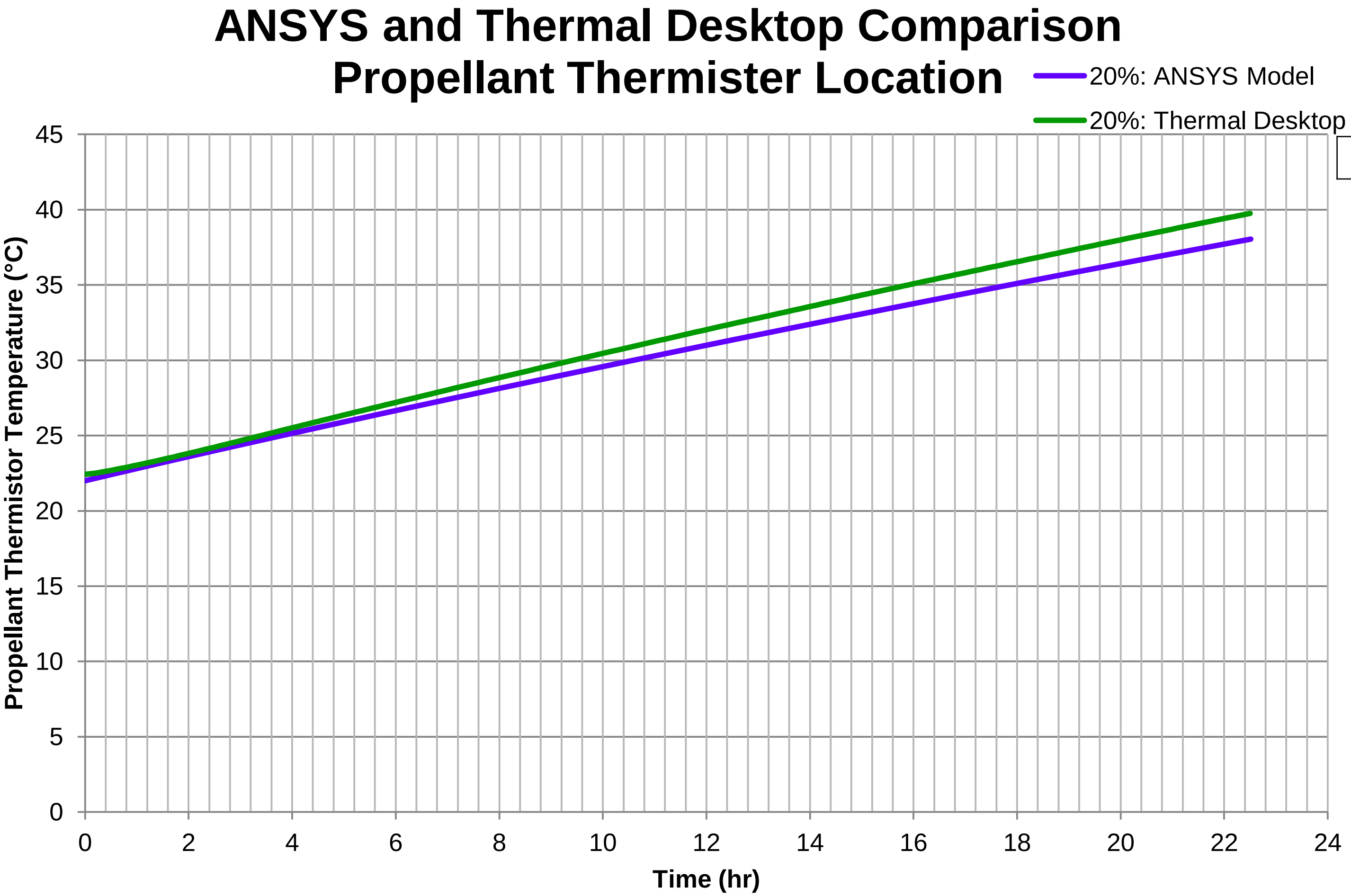
A Internal Heat Gen: Heater +Y Top: 40561 W/m^3
B Internal Heat Gen: Heater +X Top: 93026 W/m^3
C Internal Heat Gen: Heater -X Top: 93026 W/m^3
D Internal Heat Gen: Heater +Z Upper: 1.3978e+005 W/m^3
E Internal Heat Gen: Heater +Z Middle: 1.3978e+005 W/m^3
F Internal Heat Gen: Heater -X Lower: 93026 W/m^3
G Internal Heat Gen: Heater +X Lower: 93026 W/m^3

*ANSYS has ability to model this behavior; behavior not included in this analysis

Analysis Test Cases

- **Three different EOL propellant loading cases were simulated using the ANSYS transient thermal model**
  - Case #1: 20% propellant load
  - Case #2: 15% propellant load
  - Case #3: 10% propellant load
- **Thermal model for each case was the same, but the propellant and gas volumes were updated to reflect the propellant mass used**
- **The model was validated by comparing results to independently created Thermal Desktop model**

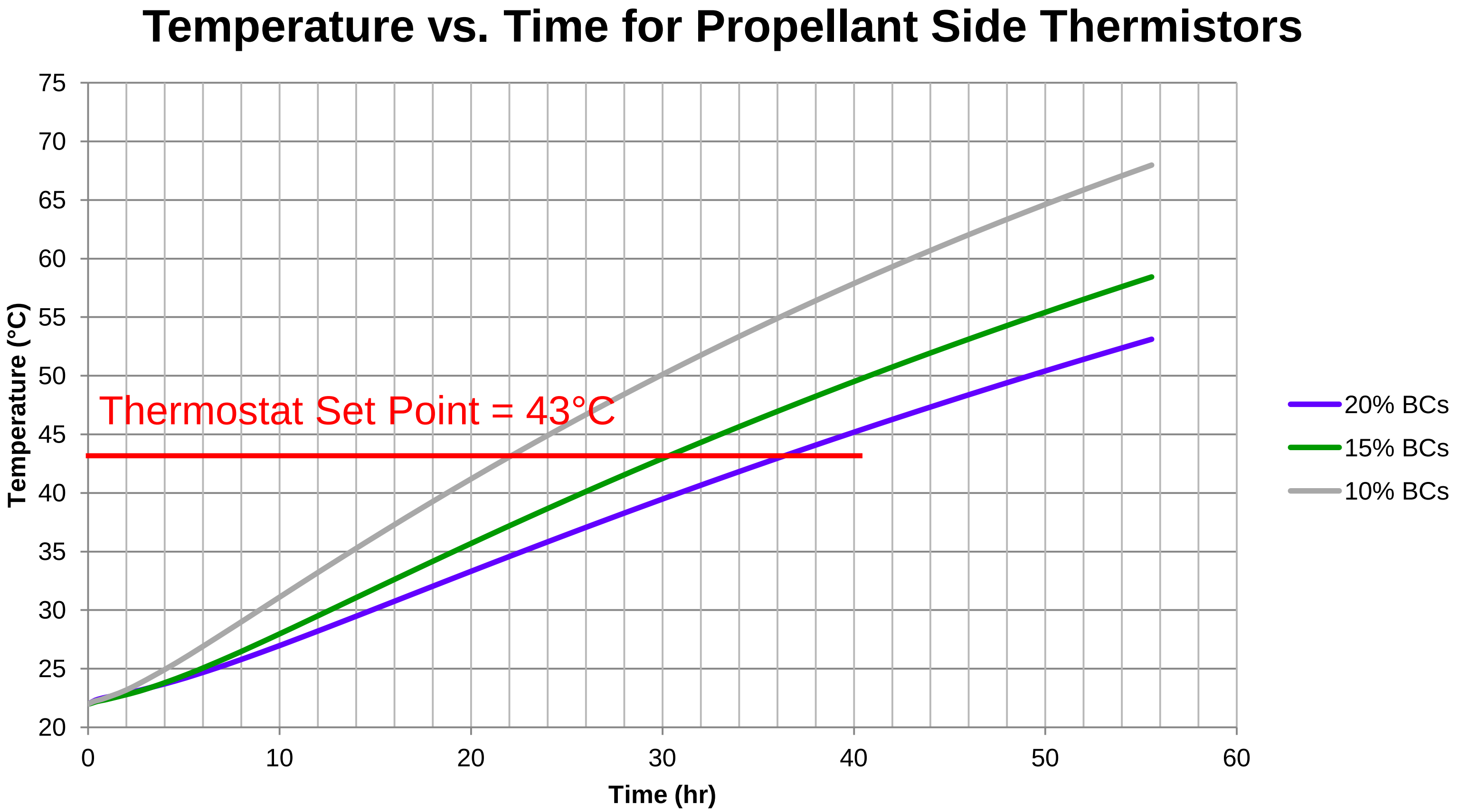
Model Validation



Max % Difference:	4.27

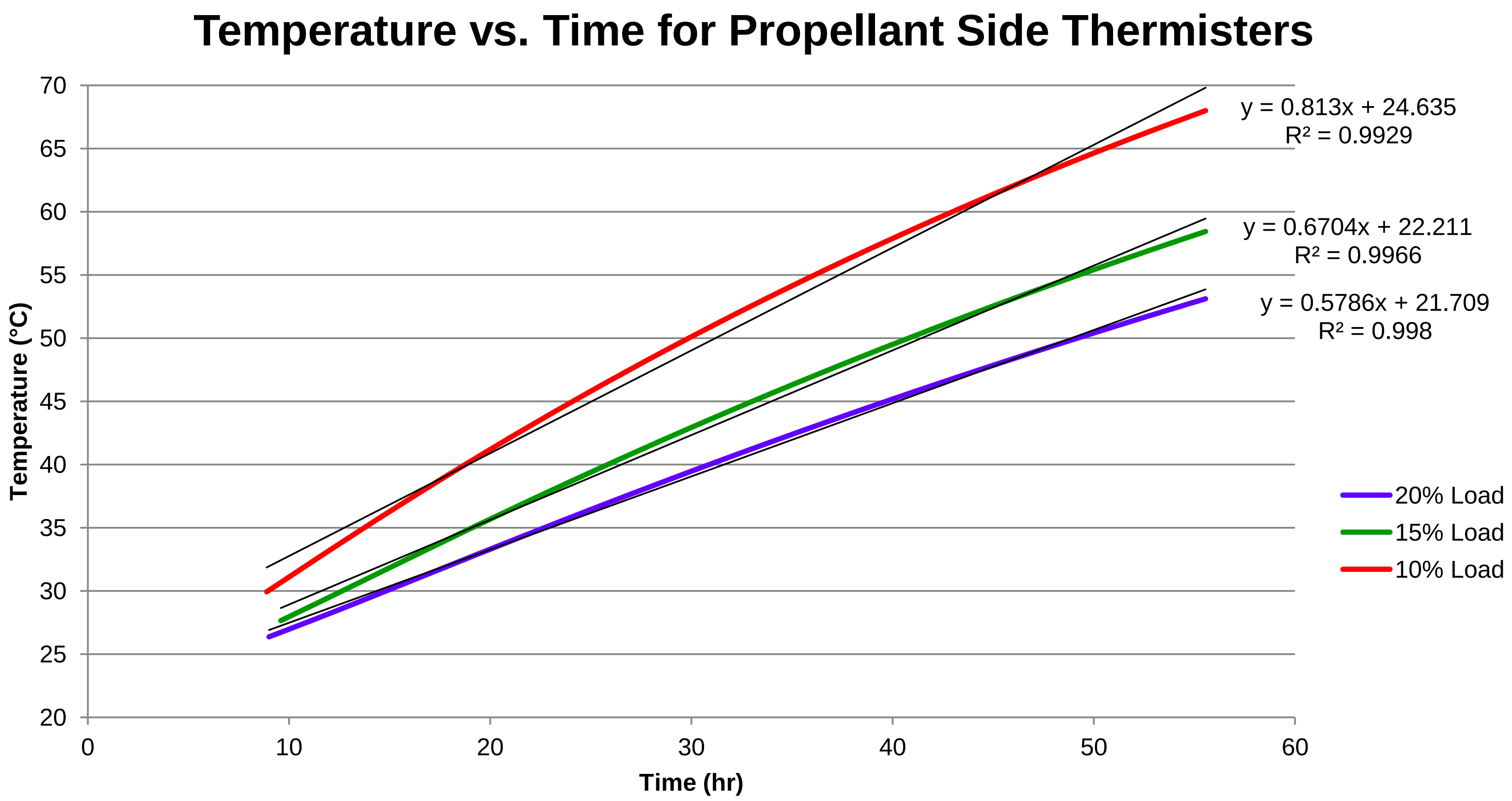
ANSYS Model Results

Results



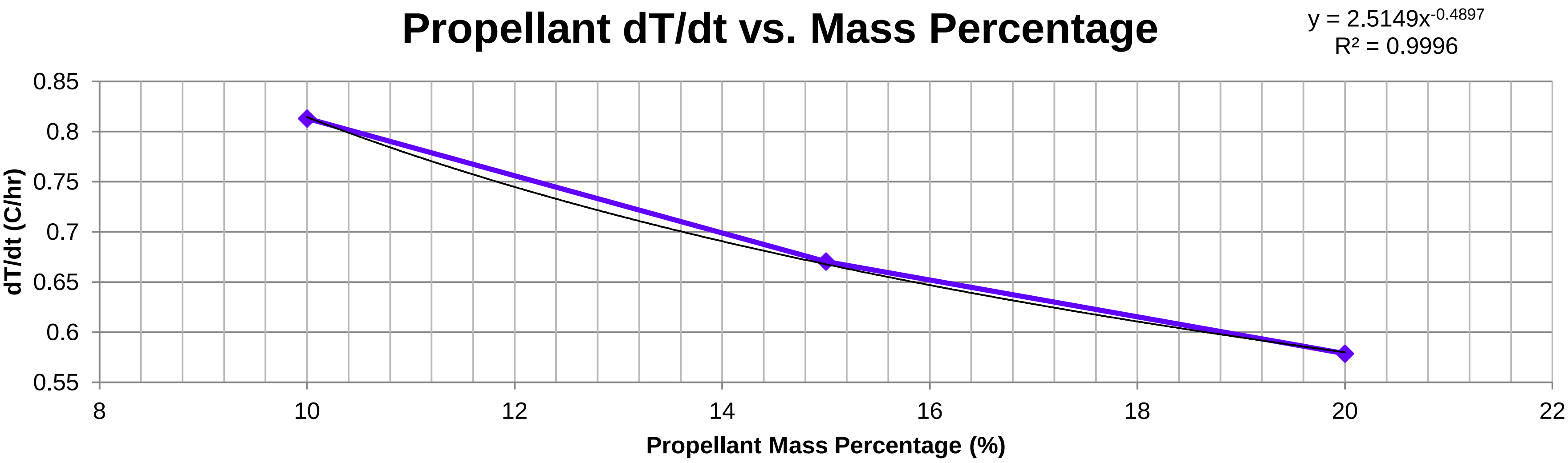
- **Can clearly discriminate (min. 1°C difference met) masses from temperature data after ~9 hrs**
  - Need at least 1°C difference to account for A/D conversion errors and thermistor calibration error.
- **dT/dt behavior is nearly linear after ~9 hrs of simulation**
- **Time heaters turn off (TStat set point reached) widely separated in time & can be used to estimate propellant mass**

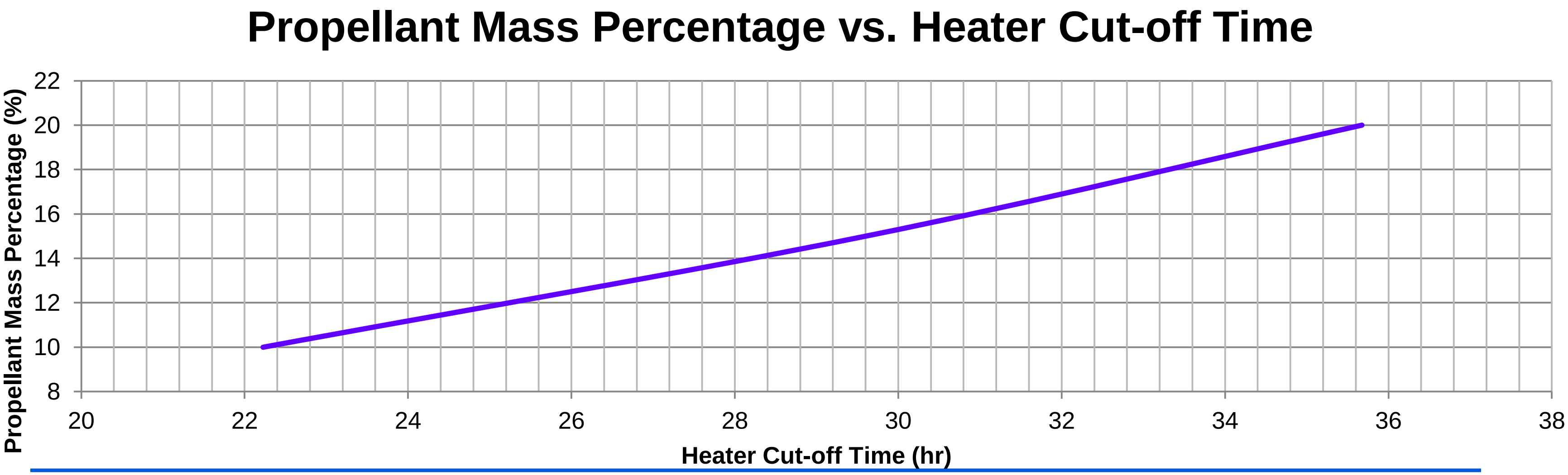
Results



- **Linear curve fits produce good R^2 values**

Results


Propellant dT/dt vs. Mass Percentage
y = 2.5149x^-0.4897
R² = 0.9996
dT/dt (C/hr)
0.85
0.8
0.75
0.7
0.65
0.6
0.55
8
10
12
14
16
18
20
22
Propellant Mass Percentage (%)


Propellant Mass Percentage vs. Heater Cut-off Time
Propellant Mass Percentage (%)
22
20
18
16
14
12
10
8
20
22
24
26
28
30
32
34
36
38
Heater Cut-off Time (hr)

Results

- **Analysis of the preceding charts shows that a closed form solution can be derived from the simulation data**
- **From the T vs. t Chart and mass vs. dT/dt charts, mass percentage can be derived**
- **Results in:**

$$m = \left(\frac{T - 22.85}{2.51t}\right)^{-\frac{1}{0.49}} \quad \text{for} \quad \begin{cases} 30 \leq T \leq 43°\mathrm{C} \\ 9 \leq t \leq 21\ hr \end{cases}$$

- **Propellant mass percentage estimate error can be determined by taking the derivative of above equation:**

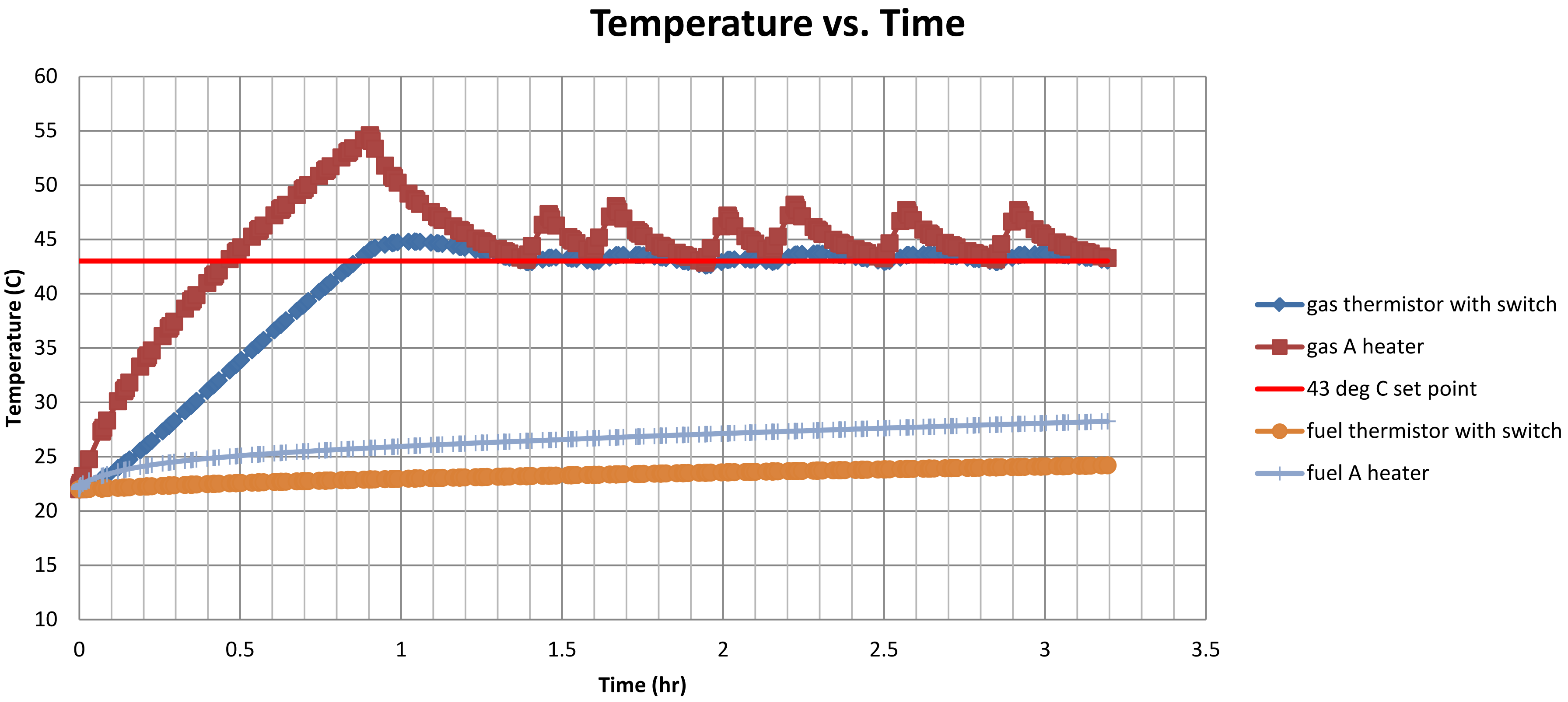
$$\Delta m = \frac{-0.81}{t}\left(\frac{T - 22.85}{2.51t}\right)^{-3.04} \Delta T$$

- **Example:**
  - A 1°C error in temperature at a temperature reading of 37°C at 20 hours yields a mass uncertainty of 1.90%.
  - Improvements in error estimation can be made by running more propellant loading cases and correlating model results with test data.

ANSYS Model Refinements

ANSYS Model Refinements

- **Following refinements made to model**
  - Implemented thermostatically controlled heaters to system
  - Revised boundary conditions at tank to match on-orbit behavior predicted by Thermal Desktop model
  - Modeled heater power using nominal as-built heater resistances



Conclusions & Continuing Work

Conclusions:

- **Propellant load can be estimated using four different indications**
  - 1.) Using the temperature vs. time plot
  - 2.) By propellant side heater cut-off time
  - 3.) By slope (dT/dt) of temperature curve
  - 4.) By a closed-form expression

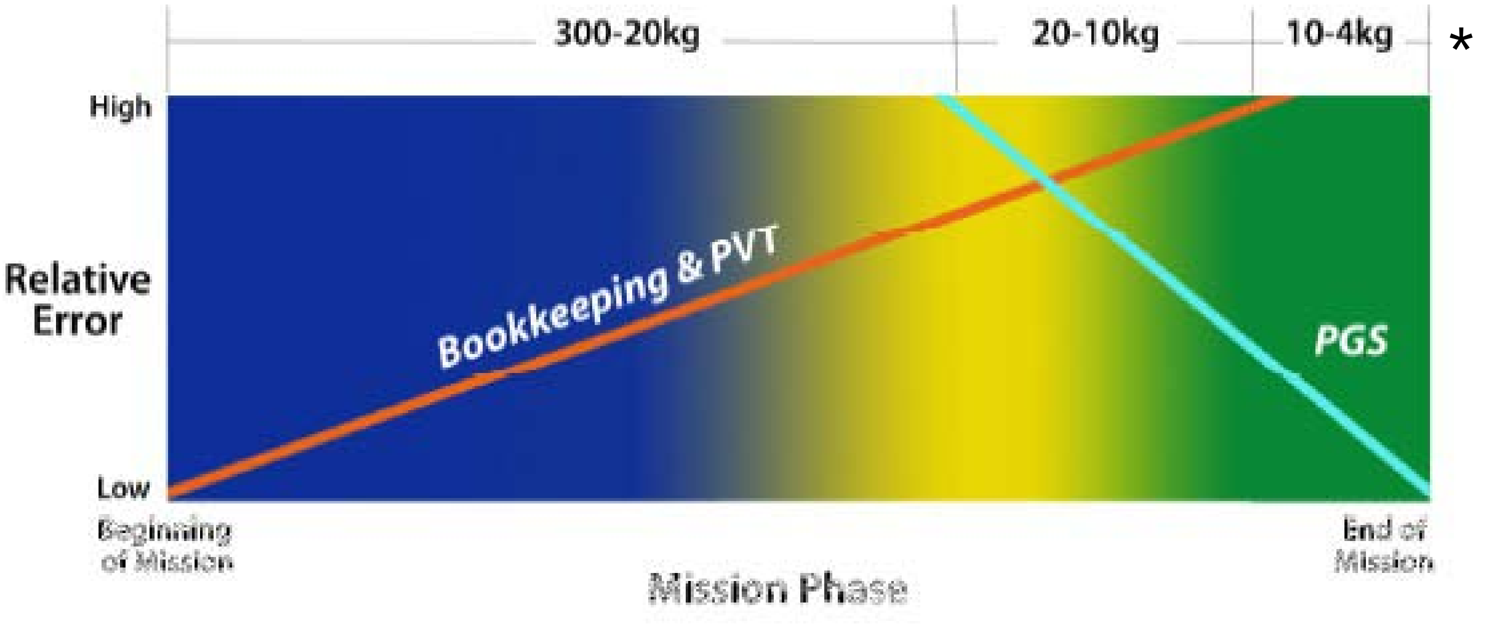
Continuing Work:

- **Validate model by test using three methods**
  - 1.) Propulsion Module Chill Down Test
    - Conducted at atmospheric pressure to verify thermostat operation
    - No propellant in tank
    - Minimal convection effects
  - 2.) Water Off-Loading
    - Perform thermal propellant gauging "maneuver" after water offloading operations when 10 kg of propellant in tank.
    - Conducted at atmospheric pressure.
    - Minimal convection effects
  - 3.) Thermal Balance Test
    - Performed during spacecraft level thermal balance testing
    - Conducted in near vacuum
    - No propellant in tank

Questions?

Backup Slides

Propellant Gauging System Errors



*Aparicio, A., and B. Yendler. "Thermal Propellant Gauging at EOL, Telstar 11 Implementation." *AIAA-2008-3375*. (2008): p.2.

Thermal Capacitance: Theory

- **Basic Concept of Thermal Capacitance PGS**
  - Heat tank, look at the change in temperature over time
  - Ultimately want to compare the dT/dt of the model to the dT/dt from on orbit telemetry
- **From Energy Conservation**

$$Q_{input} = Q_c + Q_{loss} \qquad (1)$$

Where

$$Q_c = \sum_i \left(m C_p \frac{\partial T}{\partial t} \right)_c \qquad (2)$$

- Components:
  - Tank shell
  - Helium
  - Propellant
  - Struts
  - Axial pin

$$Q_{input} = Q_{heaters} \qquad (3)$$

$$Q_{loss} = Q_{rad} + Q_{cond} + \cdots \qquad (4)$$

Thermal Capacitance: Theory (cont.)

- **Heat flow (Q) and dT/dt are either known or found from**
  - ANSYS thermal model
    - Struts
    - Axial Pin
    - Radiation
    - Tank
    - Helium
  - Tank Thermal Configuration
    - Heaters each dissipate a known amount of energy
    - Number of heaters known
    - Blanket emissivity is known
    - Mass of thermal hardware is known
- **Mass (m) is known from vendor data and/or specified (propellant) for analysis**

Thermal Propellant Gauging Model Solution Process (General)

- **Regardless of the system, the overall process for developing a thermal propellant gauging model is as follows[1]**
  - 1). Develop a thermal model of the tank(s) and spacecraft
  - 2). Combine propellant tank and spacecraft thermal models
  - 3). Heat the tank on the spacecraft by turning on the tank heaters
  - 4). Simulate the propellant gauging operation for different propellant loads
  - 5). Compare flight and simulation data
  - 6). Determine tank propellant load and uncertainties of estimate

- **For MMS tank capacitance model, completed steps 1-4, with the following exceptions**
  - Modeling the spacecraft system. Boundary and initial conditions for the tank were obtained from thermal analysis performed by Thermal Branch on the MMS spacecraft
  - Simulation data compared with results from Thermal Desktop propulsion system analysis
  - No comparison of flight data to simulation data since spacecraft is not yet in operation
  - Validation of model will occur during thermal balance testing, currently scheduled for August 2013

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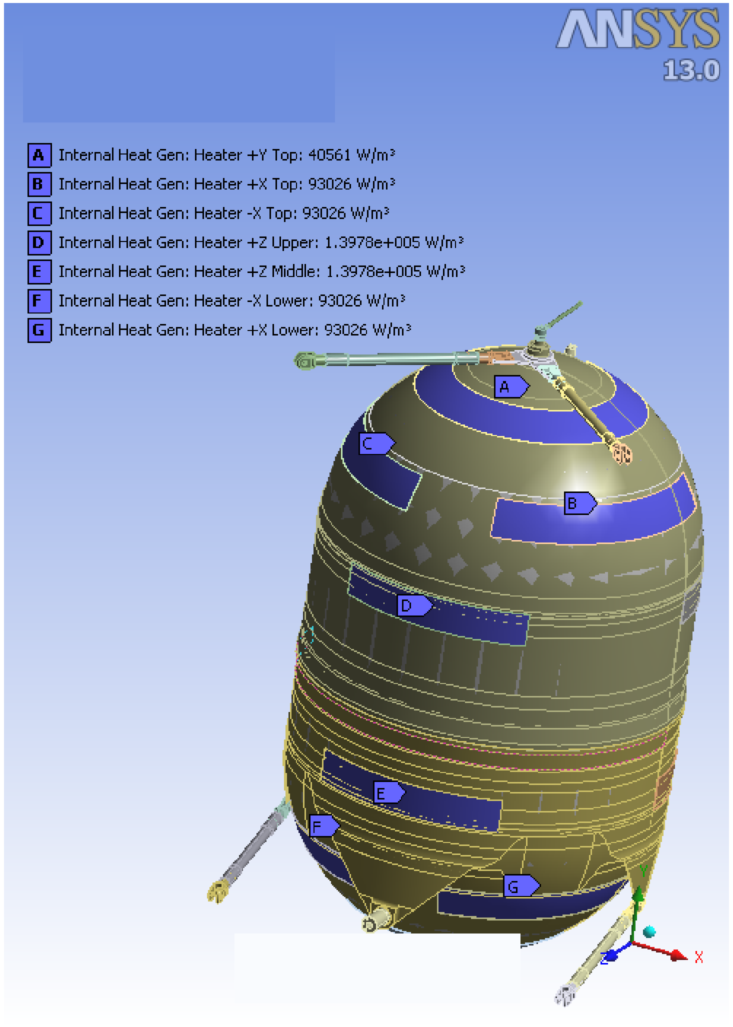
[1] Aparicio, A., and B. Yendler. "Thermal Propellant Gauging at EOL, Telstar 11 Implementation." *AIAA-2008-3375*. (2008): p.2.

Boundary Conditions

- **Flight configuration of tank contains two main heater zones: gas and propellant.**
- **Each controlled by an over-temp thermostat set at 43°C**
  - <u>Configuration</u>
    - Heaters have total heat input of 29.87W
    - Struts, inlet & outlet tubes, and axial pin set to 23°C
    - Radiation applied to tank surface using blanket effective emissivity
- **Set #1 BCs showed that gas side of tank reached over-temperature set point rapidly**
- **Defined additional set of BCs to model situation**
  - <u>Set #2: Gas Side Heaters Off</u>
    - Propellant side heaters have total heat input of 14.91W
    - Gas side of tank set to 43°C
    - Radiation remained the same



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Model Validation

- **Performed spreadsheet calculations to solve for propellant mass percent to determine model stability & convergence (<2% difference)**

Case	Target Mass Percentage	Calculated Mass Percentage	Percent Diff
10%	9.71	9.86	**1.54**
15%	14.56	14.61	**0.34**
20%	19.40	19.37	**0.15**

Model Validation

- **Hand Calculations:**
  - Analyzed heat transfer at boundary conditions
  - For presentation, show radiation and strut calculations

  - Radiation (20% case):

$$Q = A\varepsilon\sigma(T_{tank}^4 - T_{envr}^4)$$

    - Hand Calculation: Q = -5.05 W
    - ANSYS Reaction Probe: Q = -4.92 W

  - Strut Conductance (20% case):

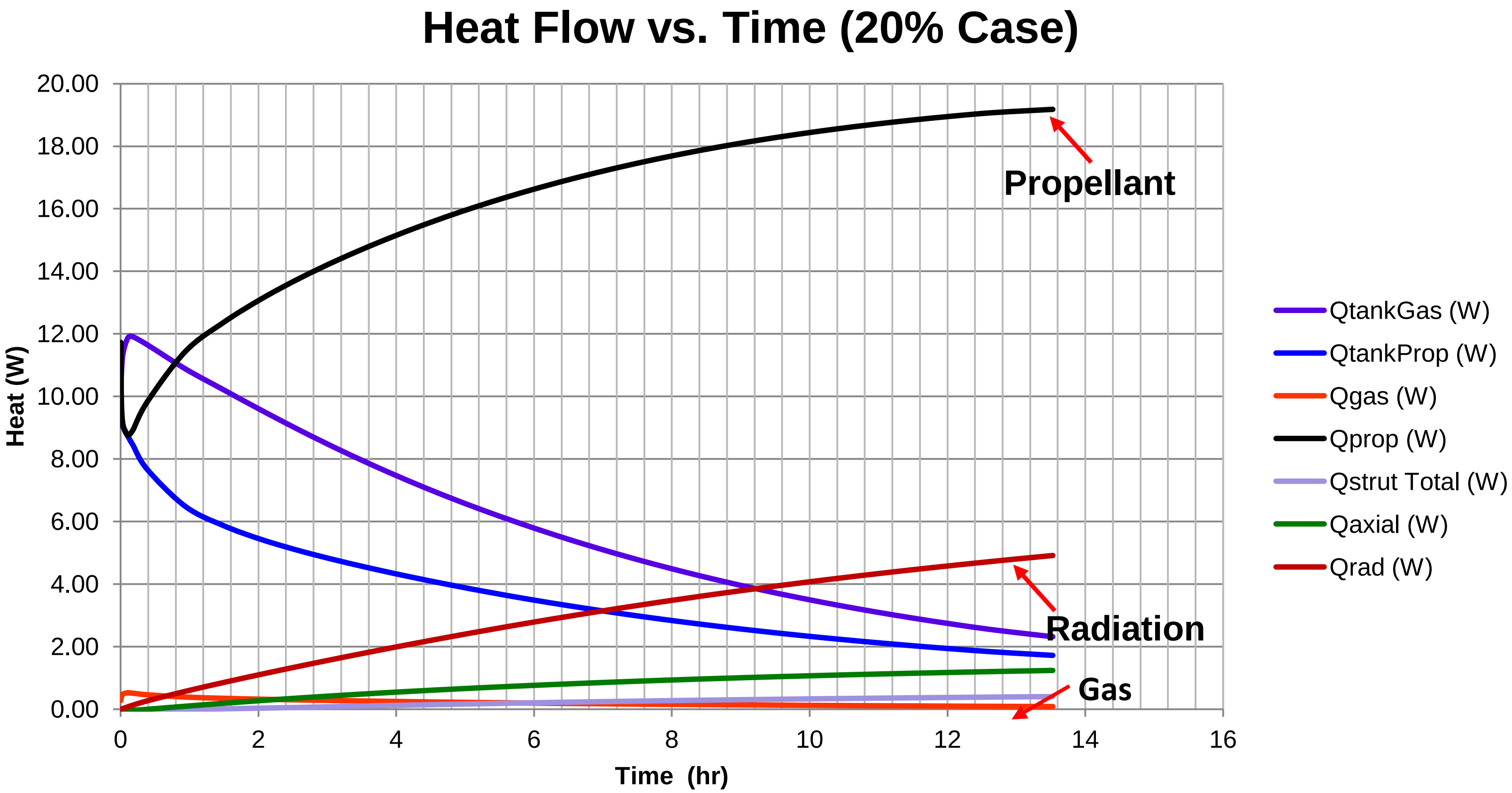
$$Q = \frac{kA}{L}(T_2 - T_1)$$

    - Hand Calculation (all struts): Q = -0.24 W
    - ANSYS Reaction Probe (all struts): Q = -0.25 W

  - Model and 2-node hand calculations show good agreement with each other

Model Validation (cont.)

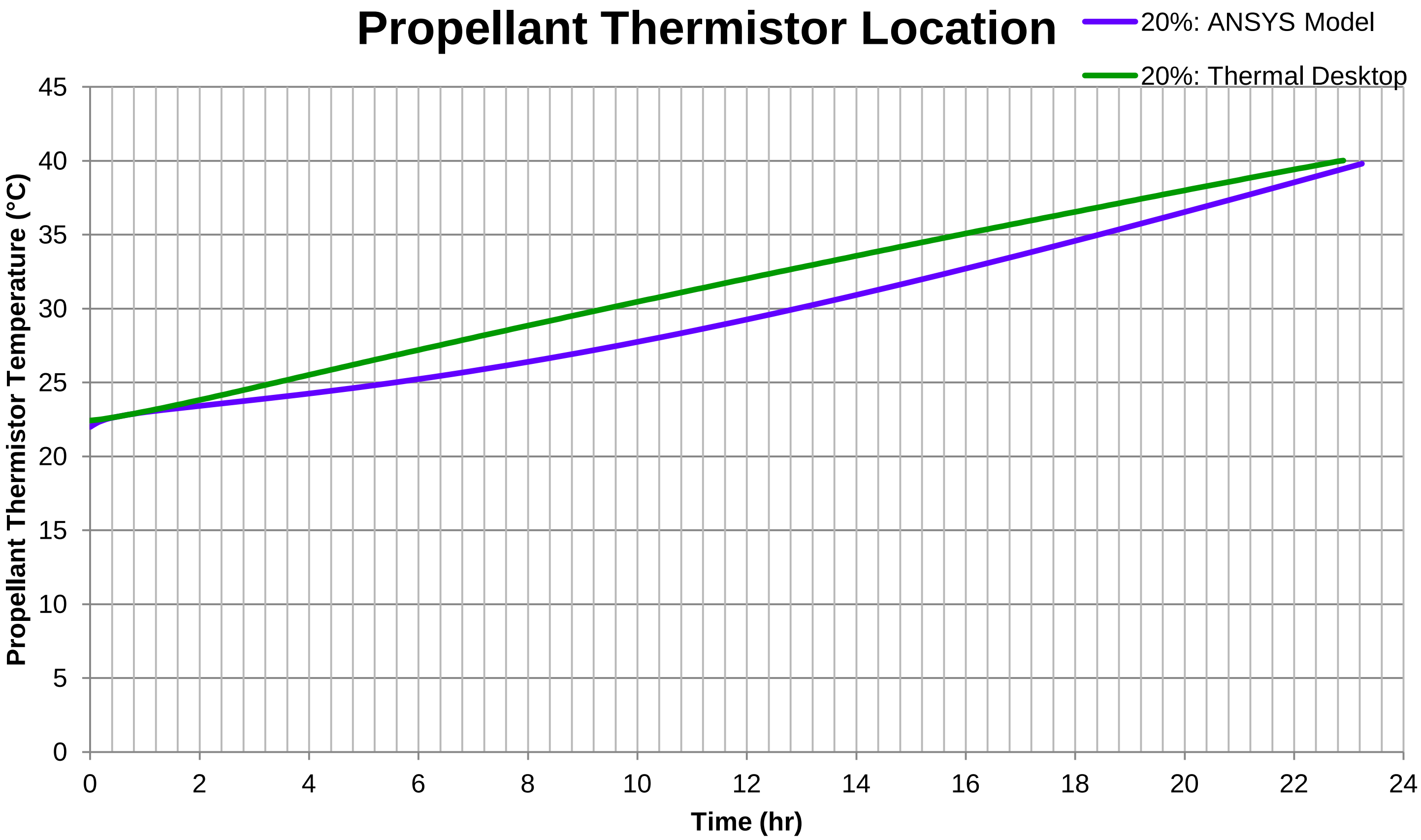
- **Spreadsheet calculations show**
  - Where heat in system is going at all times, and that the heat flow at any time step sums to heat input of heaters (conservation of energy)
  - That the energy flow from the heaters, primarily to the propellant and radiation, is consistent with what one expects from theory



Model Validation (cont.)

- **Model comparison with all heaters on:**
  - Maximum difference occurs toward middle of simulation

Max % Difference:	8.76


ANSYS and Thermal Desktop Comparison
Propellant Thermistor Location

ANSYS Transient Thermal Model

- **ANSYS model is both Transient and Non-linear**
  - Time-varying thermal behavior
  - Heat capacitance of materials
  - Temperature-varying material properties
  - Model is solved iteratively for each time-step; thermal solutions given at each time-step
- **Material Properties**
  - Obtained primarily from the Aerospace Structural Metals Handbook, 1998 Edition
    - Graphs were digitized and data extracted from charts
  - Hydrazine properties were found from “Hydrazine and Its Derivatives” 2nd Edition by Schmidt.
  - Helium Properties (conductivity, primarily) were found from the Journal of Engineering Physics and Thermo Physics, Vol. 32, No. 5.
  - Materials not found in the above sources were found using
    - Vendor-supplied material data (ex., heater information was found from Honeywell, the maker of Kapton polyimide film)
- **Materials Used in Model:**
  - 6AL-4V Titanium
  - 3AL-2.5 V Titanium
  - Helium
  - Hydrazine
  - 304 SS
  - Kapton Polyimide Film

ANSYS Transient Thermal Model (cont.)

- **Boundary Conditions: heaters always on**
  - Obtained from Thermal Branch MMS thermal model
  - Initial Temperature: 22°C

Tank Radiation

e*†	Tank Area (m^2)	Environ. Temp.(°C)
4.50E-03	1.92	22

Temperature

Component	B.C.
Strut 1	23°C
Strut 2	23°C
Strut 3	23°C
Strut 4	23°C
Axial Pin	23°C
Gas Tube	23°C
Fuel Tube	23°C

Internal Heat Generation

Heater	Model Volume (m^3)	Q (W/m^3)
-X Top	2.29E-05	9.30E+04
+X Top	2.29E-05	9.30E+04
-Z Top	2.29E-05	9.30E+04
+Y Top	5.26E-05	4.06E+04
+X Upper	1.53E-05	1.40E+05
-X Upper	1.53E-05	1.40E+05
+Z Upper	1.53E-05	1.40E+05
+X Middle	1.53E-05	1.40E+05
-X Middle	1.53E-05	1.40E+05
+Z Middle	1.53E-05	1.40E+05
-X Lower	2.29E-05	9.30E+04
+X Lower	2.29E-05	9.30E+04
-Z Lower	2.29E-05	9.30E+04
-Y Lower	5.26E-05	4.06E+04
Q_{htr} (W):	**2.13**	
Total Heater Power (W):	**29.87**	

†From 461-TCS-RPT-0039

ANSYS Transient Thermal Model (cont.)

- **Boundary Conditions: Gas side of tank set at TStat over temp set point**
  - Gas side of tank set to 43°C
  - Heaters on gas side “turned off”
  - Initial Temperature: 22°C

Tank Radiation

e*†	Tank Area (m^2)	Environ. Temp.(°C)
4.50E-03	1.923	22

Temperature

Component	B.C.
Strut 1	23°C
Strut 2	23°C
Strut 3	23°C
Strut 4	23°C
Axial Pin	23°C
Gas Tube	23°C
Fuel Tube	23°C
Lower Tank	43°C

Internal Heat Generation

Heater	Model Volume (m^3)	Q (W/m^3)
-X Top	2.29E-05	9.30E+04
+X Top	2.29E-05	9.30E+04
-Z Top	2.29E-05	9.30E+04
+Y Top	5.26E-05	4.06E+04
+X Upper	1.53E-05	1.40E+05
-X Upper	1.53E-05	1.40E+05
+Z Upper	1.53E-05	1.40E+05
+X Middle	1.53E-05	0
-X Middle	1.53E-05	0
+Z Middle	1.53E-05	0
-X Lower	2.29E-05	0
+X Lower	2.29E-05	0
-Z Lower	2.29E-05	0
-Y Lower	5.26E-05	0
Q_{htr} (W):	**2.13**	
Total Heater Power (W):	**14.91**	

†From 461-TCS-RPT-0039

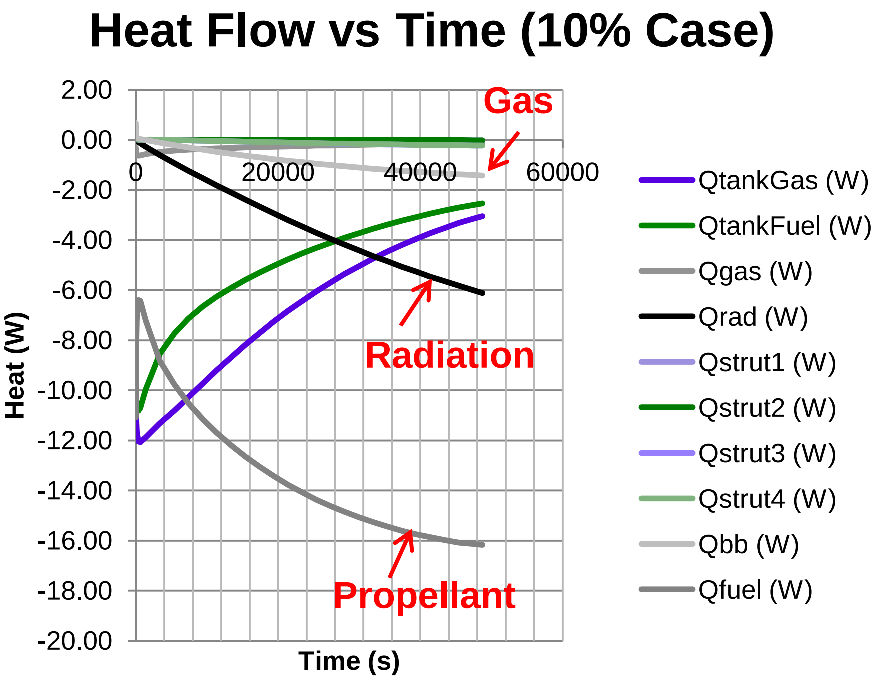
Internal Heat Generation Explanation

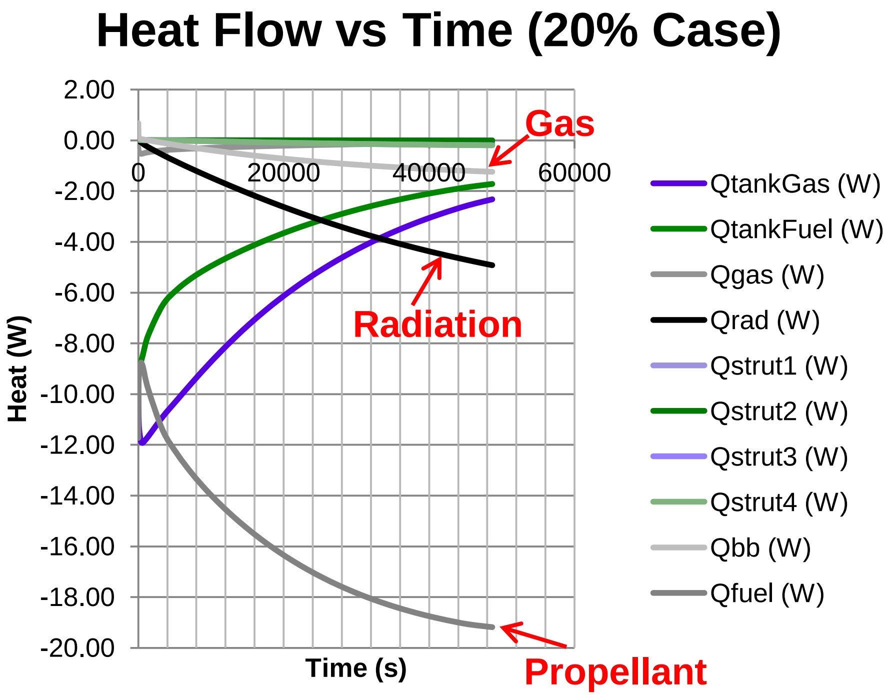
- **ANSYS defines "Internal Heat Generation" as energy/time/volume.**
  - Applies a uniform generation rate internal to a body*
- **Chosen as method to model heaters since this best physically describes what a heater does.**
- **Internal heat generation loads were calculated by taking the volume of the ProE model of a given heater, and dividing the heater wattage by the heater volume.**
- **Heaters could have been modeled using a heat flux (energy/time/area).**
  - Case was tried in ANSYS and results were the same as when modeled with IHG

*From ANSYS Release 11.0 Documentation for ANSYS Workbench

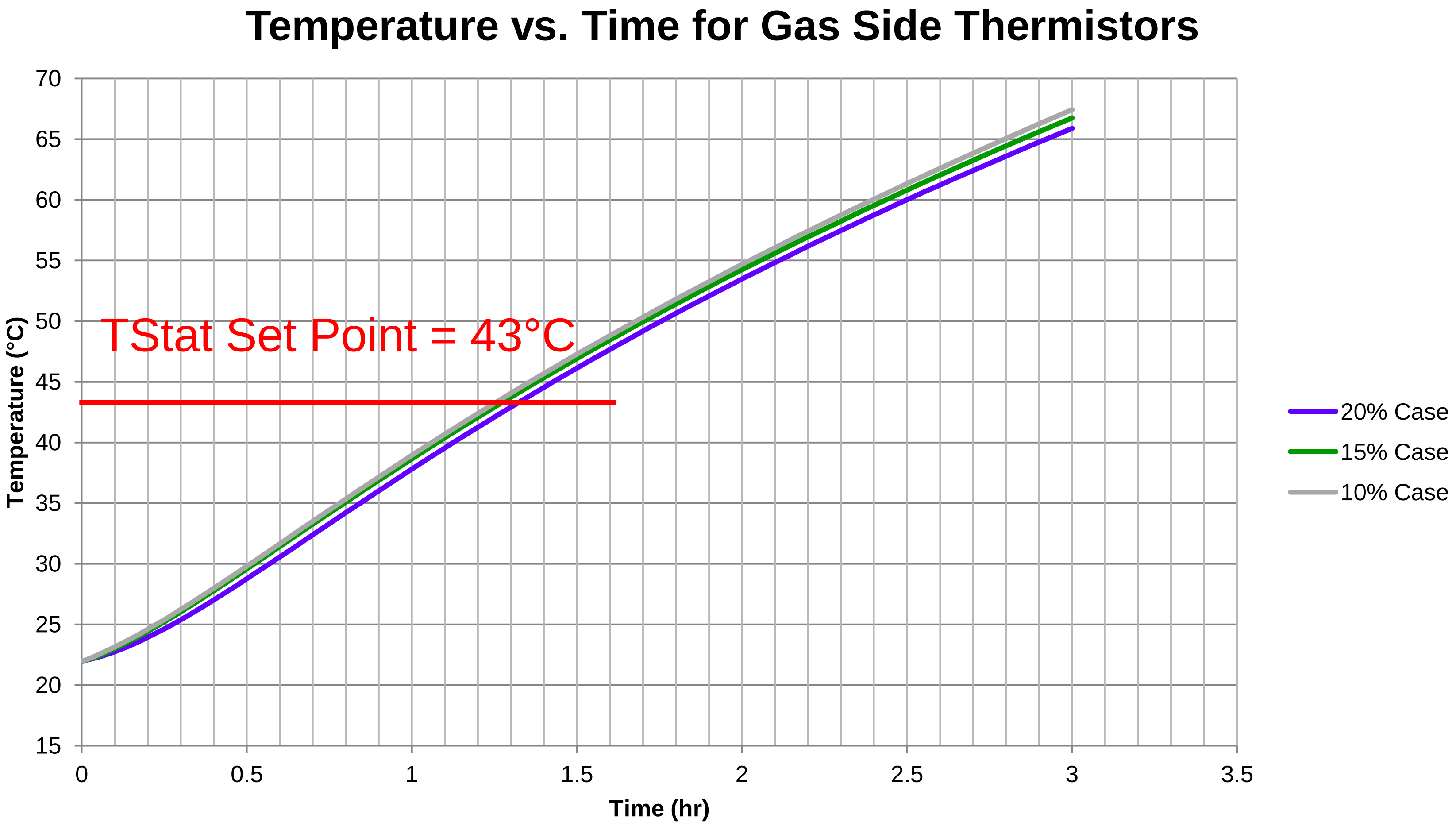
Heat Flow (10 & 20% Cases)

- **Charts showing heat flow vs. time for 10 & 20%case.**
  - 15% case fits between these two extremes





Analysis Results: 3 hr Simulation



- Gas side thermistors do not provide enough resolution to discriminate between propellant masses
  - Need at least 1°C difference to account for A/D conversion errors and thermistor calibration error.
- TStat set point of 43°C reached in approximately 1.3 hours

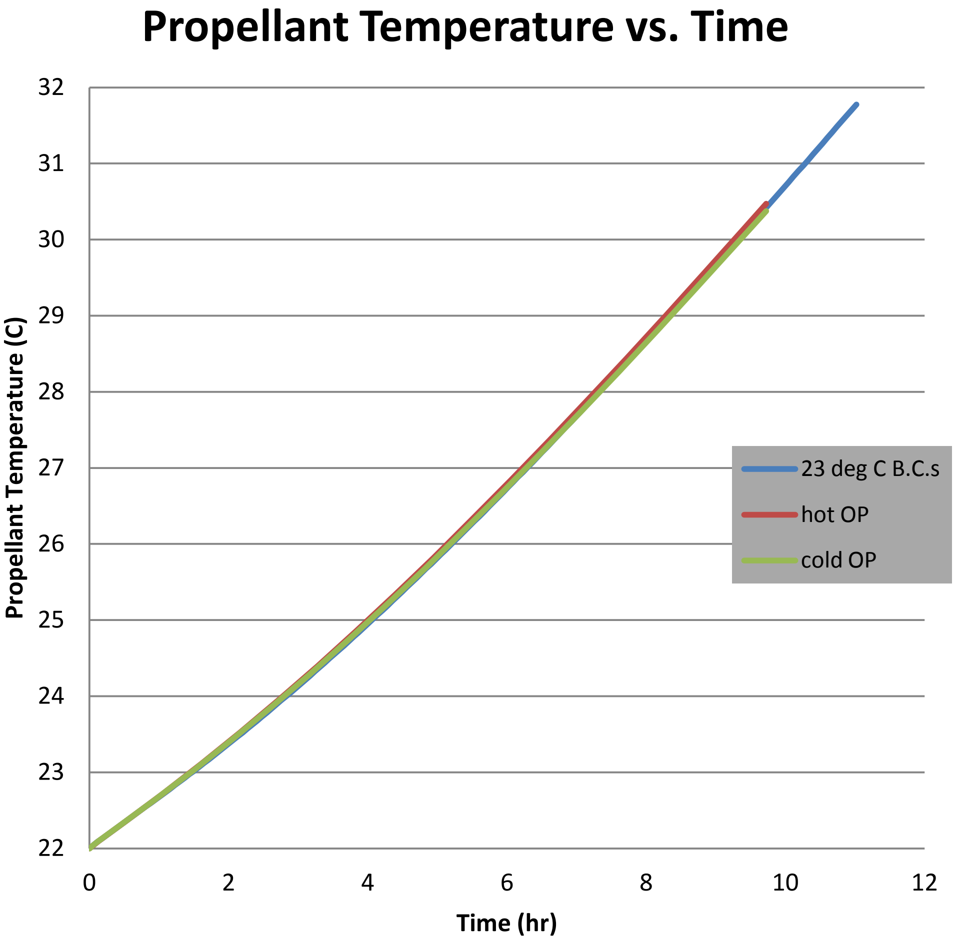
Initial Model Conclusions

- **Gas side thermistor data cannot be used for propellant gauging**
- **Propellant mass shown to be adequately determined from propellant side thermistors**
  - Difference of at least 1°C between load cases seen at ~9 hours into simulation
- **Temperature rise as measured by propellant thermistors is linear over long time periods**
  - True for propellant but not gas
- **Model refinements bringing analysis closer to actual setup.**
  - Will need to do future testing/validation to refine model

Model Refinements

Revised Boundary Conditions

- **Tank Interfaces (Struts, axial pin, inlet/outlet tubes)**
  - Modeled interface temperatures to reflect extremes expected during different mission phases
    - Hot Operations (max 29°C)
    - Cold Operations (min -5°C)
  - Comparison made with initial assumption of 23°C
  - Result: boundary conditions play a negligible effect on the propellant temperature over time
- **Determined that initial assumption of 23°C was sufficient.**
  - Shows that on orbit, knowledge of exact temperature of tank interface not needed.



Revised Boundary Conditions (cont.)

- **Heaters**
  - Initially assumed a total heat input of 29.87W (at bus voltage of 34V), evenly distributed over all 14 tank heaters
  - Using updated bus voltage data, recalculated heater power using bus voltage of 32V and nominal flight heater resistances
  - Implemented code in ANSYS model to thermostatically control heaters
    - Thermostats now turn off heaters if temperature at thermostat exceeds 43°C.
    - Turns them back on once temperature drops below 43°C

Old Power Distribution

Heater	Power [W]	Q [W/m^3]
GAS-A	2.13	40600
GAS-B1	2.13	93000
GAS-B2	2.13	93000
Gas-B3	2.13	93000
GAS-C1	2.13	140000
GAS-C2	2.13	140000
GAS-C3	2.13	140000
LIQ-A	2.13	40600
LIQ-B1	2.13	93000
LIQ-B2	2.13	93000
LIQ-B3	2.13	93000
LIQ-C1	2.13	140000
LIQ-C2	2.13	140000
LIQ-C3	2.13	140000
Total:	**29.87**	

New Power Distribution

Heater	Power [W]	Q [W/m^3]
GAS-A	4.76	90554
GAS-B1	1.55	67450
GAS-B2	1.55	67450
Gas-B3	1.55	67450
GAS-C1	1.55	101352
GAS-C2	1.55	101352
GAS-C3	1.55	101352
LIQ-A	4.76	90554
LIQ-B1	1.55	67450
LIQ-B2	1.55	67450
LIQ-B3	1.55	67450
LIQ-C1	1.55	101352
LIQ-C2	1.55	101352
LIQ-C3	1.55	101352
Total:	**28.12**	

Note about results in ANSYS

- **When an area or part of a model is selected, ANSYS will automatically average the nodal solutions of the selected area.**
- **Depending on the nodal results, one selected area might have different results than the same selection location, but with a larger (or smaller) selected area.**
- **Nodal solutions for any body or area in a model can all be analyzed and evaluated, but this process becomes tedious with increasing model complexity (due to increased number of elements/nodes).**
- **With a sufficient mesh, differences in average nodal results for different selected areas will be minimized.**

Volume-Weighted Temperature Average Algorithm

- **This algorithm works as follows:**
  - 1). A body in the given model is selected by the user
  - 2). The element volume and temperature of the selected body is retrieved
    - The element temperature, when retrieved from the ANSYS solver, is the average temperature of all the nodes on the given element.
  - 3). The element volume and temperature are multiplied together.
  - 4). Step 3) is repeated for all elements in the selected body
  - 5). The sum in Step 4) is then divided by the total volume of the selected body
- **The result of the above is a volume-weighted average temperature for a selected body in the model.**

Acknowledgements

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  - Dr. Eric Cardiff, Code 597
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  - Amanda Steckel, Cornell University
  - Dave Steinfeld, Code 545
  - Kurt Wolko, Code 597
  - Rommel Zara, Code 545