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Poor Uncertainty Estimation: MER Prop. Distribution Module

Propulsion Distribution
Module consists of
valves & electronics

Design is totally passive;
sensitive to solar array
parasitic heat paths from
plumbing not modeled



Predicted worst-case hot temp. = 28 °C

Temperature margin = 27 °C

Max allowable temp. limit = 55 °C

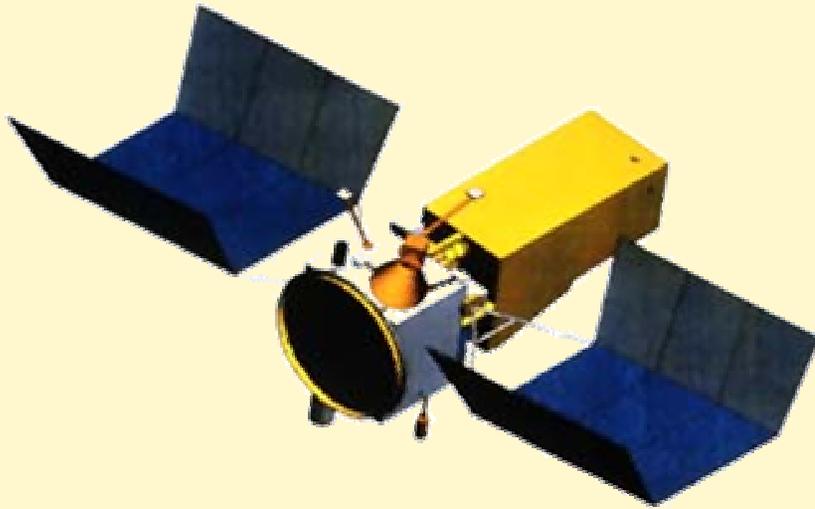
Cruise 1 test (worst-case hot) = 57 °C



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Blown Margin Example: Clark



Predicted time to complete = 1.8 years
Schedule margin = 0.2 years
Total schedule allocated = 2.0 years
*Actual time to complete = 3.6 years**

Predicted cost to complete = US\$44M
Cost margin = US\$5M
Total cost allocated = US\$49M
*Actual cost to complete = US\$55M**

**cancelled at this point*



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Margin Determination in the Design and Development of a Thermal Control System

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El Segundo, CA



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Presentation Overview

- Purpose & motivation
- Uncertainty classification for complex multidisciplinary systems
- Uncertainty mitigation and propagation
 - current approach
 - new approach
- Application to the Mars Exploration Rover (MER) thermal control system
- Conclusions & future works



Purpose & Motivation

- Spacecraft are complex multidisciplinary systems
 - take too long to design and build (many years)
 - too expensive (unit costs are too high)
 - upgrading and extending capabilities of systems in orbit is prohibitively expensive and difficult
- Decisions made early in design and development are often influenced by uncertainty
 - leads to systems that are delivered late, over budget, etc.
 - leads to systems that are over designed and not competitive
- *Goal:* reduce effort to design and build complex systems



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Complex Multidisciplinary Systems

- Multidisciplinary systems are intrinsically difficult to model and understand because no single person has the detailed knowledge in all discipline areas that is required
- Systems often become complex and multidisciplinary to reduce uncertainty and allow for reliable predictability
 - missiles have added sensors, actuators, and computers to counter uncertainties in atmospheric conditions, release conditions, and target movement
 - spacecraft operate in constellations to counter uncertainties in where a signal (phone call, missile launch, etc.) may be generated



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Examples of Complex Multidisciplinary Systems



Power Plants



Missiles



Submarines



Spacecraft



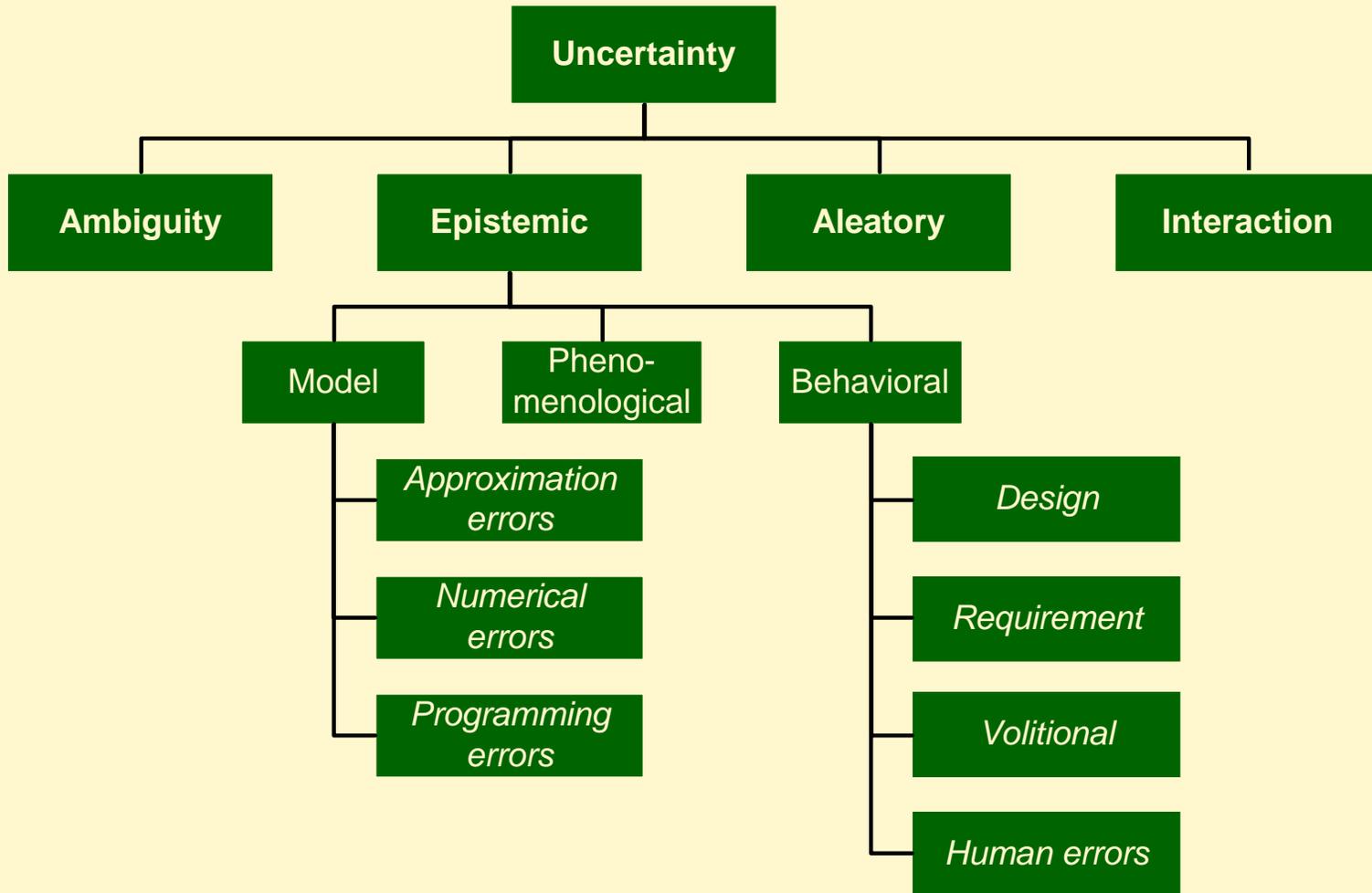
Aircraft



Automobiles



Uncertainty Classification for Complex Systems





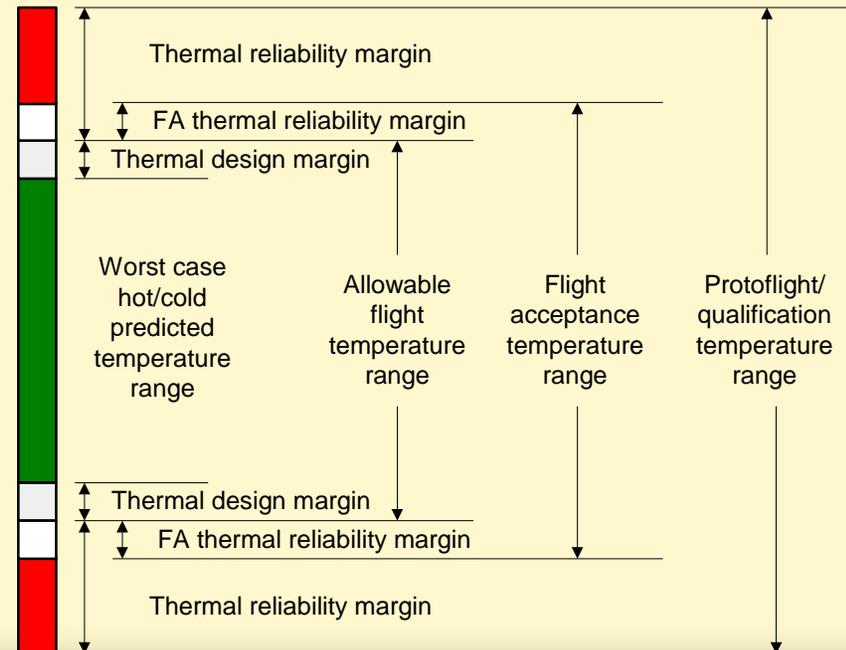
Uncertainty Mitigation: Present Approach

- Margins in space systems are variations in design parameters measured relative to worst-case expected values
 - implemented to allow work to be done in parallel
 - applied ex-post facto and sometimes not at all

$$\% \text{ Margin} \Big|_{\text{current}} = \frac{WCE - CBE}{CBE} \cdot 100$$

where *WCE* = worst case estimate;
CBE = current best estimate

- Thermal margins
 - thermal uncertainty
 - protoflight/qualification



Welch, "Thermal Testing," p. 724



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Uncertainty Mitigation: Issues with Present Approach

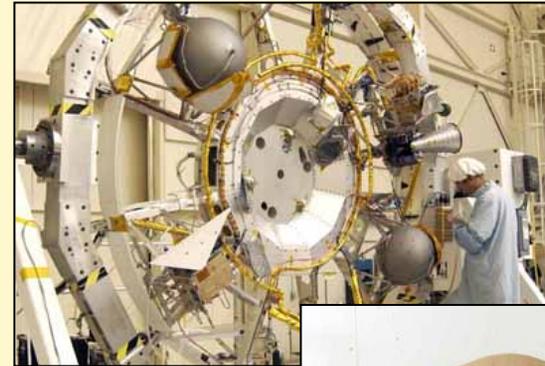
- Margins maintained vary organization-to-organization, individual-to-individual
- Margins encompass all uncertainties (ambiguity, epistemic, aleatory, etc.) and risk tolerances of decision maker(s)
 - allocation is often capricious and/or “hope oriented”
 - based on historical data and crudely quantitative; no formal method to address uncertainty types
- For example:
 - thermal uncertainty margin appears to primarily handle model (epistemic) uncertainty yet accounts for aleatory uncertainties as well
 - qualification or protoqualification margin appears to primarily handle design and requirement uncertainty
 - qualification margin appears to tackle phenomenological and interaction uncertainties.
- Margins fail routinely to predict uncertainties



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Example: Mars Exploration Rover (MER)

- Launch: June 10, 2003 (MER-A)
July 7, 2003 (MER-B)
- Landing: January 2004
- Mass: 1072 kg at launch, fueled
- Cruise stage, lander, & rover
- Rover science instruments
 - panoramic camera
 - two engineering cameras
 - microscopic imager
 - miniature thermal emission spectrometer
 - Mössbauer spectrometer
 - alpha particle x-ray spectrometer
 - rock abrasion tool
 - magnet array





MER: Flight System Margins

Commodity	Time Phased Flight System Margins			
	PDR (10/00)	CDR (8/01)	ATLO Start (2/02)	Ship to Cape (1/03)
Mass	15/5%	10/2.5%	5/1%	2/0%
Energy/Power	10/10/10%	10/10/5%	10/0/5%	10/0/0%
Power switches	30%	20%	10%	10%
Pyro switches	30%	20%	10%	10%
Central Processing Unit (CPU) utilization	50%	50%	50%	40%
Memory				
Dynamic Random Access Memory (DRAM)	50%	40%	25%	25%
Flash	30%	25%	20%	10%
Electrically Erasable Read Only Memory	50%	50%	50%	40%
Propellant (tank margin)	30%	20%	10%	10%

*PDR = Preliminary Design Review; CDR = Critical Design Review; ATLO = Assembly Test & Launch Operations
X/Y% = margin/additional margin; X/Y/Z% = operational/flight system/project manager margins*

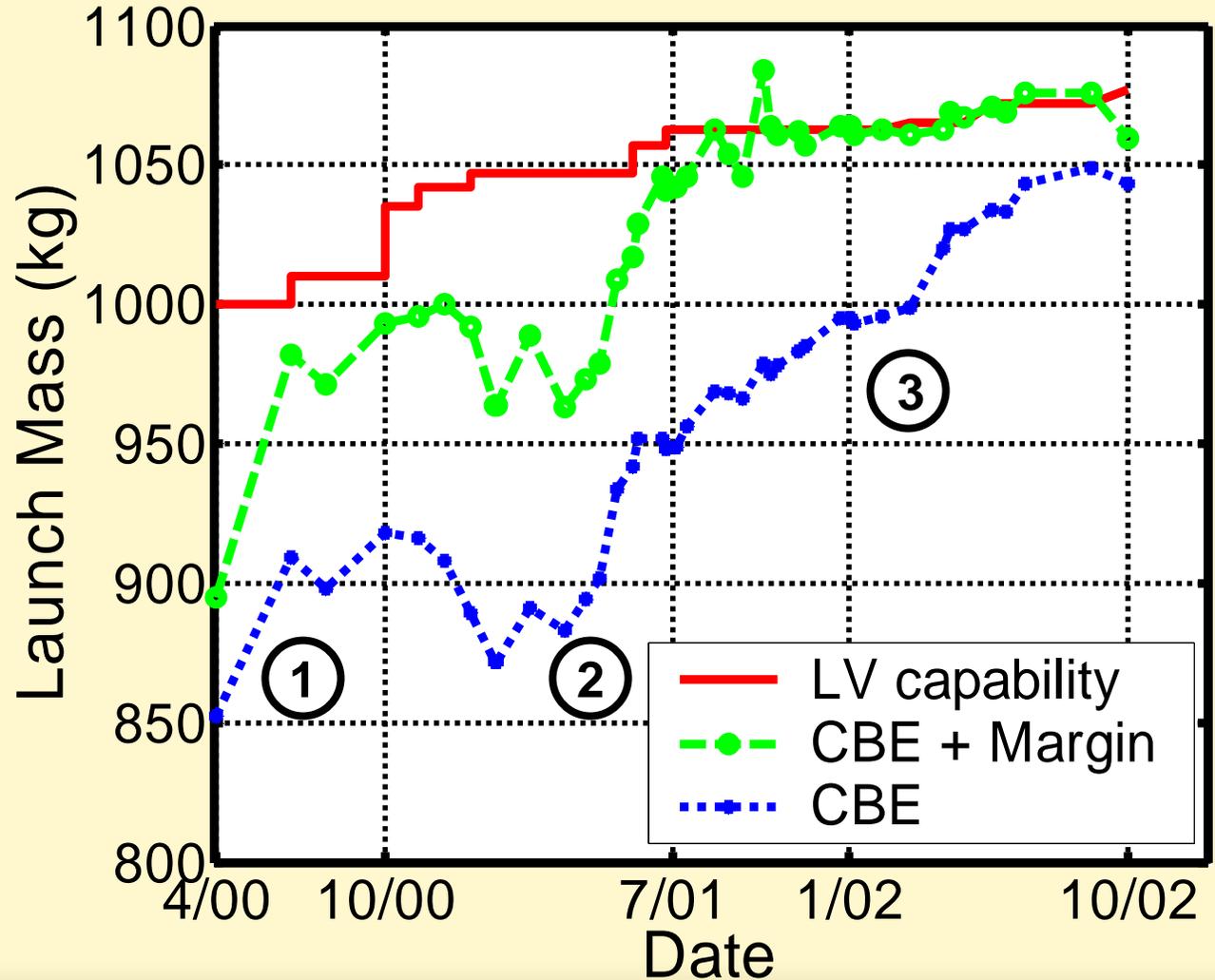


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MER:

Launch Mass History vs. Limits

- ① *conceptual/ preliminary design*
- ② *detailed design & fabrication*
- ③ *assembly & test*



LV = launch vehicle



Uncertainty Mitigation: New Approach



- Develop a rigorous foundation for the determination of margins to mitigate uncertainty
 - that is repeatable and tenable
 - that allows trading of these margins against each other based on the risk tolerance of the decision maker(s)
 - based on well established mathematical techniques
 - applicable at a multidisciplinary level
 - that is practical to implement in industry and not a purely academic endeavor

- Proposed new margin definition: $Margin|_{proposed} = \frac{P_x - R_{det}}{R_{det}}$

where $P_x = x^{th}$ percentile value (e.g. 95%, 99%, or 99.9%) and R_{det} = deterministic result value

- Make uncertainty an integral part of the decision making process during design and not an afterthought



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Summary of Current Approach

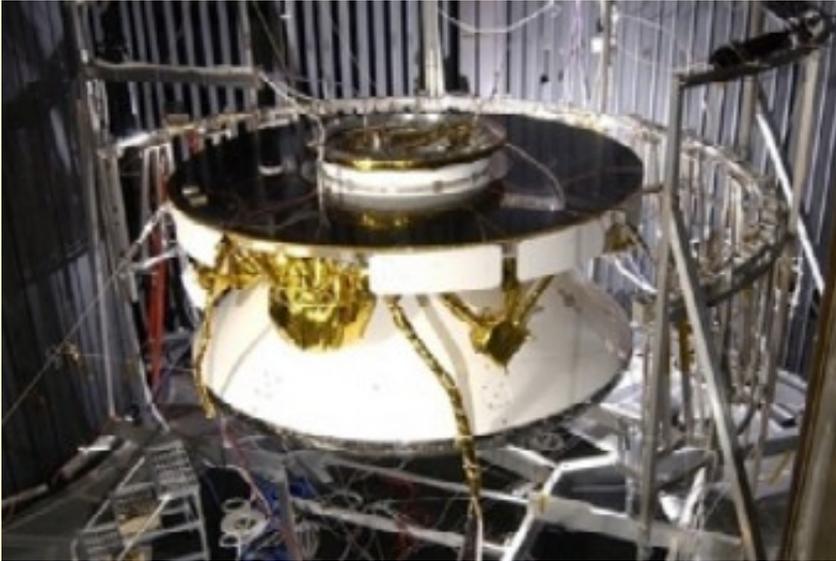
- Uses probabilistic methods to determine margins based on the risk tolerance of the decision maker and are measured relative to median expected system performance
 1. Determination of tradable parameters
 2. Model formulation
 3. Classification of variables (aleatory, design, requirements, model)
 4. Probabilistic modeling of variables
 5. Simulation
 6. Analysis & iterate
- Continuing to develop method for the design of increasingly complex multidisciplinary systems and uncertainty types



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Application of Method: Thermal Control System



Used the design and development of the Mars Exploration Rover (MER) cruise mission as a case study to support the evolution and verification of this research

- Replica of 1996-1997 Mars Pathfinder system? Not quite
- System comprises
 - mechanically-pumped fluid loop known as the heat rejection system (HRS) ←
 - shunt radiator
 - multilayer insulation (MLI)
 - miscellaneous components
- Tradable parameters (margins held for the MER thermal control system during conceptual design)
 - **component temperatures** ←
 - total system mass
 - maximum power required
 - schedule
 - cost



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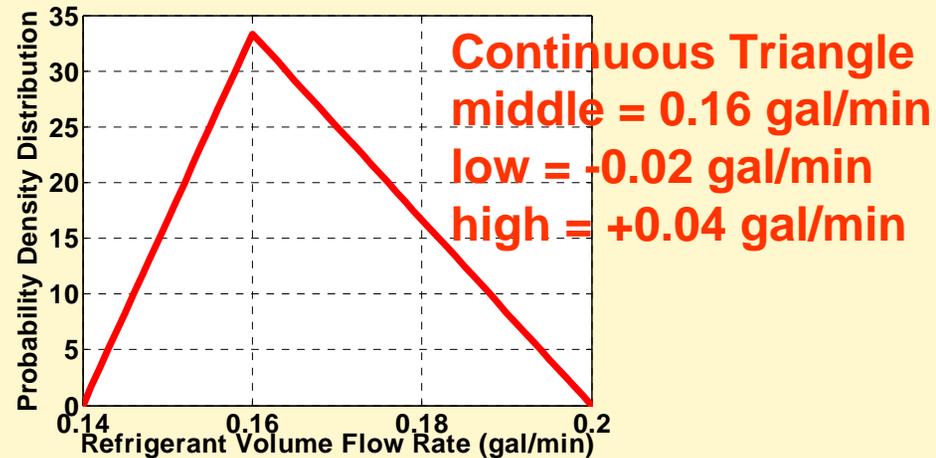
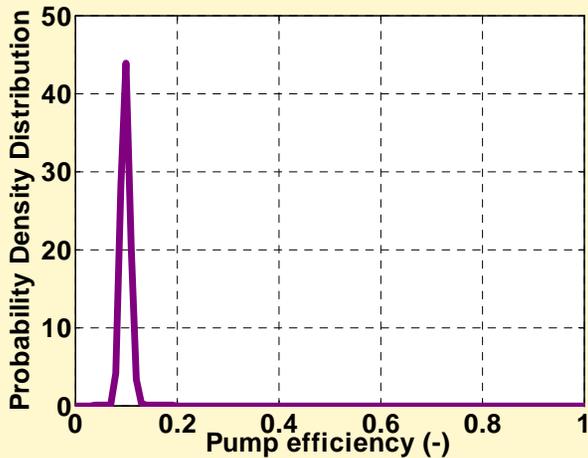
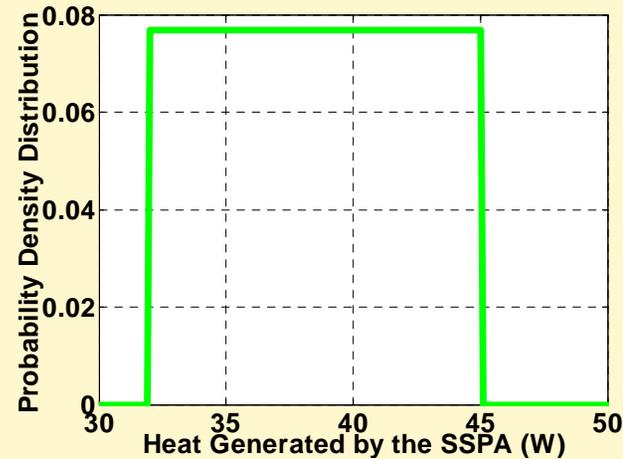
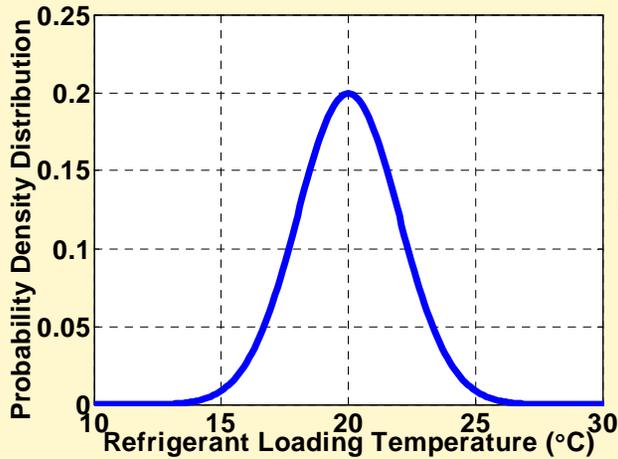
Temperature Model: SINDA/FLUINT via SinapsPlus®

- SINDA/FLUINT* (version 4.6)
 - network style thermal simulator
 - NASA-standard analyzer for thermal control systems
 - reliability engineering module used
 - wraps around existing code
 - minor pre- and post-processing additions
- A single analysis takes ~2 minutes on a 1 GHz Pentium III laptop
- MER SINDA model uses over 900 nodes assumed
- The four most critical nodes (components) explicitly tracked
 - rover electronics module (REM)
 - **rover battery** ←
 - small deep space transponder (SDST)
 - **solid-state power amplifier (SSPA)** ←
- Only worst-case hot analysis completed
- +/- 5 °C (2 σ) model uncertainty

*SINDA/FLUINT and SinapsPlus are distributed by Cullimore & Ring Technologies, Inc. (Littleton, CO)

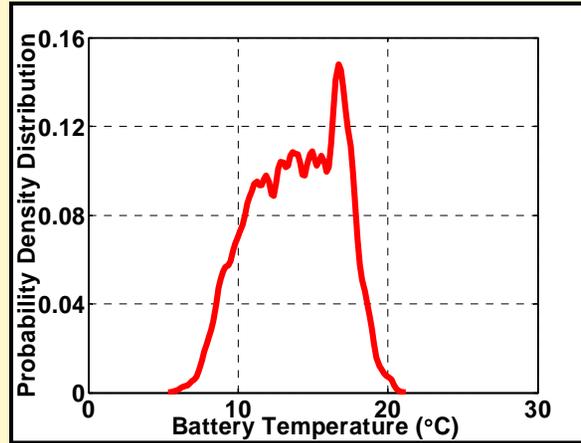
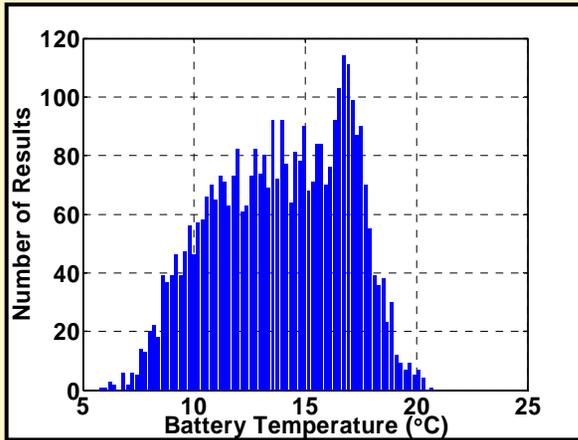


Probability Density Distribution Inputs





Summary of Results for the Battery (3,782 samples)



Deterministic result:

16.7 °C

Allocated temperature (@ PDR):

10.0 °C

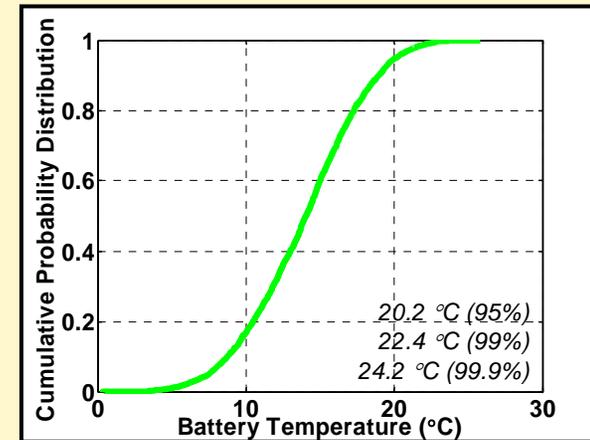
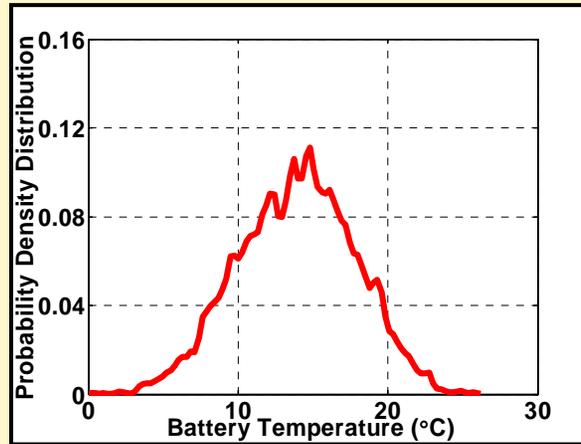
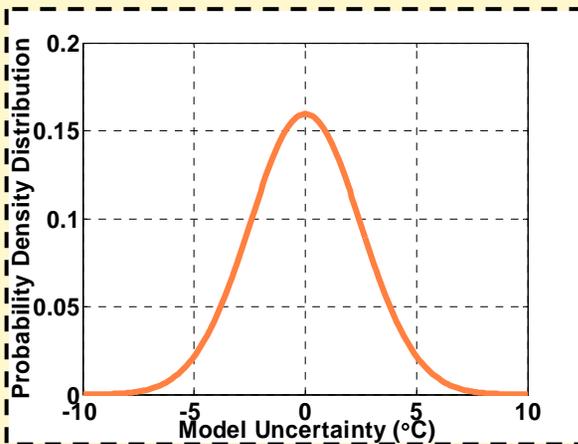
MARGIN (ALLOCATION)

CONFIDENCE:

Low: 3.5 °C (20.2 °C)

Medium: 5.7 °C (22.4 °C)

High: 7.5 °C (24.2 °C)

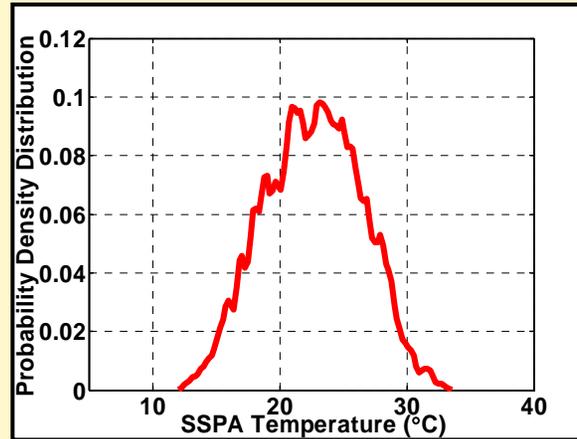
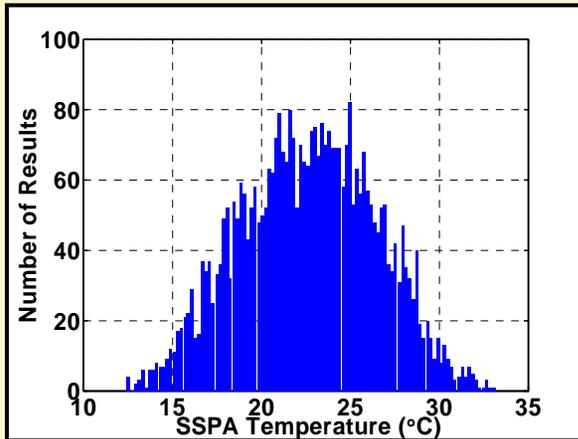




Results for the Solid State Power Amplifier (3,782 samples)



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Deterministic result:

27.8 °C

Allocated temperature (@ PDR):

50.0 °C

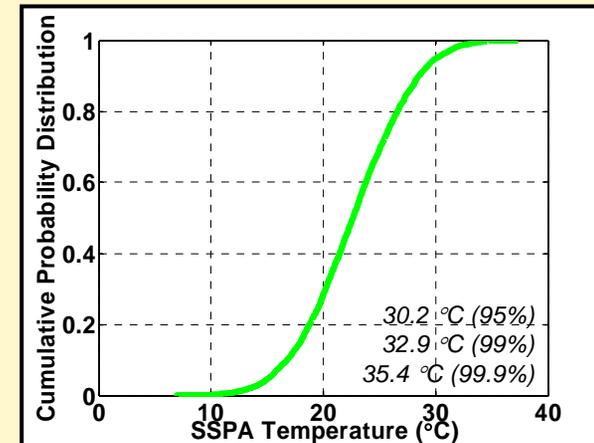
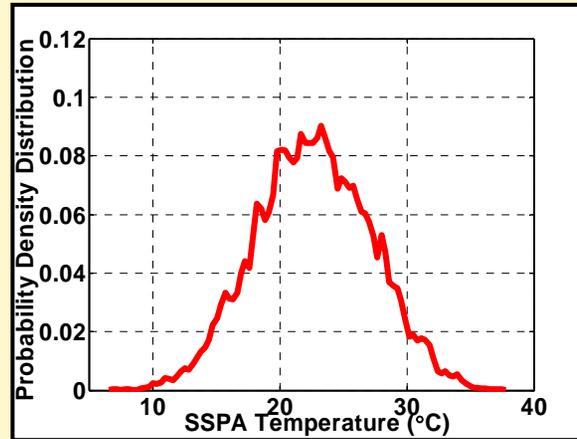
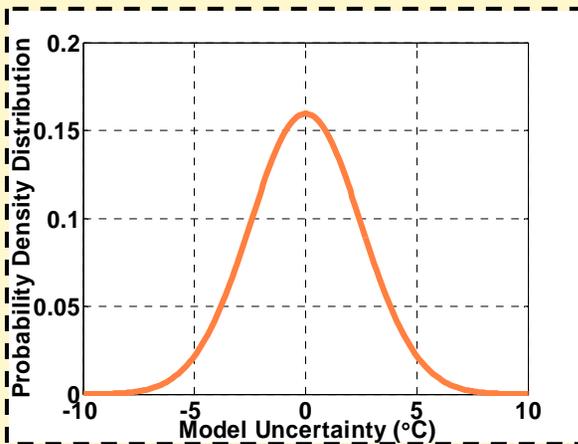
MARGIN (ALLOCATION)

CONFIDENCE:

Low: 2.4 °C (30.2 °C)

Medium: 5.1 °C (32.9 °C)

High: 7.6 °C (35.4 °C)





Comparison of Current and Proposed Method to MER Actuals



Tradable Parameter	Actual Value	Current Method			Proposed Method (99% conf)		
		Predicted	Margin	Allocation	Predicted	Margin	Allocation
Max. REM Temperature	19.6 °C	n/a	n/a	50 °C	17.0 °C	5.5 °C	22.5 °C
10 °C							
Max. SDST Temperature	19.6 °C	n/a	n/a	50 °C	16.7 °C	5.5 °C	22.2 °C
50 °C							
Thermal Mass	29.1 kg	34.3 kg	1.9 kg	36.2 kg	29.3 kg	2.1 kg	31.4 kg
Max. Power Required	93.1 W	94.5 W	9.5 W	104.0 W	97.5 W	31.3 W	128.8 W
Schedule	749 days	738 days	32 days	770 days	710 days	76 days	786 days
Cost	\$12.8M	\$9.9M	\$2.6M	\$12.5M	\$11.2M	\$1.6M	\$12.8M

Bold green values = method succeeded

Bold red (pink) values = method failed by under (significantly over) estimating



Conclusions

- A rigorous foundation for the determination of margins and contingency levels to account for uncertainty in the design of complex systems is being developed
- Method redefines the concept of design margin
 - margins are a function of risk tolerance and are measured relative to median expected system performance, not variations in design parameters measured relative to worst-case expected values
- Method applied to the MER thermal control system
 - important difference in calculated margins from margins that are typically assumed at the conceptual design stage
- Method should have a profound impact on how these systems are designed and built



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Future Works

- Multidisciplinary analysis:
 - apply method to two other disciplines (attitude control and mission design)
 - combine thermal, attitude control, mission design, with propulsion to investigate multidisciplinary uncertainty interactions
- Sampling methods
 - reduce number of samples required to determine margin levels for expensive analyses
- Incorporating other uncertainties and their associated mathematical techniques
- *A priori* understanding of which uncertainties are most important and which can be neglected

Thank you!