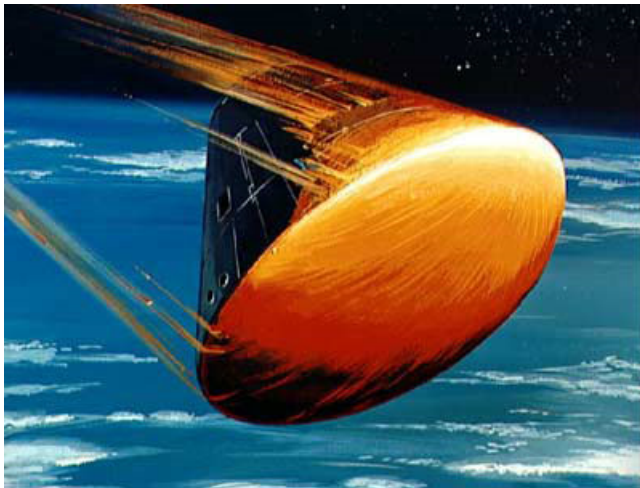


Ablative Thermal Protection System (TPS) Margin Study



An artist's rendering of the Apollo command module's re-entry into the Earth's atmosphere. Image courtesy NASA.
<http://science.howstuffworks.com/apollo-spacecraft7.htm>

Steven Rickman (NASA JSC)

Lawrence Green (NASA LaRC)*

Brian Remark (NASA JSC)

Stan Bouslog (NASA JSC)

Jeremy Vander Kam (NASA ARC)

Mohammad Khalessi (PredictionProbe, Inc.)

*Vehicle Analysis Branch (E401)

NASA Langley Research Center (LaRC)

Hampton, VA 23681

lawrence.l.green@nasa.gov

Talk Outline

- Introduction
- Design of Experiments
- Reliability Assessment
- Conclusions



Introduction

- Mission trajectory test flight(s)
 - Extremely limited and expensive
 - Continuously varying 3-D environmental conditions (from benign to ablative)
 - Mixture of laminar, transitional and turbulent flows
 - Three trajectories initially considered: 1) very high heat flux, **2) intermediate heat flux, and 3) low heat flux and high heat load**
- Arc Jet experimental testing (NASA Ames and NASA Johnson)
 - Small sample size (30) testing of sample materials; facility limitations
 - Axisymmetric approximation of discrete ablative conditions
 - Extended durations of laminar flow
 - Large reproducibility uncertainty
- Mission trajectory computational simulations (STAB code version 2.18)
 - Essentially infinite sample sizes
 - 1-D approximation of discrete or varying ablative behaviors
 - Usually modeled as fully turbulent flows (conservative assumption)

Introduction (2)

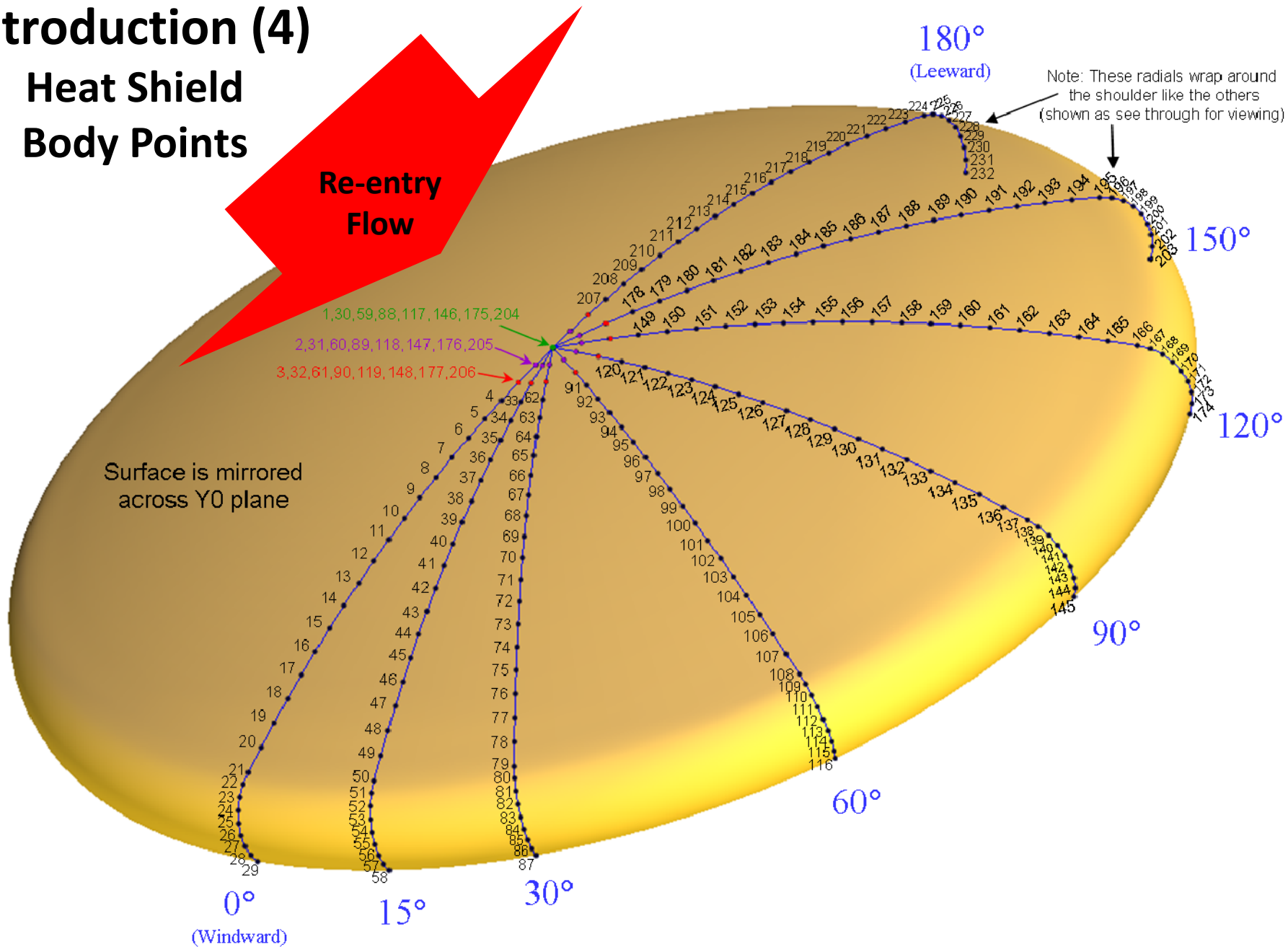
- Work commenced in early April 2011
- **Objectives:**
 1. **Provide input to a planned arc jet testing campaign**
 2. **Assess the reliability of a current and proposed TPS designs**
 3. **Provide sensitivity input to the TPS margin and design process**
- Capabilities employed:
 - General statistical analysis (Excel)
 - Design of Experiments (DOE) and Uncertainty Quantification (UQ)
 - Analysis of Variance (ANOVA) statistical technique
 - **Design-Expert (DX8) software from Stat-Ease, Inc., version 8.0.5**
 - Uncertainty Propagation via probabilistic methods
 - Monte Carlo Simulation (MCS) and Reliability Methods (FORM / SORM)
 - **UNIPASS software from PredictionProbe, Inc., version 5.96**
 - **SPISE software from PredictionProbe, Inc., version 1.0.797**
- Limitations
 - Key reliability metric not measured
 - Few comparisons between test and computation

Introduction (3)

- Dependent variables (responses) of interest:
 - Bondline temperature response (Reliability Analysis)
 - Thermo-couple (TC) response at various depths within the TPS
 - Recession amount
 - Recession rate
- Independent variables (factors) / uncertainty sources:
 - Material properties (minimum of 11 variables)
 - Environmental variables (minimum of 6 variables)
 - Structural design variables (minimum of 4 variables)
- General considerations for the task:
 - Response average values
 - Response values at a given level of confidence (e.g., 90% confidence)
 - Response sensitivities
 - Modeling / reproducibility uncertainties
 - The effect of various factors of safety and margin policies

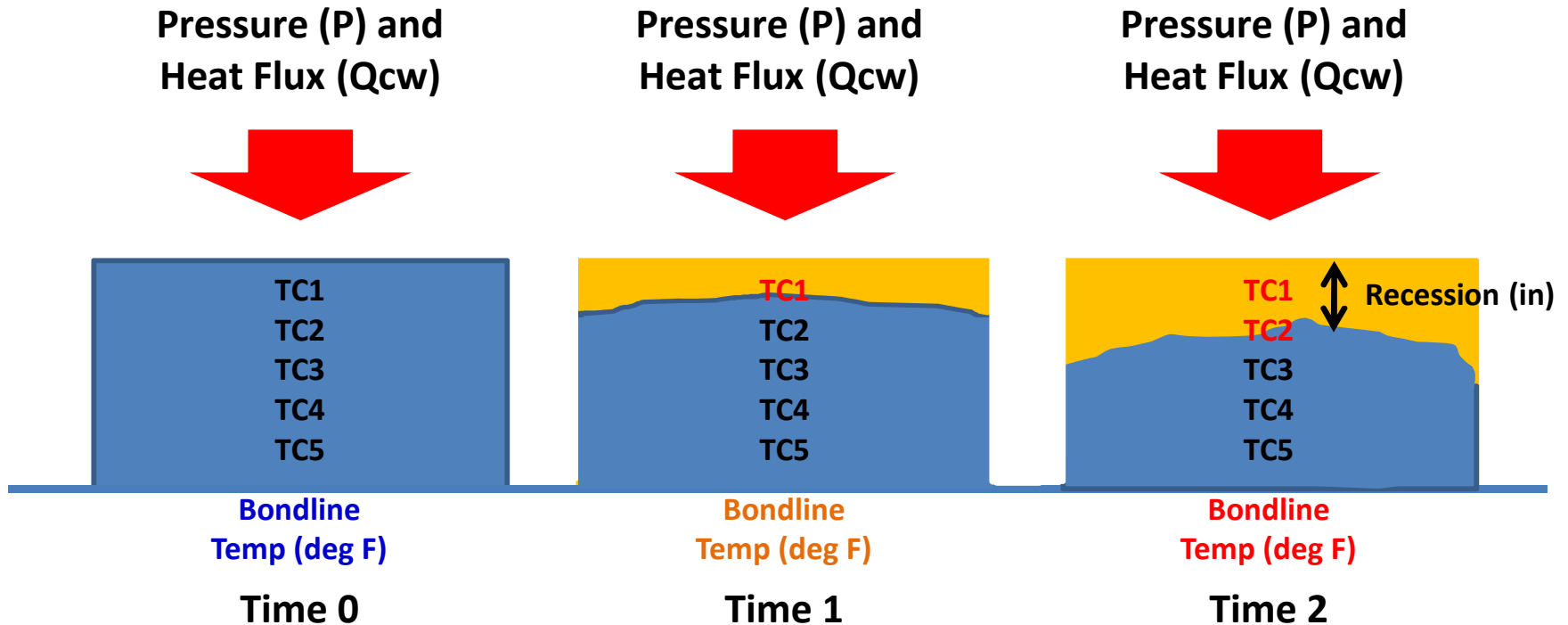
Introduction (4)

Heat Shield Body Points



Introduction (5)

Arc Jet Testing Illustration



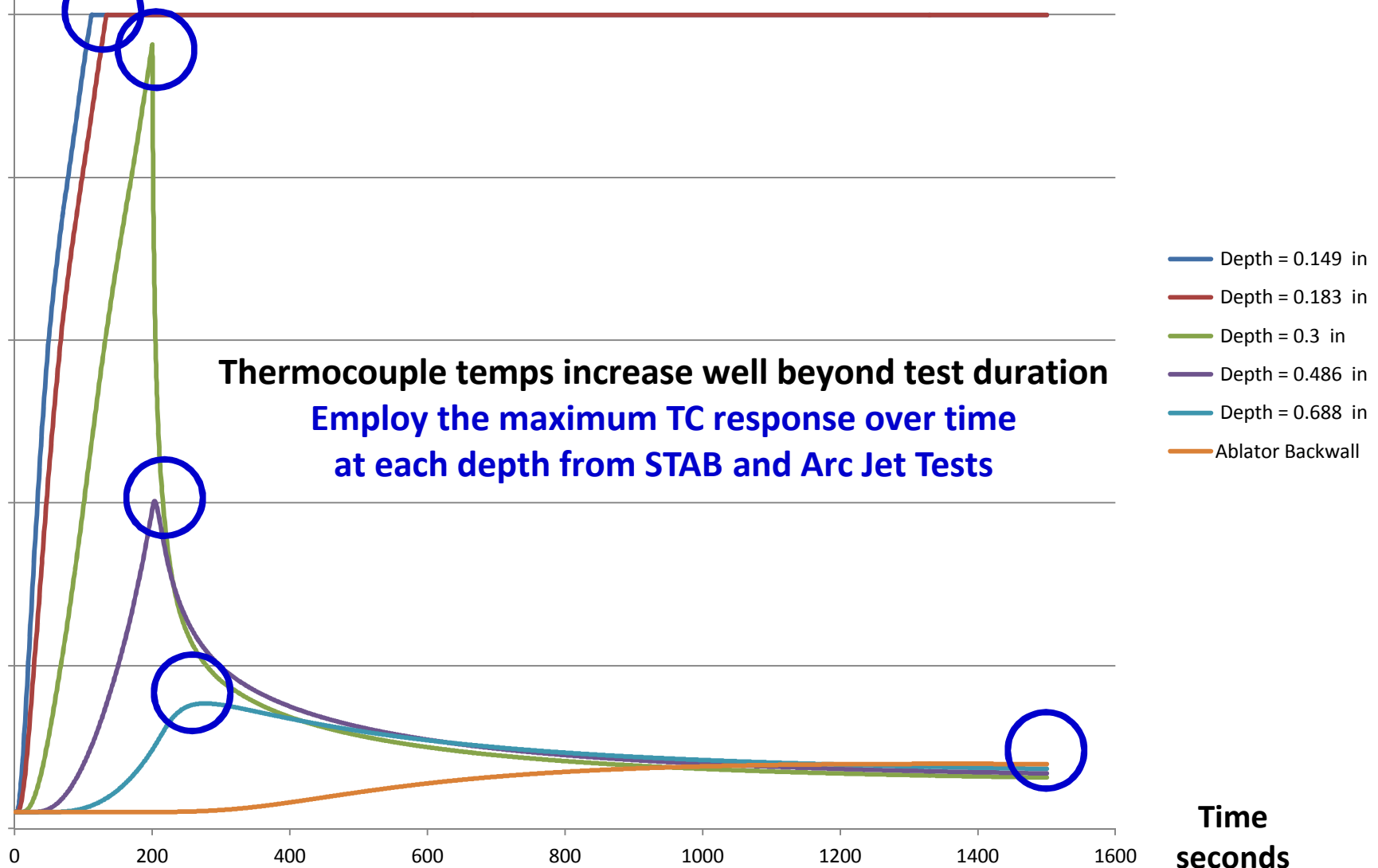
Tests are typically conducted over durations of up to 300 seconds
The bondline temperature is currently used to establish the TPS reliability.

**However, bondline temperature was not measured, it is only simulated.
There is considerable uncertainty in this aspect of the reliability assessment,
as there were only 24 comparisons between test and computation available!**

Introduction (6)

Simulated Thermocouple Response (STAB)

Temp
Deg F

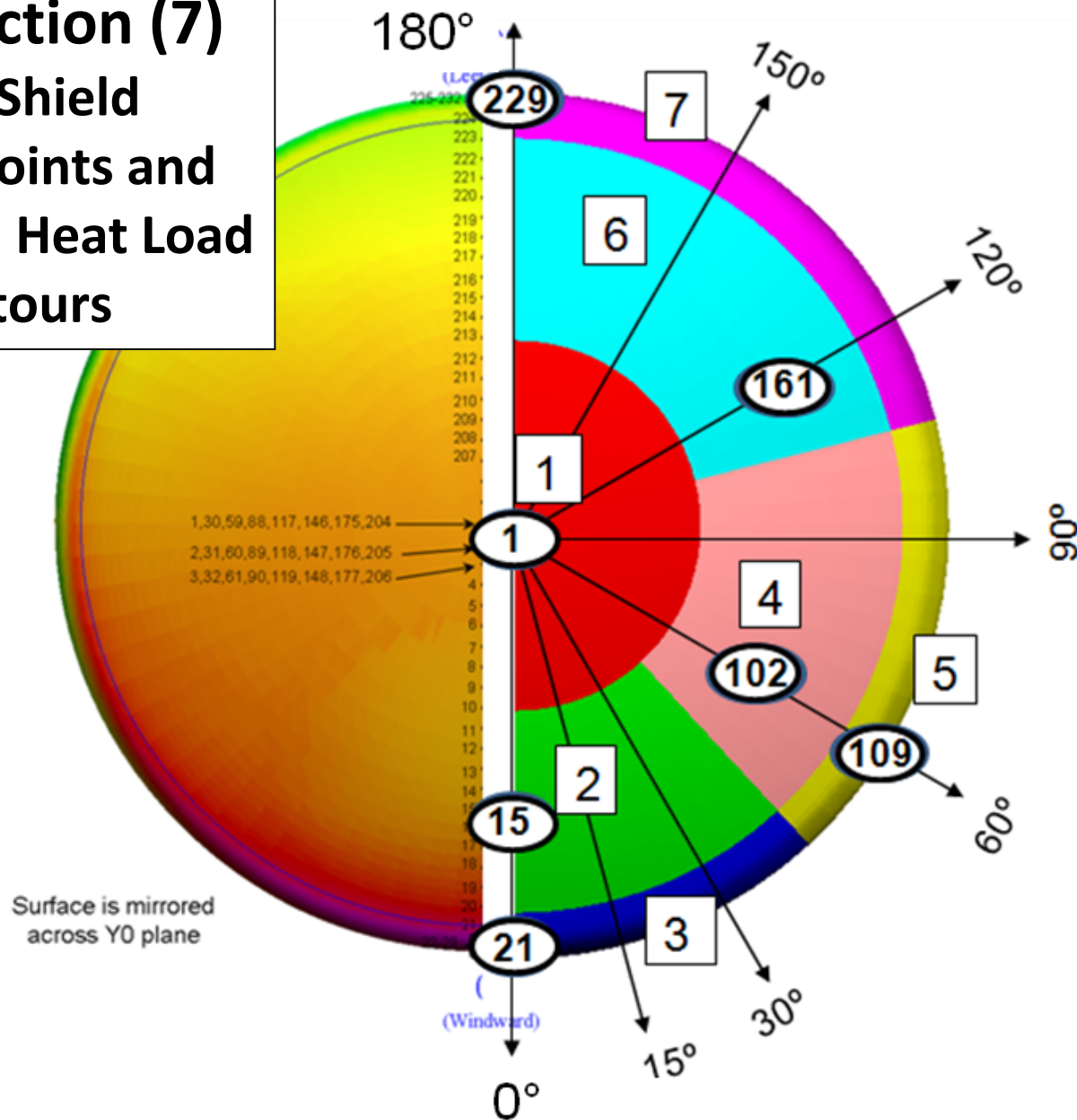


Time
seconds

Introduction (7)

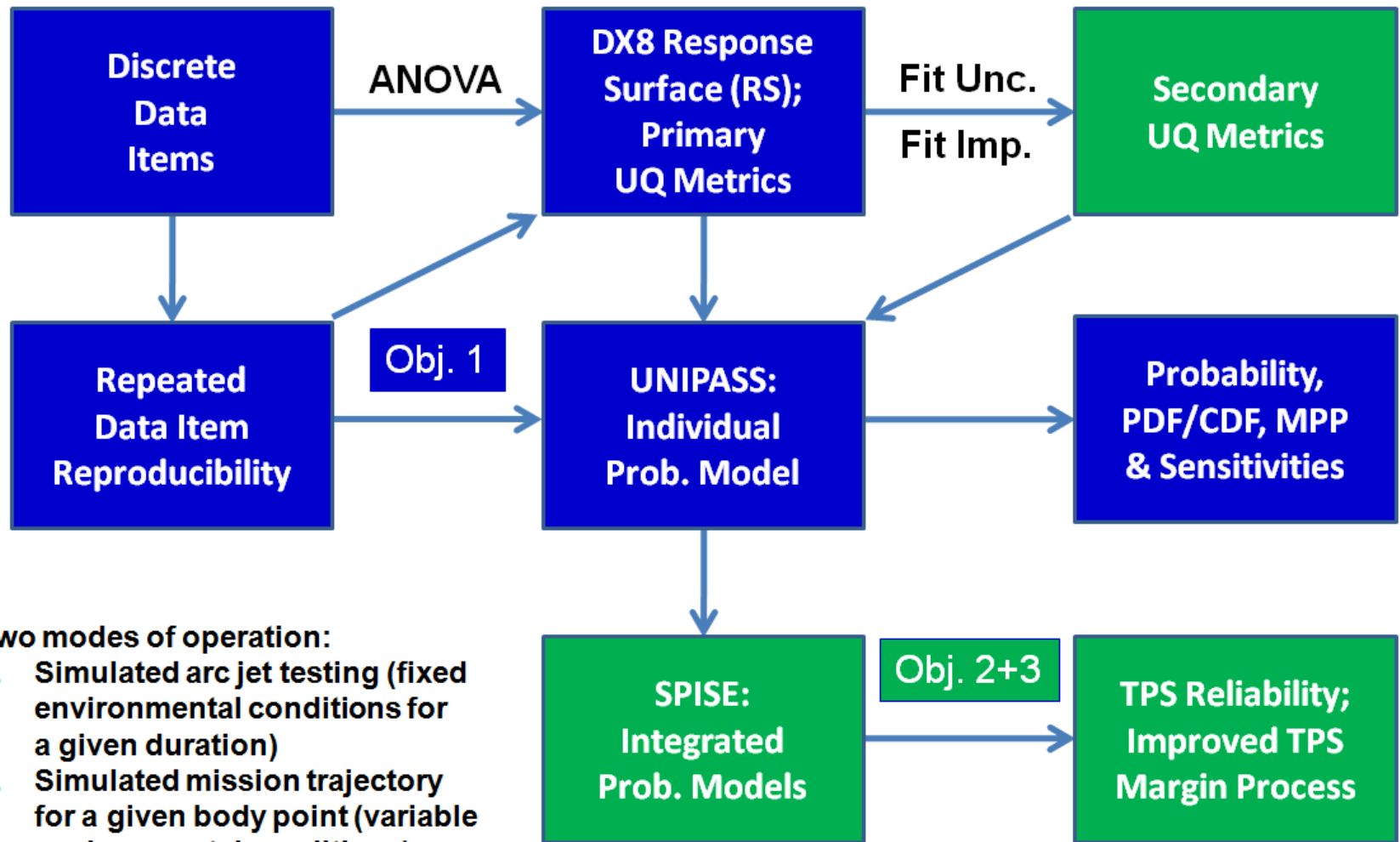
Heat Shield

Design Points and Integrated Heat Load Contours



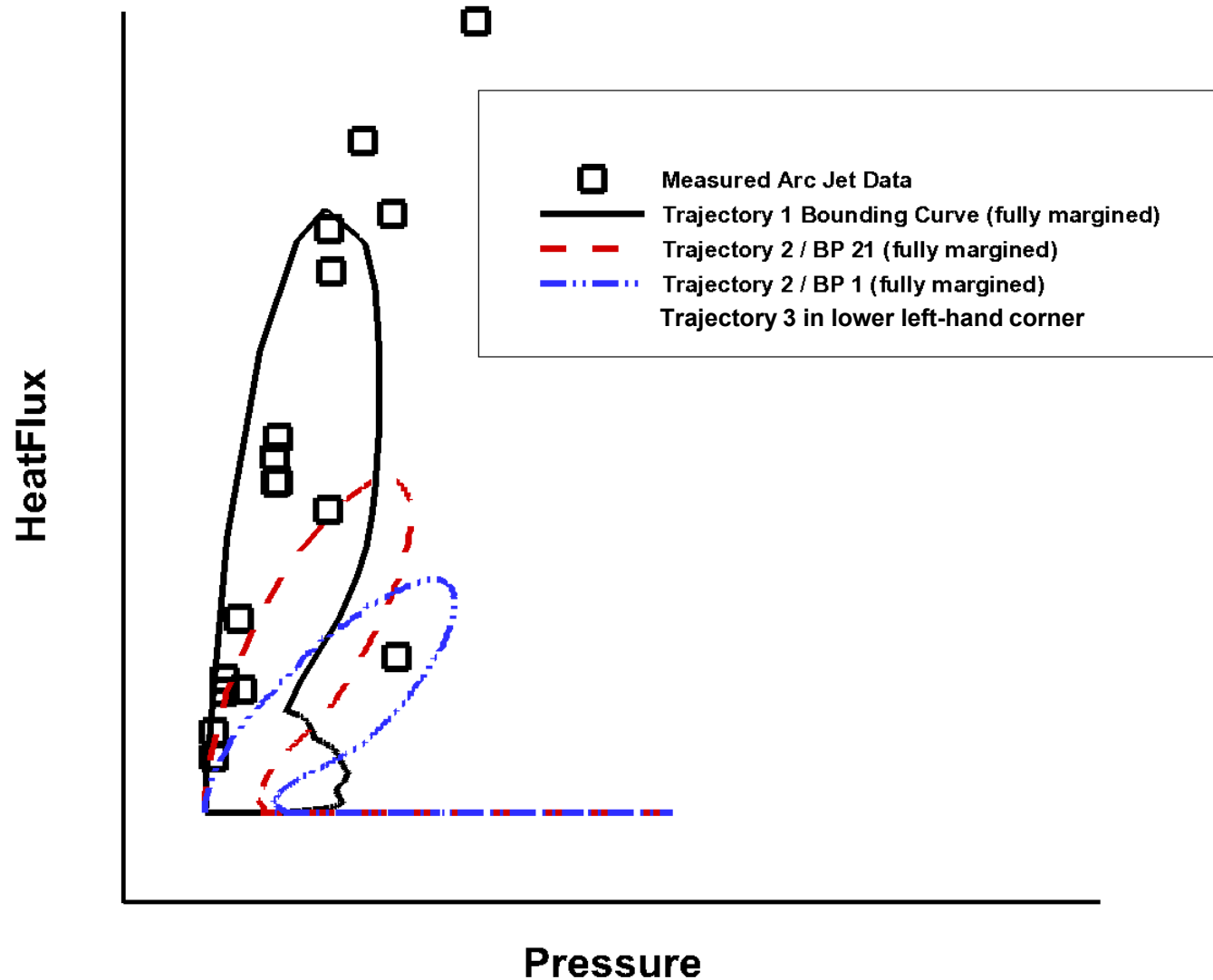
Introduction (8)

Notional Uncertainty Quantification Process

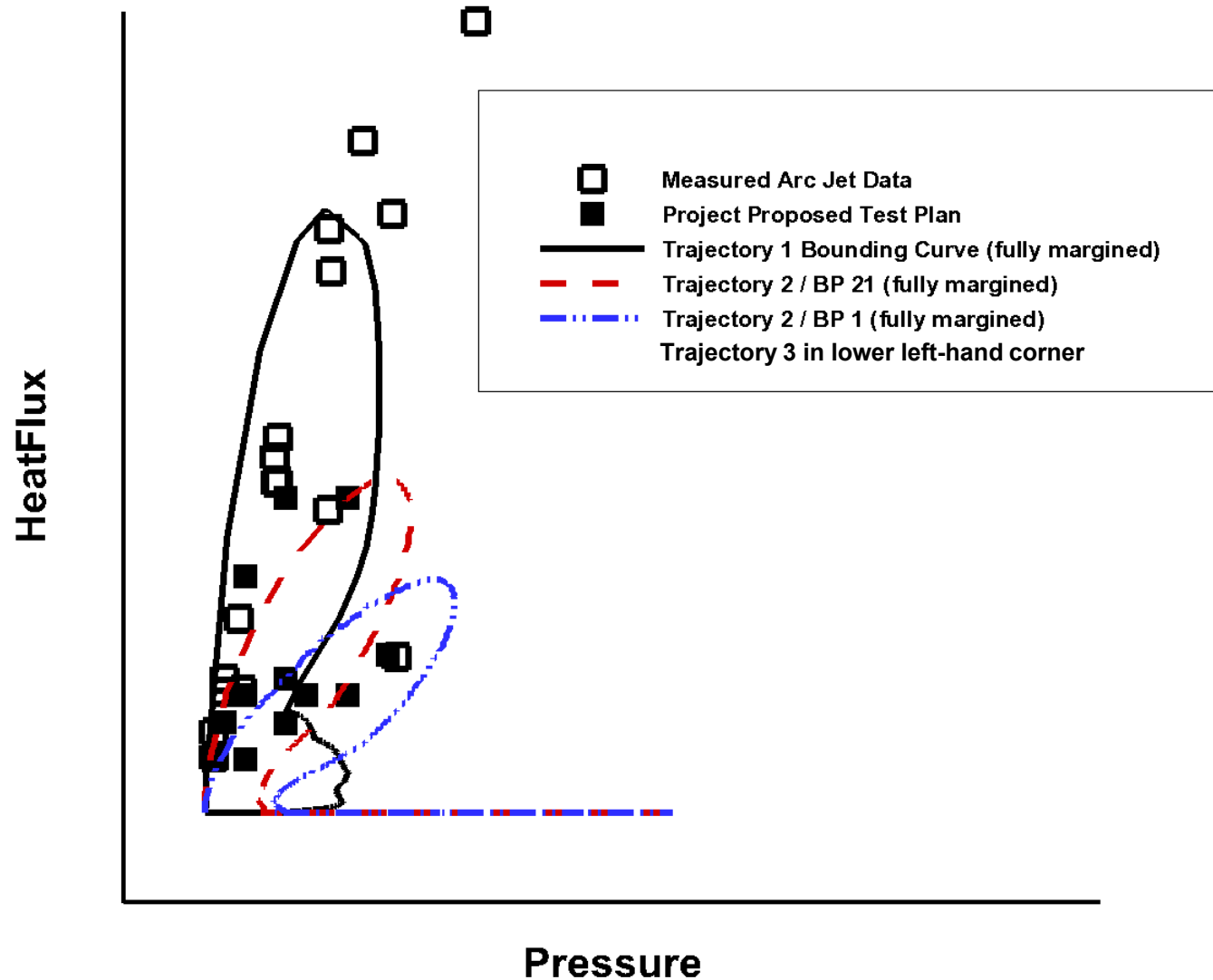


Design of Experiments

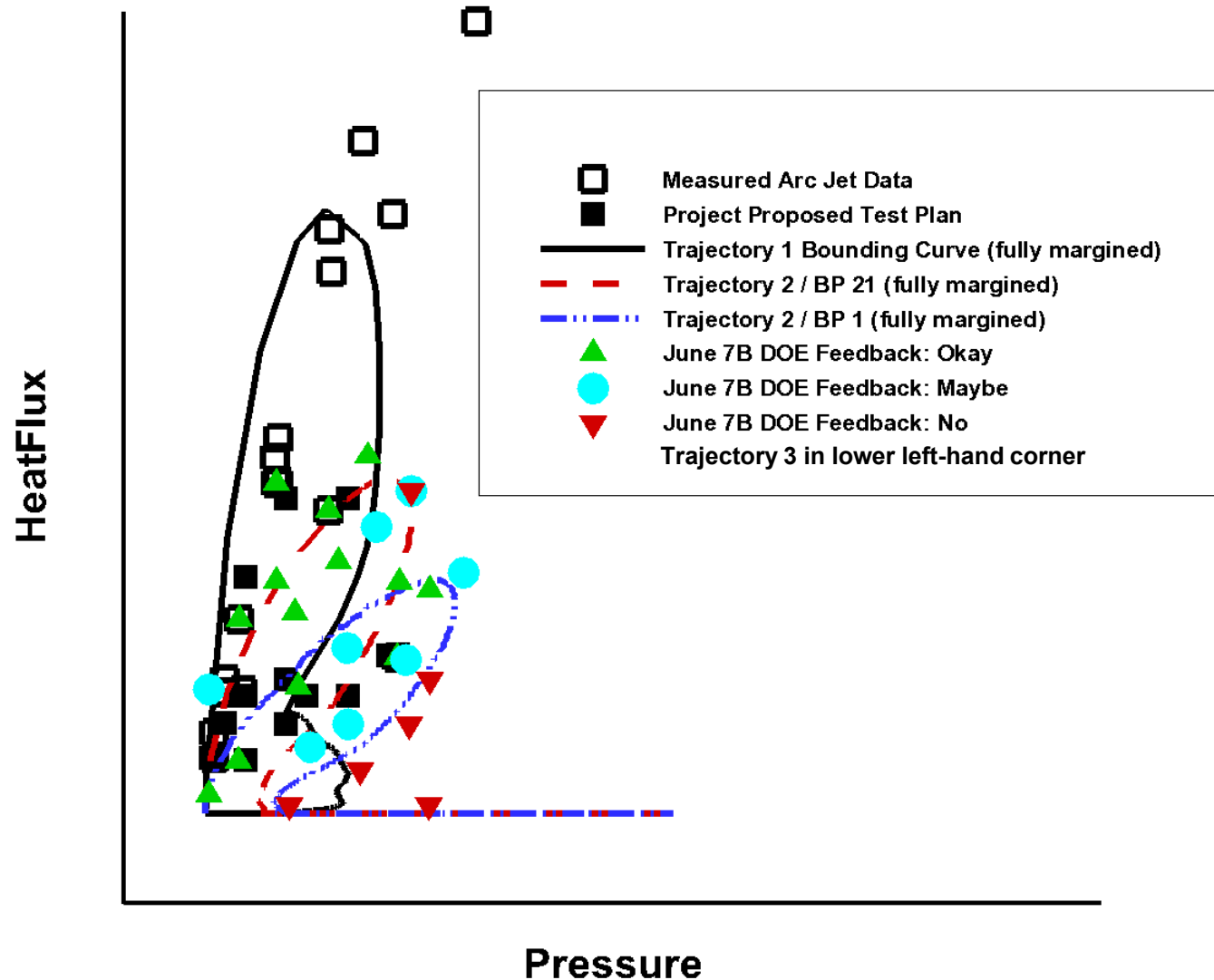
Design Of Experiments (1)



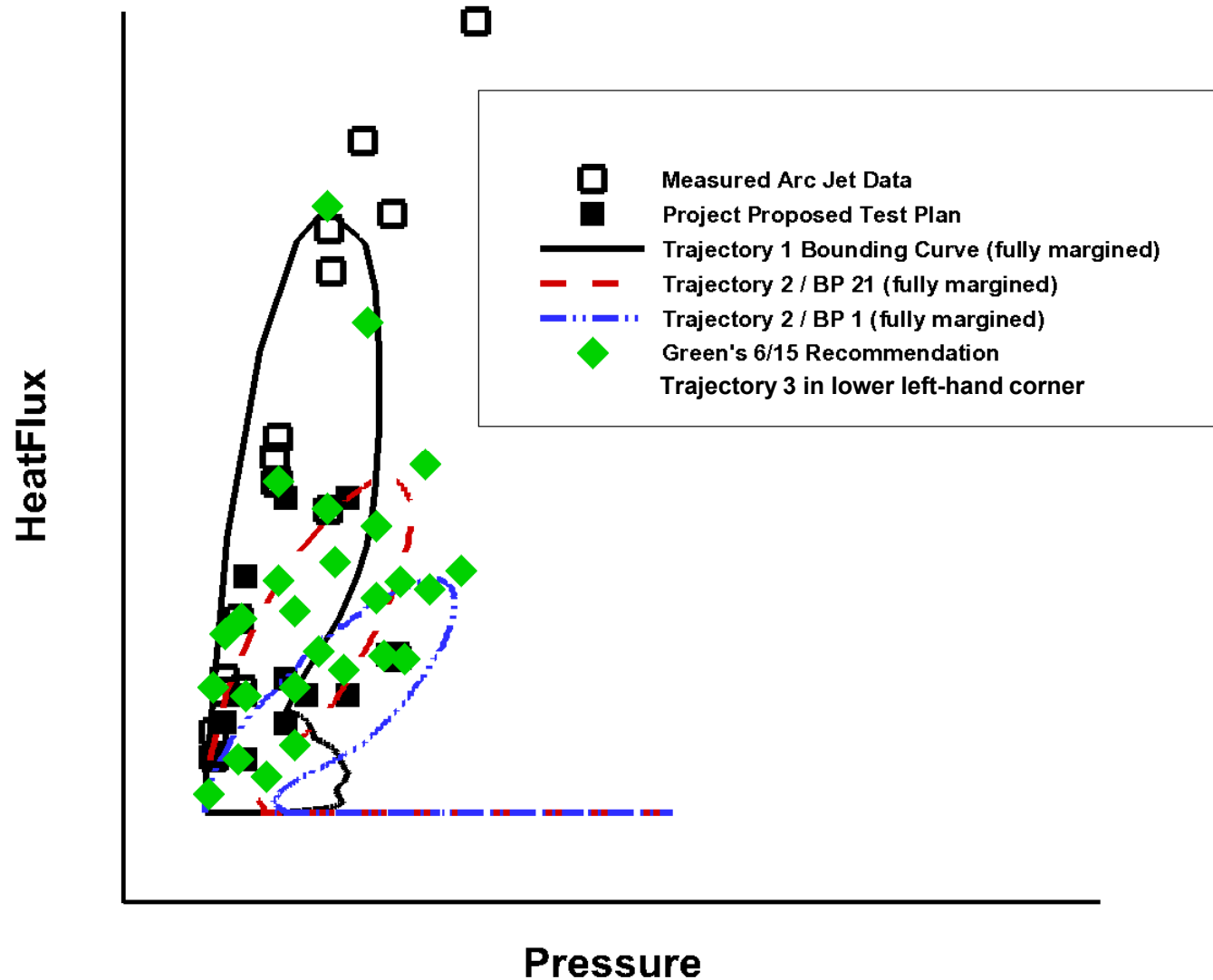
Design Of Experiments (2)



Design Of Experiments (3)



Design Of Experiments (4)



Design of Experiments (5)

Recession

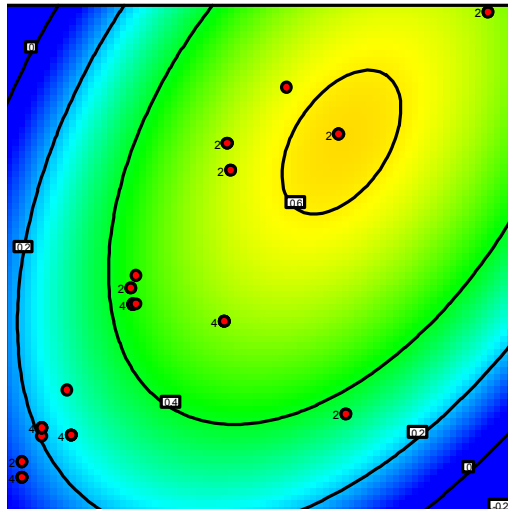
Design-Expert® Software
Factor Coding: Actual
Recession

● Design Points
0.763
0.07

X1 = A: P
X2 = B: Qcw

Original
Data
(1)

B: Qcw



Metric	(1)	(2)	(3)
StDev	0.0716	0.0515	0.0597
PRESS	0.2574	8.7359	3.7370
R-Sq	0.8980	0.9802	0.9832
Adj R-Sq	0.8788	0.9635	0.9699
Pred R-Sq	0.8397	-0.8969	0.5404
Adeq Prec	19.9239	42.9057	51.6837

Average metrics
over 10 samples

Highlights show
the better of the
two metrics

Rec = Rec(P, Qcw);
Dur dependence
ignored here for
the sake of
illustration

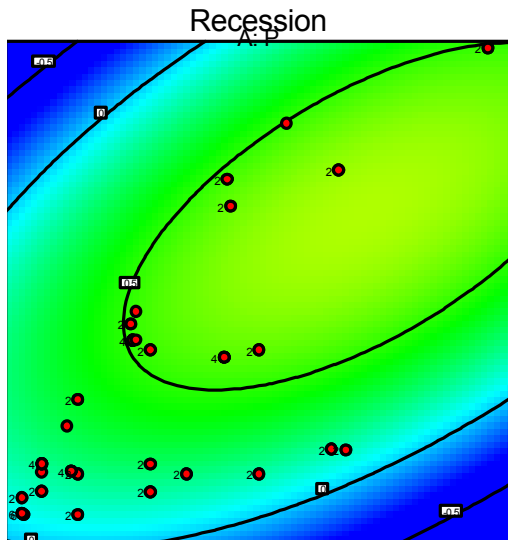
Design-Expert® Software
Factor Coding: Actual
Recession

● Design Points
1.16814
-0.297814

X1 = A: P
X2 = B: Qcw

Original data
+ Program
Proposal
(2)

B: Qcw



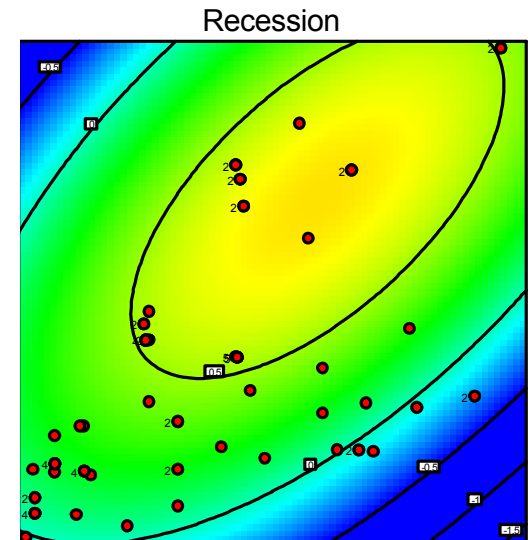
Design-Expert® Software
Factor Coding: Actual
Recession

● Design Points
1.01411
-0.48204

X1 = A: P
X2 = B: Qcw

Original data
+ Green
Proposal
(3)

B: Qcw



Reliability Assessment Process

Reliability Assessment

Problem Statement

- The heat shield reliability will be computed for
 - The STAB 2.18 computational model, **Presumed Safe Temp Limit**
 - Current heat shield design thickness
 - Current carrier structure (composite material)
 - Two trajectories analyzed (trajectories #2 and #3)
 - The following environments will be looked at for each trajectory
 - **Transitional heating**
 - **No trajectory dispersion, no aeroheating uncertainty (fully turbulent)**
 - **Trajectory dispersion only (fully turbulent)**
 - **Aeroheating uncertainty only (fully turbulent)**
 - **Trajectory dispersion and aeroheating uncertainty (fully turbulent)**
 - Seven body points: one from each of the trajectory dispersion zones.
 - **The body points are 1, 15, 21, 102, 109, 161, and 229.**
 - A structural failure temperature distribution was used (i.e., if $T = T_{\text{Safe}} + 1$, the vehicle does not fall apart 100% of the time), for example:
 - **At $T_{\text{Safe}} + 1$, there is a 1% chance of system failure**
 - **At $T_{\text{Safe}} + X$, there is a 50% chance of system failure**
 - **At $T_{\text{Safe}} + Y$, there is a 100% chance of system failure**

70 Total Reliability Assessments
2 traj X 5 cases X 7 body points

Reliability Assessment

Reliability Cases

Margining Process Case Identifier	Description
0	No trajectory dispersion, no aerothermal margin, transitional heating
1	No trajectory dispersion, no aerothermal margin, fully turbulent
2	No trajectory dispersion, aerothermal uncertainty, fully turbulent
3	Trajectory dispersion, aerothermal uncertainty, fully turbulent
4	Trajectory dispersion, no aerothermal uncertainty, fully turbulent

“Best Estimate”
Trajectory



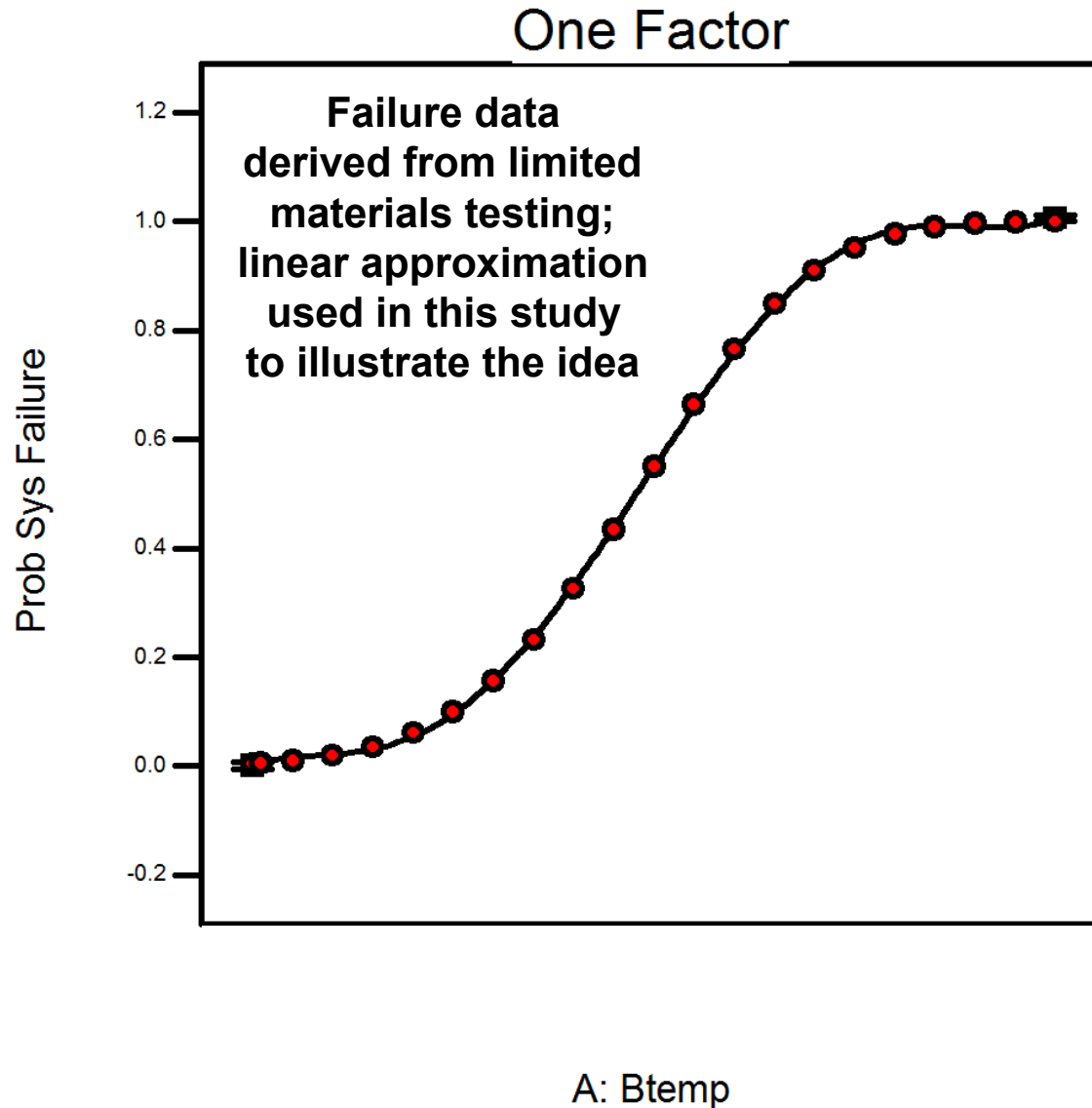
Bracket
the results



“Fully Margined”
Trajectory

Reliability Assessment

Composite Material System Failure Criterion

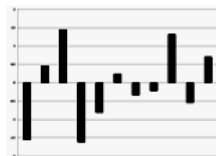
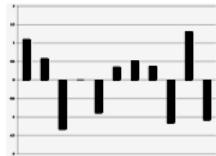


Reliability Assessment

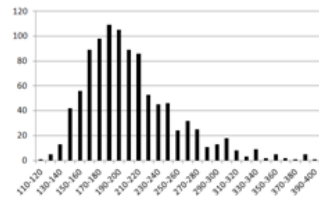
Response Surface Generation

1000 case STAB
run template of
prescribed, random
departures from
nominal values
for 11 material
properties

Select
reliability case
(70 possible)



Bounded distribution;
easy to implement



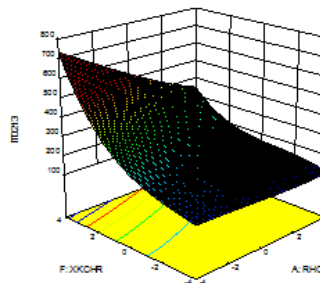
$Btemp = \text{Beta}(MV, SD, XL, XU)$
MV = mean value; SD = stdev
XL = lo bound; XU = hi bound
or, $Btemp = \text{Uniform}[XL, XU]$

lumped material properties

Implemented in
UNIPASS by Green
using MCS

Or

Design-Expert® Software
Factor Coding: Actual
ITG13
512.4
119.7
X1 = A: RHOV
X2 = P: XKDHR
Actual Factors
B: RHOC = 0.00
C: O: PWR = 0.00
D: O: PWR = 0.00
E: XKVRO = 0.00
G: BMCT = 0.00
H: BMVT = 0.00
J: ROLGHT = 0.00
K: ZBPRH = 0.00
L: OPGAS = 0.00



$Btemp = f(X1, X2, \dots, X11)$
11-dimensional cubic RS

distinct material properties

Implemented
in SPISE by PPI
using FORM

Reliability Assessment

Reliability Assessment Process

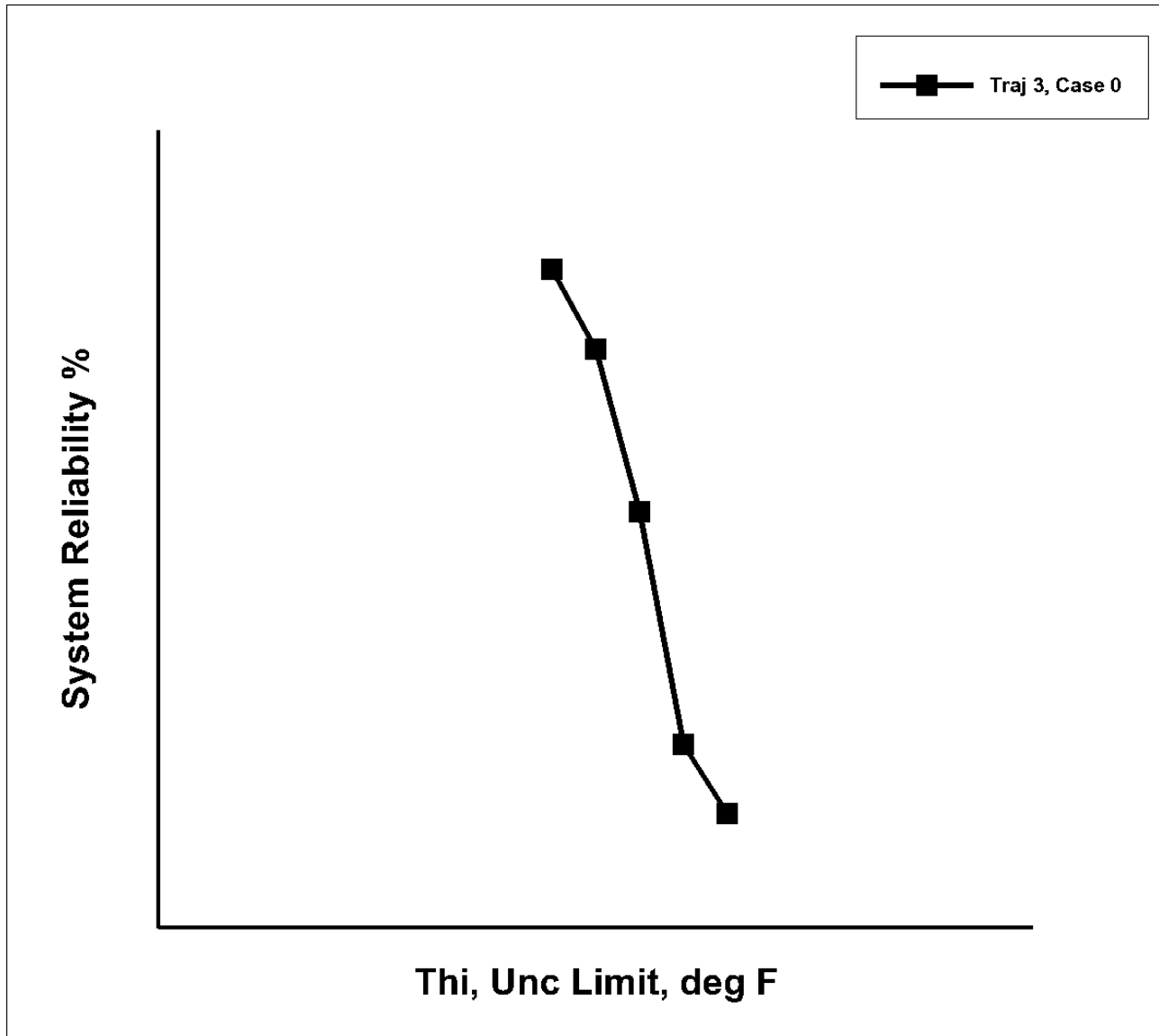
3 Nested loops:

1. Outermost loop: problem setup
 - Select **“safe” bond line temperature**
 - Select the **exact form of the reliability formulation**:
 - Material property variation RS form
 - Failure constraint
 - Number of MCS samples
 - Confidence level, convergence tolerances, etc.
2. Intermediate loop: select **user input** value of T_{Hi}
 - Upper bound of model form correction uncertainty term
 - Model term as uniform distribution $[T_{Lo}, T_{Hi}]$
3. Innermost loop: conduct **reliability assessment** subject to **material property variations** (11-D cubic, or 1-D Beta / Uniform RS) with
 - Added model form correction uncertainty term from loop 2
 - Failure constraint associated with **“safe”** temperature from loop 1

Reliability Assessment Results

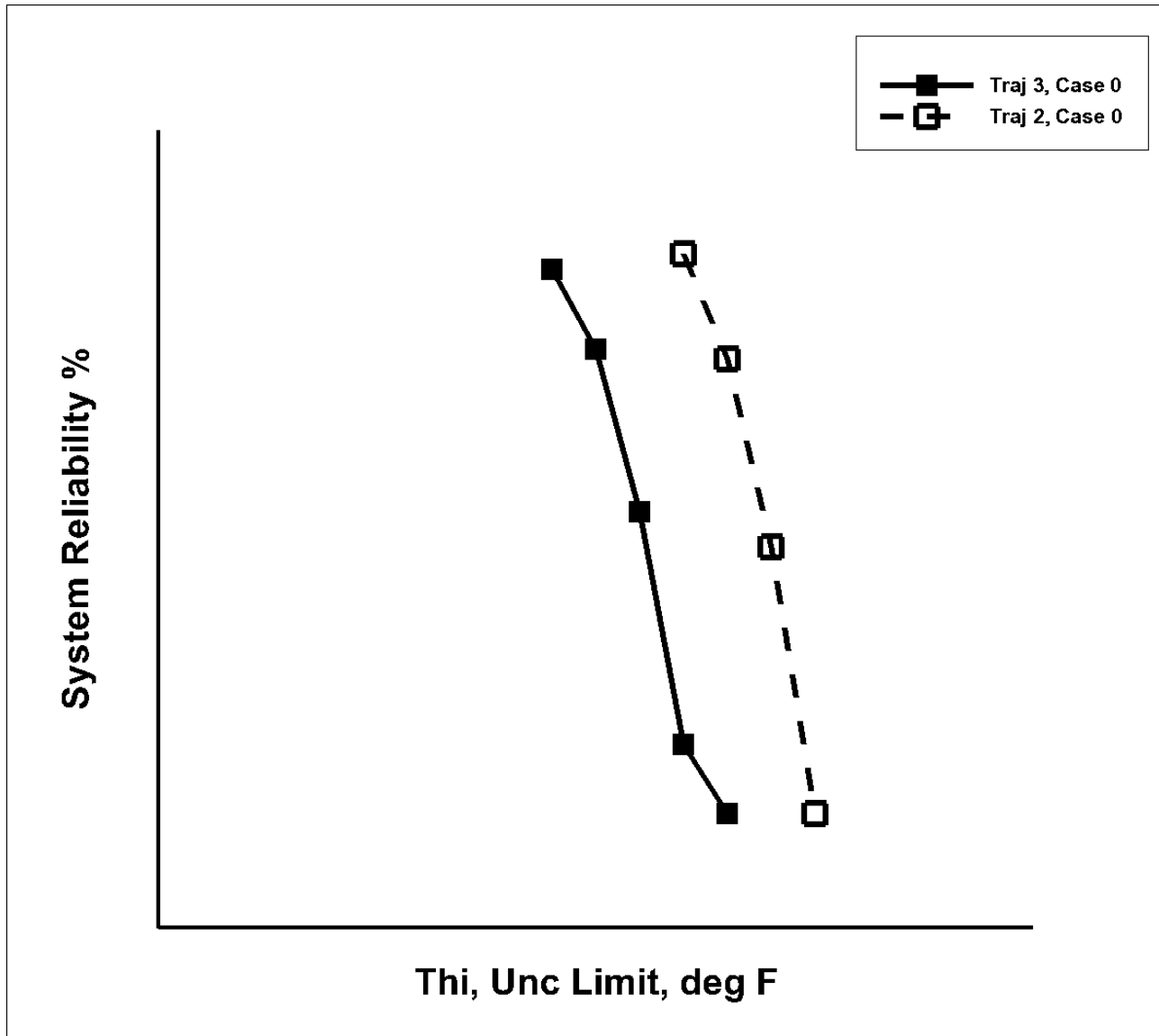
Reliability Assessment

Trajectory 3, Case 0



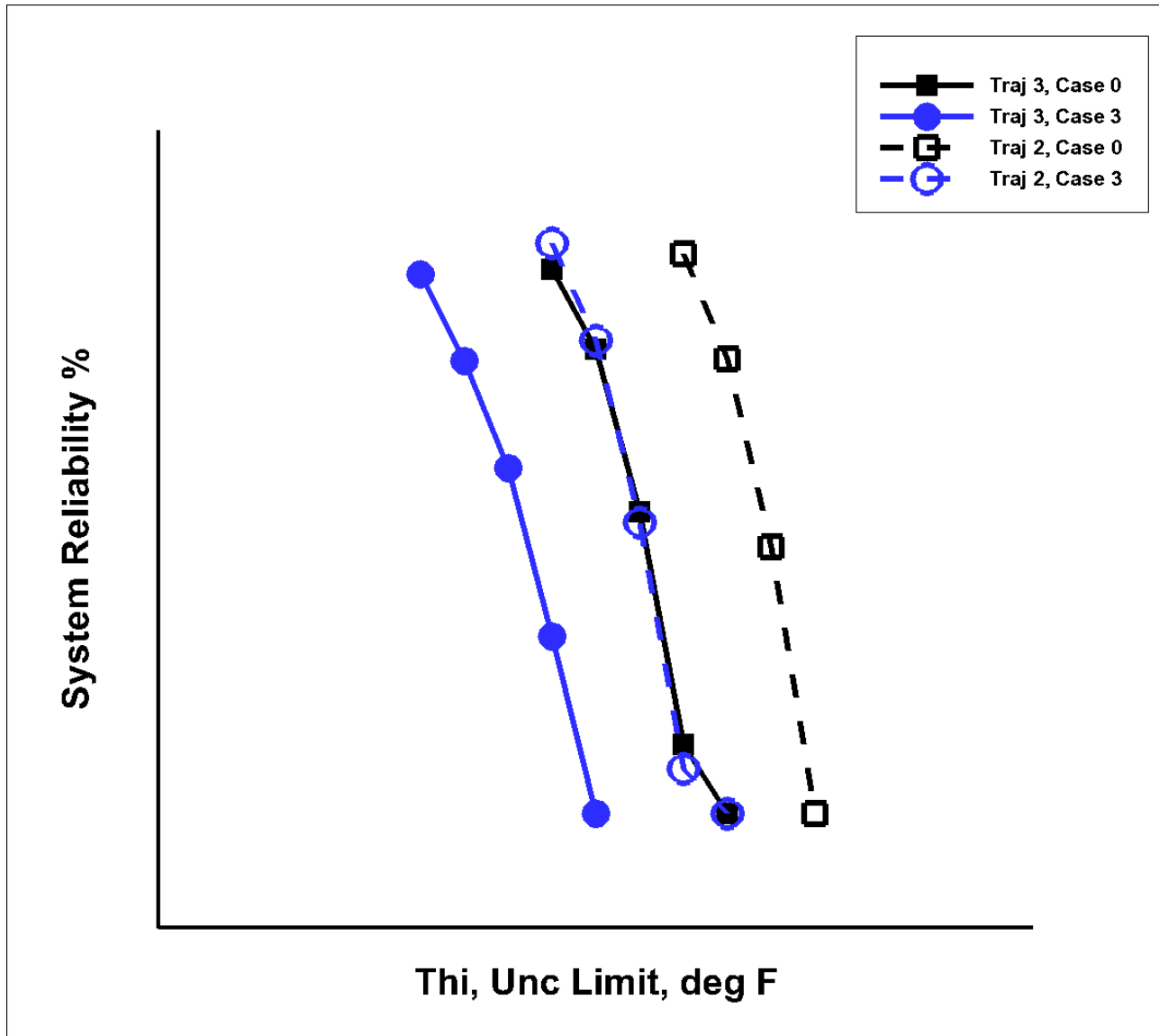
Reliability Assessment

Trajectory 2 and 3, Case 0



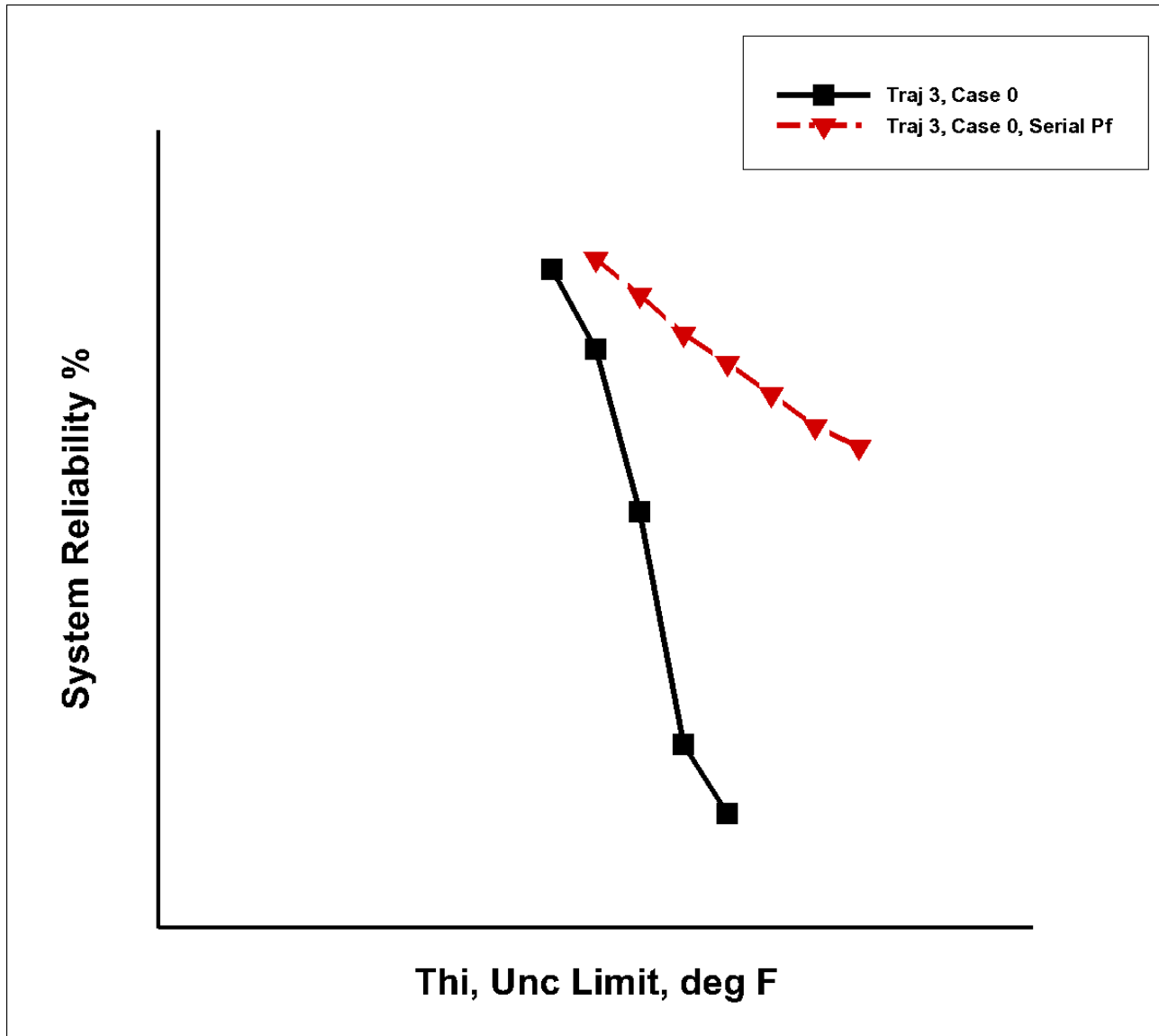
Reliability Assessment

Trajectory 2 and 3, Case 0 and 3



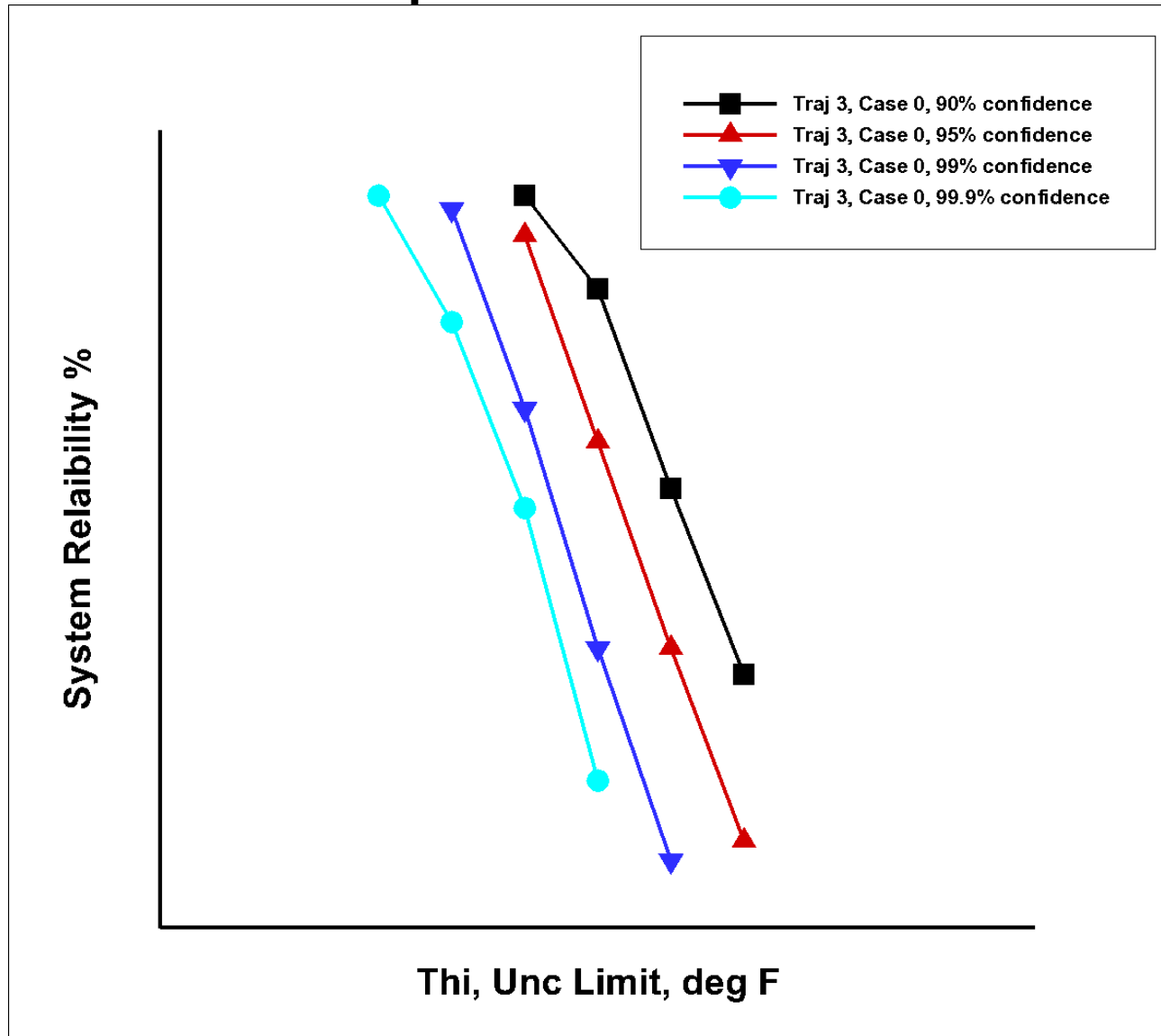
Reliability Assessment

Trajectory 3, Case 0, Composite and Serial Failure Modes



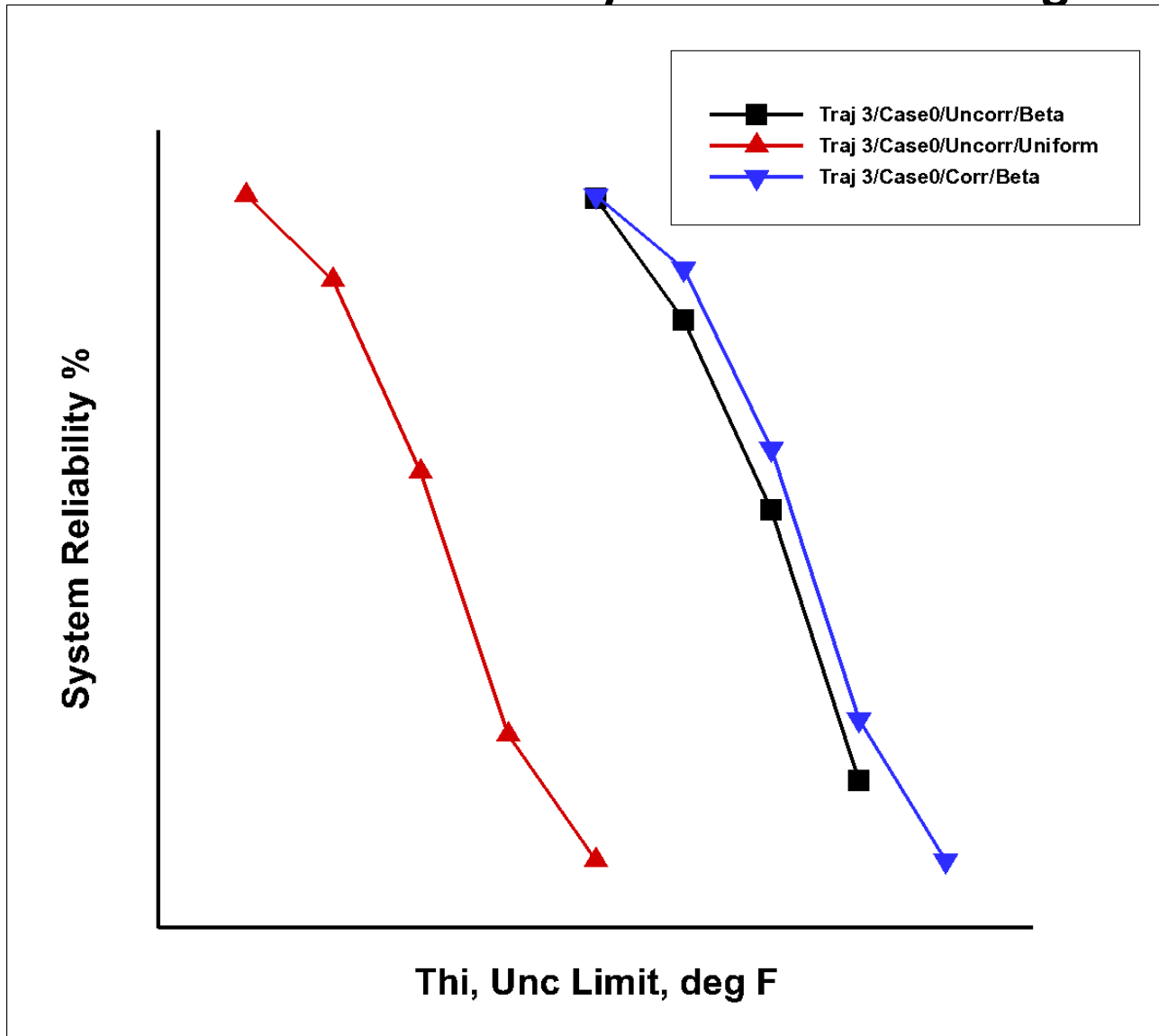
Reliability Assessment

Trajectory 3, Case 0, Effect of CDF Confidence Level, Composite Failure Mode



Reliability Assessment

Trajectory 3, Case 0, Effect of Material Property Variations, Correlation and Beta/Uniform Modeling



Reliability Assessment Assumptions

- Arc jet test data correctly represents the ablative flow physics of flight
- The existing data and computational models can be used to predict behaviors for newer versions of the material
- Limited / deepest buried arc jet test data and computations are sufficient to characterize the bond line temperature uncertainty
- Material property variations are adequately represented in the STAB code
- Trajectory / margin variations are adequately represented in the STAB code
- The composite material safe bond line temperature
- The composite inter – laminar strength can be used to describe the failure mode
- The arc jet – STAB model form correction term uncertainty can be adequately represented by a uniform distribution of a user input magnitude
- The reliability of the Orion TPS can be adequately represented by conventional probabilistic techniques (MCS and FORM) despite a large model form correction term uncertainty (i.e., we don't need to use probability boxes to explicitly model lack of knowledge intervals within the reliability assessment)
- Various forms of the reliability assessment formulation are equally valid so as to enable a fair comparison

Study Closeout

- Key findings:
 - **Three sources of uncertainty within the system wide analysis were found to have a dominant effect on the reliability assessment**
 - **Different forms of the reliability assessment formulation yielded very different reliability assessment results**
 - **The DOE process for test planning resulted in a technically improved test matrix for the thermal response tests**
- Numerous observations and recommendations
- Numerous tasks were suggested for possible follow-on work; these are now being considered for funding