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Verification & Validation (V&V) in a Structural Dynamics Application

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Outline

- Introduction to V&V terminology

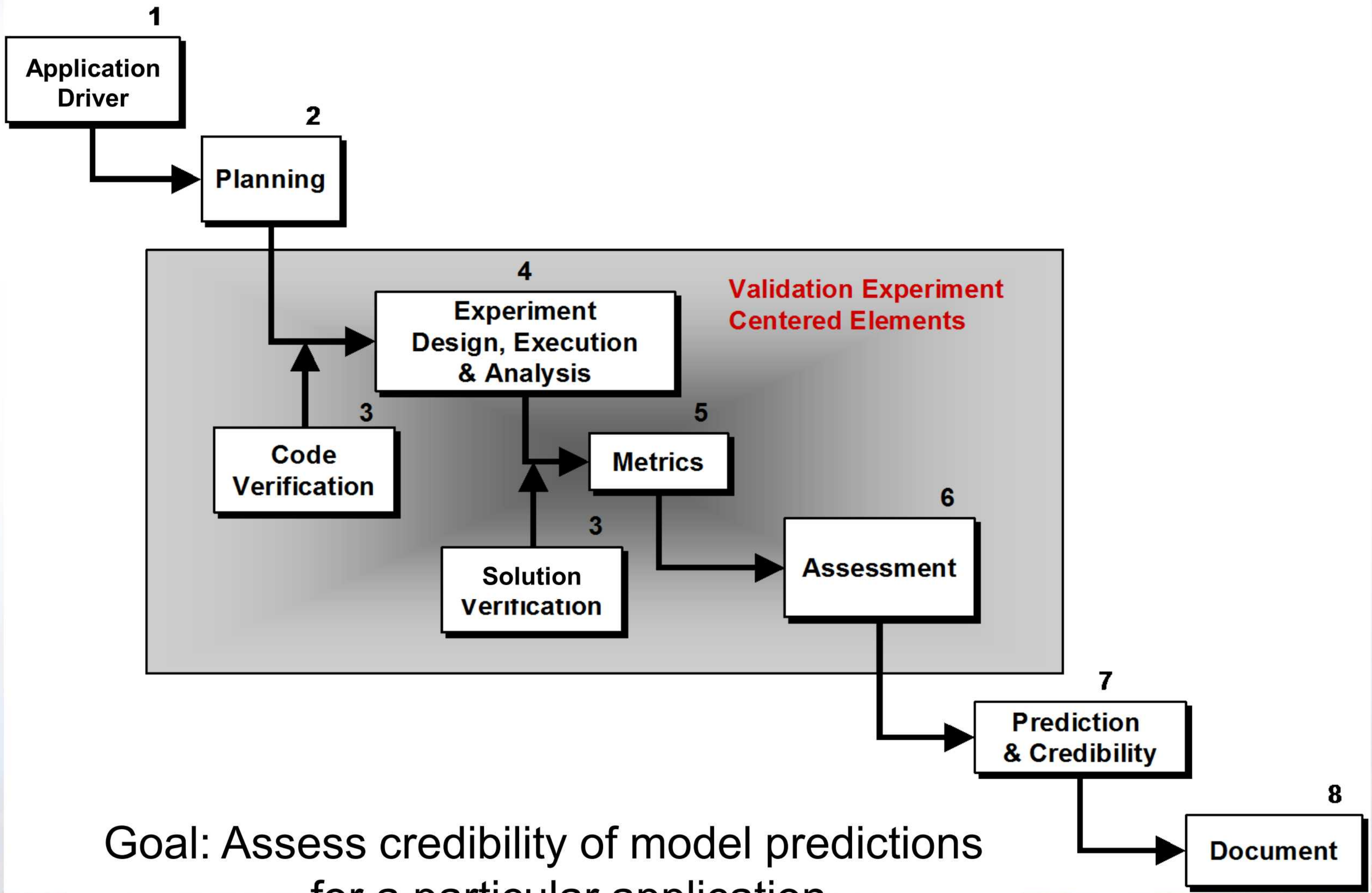
- The Sandia V&V Process in Action
  - A walk thru the process using a structural dynamics example
    - » Application driver
    - » Planning (PIRTS)
    - » Code and Solution Verification
    - » Uncertainty Quantification
    - » Validation
    - » Prediction and Credibility

- Summary

Verification, Validation, and Uncertainty Quantification are the Science Behind QMU

- Verification – “Are we solving the equations correctly?”
  - Correctness of implemented mathematical algorithms.
  - Convergence to the correct answer, at the correct rate, as model is refined.
- Validation – “Are we solving the right equations?”
  - Correctness of physical models and sufficiency for the application.
  - Model Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model
- Uncertainty Quantification (UQ):
  - Statistical propagation of uncertainty through a simulation model, and statistical interpretation of model response.
- Quantification of Margins and Uncertainties (QMU):
  - Using the simulation model to make system performance predictions with quantified uncertainty, and with quantified margins with respect to system performance requirements.

Overview of the Sandia V&V Process



Goal: Assess credibility of model predictions for a particular application

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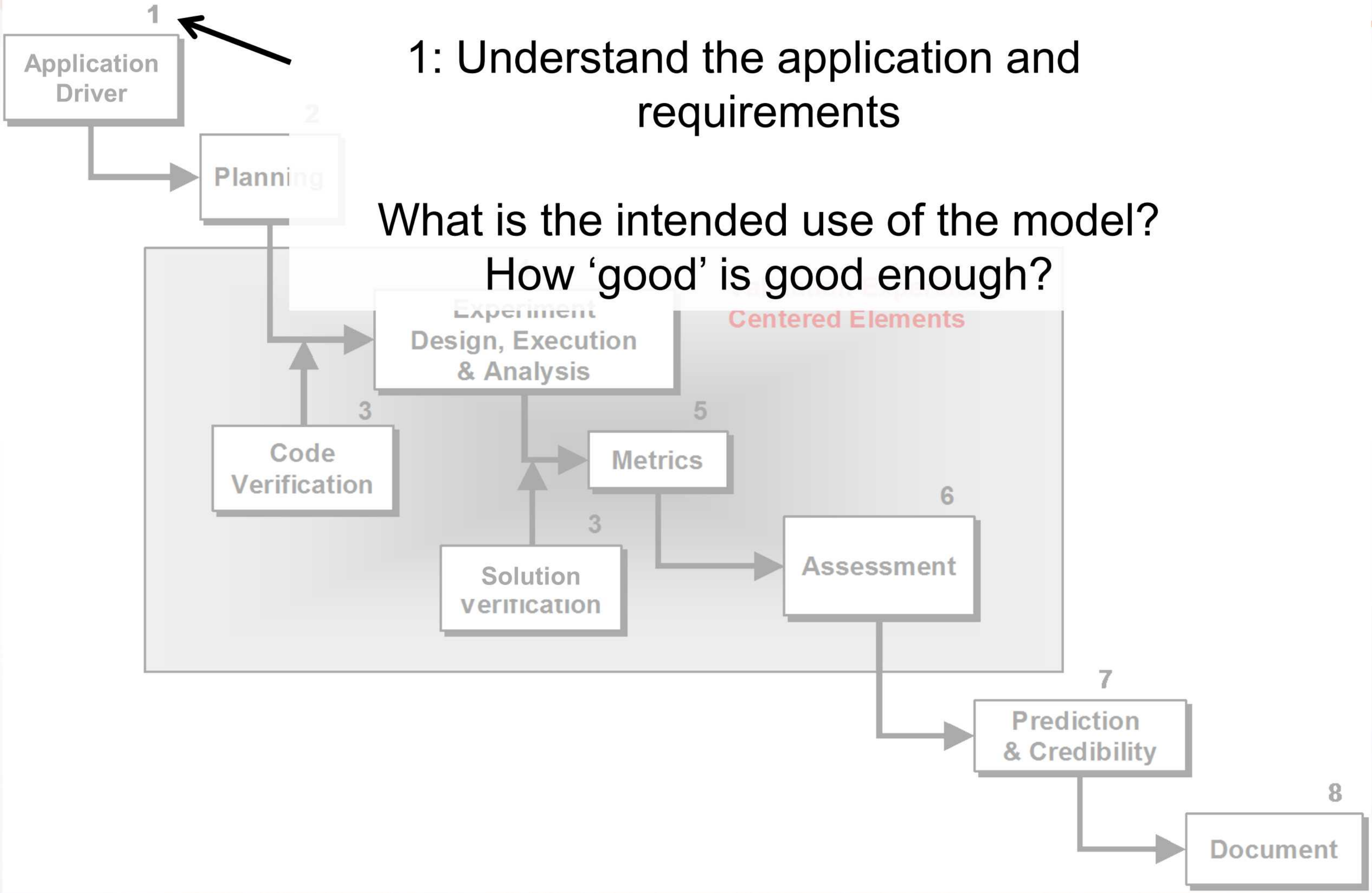
Overview of the Sandia V&V Process

1: Understand the application and requirements

What is the intended use of the model?
How 'good' is good enough?



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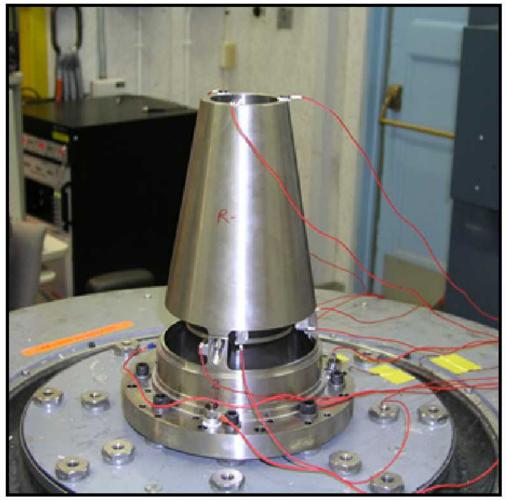
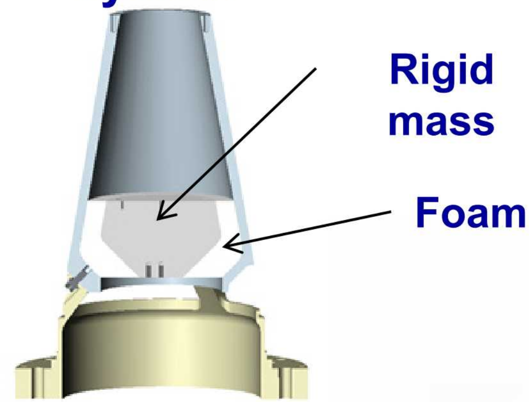
Example: Physical System

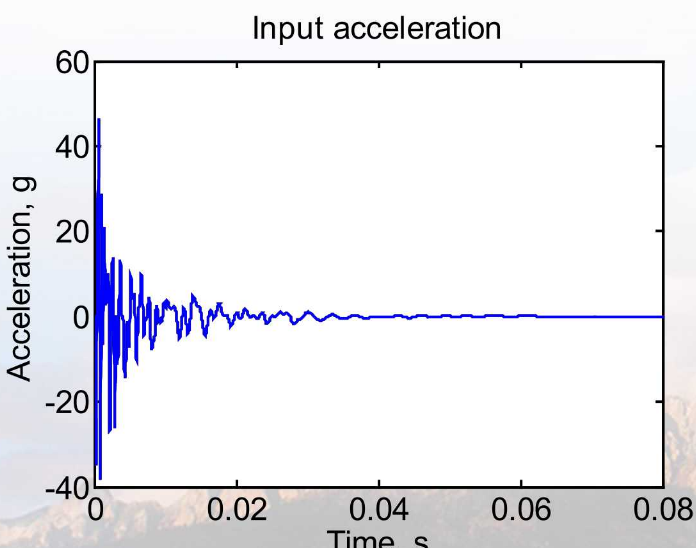
System consists of:

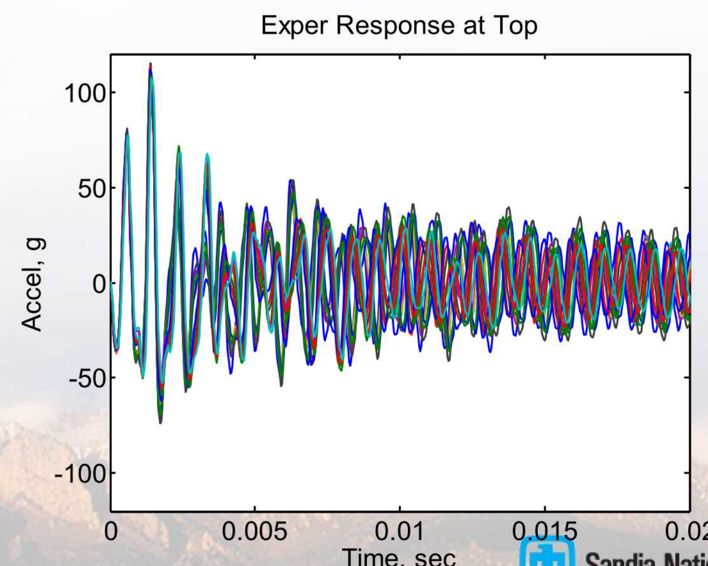
- a bolted interface (@ 3 locations) and
- a rigid component encapsulated in foam
- subjected to a blast-type excitation.



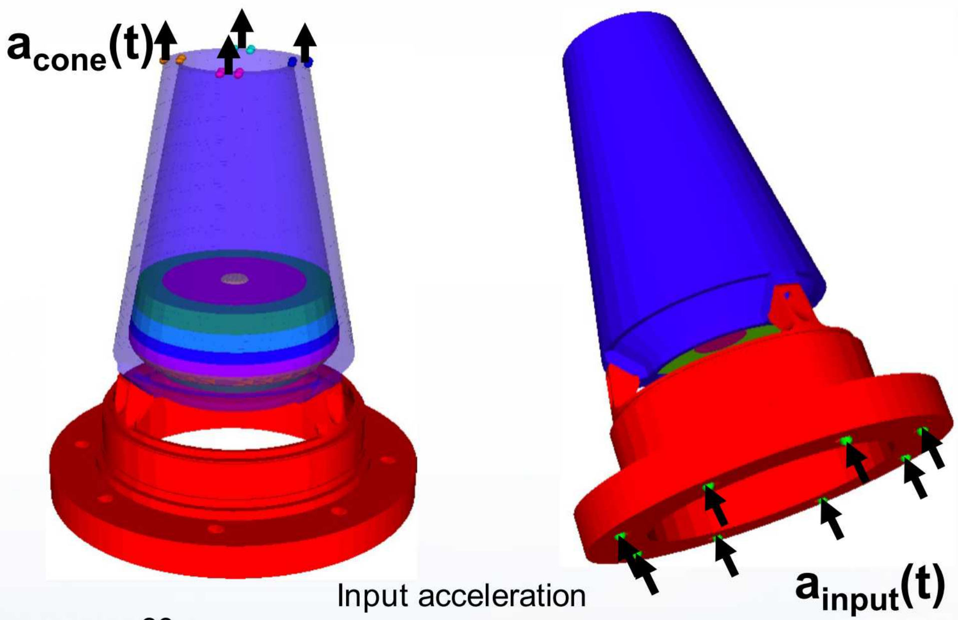
Cut-away of system



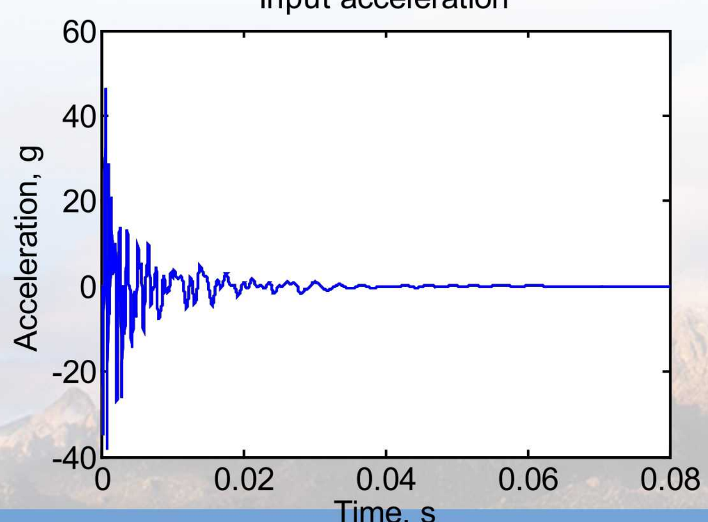


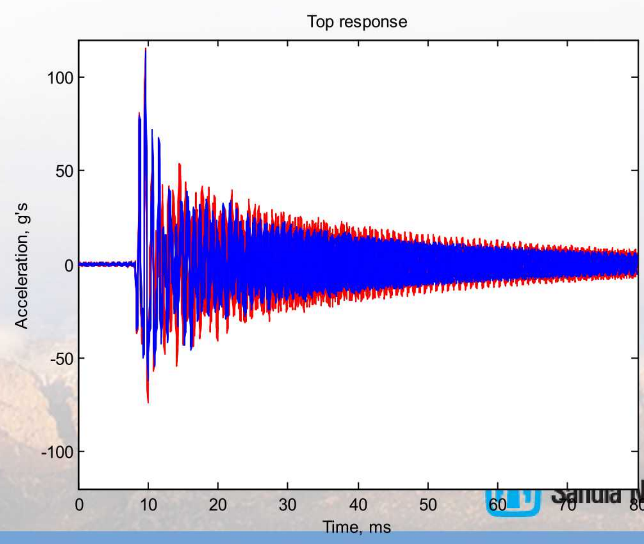


Example: Finite Element Model

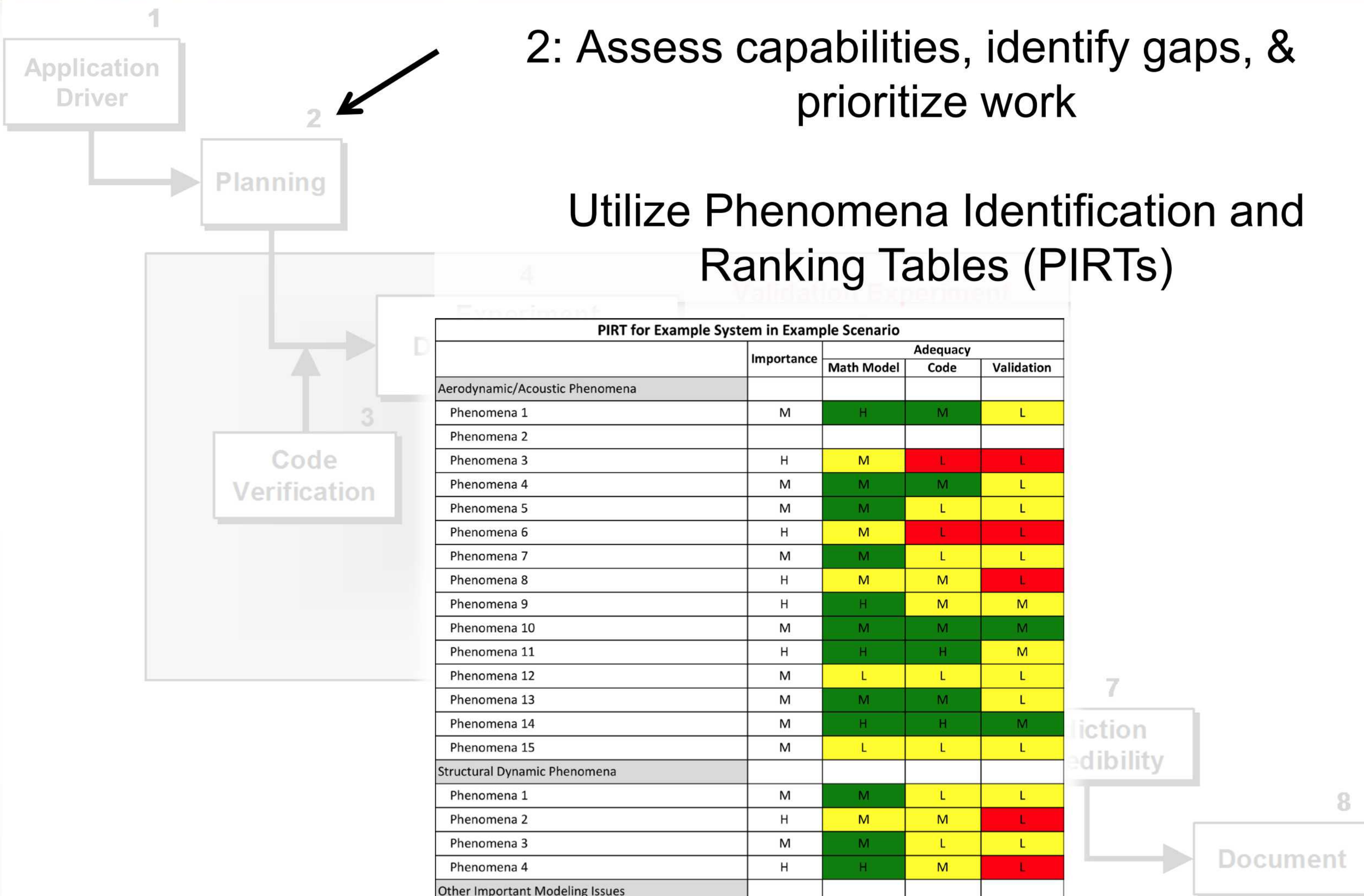


- Encapsulating foam model via elastic formulation and treated stochastically
- Bolted interface modeled via Iwan model and also treated stochastically
- Nonlinear transient analysis using Sierra/SD
- UQ analysis using DAKOTA





Overview of the Sandia V&V Process



2: Assess capabilities, identify gaps, & prioritize work

Utilize Phenomena Identification and Ranking Tables (PIRTs)

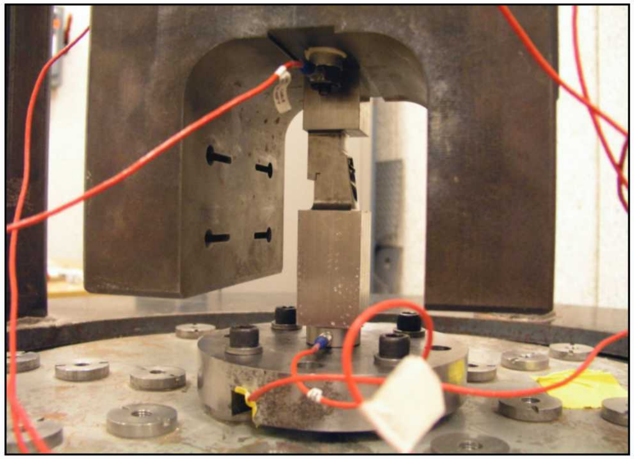
PIRT for Example System in Example Scenario				
	Importance	Adequacy		
		Math Model	Code	Validation
Aerodynamic/Acoustic Phenomena				
Phenomena 1	M	H	M	L
Phenomena 2				
Phenomena 3	H	M	L	L
Phenomena 4	M	M	M	L
Phenomena 5	M	M	L	L
Phenomena 6	H	M	L	L
Phenomena 7	M	M	L	L
Phenomena 8	H	M	M	L
Phenomena 9	H	H	M	M
Phenomena 10	M	M	M	M
Phenomena 11	H	H	H	M
Phenomena 12	M	L	L	L
Phenomena 13	M	M	M	L
Phenomena 14	M	H	H	M
Phenomena 15	M	L	L	L
Structural Dynamic Phenomena				
Phenomena 1	M	M	L	L
Phenomena 2	H	M	M	L
Phenomena 3	M	M	L	L
Phenomena 4	H	H	M	L
Other Important Modeling Issues				
Phenomena 1	H	L	L	L
Phenomena 2	M	N/A	N/A	L
Phenomena 3	H	N/A	N/A	M

Physics and Material Model Fidelity (PMMF)

How science-based and accurate are the physics and material models?

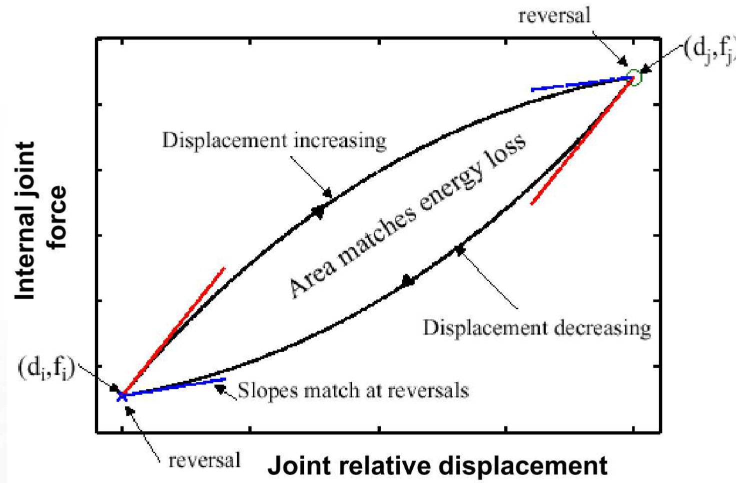
- Describe the key physics models you anticipate using in your computational model, and your assessment of how well tested/validated they are
  - Linear vs non-linear
  - Polynomial model with *n* or *m* terms
  - Simple (viscous damping) vs. complex energy dissipating model

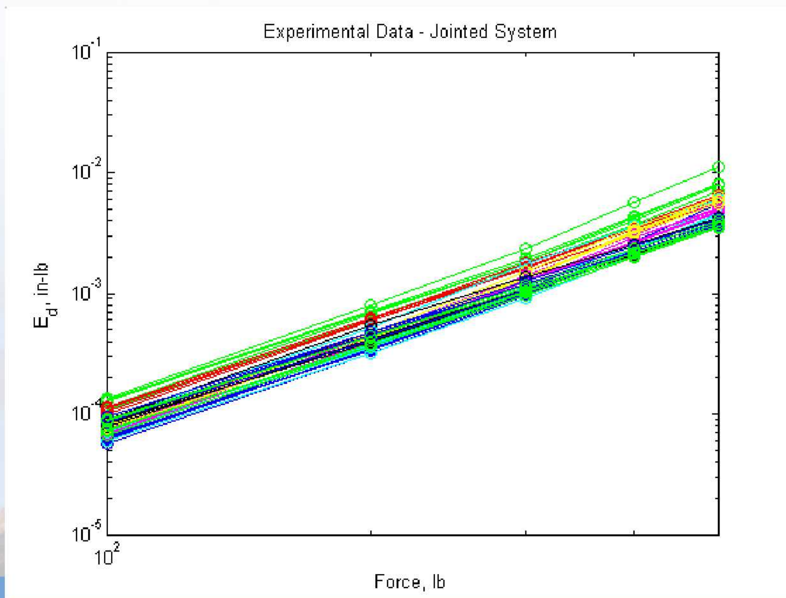
Physics Characterization - joints



Smallwood model

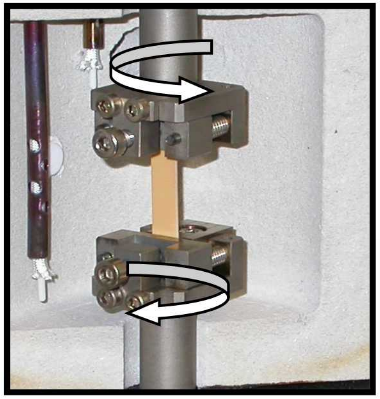
$$F_j = klin\left(d_j - d_i\right) - knon\left(d_j - d_i\right)^{npow} + F_i$$

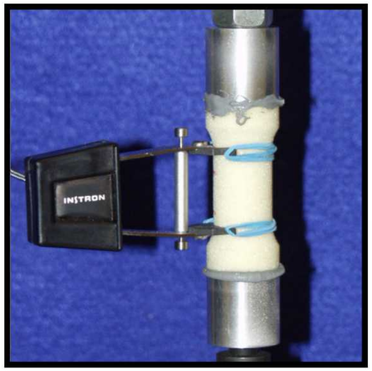




- Data from 45 tests with a sinusoidal excitation are used to calculate curves of energy dissipated, E_d vs. force, F
- Slope of each experimental curve of E_d vs. F, in log-log space, is parameter *npow*.
- *klin* and *knon* parameters are calibrated from hysteresis curve shown above

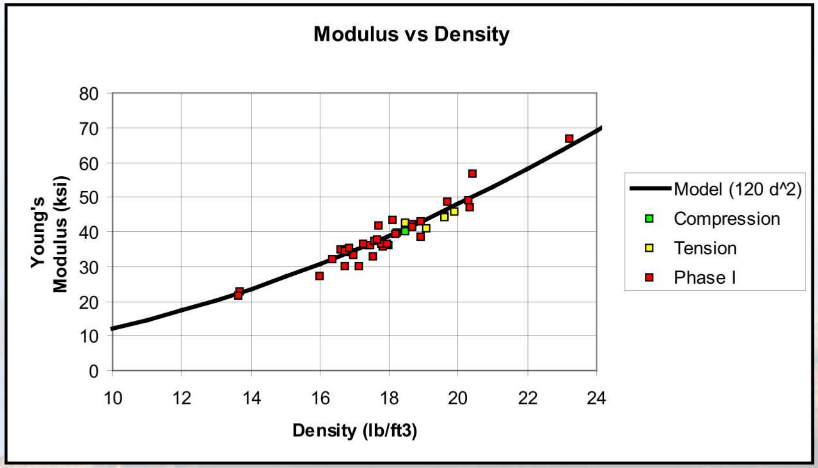
Physics Characterization - foam





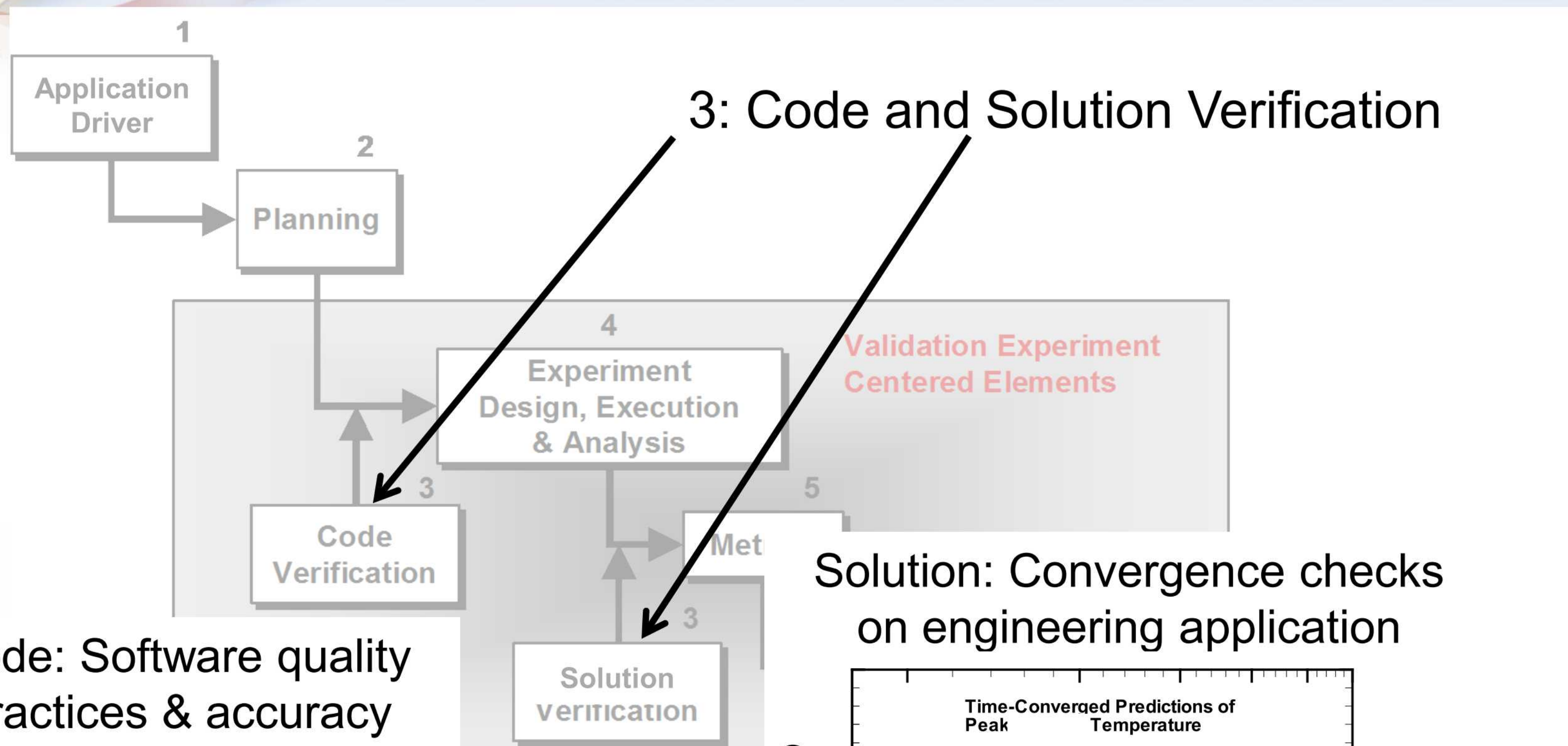
Foam constitutive model

$$E = c_1 * (\rho)^{pow}$$



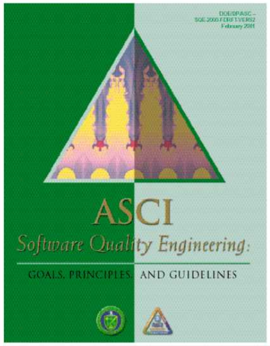
- Data from torsion, tension and compression experiments are used to obtained data on modulus of elasticity (E) versus density, (ρ)
- Coefficient, c_1 and exponent, *pow* in foam model are estimated using available data

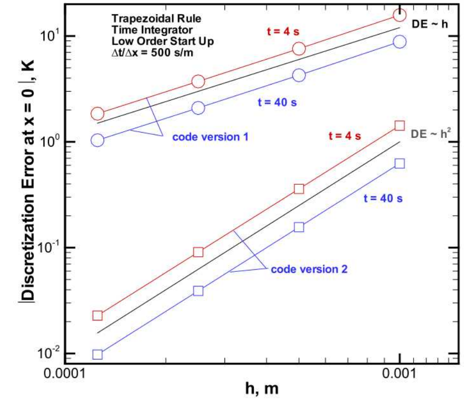
Overview of the Sandia V&V Process



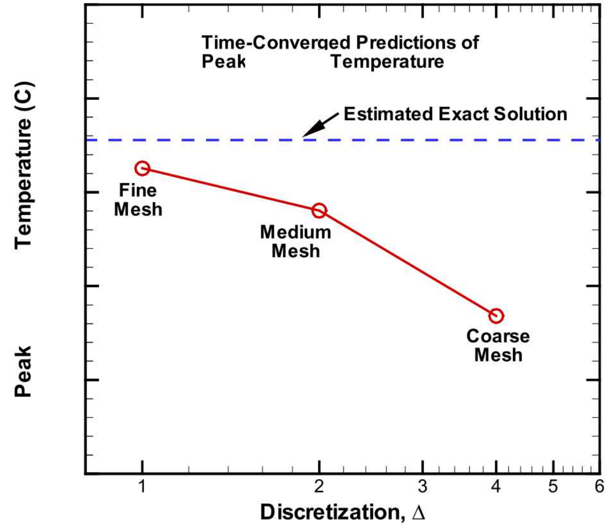
3: Code and Solution Verification

Code: Software quality practices & accuracy checks on test problems





Solution: Convergence checks on engineering application



Code Verification (CVER)

Are software errors or algorithm deficiencies corrupting the simulation results?

- How similar is the code input deck you will use as compared to test problems in the simulation code's verification test suite and regression test suite? That is, how well tested are the features you plan to use for your code runs?
  - The Feature Coverage Tool (FCT)

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Solution Verification (SVER)

Are human procedural errors or numerical solution errors corrupting simulation conclusions?

- Ensure that the simulation code is giving converged results
  - Are you performing a sequence of mesh convergence studies?
  - Are you going to quantify the convergence rate and also estimate the "fully mesh converged" values for your quantities of interest?
  - Are you going to use automatic mesh refinement tools with error estimation (if appropriate)?
  - Do you have a plan to run nominally identical simulations using different: (a) numbers of processors?, (b) types of computers? (c) a different restart sequence?

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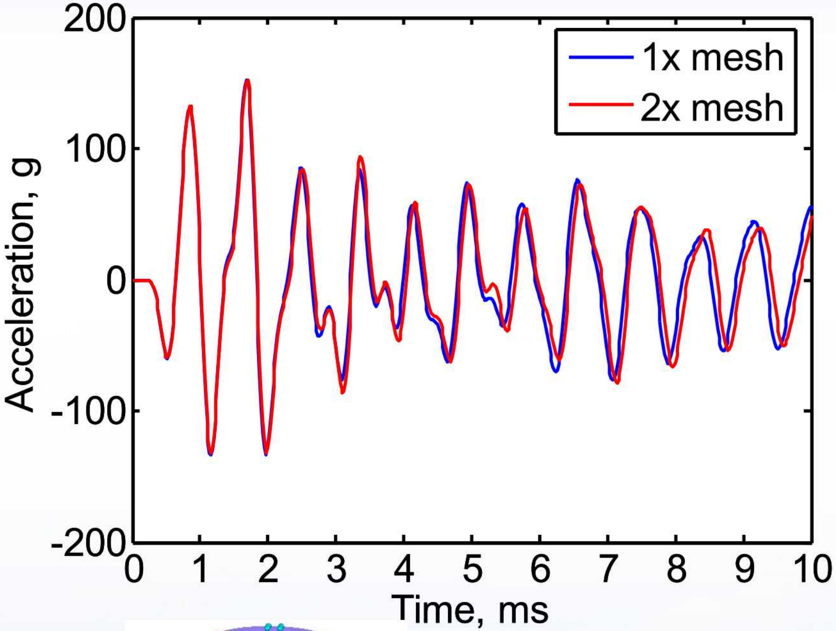
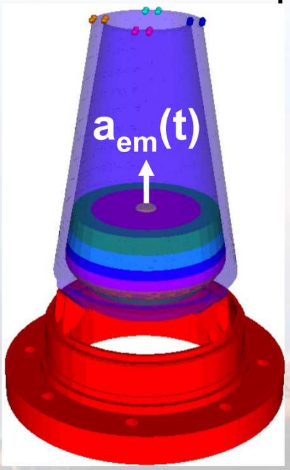
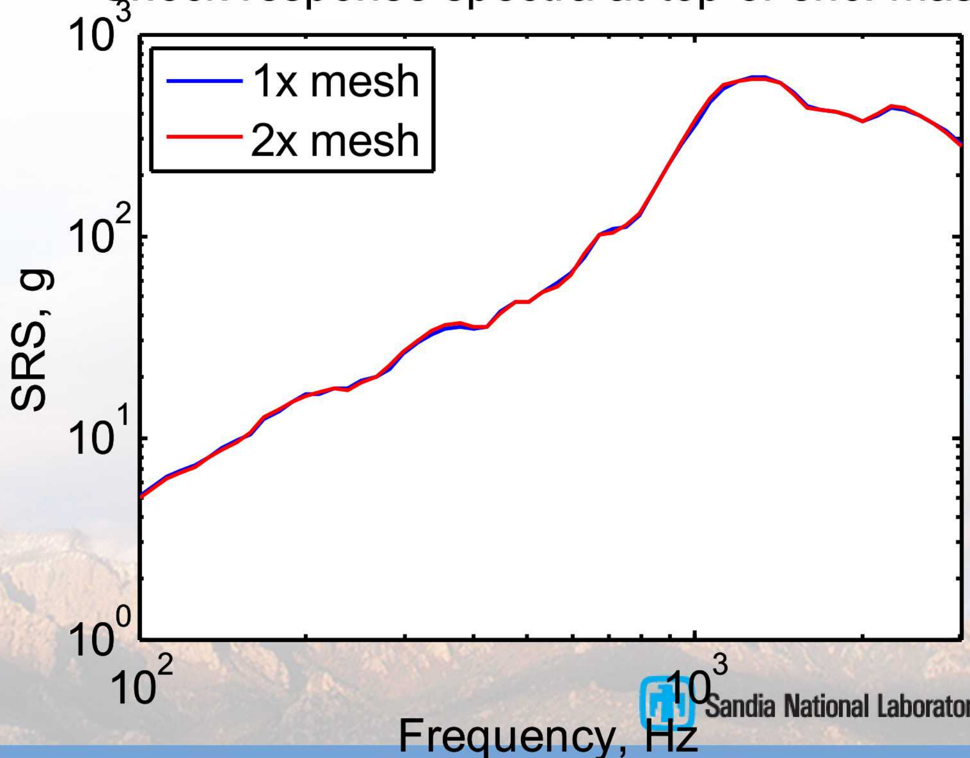
Solution Verification (SVER)



Max. relative error between SRS: +/- 5%



Structural Dynamics



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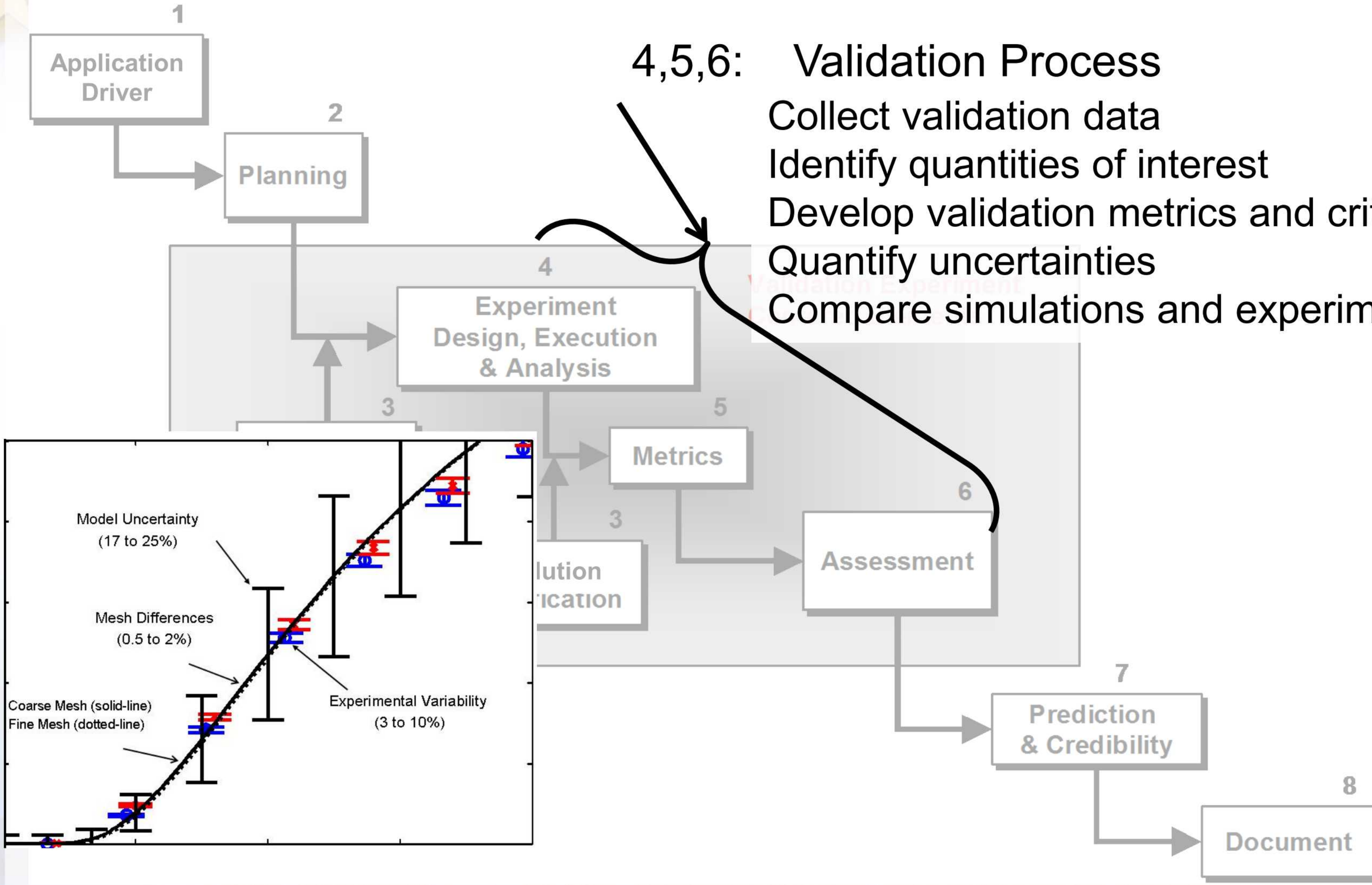
4,5,6: Validation Process

- Collect validation data
- Identify quantities of interest
- Develop validation metrics and criteria
- Quantify uncertainties
- Compare simulations and experiments



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Validation (VAL)

How accurate are the integrated physics and material models?

- What are the quantities of interest that you will be comparing from test data and simulation data?
- What is the source of the test data?
  - Do you have uncertainties on the test data?
    - » If not, how do you plan to compute/estimate uncertainties on the test data?
- How do you plan to compare test data (with its uncertainties) to simulation data (with its uncertainties)
  - Plots? Statistical comparisons? Other?

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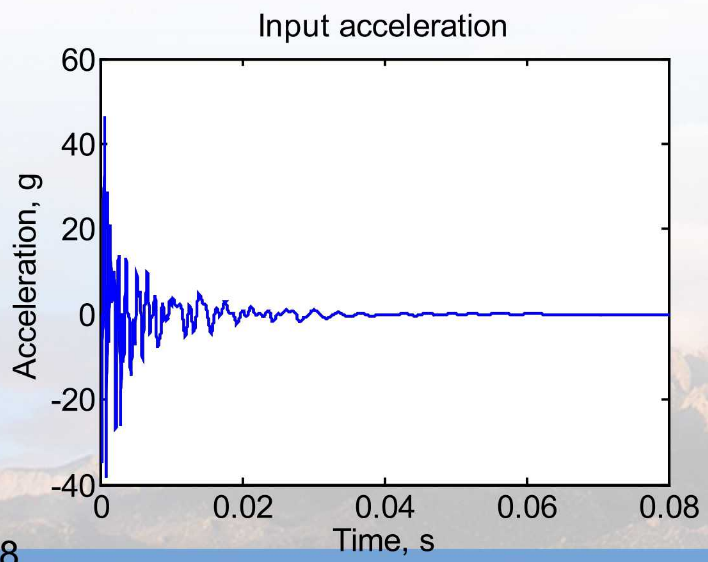
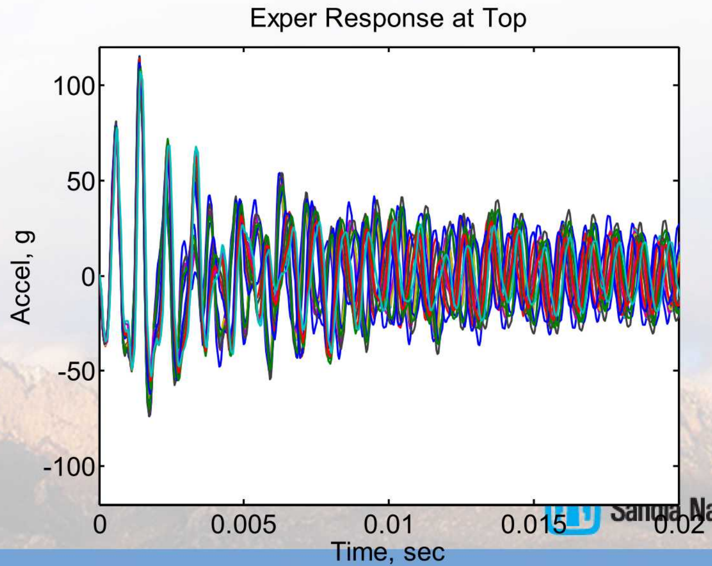
Model Validation Experiments
Unit-to-unit variability

- Hardware consists of 2 top conic sections and 3 bottom sections
- 6 total combinations of top/bottoms x 3 test repetitions = 18 total tests
- Hardware-to-hardware and test-to-test variability examined





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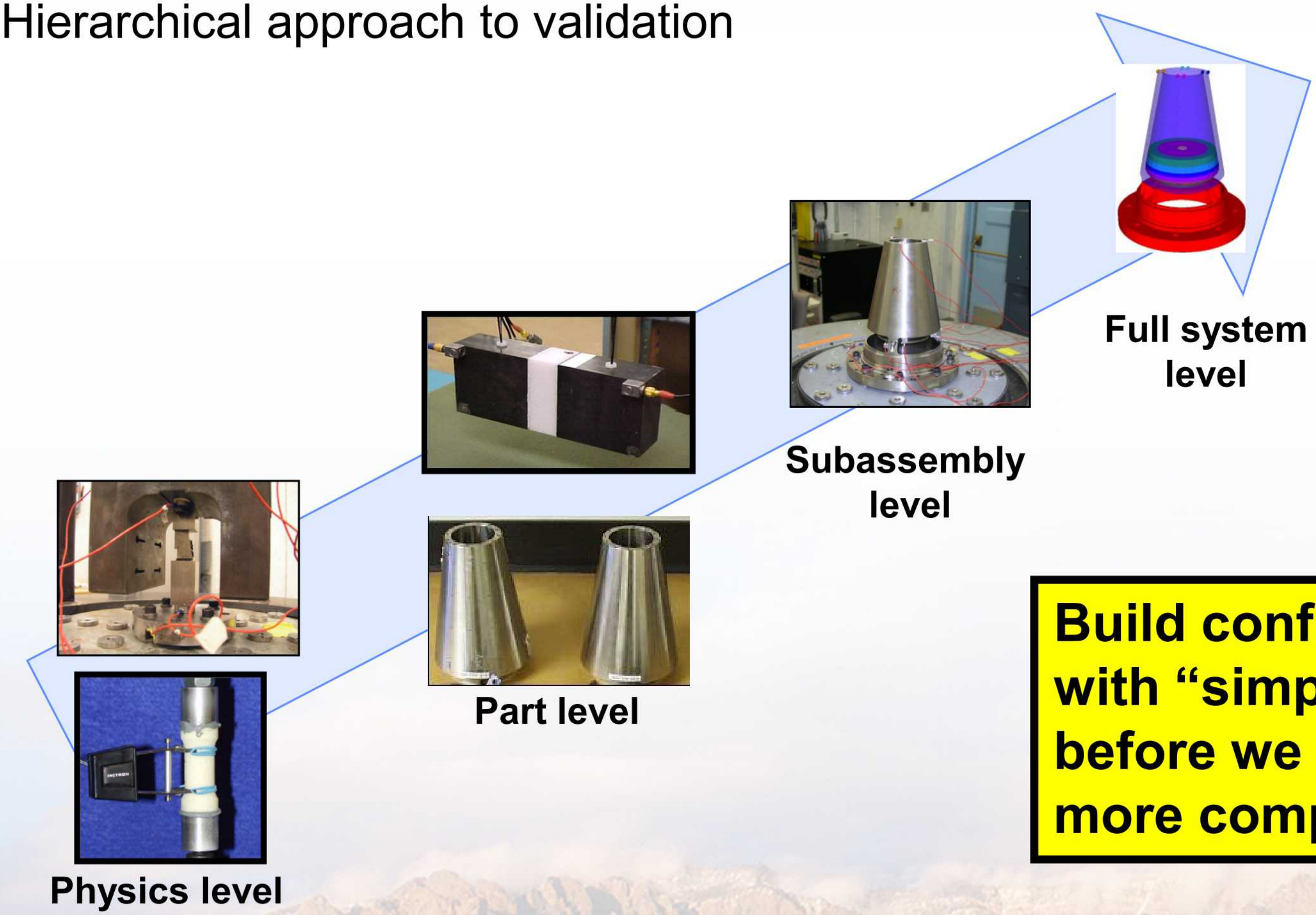
Validation Hierarchy

- Computational models must be validated to be predictive
- Hierarchical approach to validation



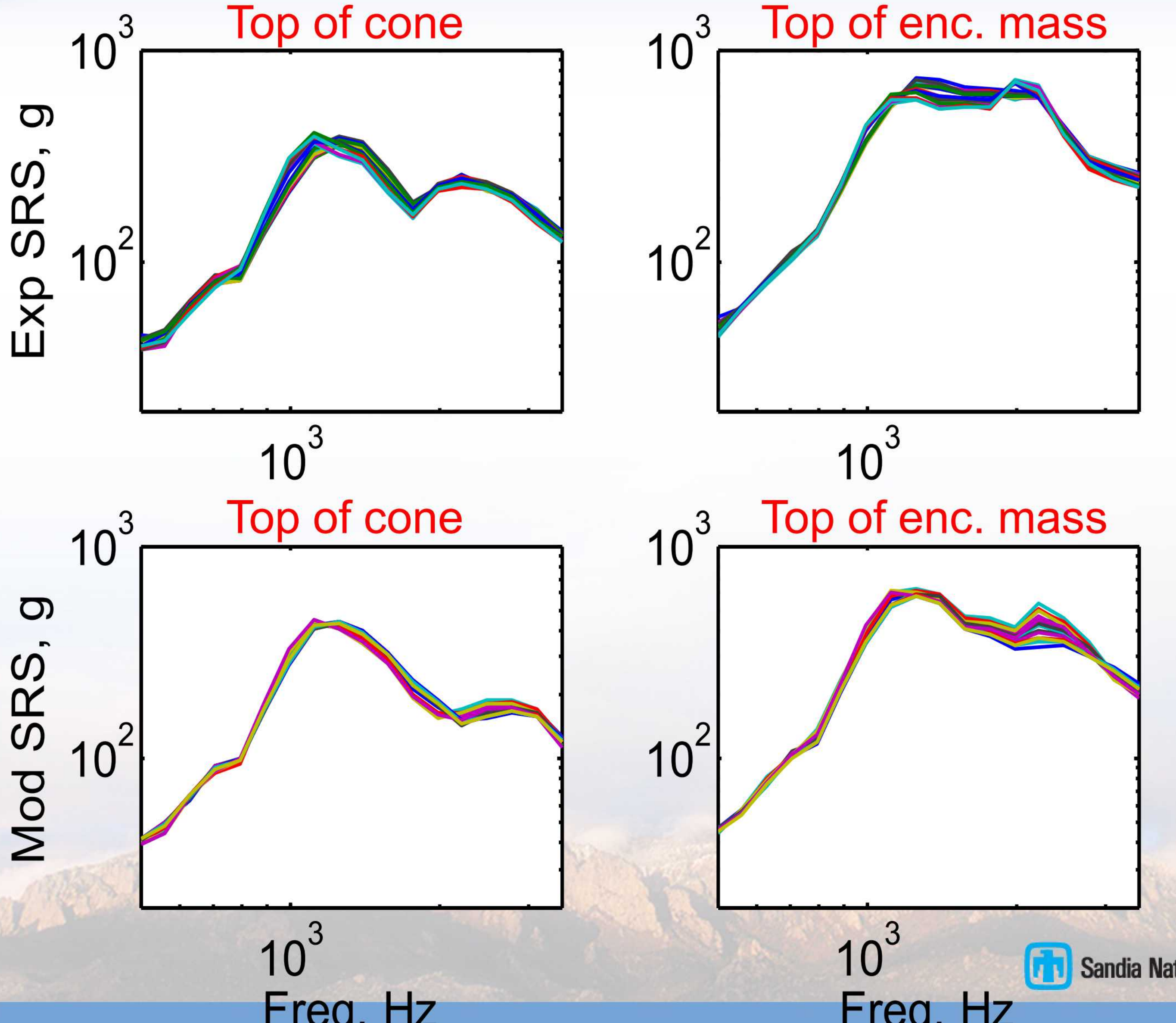
Build confidence with "simple" before we get more complex

- We often cannot test at the applications environment but we still need to assess the situation

Response Measures

- Comparing time histories directly is very difficult
- We propose measures of response based on time histories, such as:
  - Shock response spectrum (SRS)
    - » Measure of the potential of a shock motion to excite peak responses in linear systems.
  - Windowed frequency response function/Critical response/Least favorable response
    - » Integral of the product between a non-negative window and the FRF modulus.
- These measures are the “what” we are using to compare between model and measured data

Response Measure
Shock Response Spectrum



Validation Metrics

- Means for comparing model-predicted response measures to response measures from experiments
  - Deterministic intervals
  - Probability intervals
  - Hypothesis test using CDF

- For this example use a **Deterministic Interval** with the following requirement
  - Requirement:
    - » A deterministic measure of model-predicted response must fall within deterministic bounds that bracket deterministic experimental system response.

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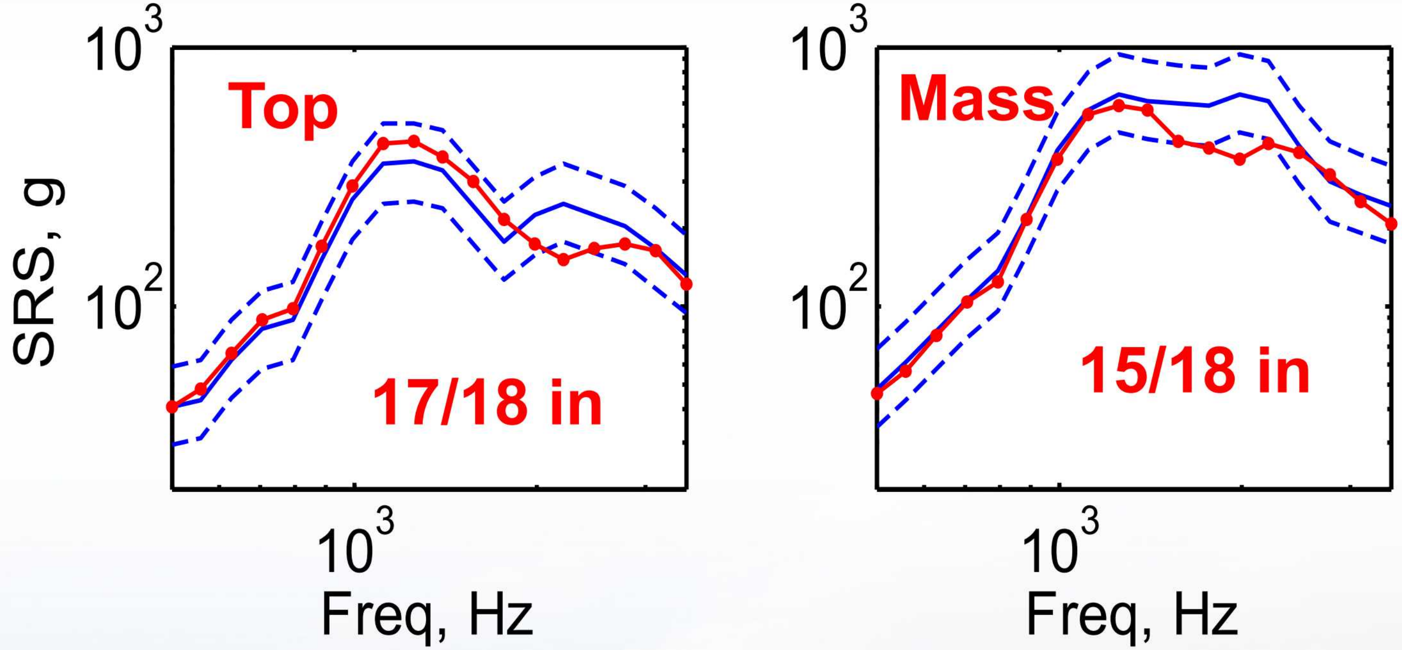
Hierarchy of Measures: Shock Response Spectra



Validation decision: Model cannot be rejected based on:

- **SRS criterion - deterministic intervals**
- **Adequacy criterion specified – 32/36>0.8 model mean SRS ordinates within +/- 3dB of mean experimental SRS ordinate, and remainder within +/- 6dB**

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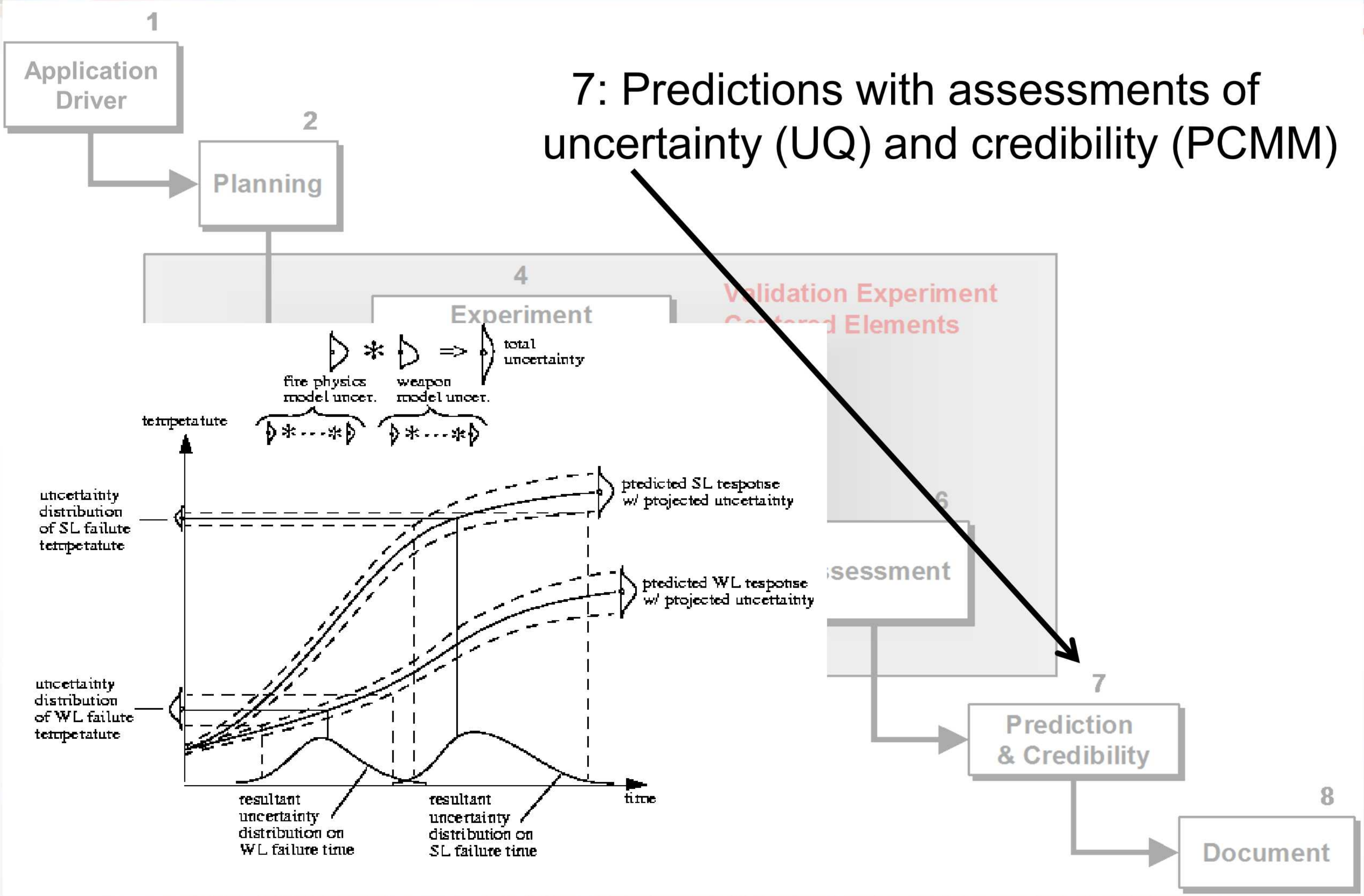
Overview of the Sandia V&V Process

7: Predictions with assessments of uncertainty (UQ) and credibility (PCMM)



Uncertainty Quantification (UQ)

What is the impact of variabilities & uncertainties on system performance and margins?

- What are the key uncertain parameters?
  - If yet to be identified, what is you process to do this?
  - If already identified, what do you know about them (bounds, probability distributions, other)?
- What are the key uncertain physics models in this study?
- How do you plan to propagate uncertainty through your simulation model (i.e. Dakota, etc)?

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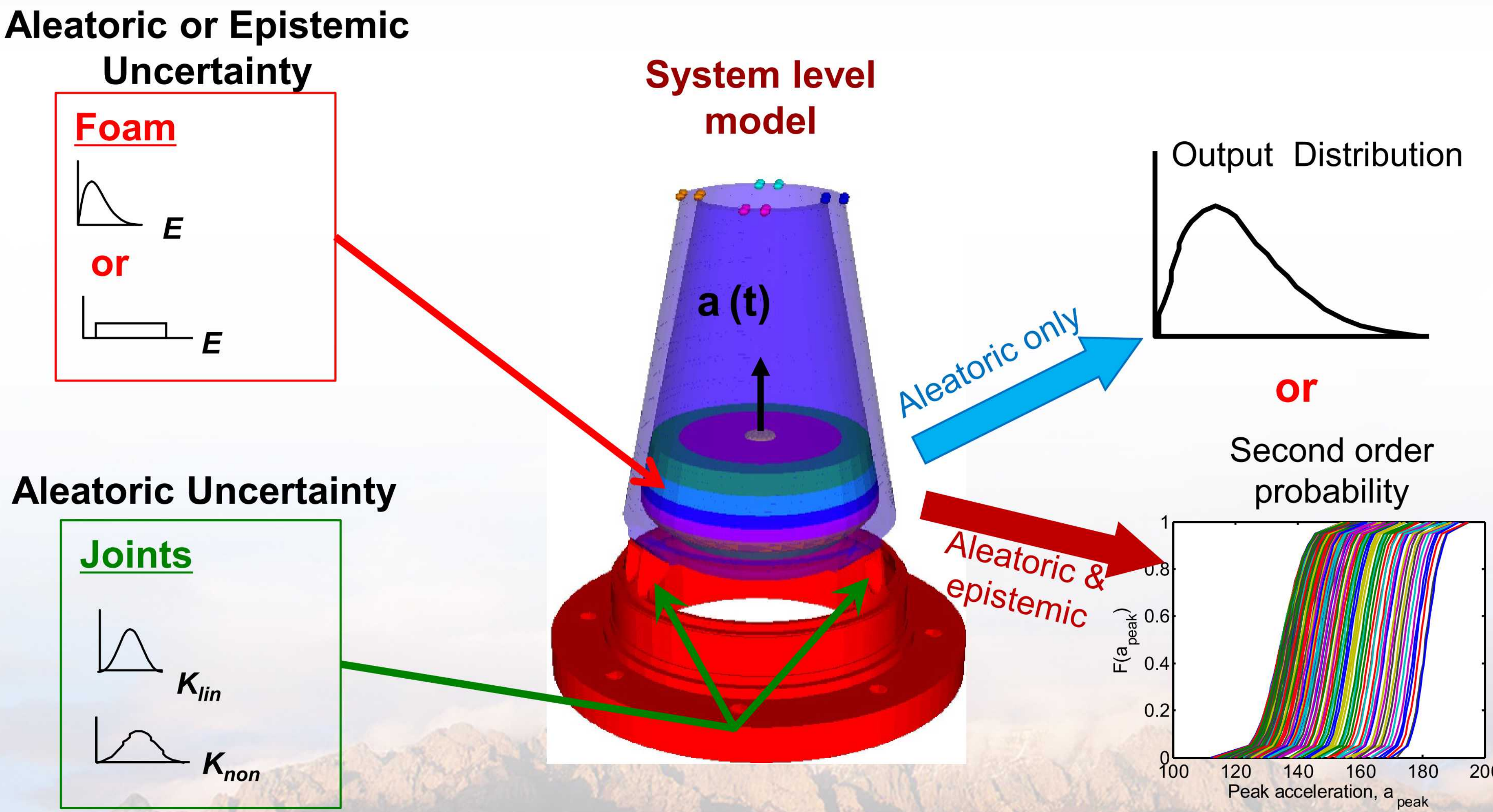
Aleatoric vs. Epistemic Uncertainties

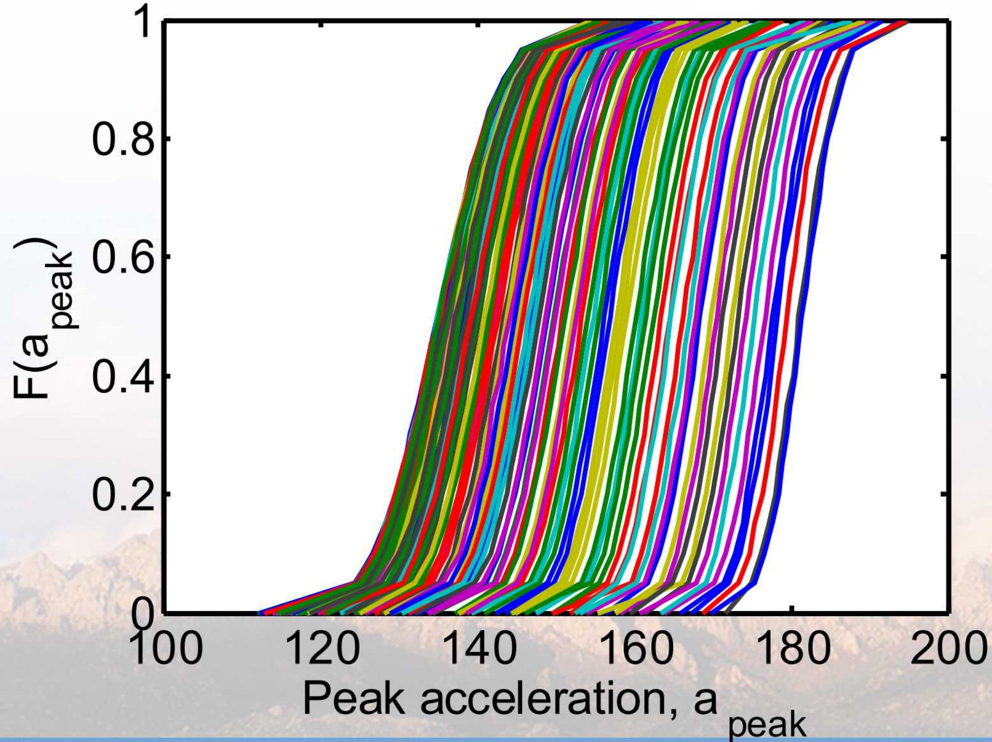
- Aleatory uncertainty: Inherent randomness in behavior of system under study (frequency interpretation)
  - Alternatives: Variability, stochastic uncertainty, irreducible uncertainty, type A uncertainty
  - Examples: component failures or material properties derived from statistically significant testing under conditions relevant to intended application
- Epistemic uncertainty: Lack of knowledge about appropriate value to use for a quantity that is assumed to have a fixed value in the context of a specific analysis (confidence or belief interpretation)
  - Alternatives: state of knowledge uncertainty, subjective uncertainty, reducible uncertainty, type B uncertainty
  - Examples: representative scenarios, unknown parameters in frequency distributions, parameters or models with defensible bounds but no sense of frequency

Uncertainty Propagation



Aleatoric and Epistemic Uncertainty – Second-Order Probability

- Treated *E* as the epistemic outer loop variable with bounds [32000,94000]
- Treated bolted joint parameters as the aleatory inner loop variables with normal distributions and statistics obtained from **Physics Level** experiments
- Performed UQ analysis using DAKOTA



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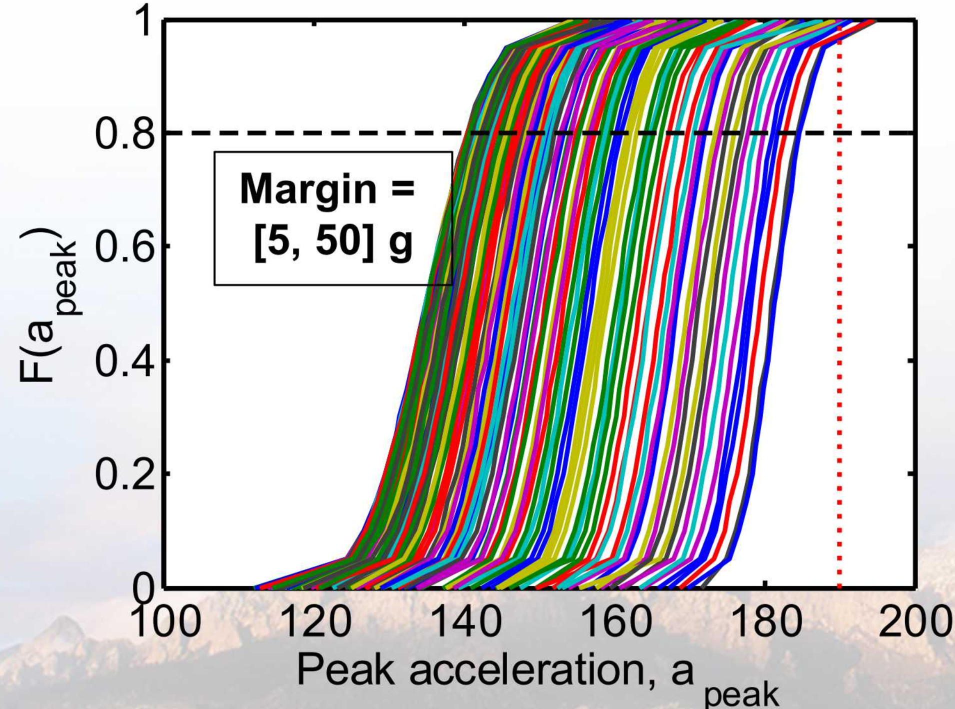
Margin Analysis: Second Order Probability

- There is a family of CDFs, which provide a bounding interval.
- Margins may be defined for moments or percentiles (e.g. the median response must be less than R). The interval on the moment as defined by the "envelope" of CDFs is used to generate an upper and lower bound on the margin.
- Using the 80th percentile, the interval on margin are:



For comparison, if source of uncertainty are treated as aleatoric, then at the 80th percentile:

Margin = 27 g.

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Summary

- The basic terminology relating to V&V was presented and the V&V process at Sandia was shown.
- A structural dynamic example was used to illustrate the V&V process.
- For brevity, the PCMM (Predictive capability maturity model) assessment was not presented but it was completed.
- One of the main reasons for having a V&V process is to increase the confidence in CompSim results.