SAND2007-2940C

Development of Experimental Model Validation Data for Viscoelastic Foam Models

7th Biennial Tri-Laboratory Engineering Conference

May 10th, 2007

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Foam Development and Validation

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Foam Development
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Foam Development

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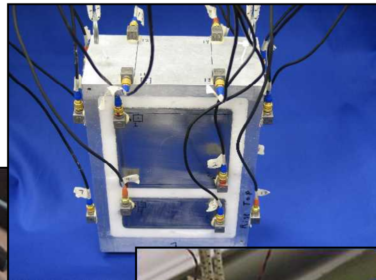
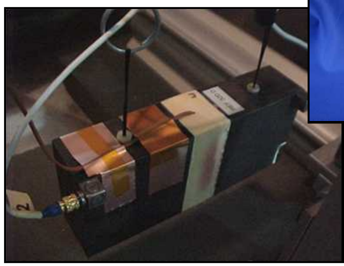
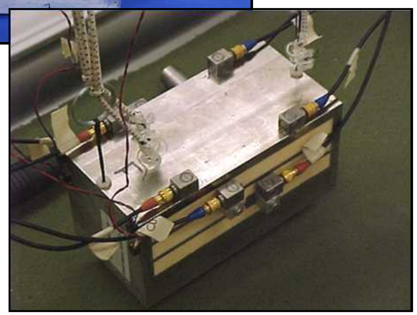
Potting Foam Validation

Phase II





Phase I



Phase III

Problem Description:

- Many weapon components use potting foam to mitigate shock and vibration
- The objective of this project is to improve the modeling capability of systems and components using foam encapsulants.

Technical Approach/Challenges:

- Complete temperature testing of Phase II and Phase III geometries
- Analyze and prepare data for use in validation process
- Support validation of Phase I, II and III models using sub-ambient and elevated temperature experimental data
- Archive data and write test and validation reports

Team Members

PI: *Chris O'Gorman, 1521*

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Computational PI:

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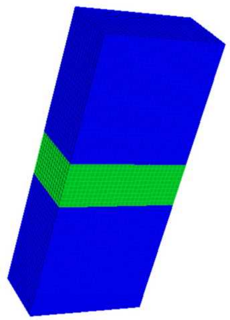
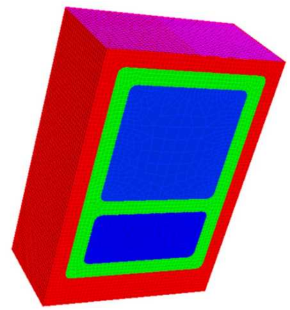
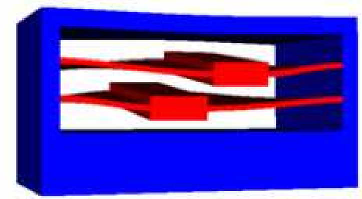
Project Objectives

Foam Development Activities

- EF-AR20
  - Constitutive, Phase I, Phase II and Phase II
  - Focus of Level II Hostile Blast Milepost
  - ECS and LFU
- REF-308
  - Constitutive, Phase I and Phase III
- REF-320
  - Constitutive and Phase I
- RSF-200
  - Constitutive and Phase I
- PMDI-8
  - Constitutive and Phase I
- TF-6070-8.5
  - Very little data (W80-3), system level tests performed

Development Process

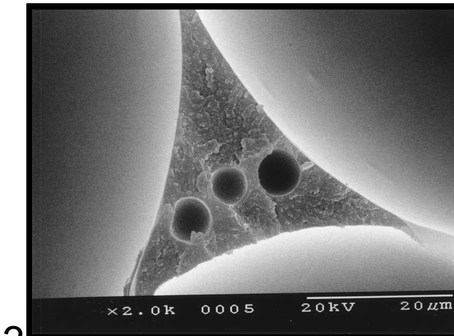
Phase 0	Phase I	Phase II	Phase III
			
Constitutive	Dumbbell	Rigid Component	Flexible Body

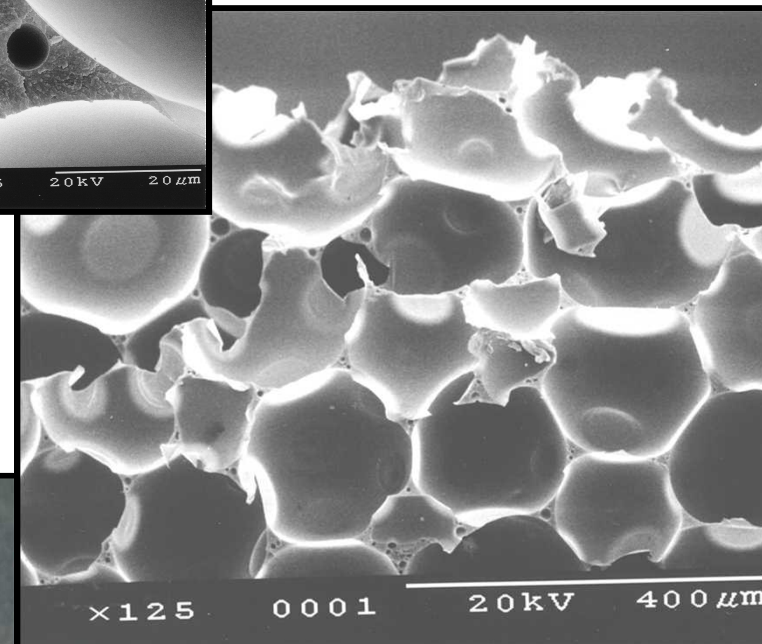
INCREASED COMPLEXITY

- Project experiments will emphasize the fundamental physics associated of foam-confined components with geometries of increased complexity
- The physical parameter space is significantly simplified, but the **environmental parameter space** involving temperature, frequency, strain and density **will be maintained**

Foam Description

- "Rigid" Epoxy Foam
- Closed-Cell
- Nominal Density - 20 lb/ft^3
- Mitigate shock and vibration
- Average cell diam. ~200 µm





Ambient Calibration Geometries

Phase 0 - Constitutive Testing with Foam Coupon Samples

- E(ω,T,ρ), G(ω,T,ρ), ν
- ω – DMA, Phase I Modes
- T – Tg, DMA, Phase I Modes

Phase I - Component Testing with Foam between end-blocks

- Phase I Samples will be characterized using Modal Tests
- Foam properties are only unknowns
- Component Response is very sensitive to Foam properties

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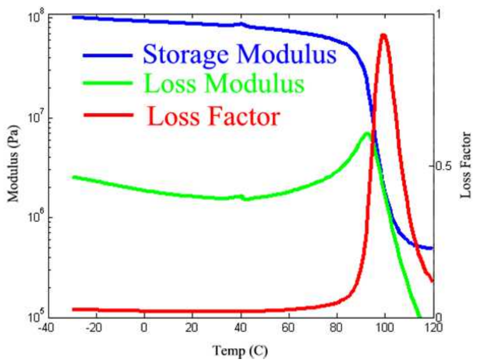
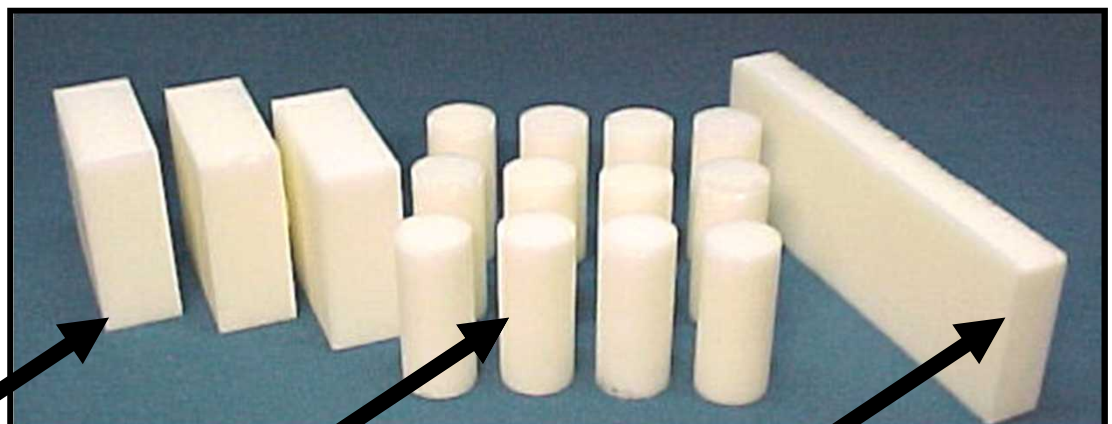
Constitutive Experiments

Foam Characterization

- **5 ea. Tensile Modulus Tests**
- **5 ea. Compressive Modulus Tests**
- **5 ea. Shear Modulus – Tg Tests**
- **5 ea. Shear Modulus – DMA Tests**

- Total of 20 data sets collected the characterize E and G
- Parameter space includes temperature and frequency
- Inherent variation as replicate samples differ in mean density





Phase I Blocks

Tensile and Compressive Modulus Blocks

Tg and DMA Block

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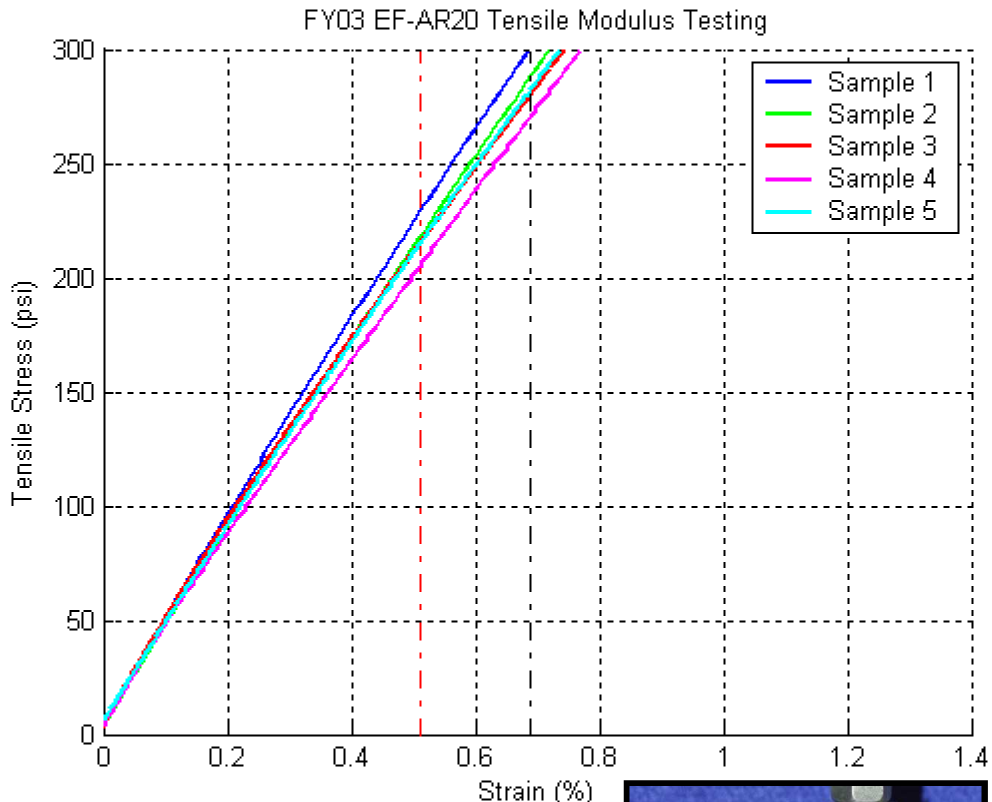
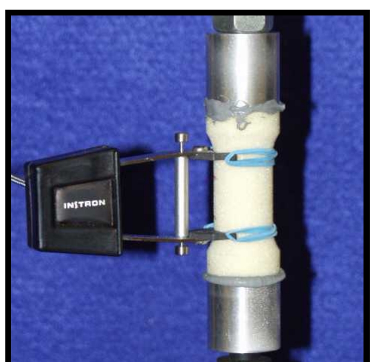
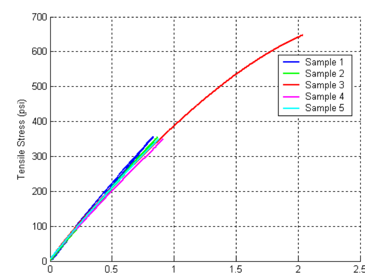
EF-AR20 Tensile Modulus Testing



Sample	Density (lb/ft3)	Strain (%)	Et (psi)
3	18.5	0.6	36,568
5	18.5	0.6	37,725
4	19.1	0.6	36,622
2	19.6	0.6	39,277
1	19.9	0.6	40,590

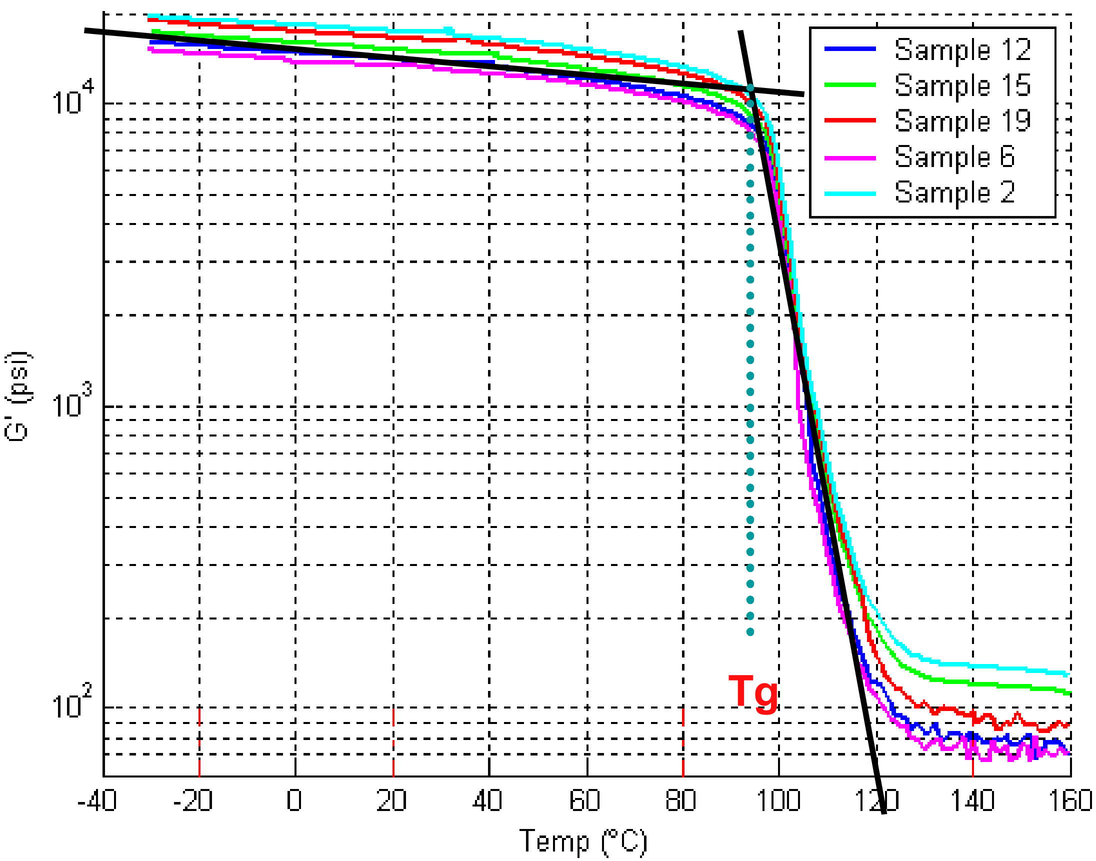
- Slightly nonlinear stress-strain relationship due to cellular interaction
- Specimen failure at ~2% strain
- Consistent failure at lower extensometer knife edge

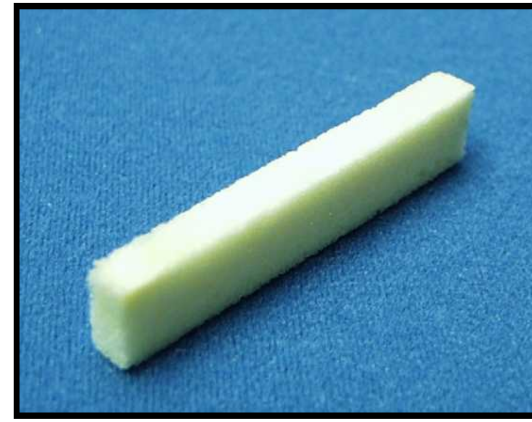




EF-AR20 Tg Calibration Data

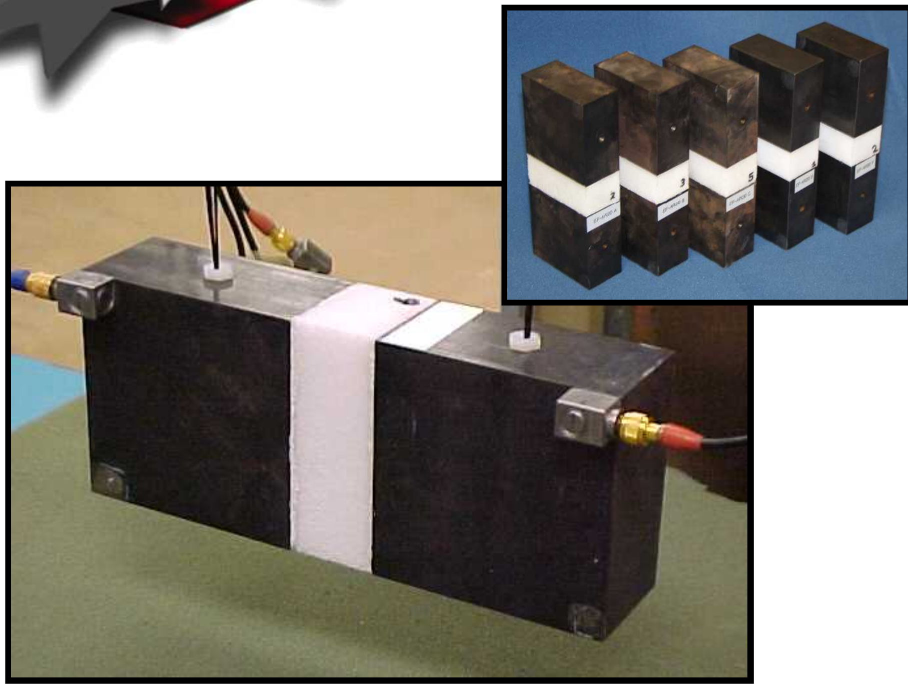
Sample	Density (lb/ft3)	G (psi) Temp -20 C	Temp 20 C	Temp 80 C	Temp 140 C
6	18.2	14,649	13,445	10,080	72
12	18.4	15,519	14,040	10,588	82
15	19.5	16,679	15,229	11,400	120
19	20.5	18,275	16,534	12,488	97
2	20.7	19,000	17,405	13,155	137

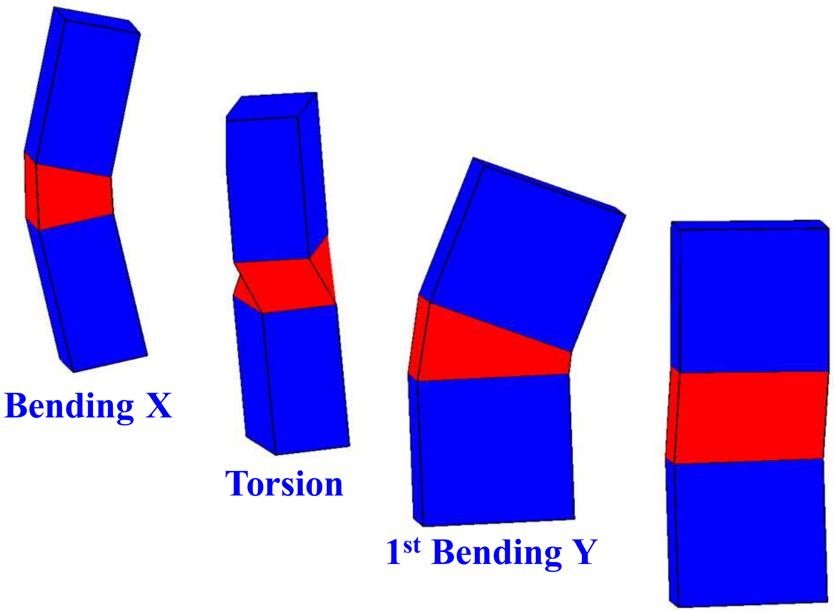




- Torsional strain at 1 Hz
- Temperature varied from -30˚C to 160˚C
- Temperatures defined by specified application space
- Modulus changes by 2 orders of magnitude from glassy to rubbery
- Tg ~ 95˚C

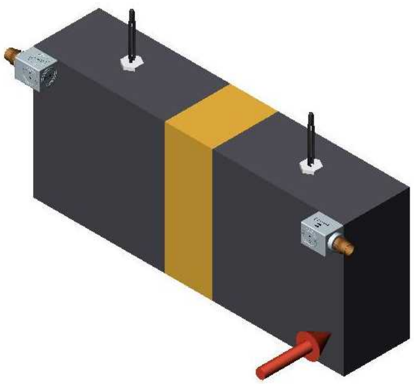
EF-AR20 Phase I Data



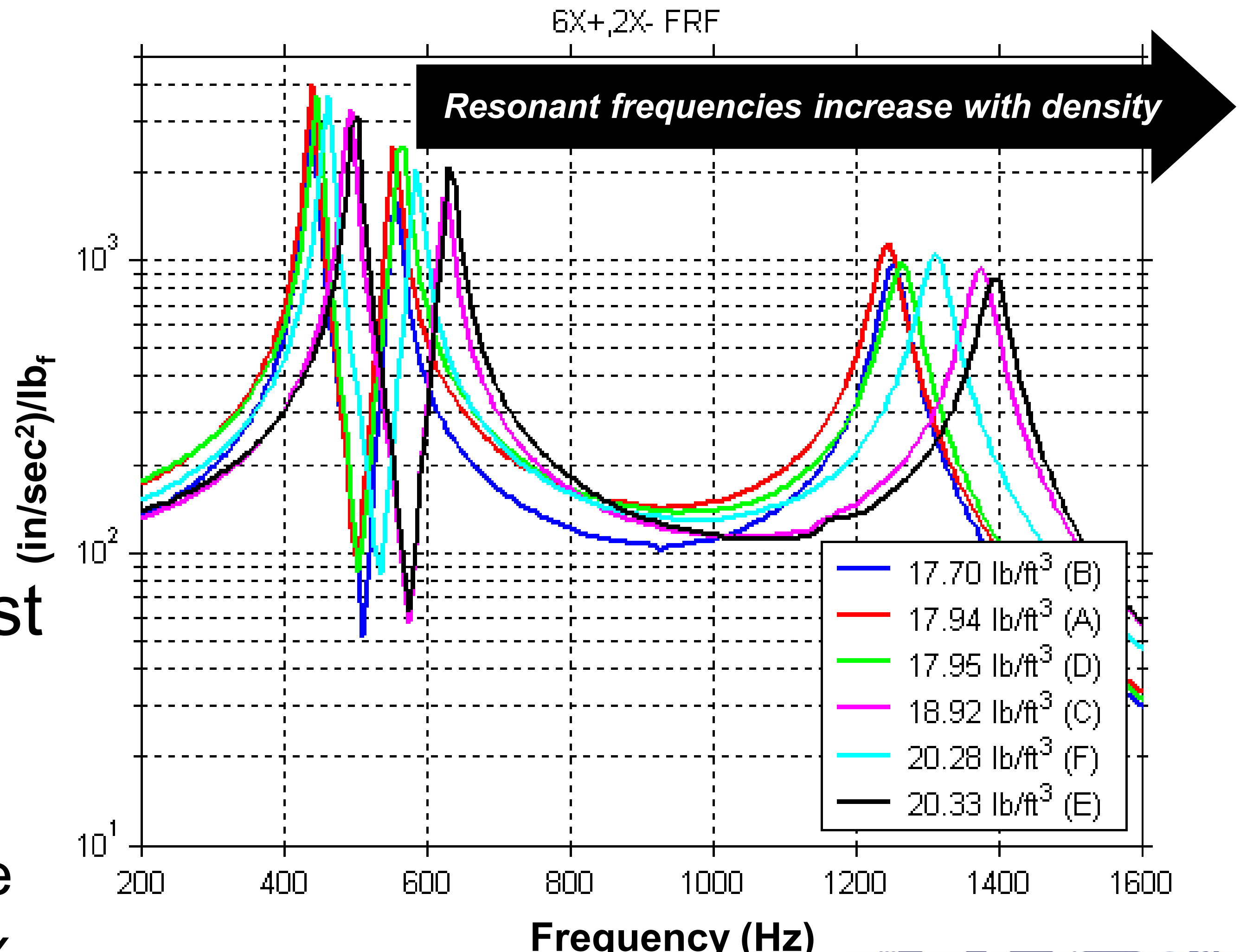


- Phase I samples used to supplement constitutive data
- Mechanism to test various frequencies at room temperature
- Low strain helps minimize uncertainties caused by cellular interaction

Calibration Data – Input 6x



- Impacts optimized to excite the most modes
  - 1^{st} bending X
  - Torsion mode
  - 2^{nd} bending X



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EF-AR20
Phase I Calibration Data Summary

Mode #	Mode Description	Sample A 17.94 lb/ft^3		Sample B 17.70 lb/ft^3		Sample C 18.92 lb/ft^3	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	1st Bending X	440.7	1.3	430.5	1.3	462.3	1.3
2	Torsion	553.7	1.3	543.3	1.3	585.4	1.3
3	1st Bending Y	724.8	1.3	710.7	1.4	755.2	1.3
4	Axial	1045.2	1.4	1038.3	1.5	1088.7	1.4
5	2nd Bending Y	1113.1	1.4	1090.0	1.4	1176.1	1.4
6	2nd Bending X	1246.1	1.5	1226.9	1.5	1312.8	1.5

Mode #	Mode Description	Sample D 17.95 lb/ft^3		Sample E 20.33 lb/ft^3		Sample F 20.28 lb/ft^3	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	1st Bending X	445.5	1.2	501.7	1.2	493.2	1.2
2	Torsion	561.0	1.3	633.8	1.2	626.9	1.3
3	1st Bending Y	730.7	1.3	814.9	1.3	807.1	1.3
4	Axial	1053.3	1.4	1159.6	1.3	1144.9	1.3
5	2nd Bending Y	1119.6	1.4	1234.6	1.4	1227.5	1.4
6	2nd Bending X	1258.7	1.5	1396.0	1.4	1375.4	1.4

Characterization of Test Uncertainty

Magnitude Error 4.7%

1. Accelerometer 4%
   - Impact Level
   - Orientation
2. Data Acquisition 2.5%
   - Meter
   - DC Offset
   - Mean Amplification
   - Amplification Uncertainty

Error Description	Error (%)
Meter Uncertainty	0.1
DC Offset	0.3
Error in Mean Amplification	2.1
Amplification Uncertainty	1.3
Total Uncertainty	2.5

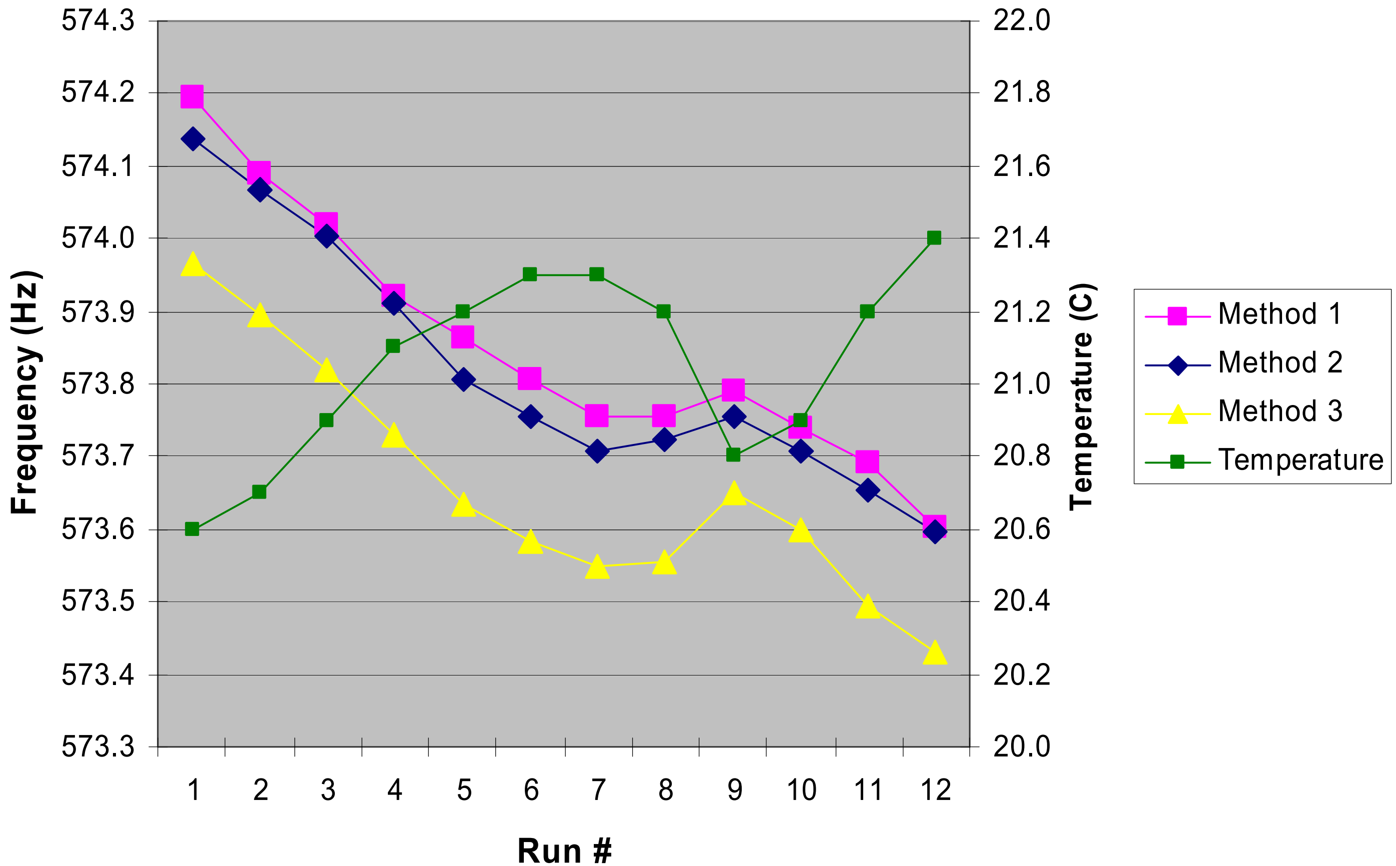
Frequency Error 2.4%

Damping Error 13.3%

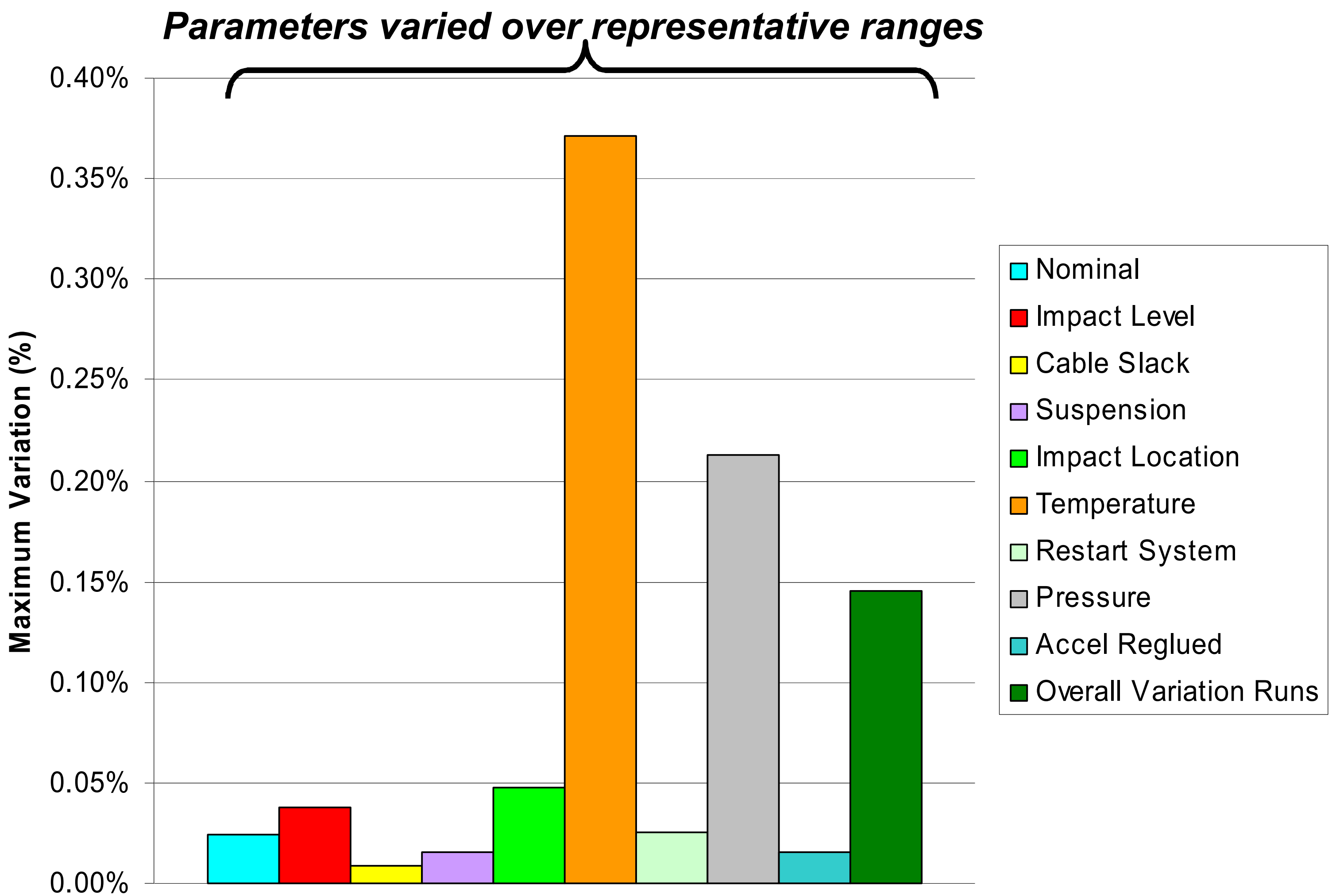
1. Test/Test
2. Setup/Setup
   - Cable Slack
   - Mass Loading/Damping
   - Impact Level
   - Orientation
   - Frequency Resolution
3. Unit/Unit
4. Environmental
   - Temperature
   - Pressure
   - Humidity
5. Other
   - Aging

Test/Test Variability

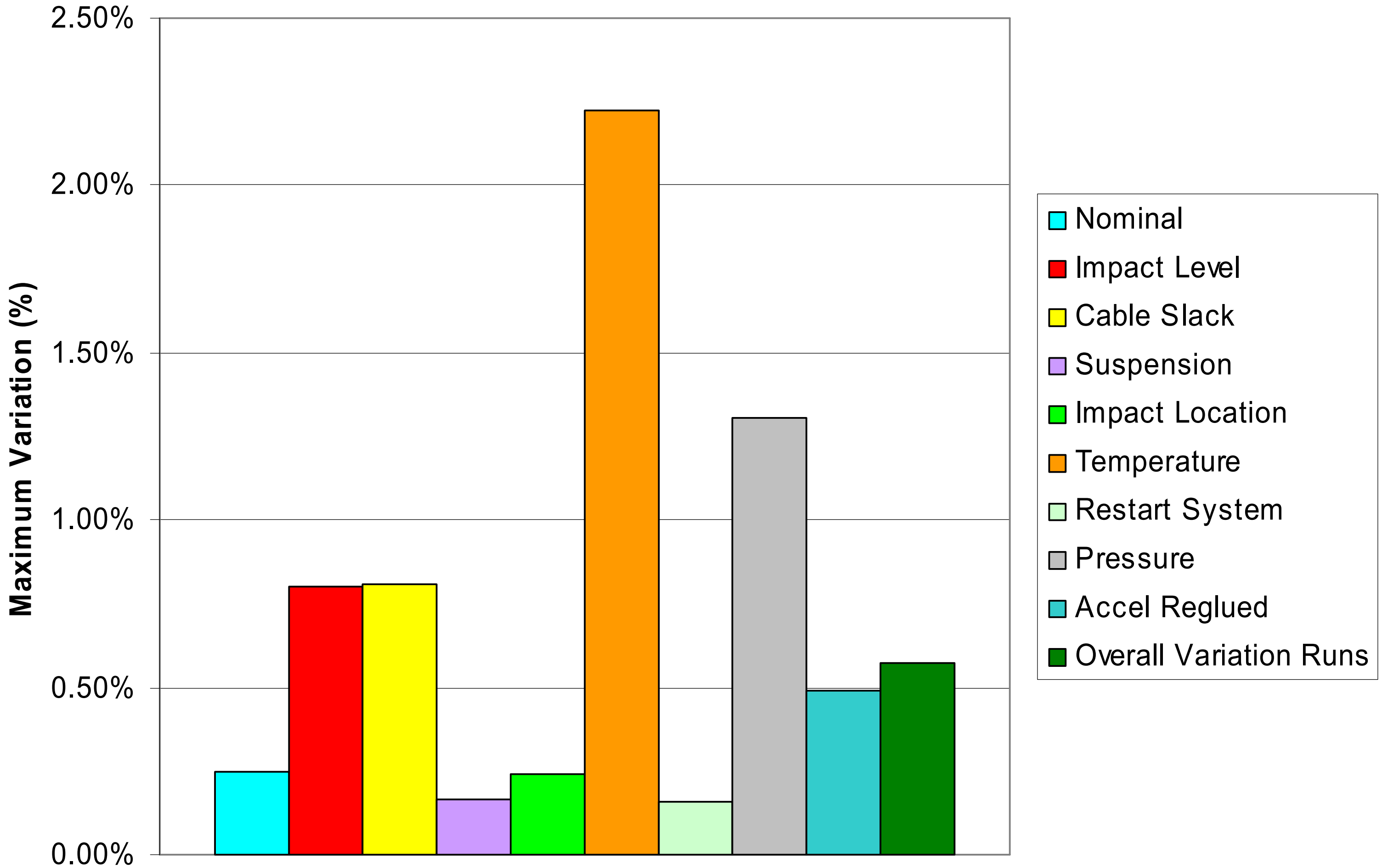
- **"Bias" variation in fit method**
- **Frequencies appear to be decreasing**
- **Minimal Test/Test variation (~0.14%)**
- **Technique able to observe small variations**



Phase I
Test Uncertainty – Frequency



Phase I
Test Uncertainty – Damping

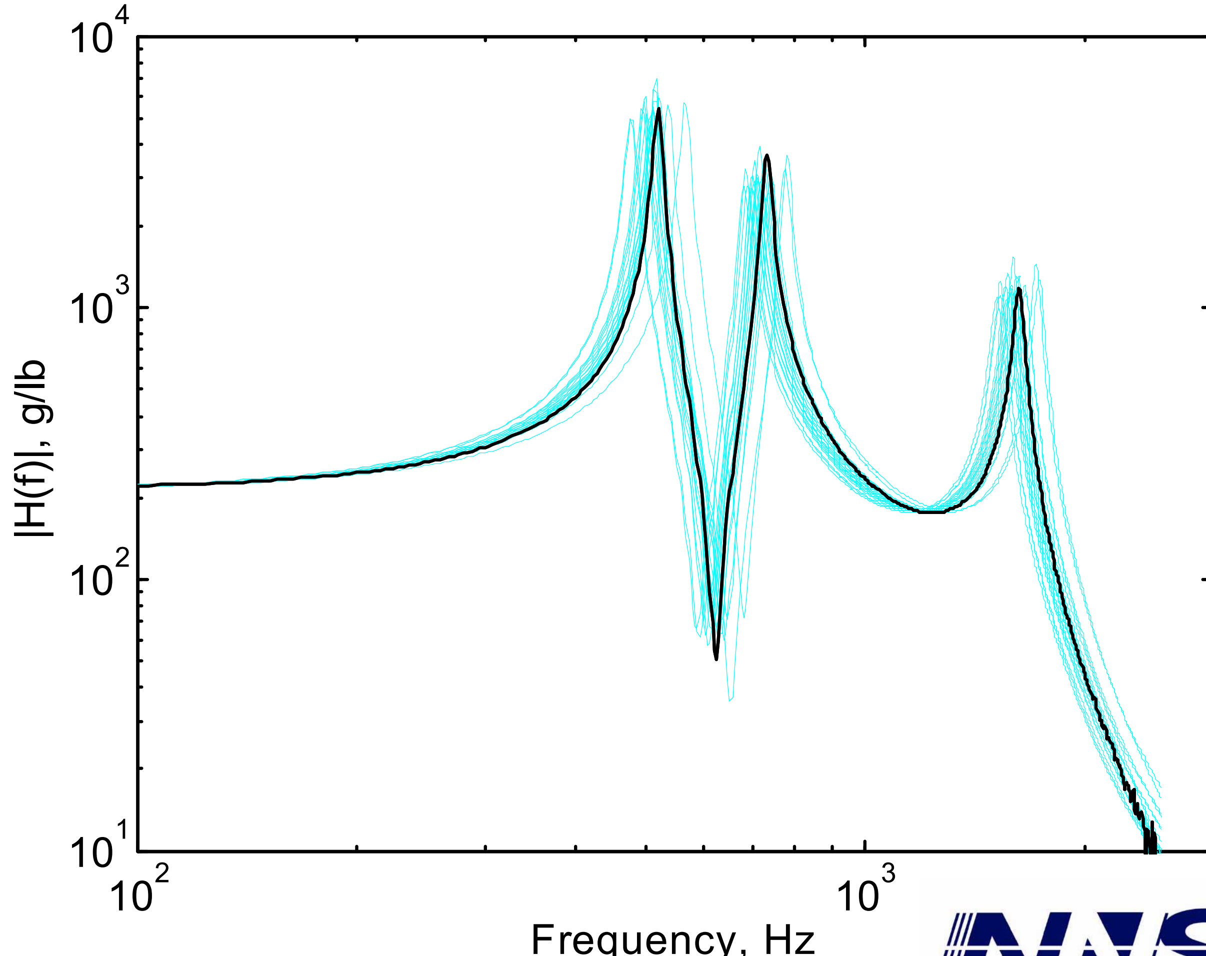


Experiment/Model Prediction

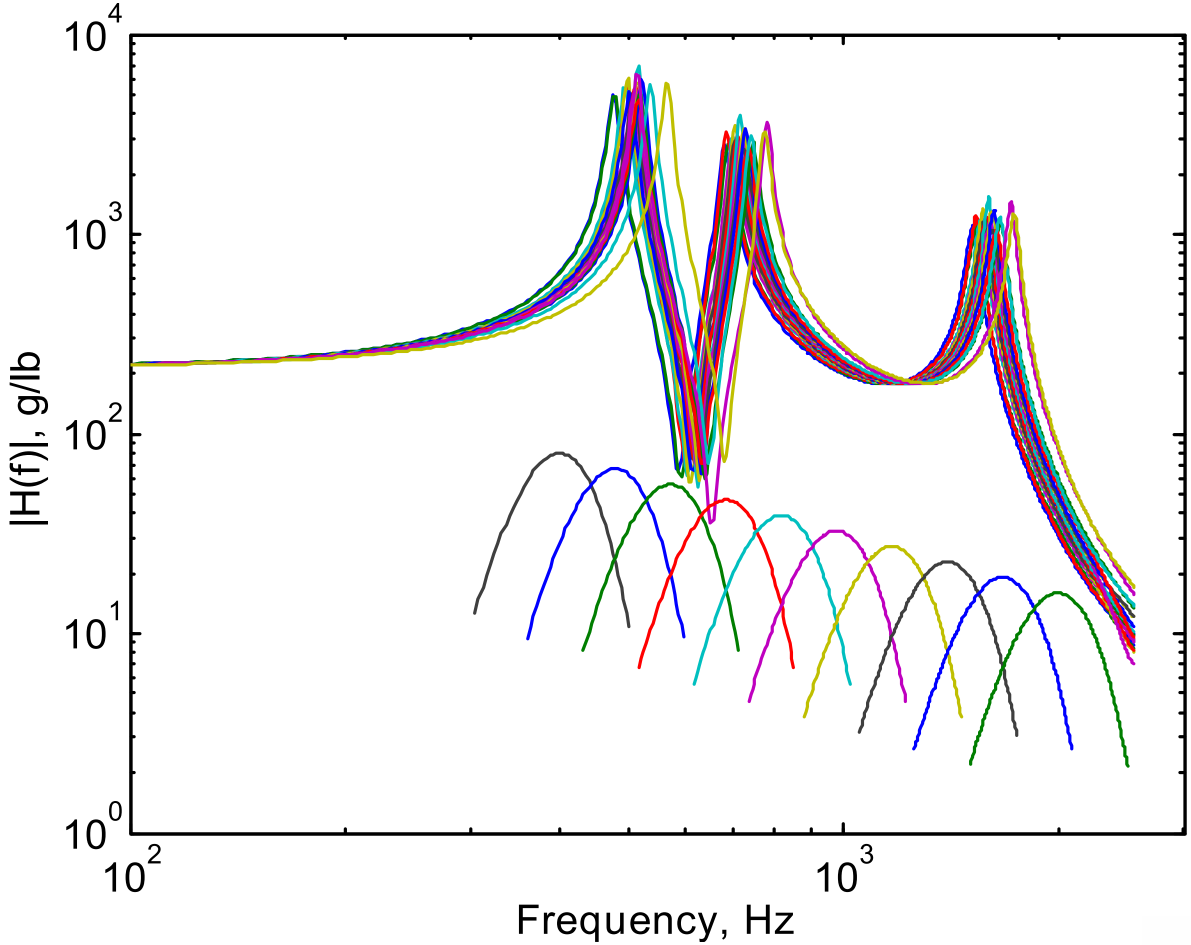
x – direction, ρ = 16.42 lb/ft^3

Experiment
- One realization
- At each of five densities
- Tested in three directions

Model
- 20 Realizations
- At each of the five densities
- Predicted in three directions

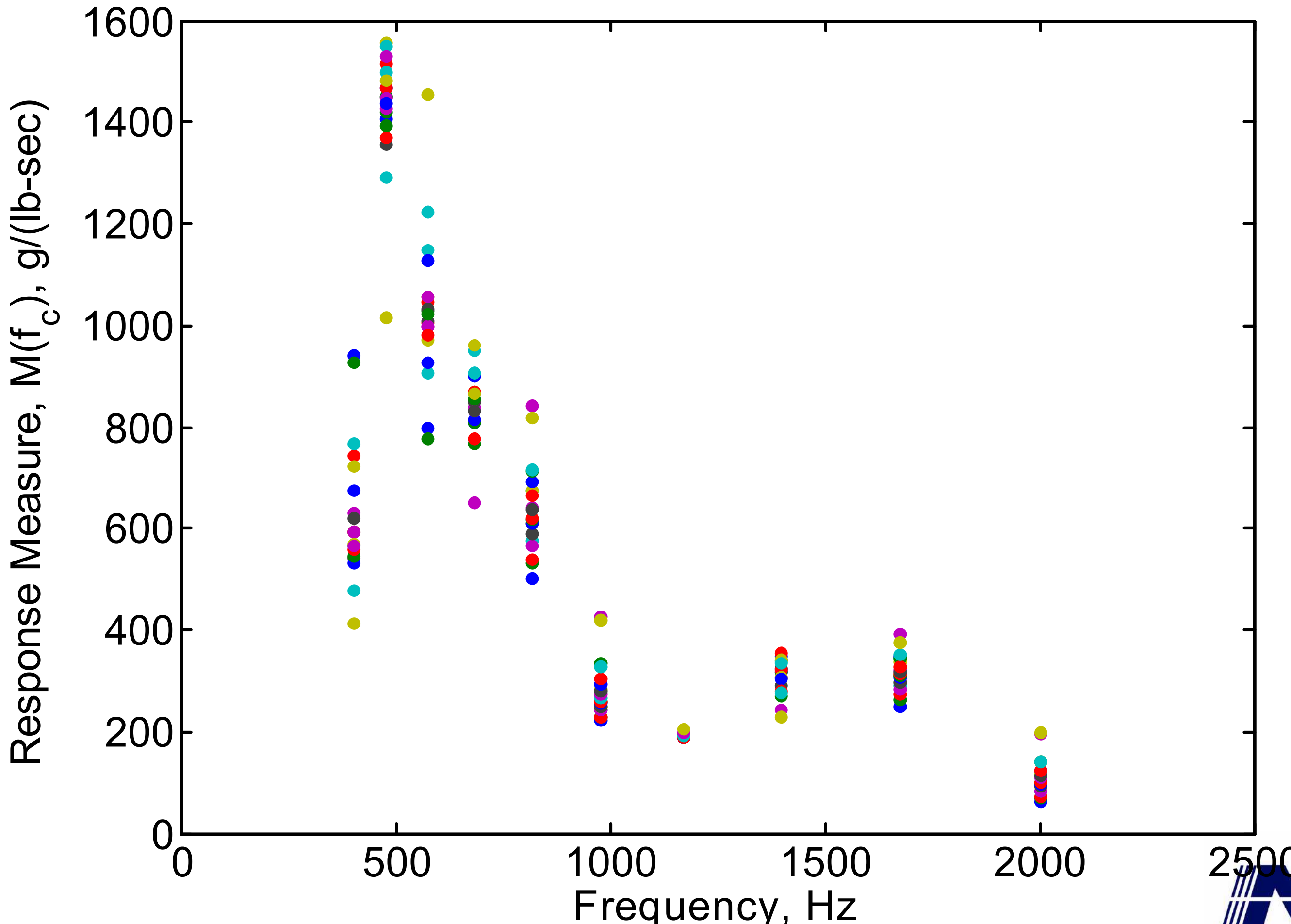


Computation Graphic



Example of the Response Measures

Phase I Validation Specimen, 16.42 lb/ft^3, *x* - direction



Validation Comparison

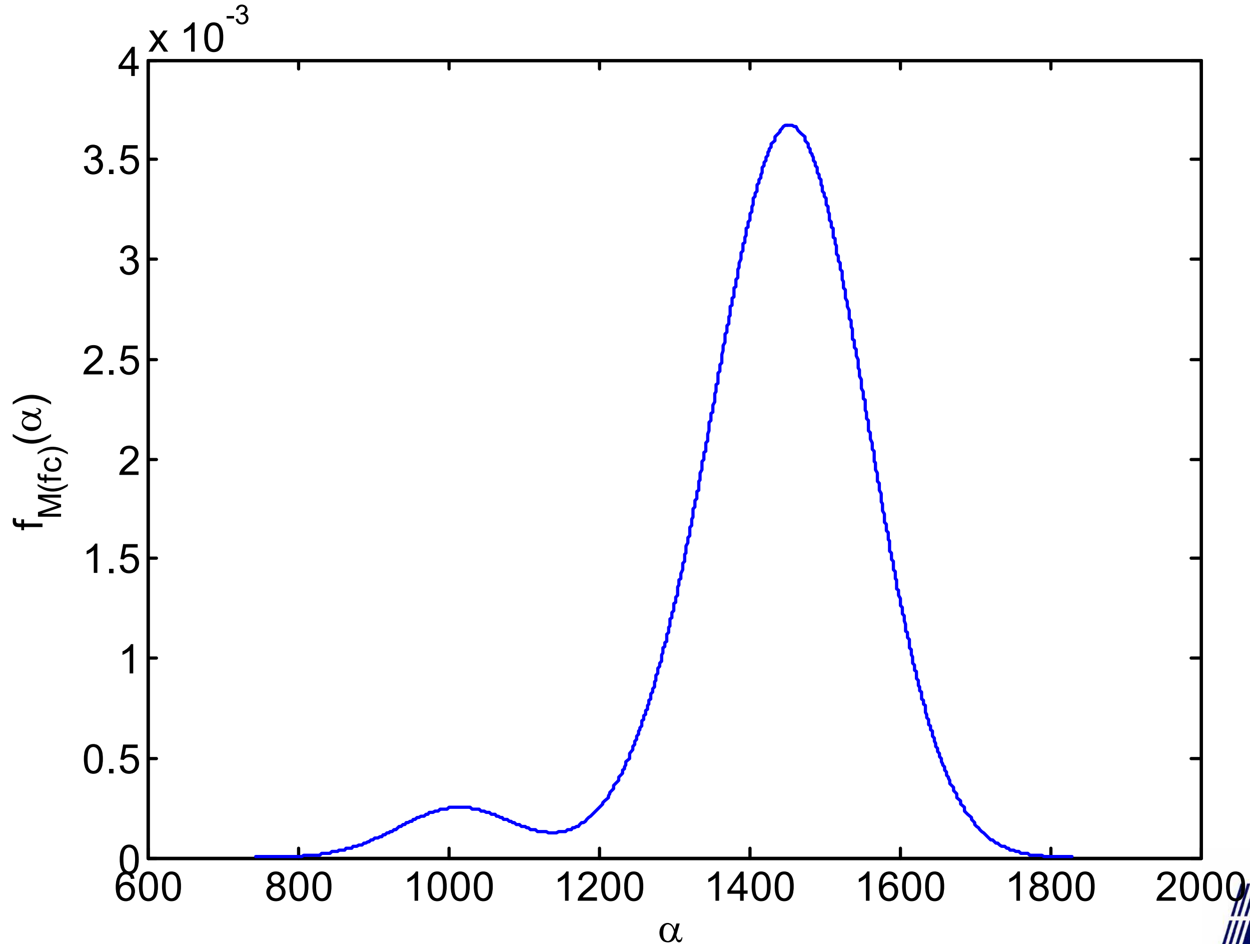
- Estimate the PDF of response measures from realizations of mathematical model FRF.
- Compute 90% probability intervals of response measures from PDFs.
- Locate experimental response measures, $M_{exp}(f_c)$, wrt 90% probability intervals $[L_{90}, U_{90}]$ of math model-predicted response measures, $M_{mod}(f_c)$.

85%

- If $M_{exp}(f_c)\ \varepsilon\ [L_{90}, U_{90}]$ model acceptable
- Else, model not acceptable

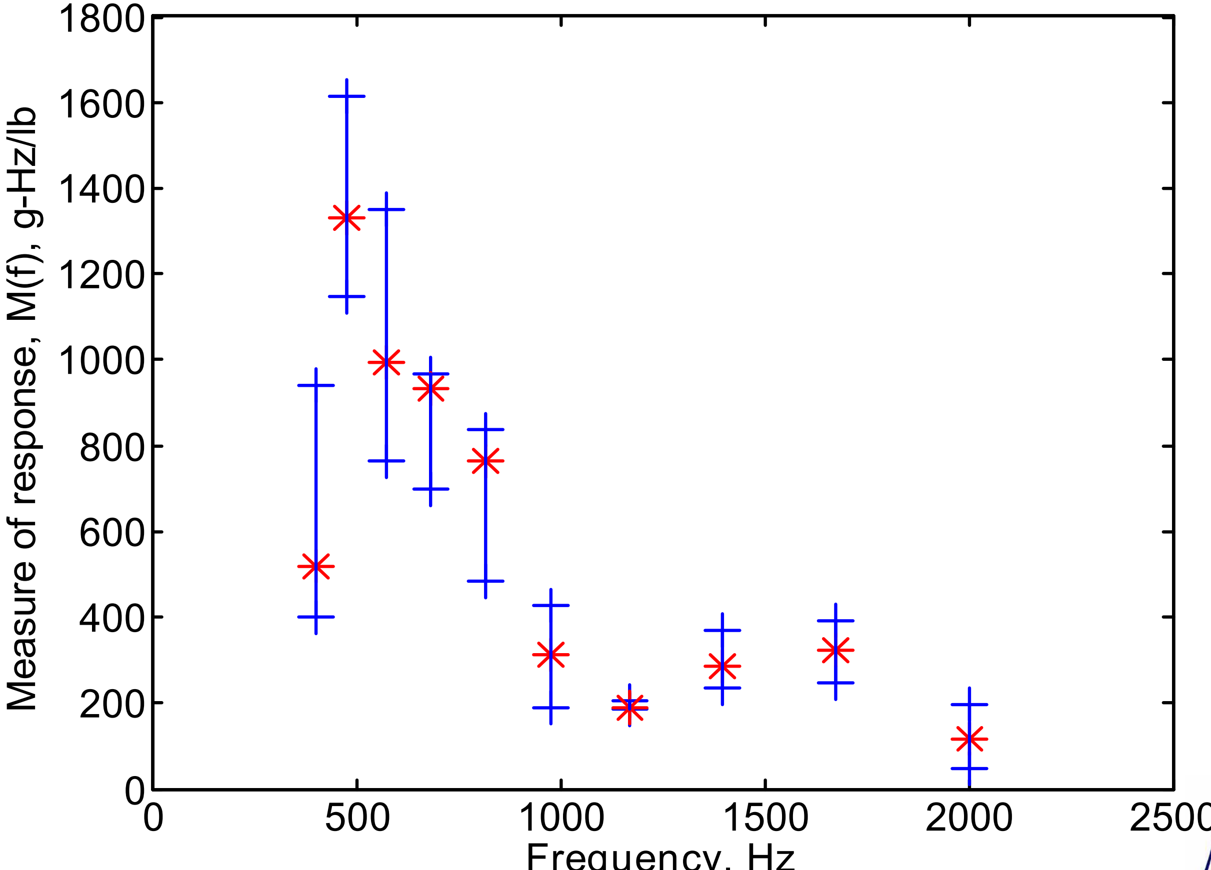
Example

Phase I Validation Specimen, 16.42 lb/ft^3, x - direction f_c = 478 Hz



Example

Phase I Validation Specimen, 16.42 lb/ft^3, x – direction, 90% prob intervals [L_{90},U_{90}] of $M_{mod}(f_c)$ and $M_{exp}(f_c)$



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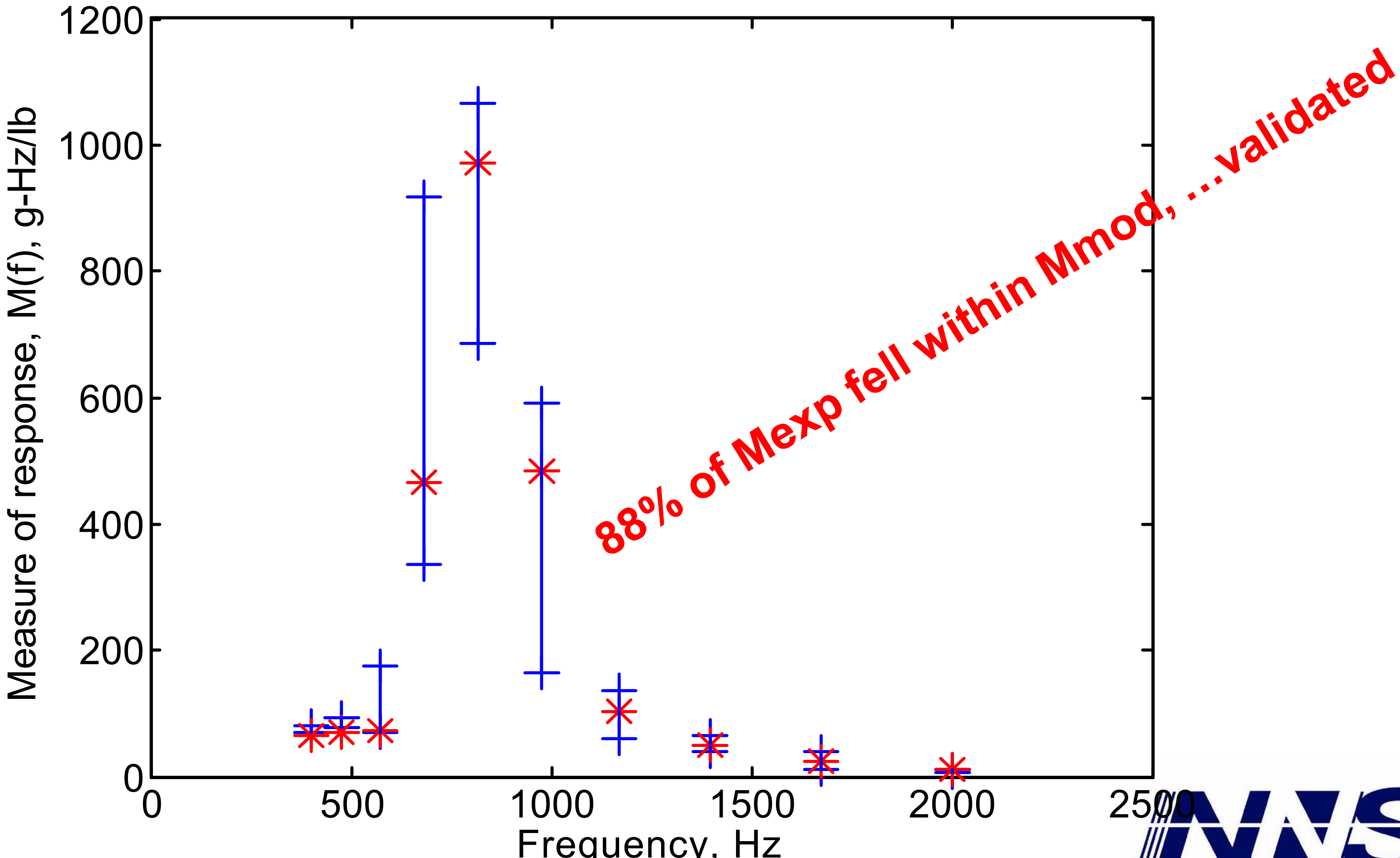
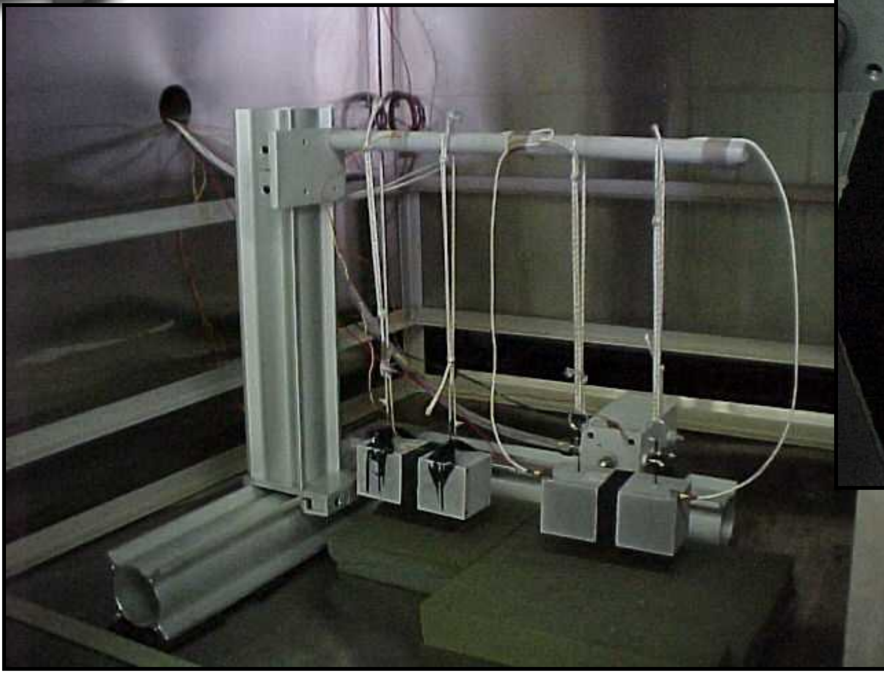
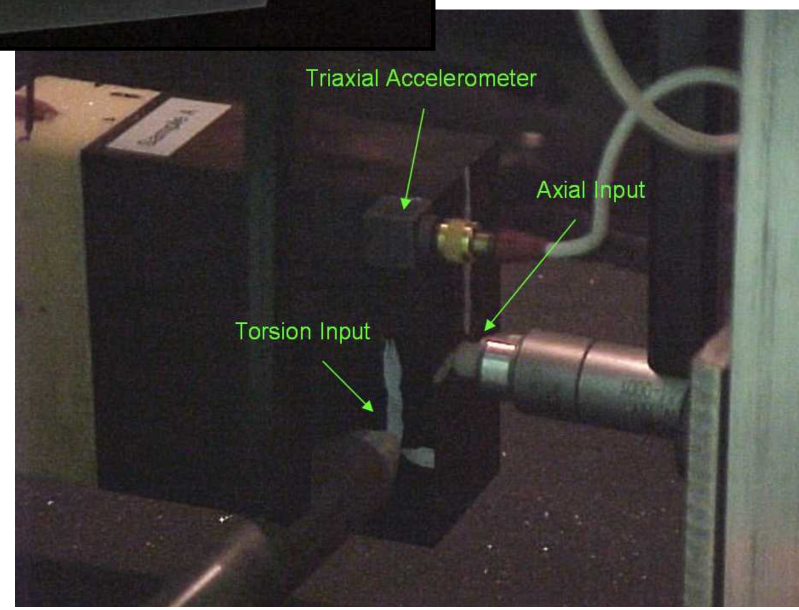
Example

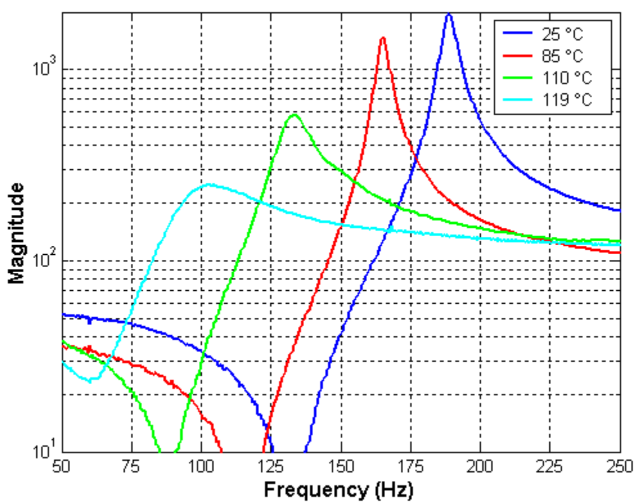
Phase I Validation Specimen, 16.42 lb/ft^3, *y* – direction, 90% prob intervals [L_{90},U_{90}] of $M_{mod}(f_c)$ and $M_{exp}(f_c)$



Testing conducted inside thermal chamber







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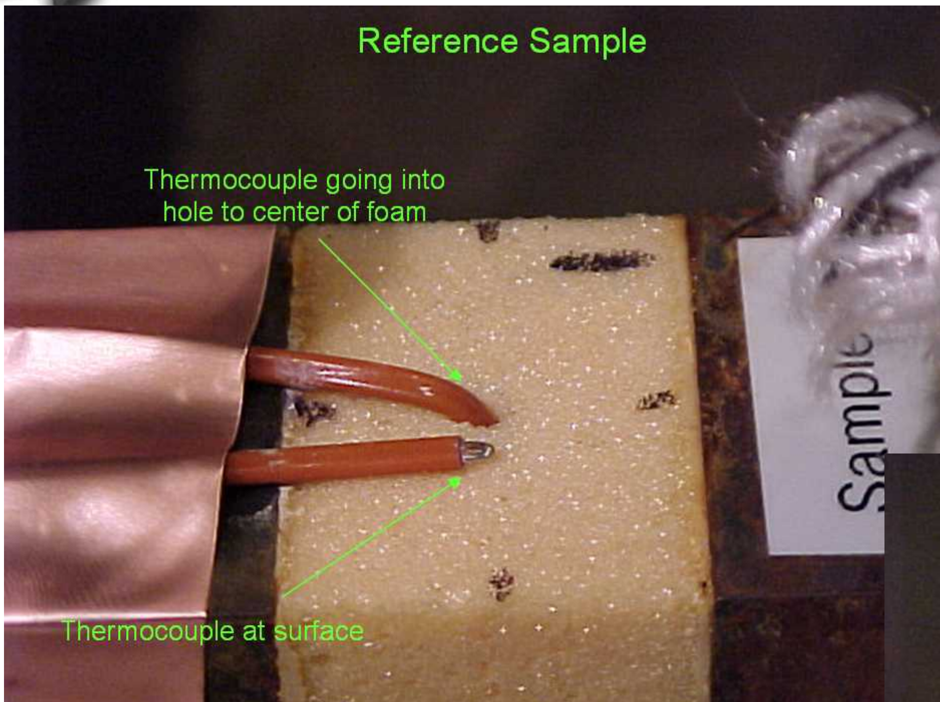
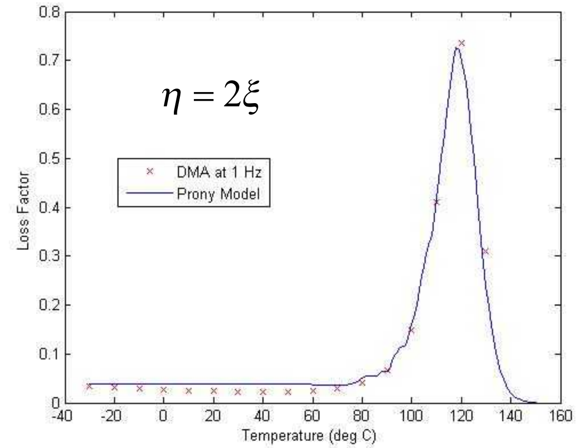
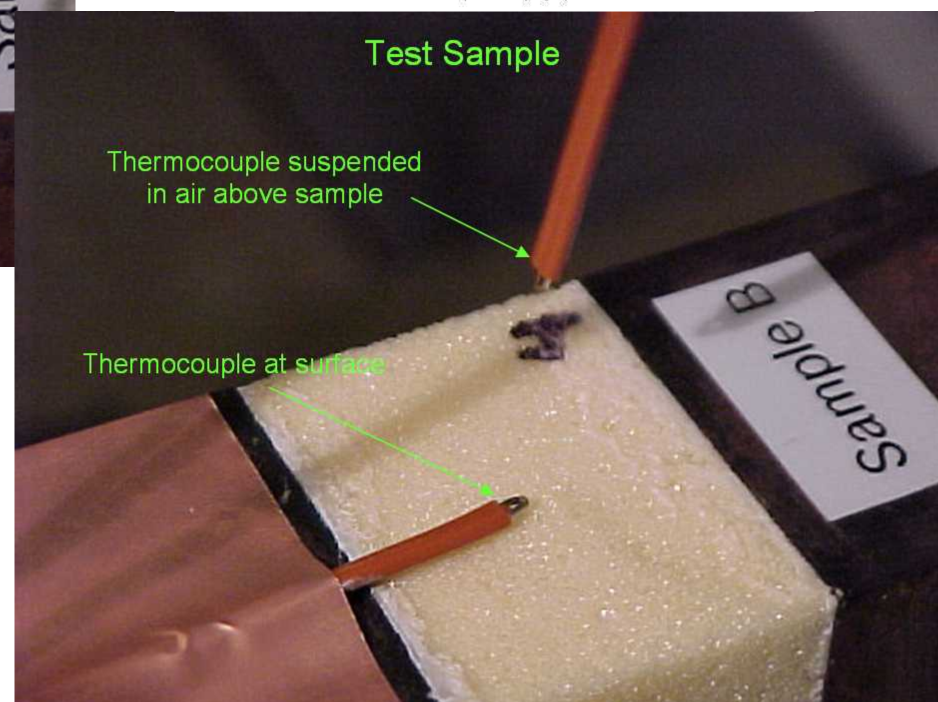
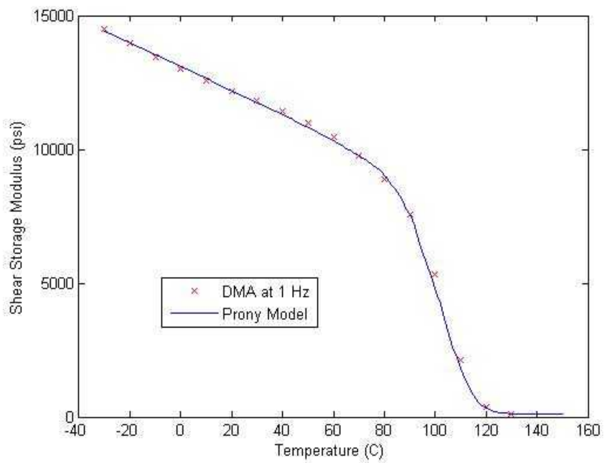
Phase I Temperature Testing

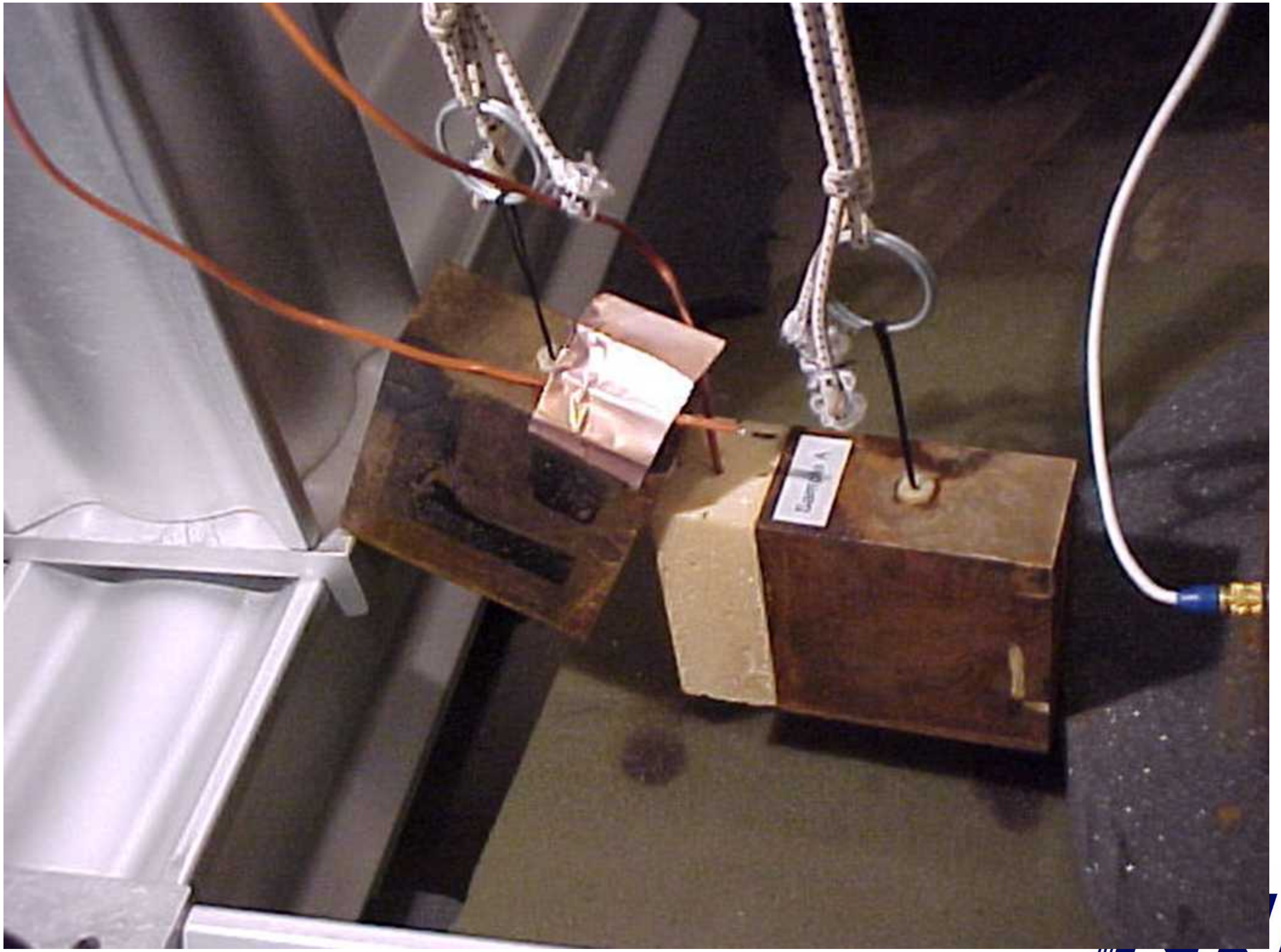




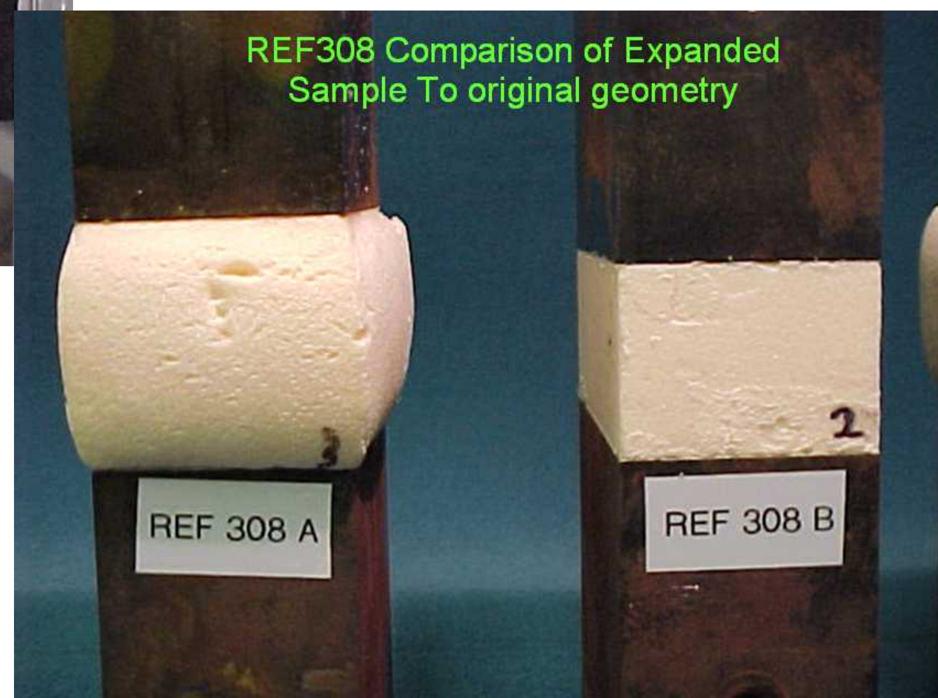




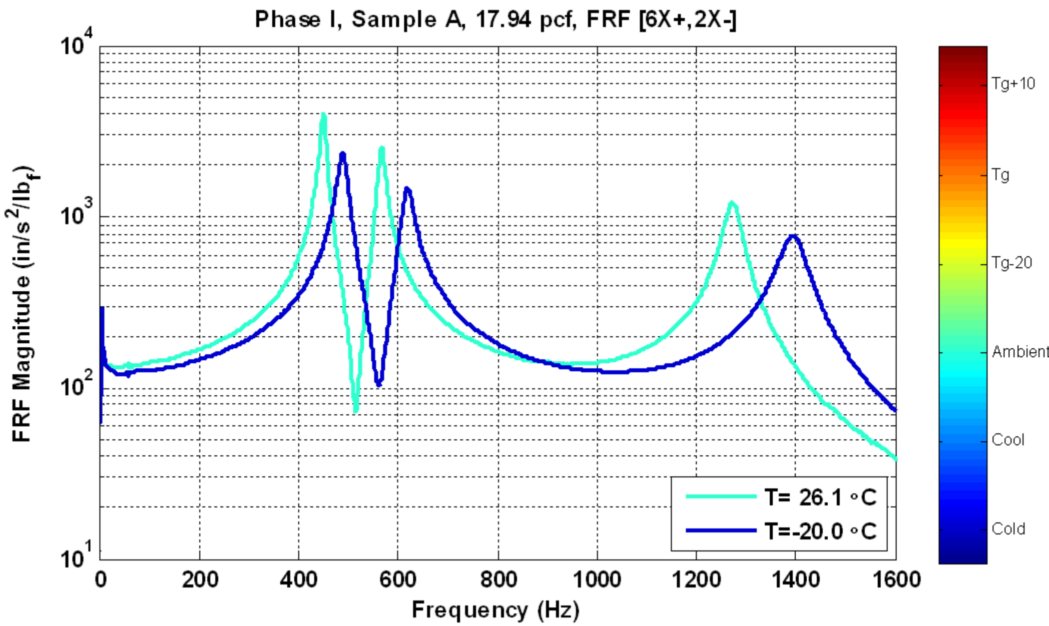
Breaking at cold temperatures

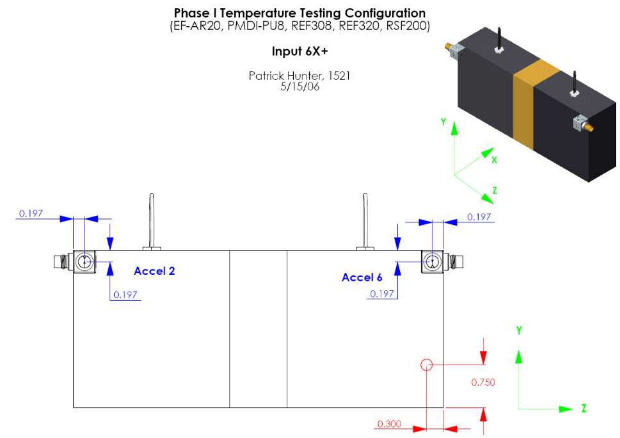


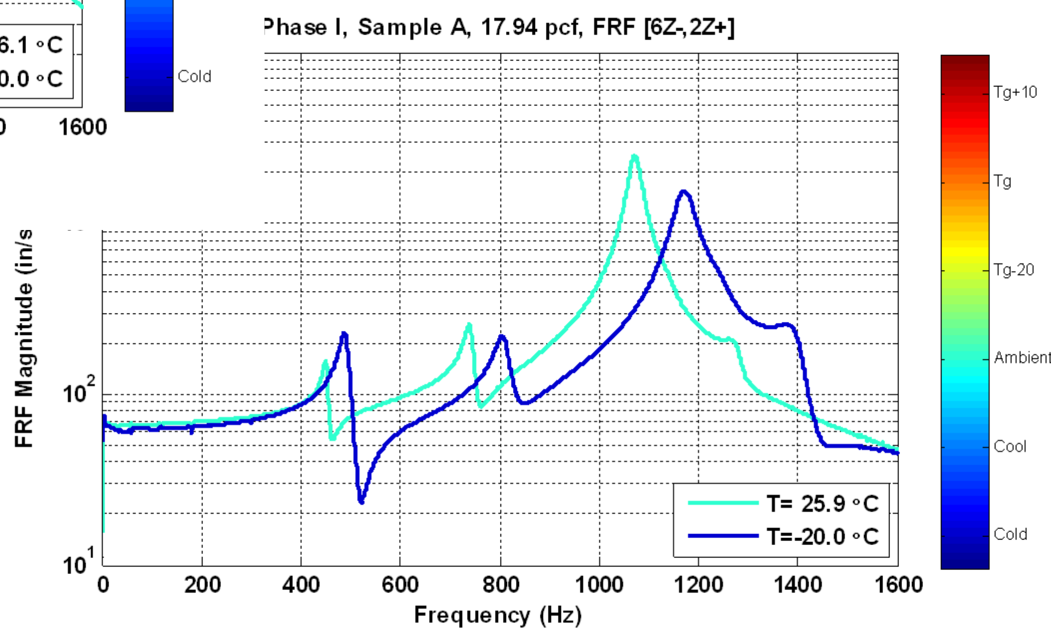
Swelling at hot temperatures



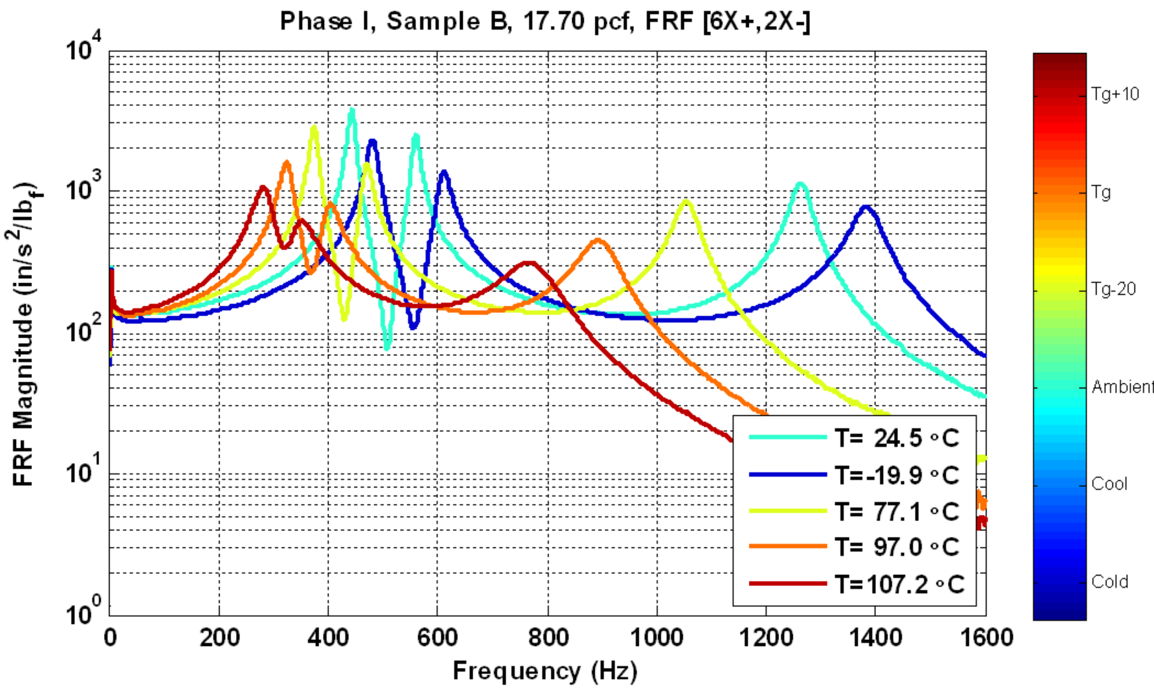
EF-AR20, Sample A

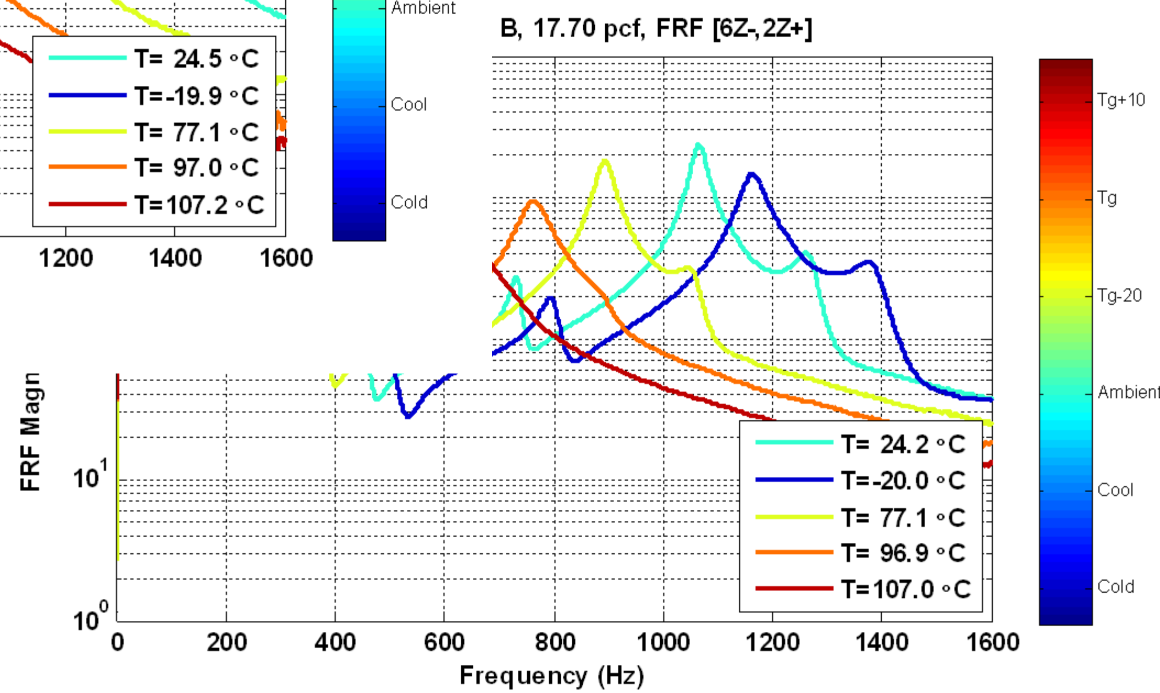






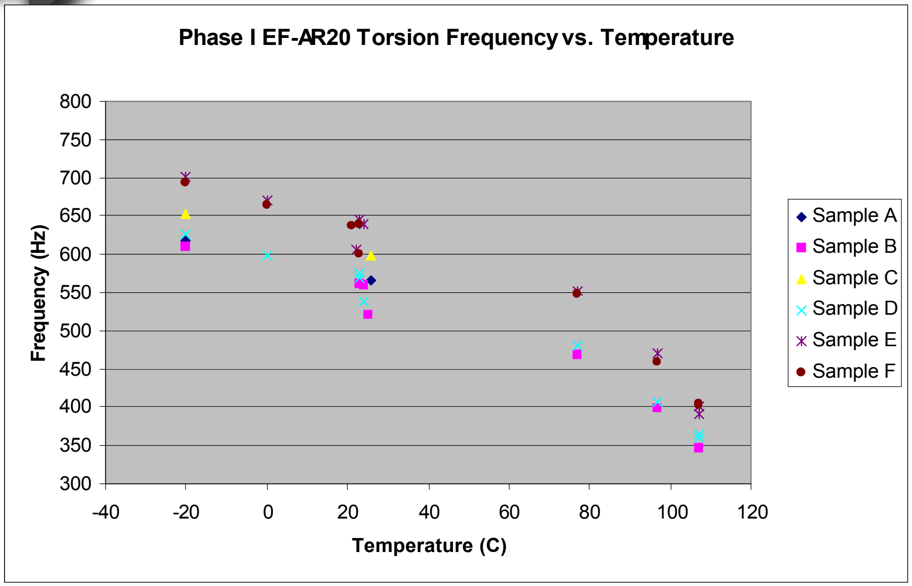
EF-AR20, Sample B

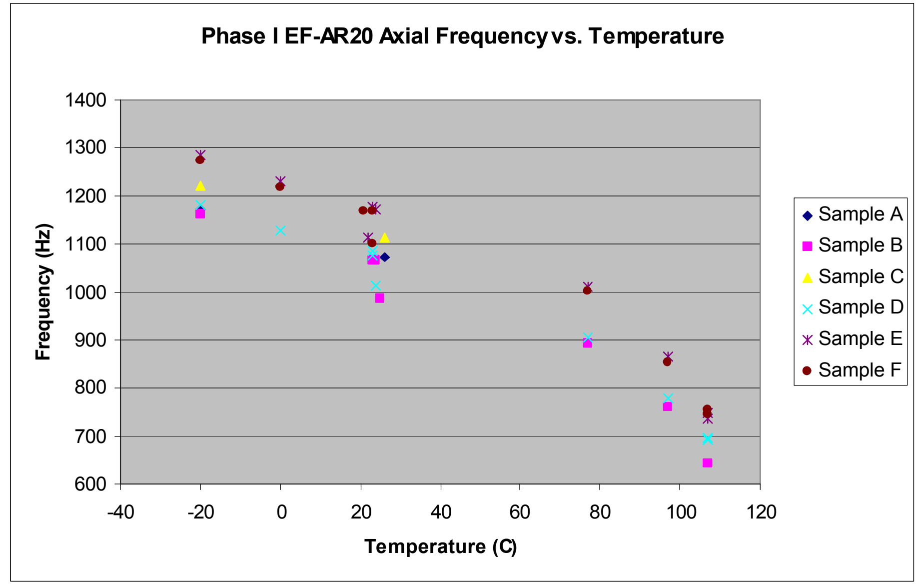


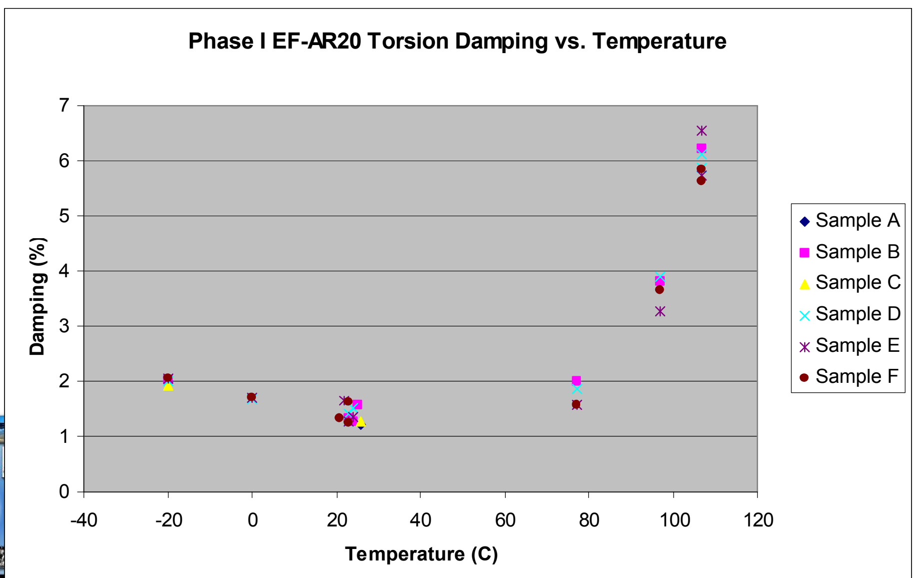


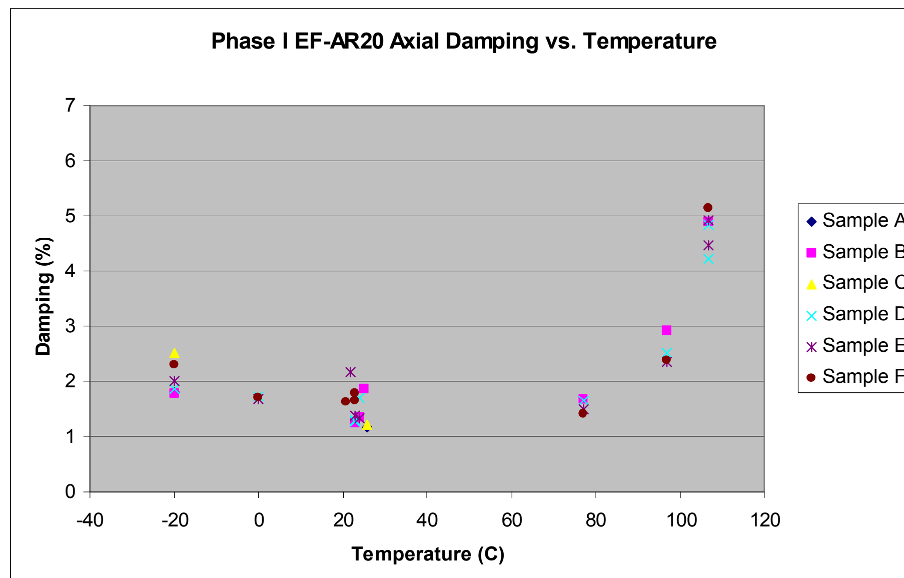
Sample C, D, E and F tested similarly

Summary
EF-AR20 Phase I Temperature Data





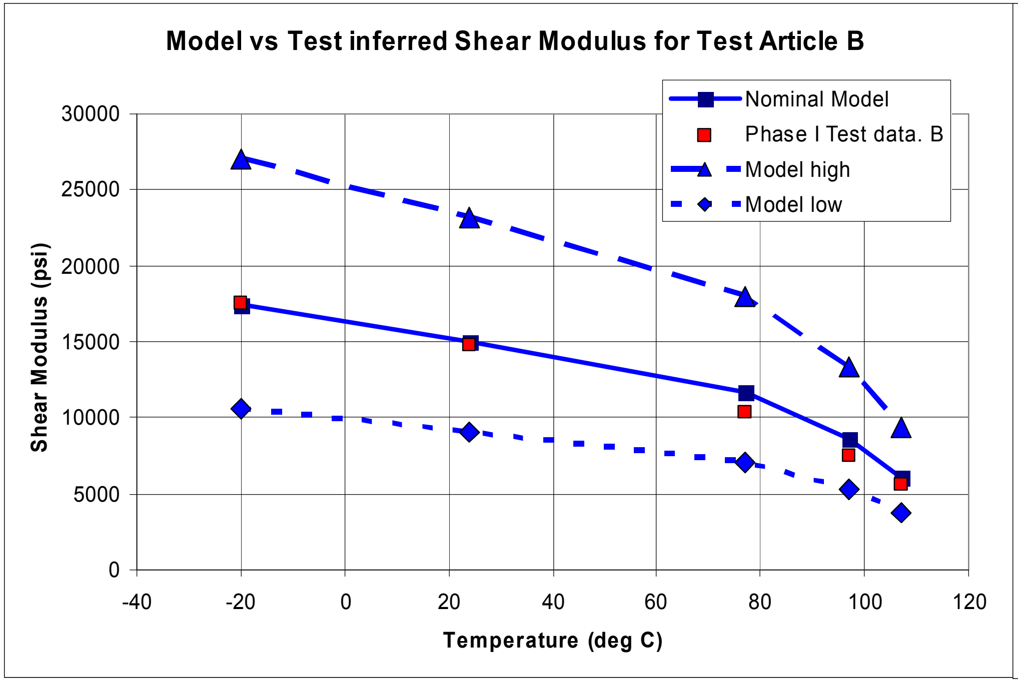


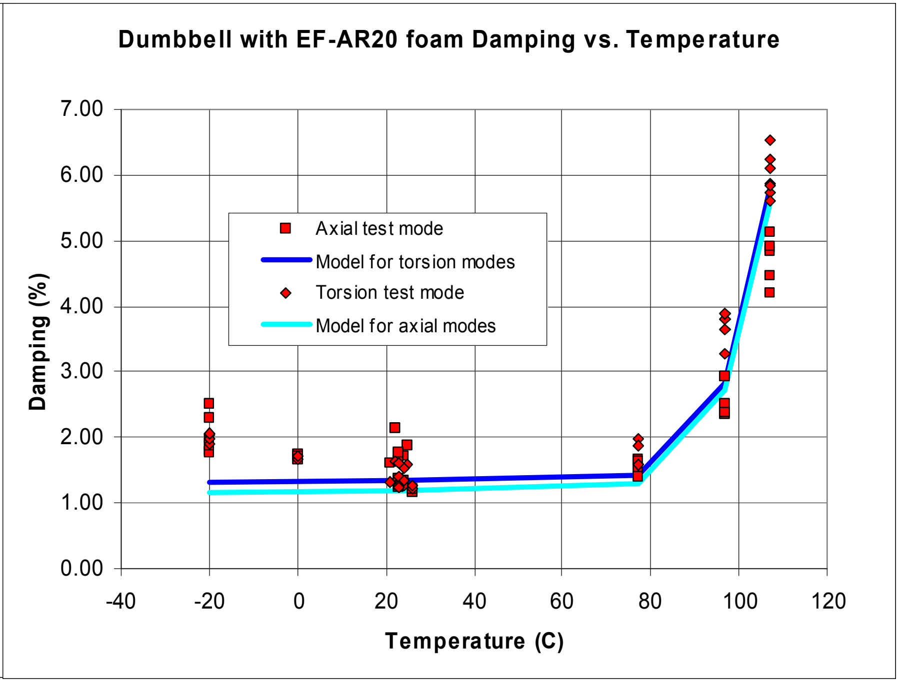


EF-AR20
Viscoelastic Model Validation

Temperature range of -20 to 107 deg C

Model predictions of modulus and damping vs. test data
- Uncertainty of foam density and modulus factored in





Shear Modulus vs. Temperature

Damping vs. Temperature

EF-AR20
SALINAS input definition for Viscoelastic Model

```
ISOTROPIC_VISCOELASTIC
density  13.2e-3
T_0 90.0
T_current  90.0
C_1 31.6
C_2 111.5
aT_1 2.5
aT_2 0.09
K_g 59978.
K_inf 203.
G_g 30926.
G_inf 104.69
K_relax
#include Prony time constants
K_coeff
#include Prony series coefficients
G_relax
#include tp.dat
G_coeff
#include mp.dat
END
```

Temperature dependence of the Glassy Shear Modulus

Gg=Gg0*2.778*(1-0.64*(T_current/T_0))

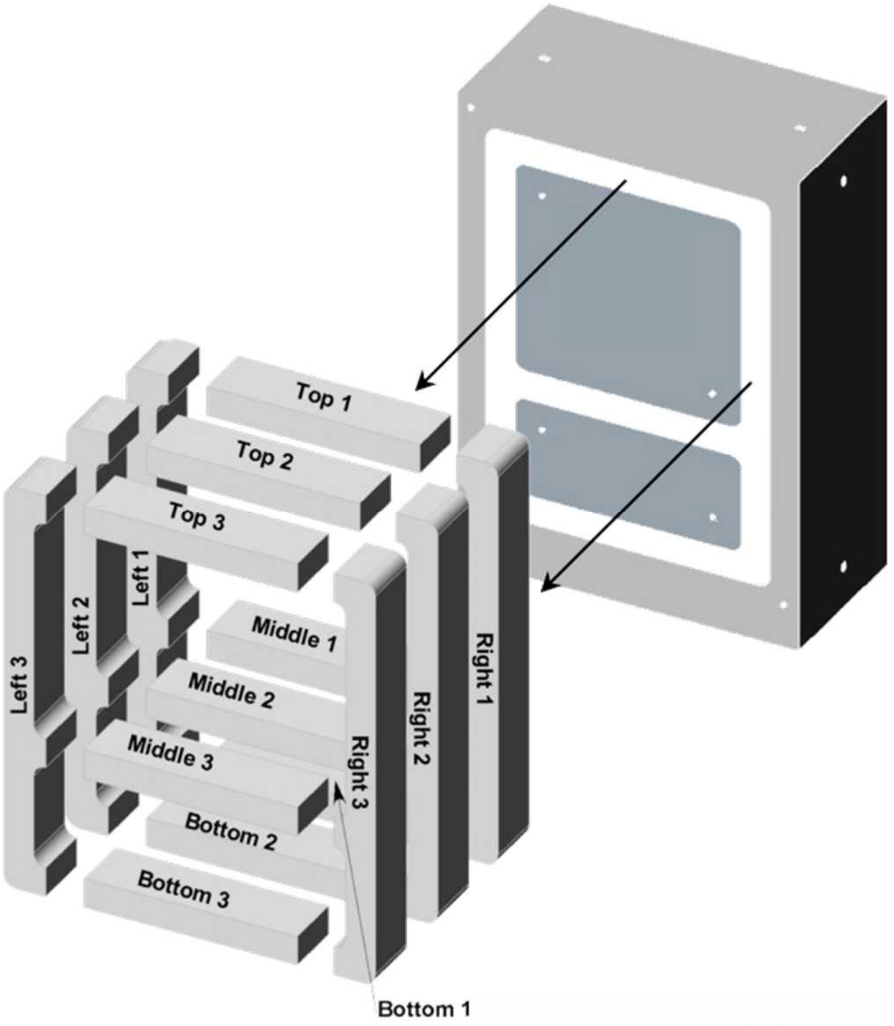
only for T_current < T_0

Kg=1.9394*Gg based on Poisson's ratio of 0.28

Match Shear Modulus to room temperature value

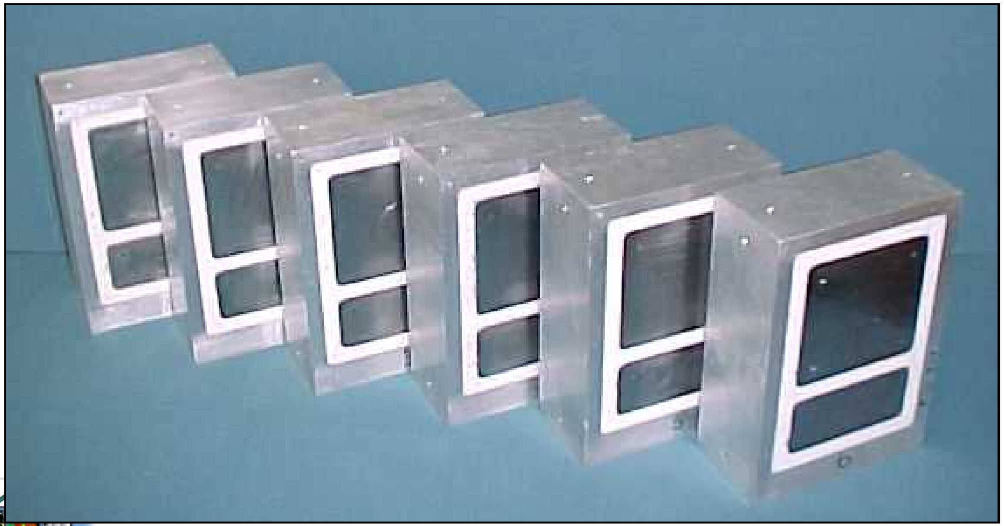
Density dependence of the Shear Modulus at room temperature: G=46*(density)^2

Foam Process Development



Phase II Samples

Benchmark Validation - Shaker Testing			
Sample #	Density (lb/ft^3)	Uncertainty (%)	Notes
1	23.0	7.7	Vented through top plate
2	20.3	8.7	
3	23.0	7.7	Did not fully rise
4	18.6	9.5	
5	20.3	8.7	
6	20.3	8.7	

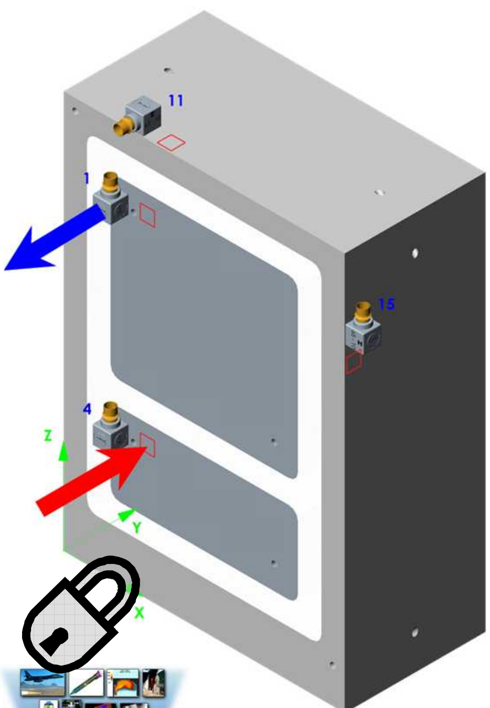


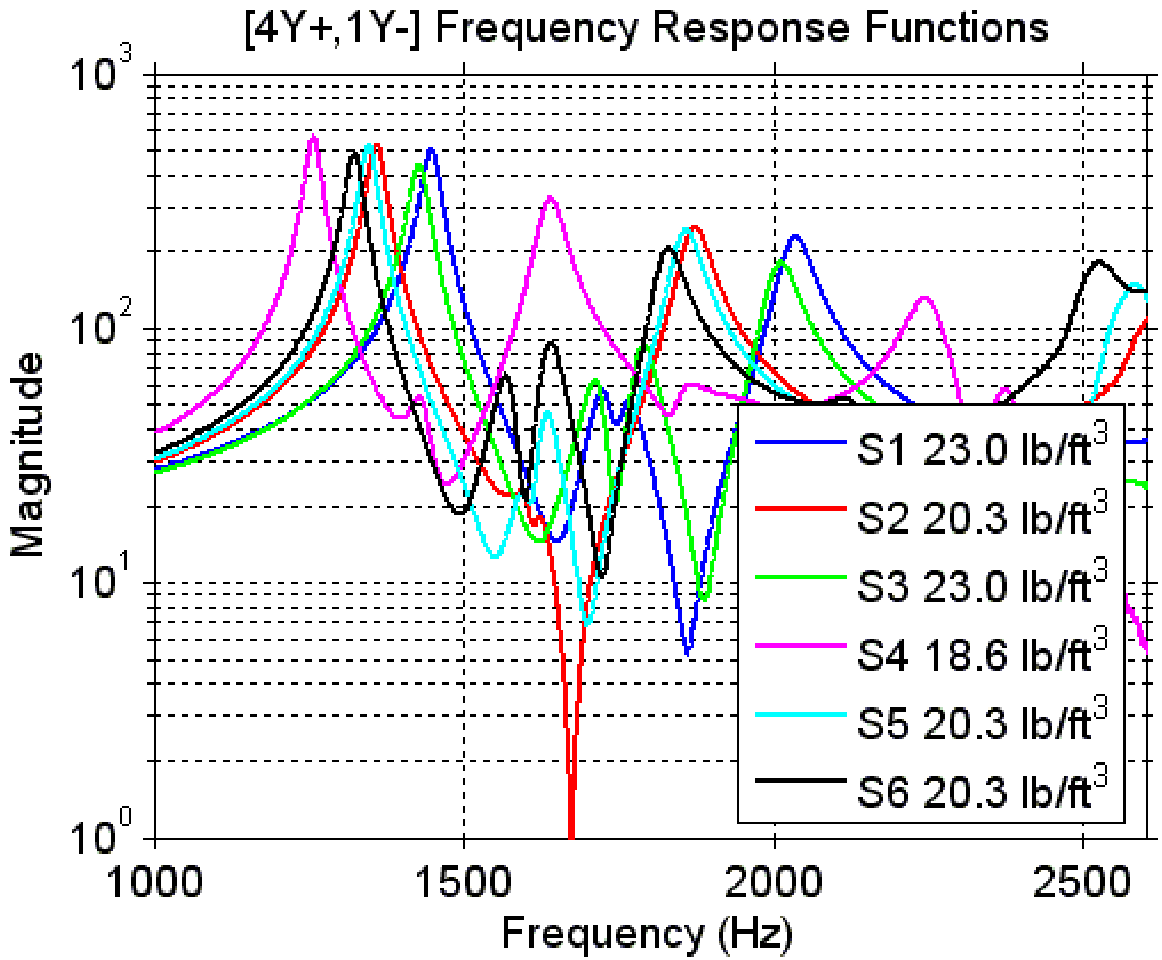
- Parameters from Foam Process Development
- 45°C Preheat, 40% Excess and 9 vent holes

Phase II Modal Validation

In-Axis

4Y+ 1Y-

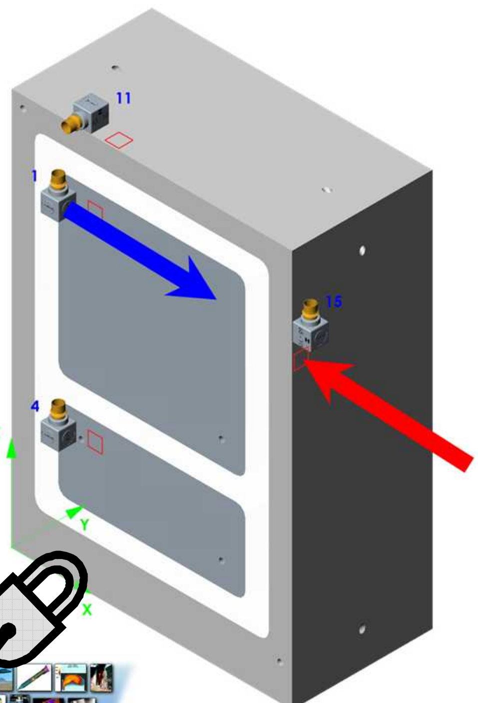


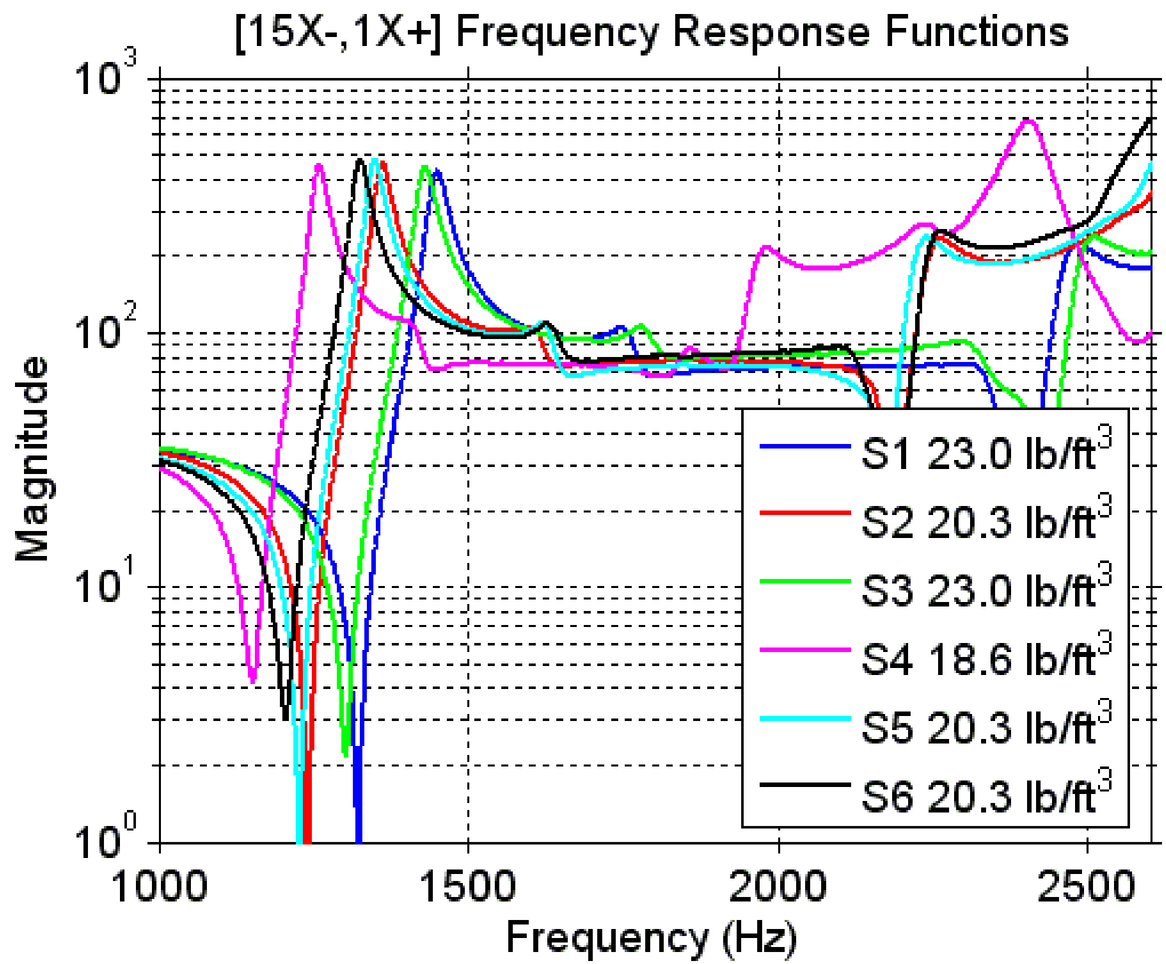


Phase II Modal Validation

In-Axis

15X- 1X+





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Phase II Modal Validation

Mode #	Sample 1 23.0 lb/ft^3 Freq. (Hz)	Damp. (%)	Sample 2 20.3 lb/ft^3 Freq. (Hz)	Damp. (%)	Sample 3 23.0 lb/ft^3 Freq. (Hz)	Damp. (%)	Sample 4 18.6 lb/ft^3 Freq. (Hz)	Damp. (%)	Sample 5 20.3 lb/ft^3 Freq. (Hz)	Damp. (%)	Sample 6 20.3 lb/ft^3 Freq. (Hz)	Damp. (%)
1	1449.0	1.1	1360.0	1.0	1429.0	1.1	1258.0	1.0	1348.0	1.0	1325.3	1.0
2	1726.7	1.1	1610.0	1.3	1718.7	1.2	1419.9	1.3	1603.8	1.2	1574.0	1.1
3	1761.0	1.3	1616.0	1.3	1787.2	1.2	1436.0	1.3	1632.0	1.2	1636.0	1.2
4	2032.0	1.4	1871.0	1.4	2007.0	1.4	1639.0	1.4	1856.0	1.4	1827.0	1.4
5	2339.3	1.3	2165.2	1.4	2324.0	1.4	1843.0	1.3	2167.2	1.3	2126.0	1.4
6	2465.0	1.3	2243.8	1.3	2489.0	1.2	1964.0	1.3	2223.8	1.3	2244.0	1.3

- Modal parameters extracted between 1000 and 2500 Hz
- Average Phase II damping is 1.2%
- Phase I calibration damping varied between 1.2% and 1.5%

Phase III
Temperature Testing

Step 1:
Ambient
Full Instrumentation

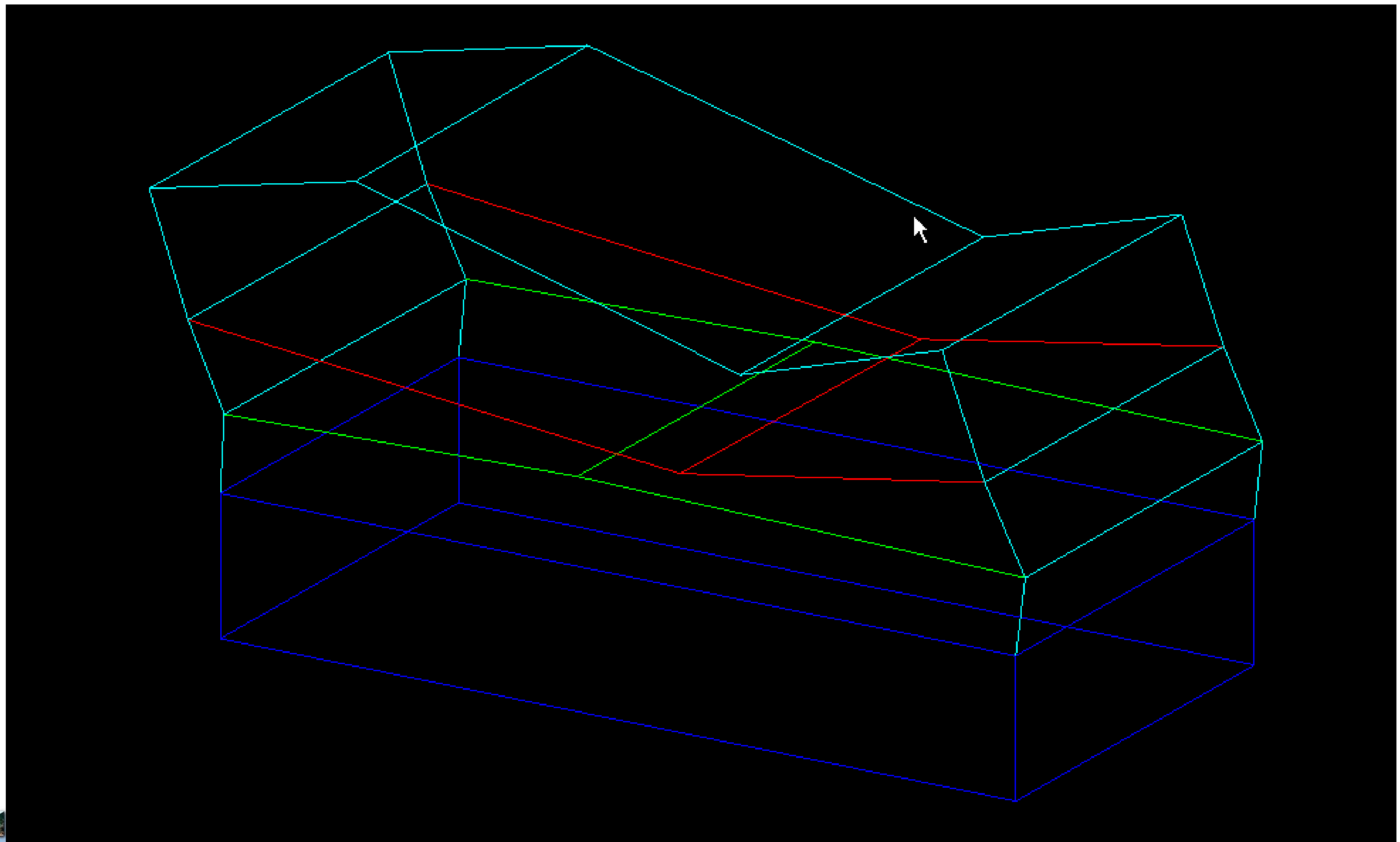
Step 2:
Ambient
Reduced Instrumentation

Step 3:
Temperature
Reduced Instrumentation

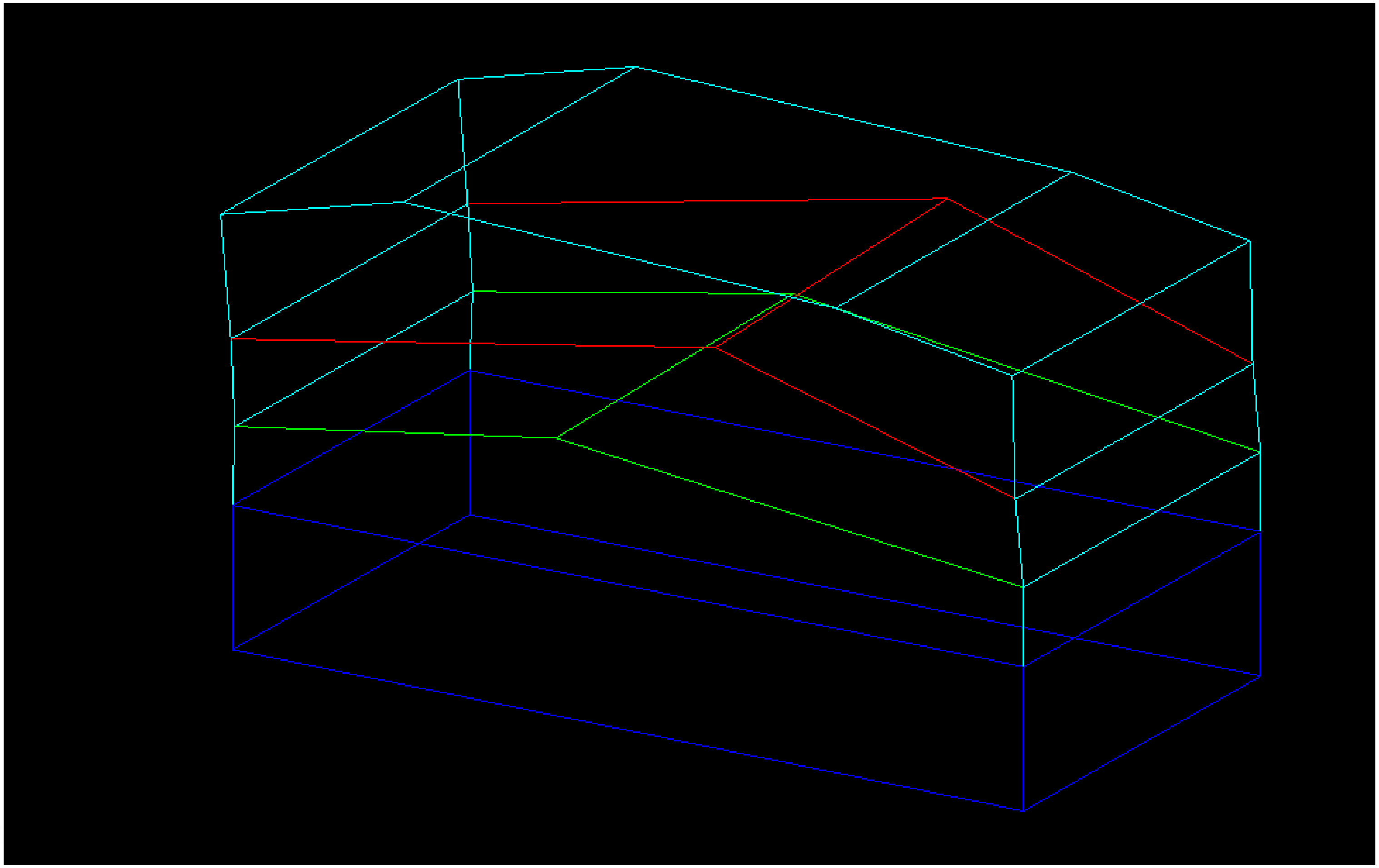
Sandia National Laboratories

NNSA
National Nuclear Security Administration

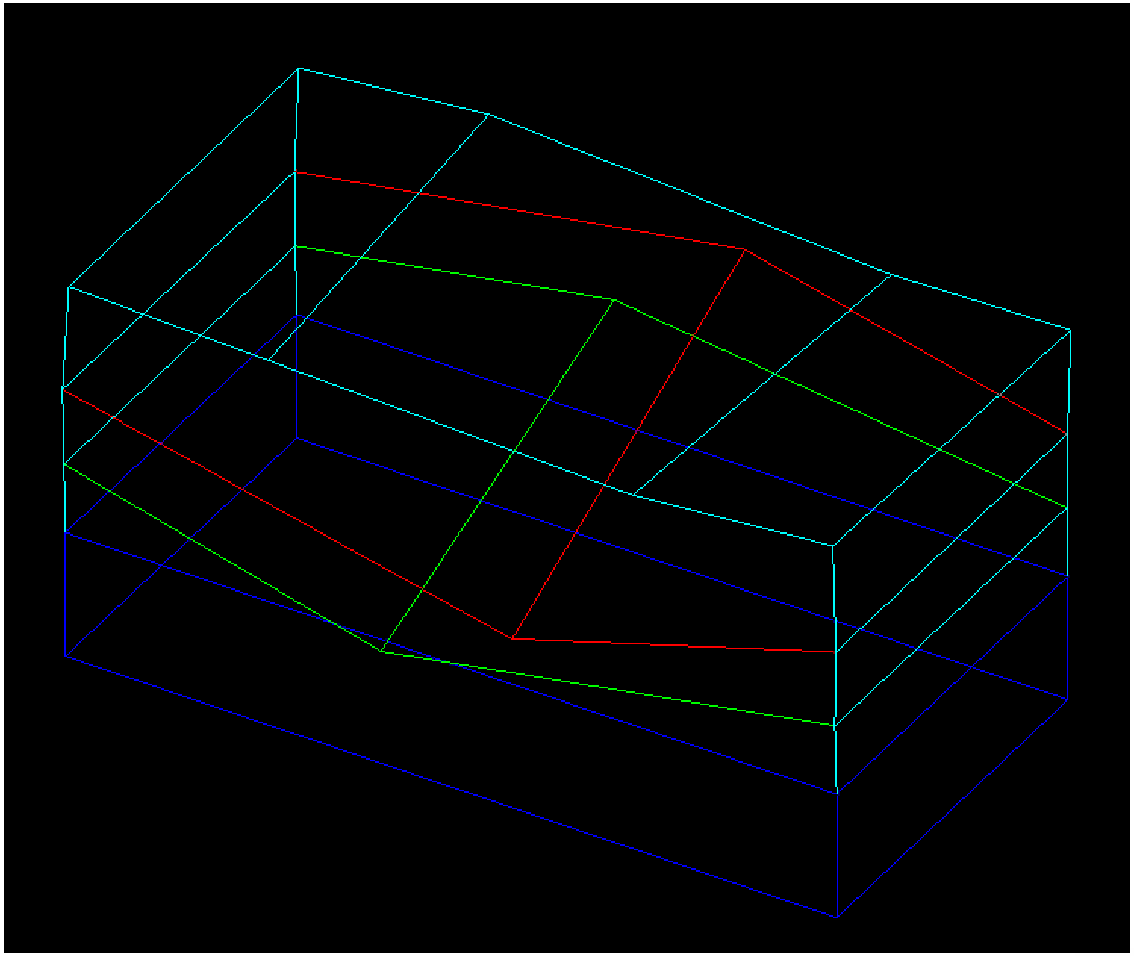
Phase III (F, 1616 Hz, 0.4%)



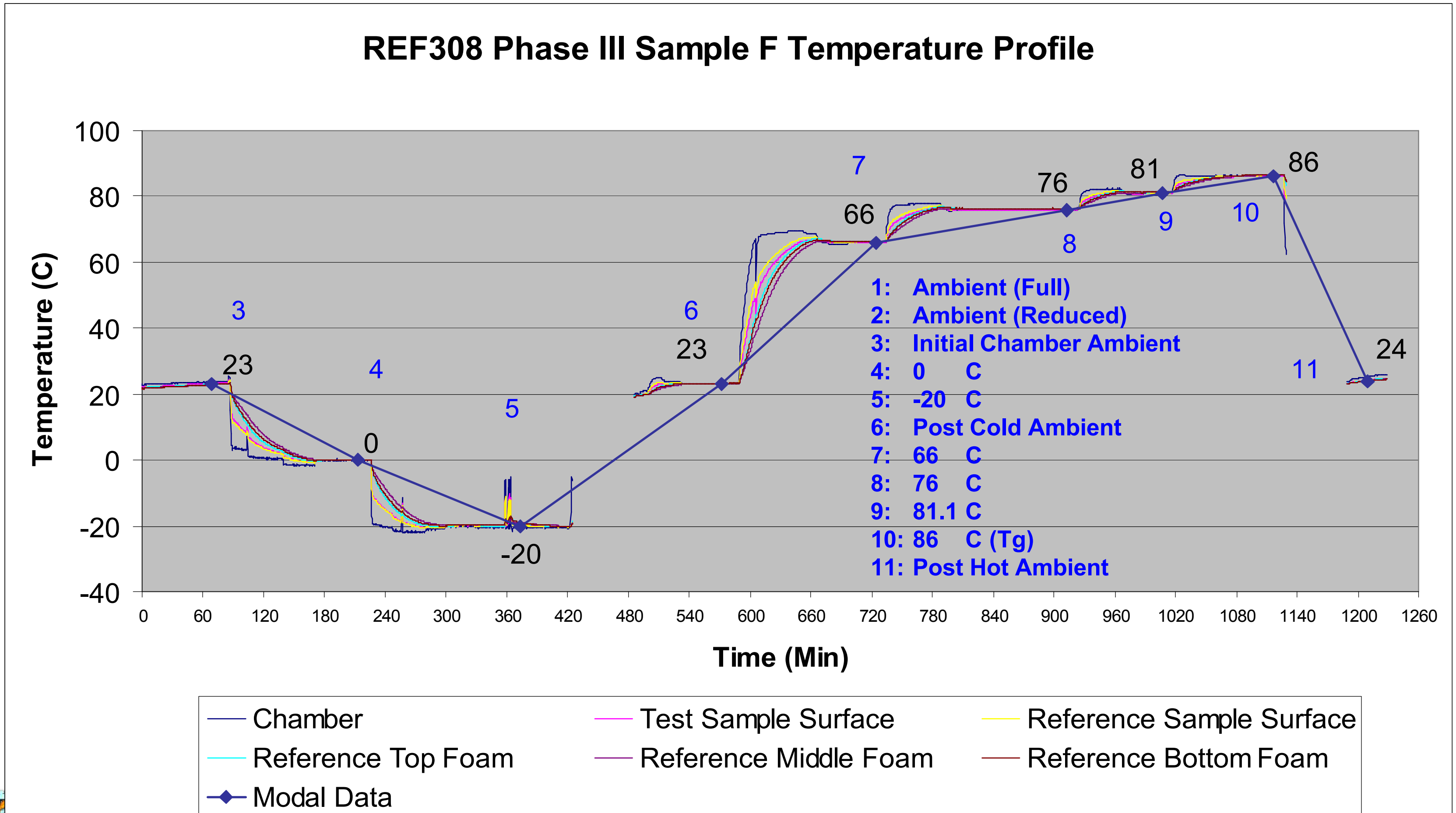
Phase III (F, 1764 Hz, 0.6%)



Phase III (F, 1899 Hz, 1.3%)



Phase III Test Temperatures



Preliminary Validation

Team Members:
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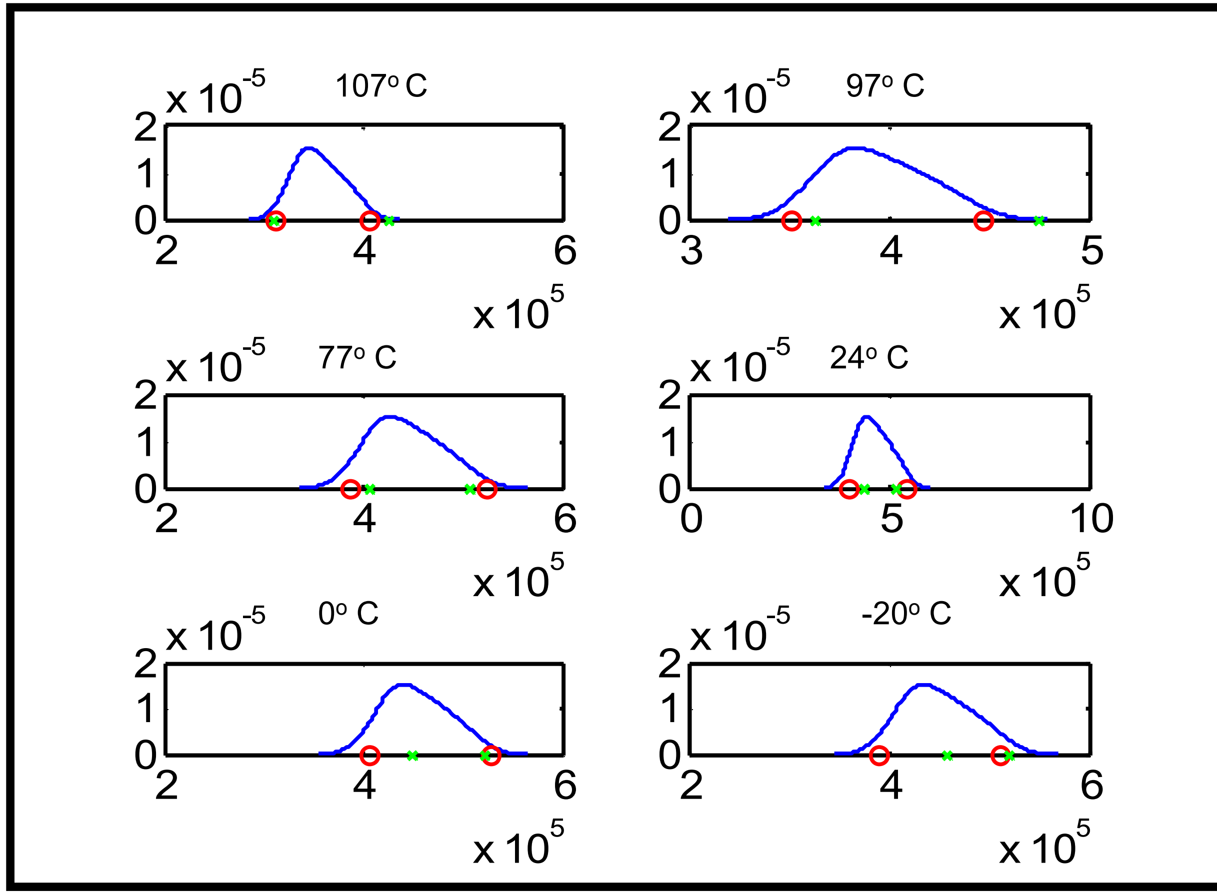
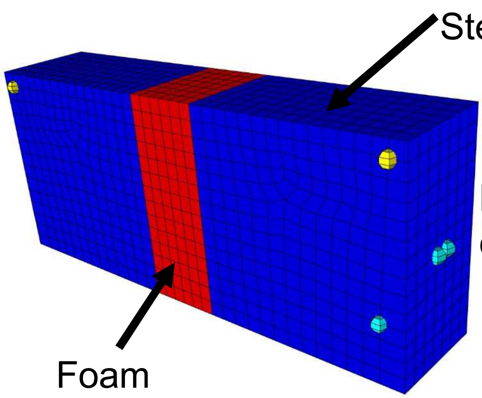
- Tom Paez, 1544
- Jordan Massad, 1526
- Chris O'Gorman, 1521
- Patrick Hunter, 1521

Peak Acceleration Results
Red circles are
95% CI Test data

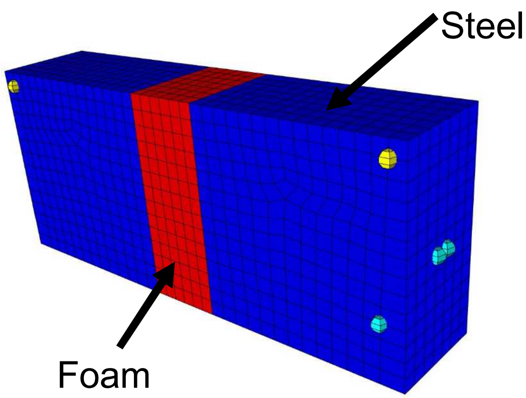
Green circles are
95% CI Model predictions

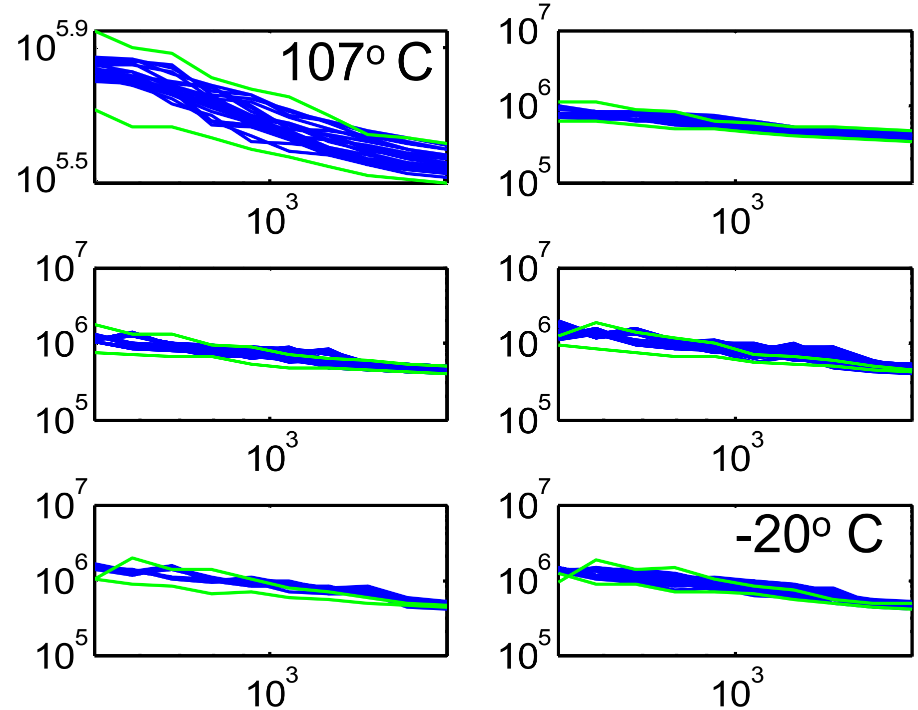




Preliminary Validation

Shock Response Spectra from Model (green) and Test data (blue)





Preliminary validation results of the Viscoelastic Model using Shock Response Spectra for EF-AR20 foam over -20 to 107 deg C.