National Aeronautics and Space Administration

NASA

Application of High Speed Digital Image Correlation in Rocket Engine Hot Fire Testing

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MARSHALL
SPACE FLIGHT CENTER

Abstract

Application of High Speed Digital Image Correlation in Rocket Engine Hot Fire Testing

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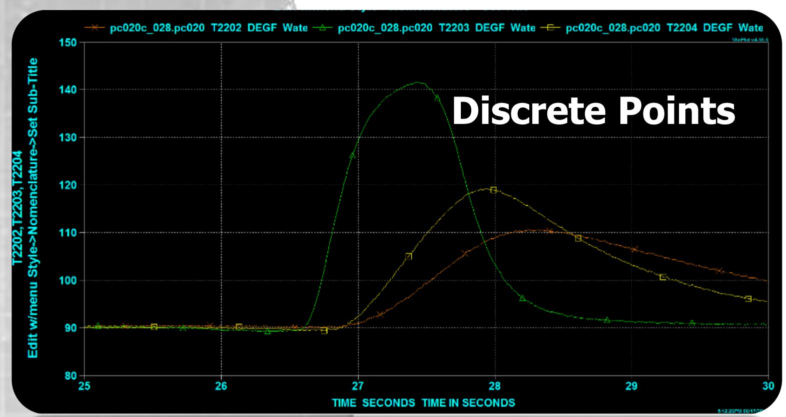
Trilion Quality Systems LLC

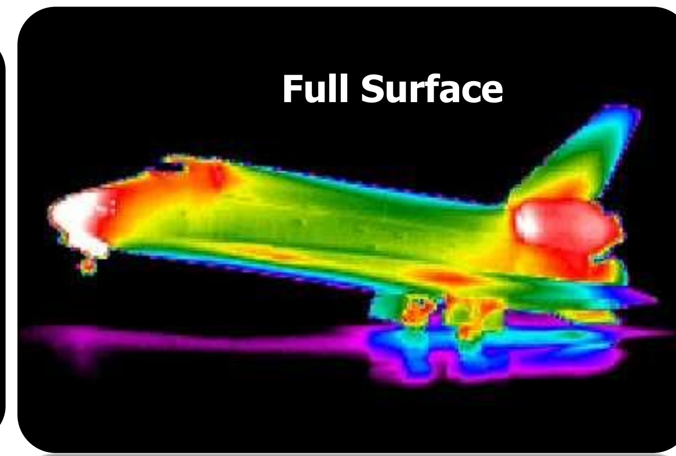
Hot fire testing of rocket engine components and rocket engine systems is a critical aspect of the development process to understand performance, reliability and system interactions. Ground testing provides the opportunity for highly instrumented development testing to validate analytical model predictions and determine necessary design changes and process improvements. To properly obtain discrete measurements for model validation, instrumentation must survive in the highly dynamic and extreme temperature application of hot fire testing. Digital Image Correlation has been investigated and being evaluated as a technique to augment traditional instrumentation during component and engine testing providing further data for additional performance improvements and cost savings. The feasibility of digital image correlation techniques were demonstrated in subscale and full scale hotfire testing. This incorporated a pair of high speed cameras to measure three-dimensional, real-time displacements and strains installed and operated under the extreme environments present on the test stand. The development process, setup and calibrations, data collection, hotfire test data collection and post-test analysis and results are presented in this paper.

Motivation for Technology

- Subscale and Full-scale testing requires expensive and labor intensive instrumentation to better understand hardware performance
  - Design Modifications and Performance Predictions based on "discrete" point instrumentation
    - Thermocouples, Pressure Transducers, Accelerometers, Strain Gages
- **Challenge: Measure highly dynamic elevated temperature components**

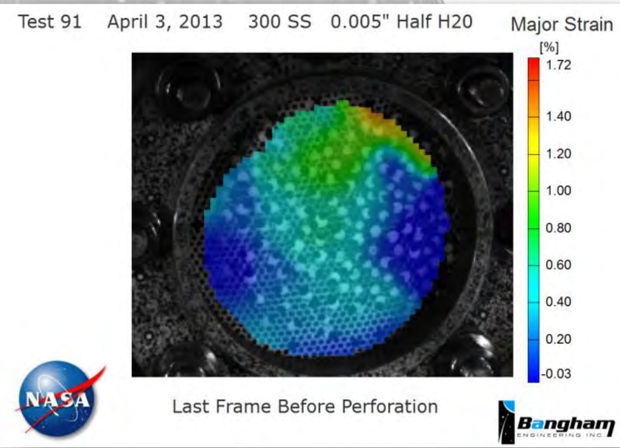
Full Surface **>** Point
IR **>** Thermocouple
D.I.C. **>** Strain Gage



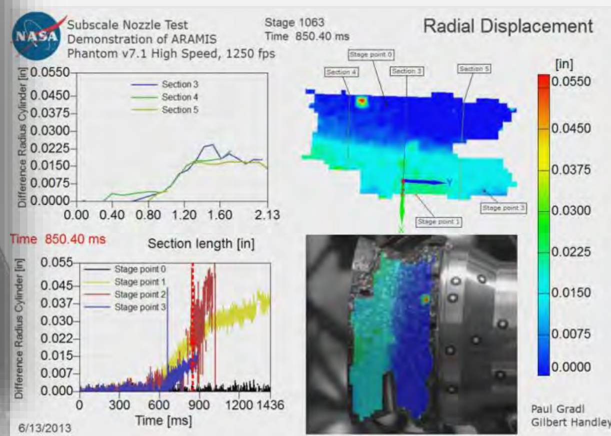


Goal: Augment Traditional Gages to gain a better understanding of hardware and environment loads to design more efficient components and systems

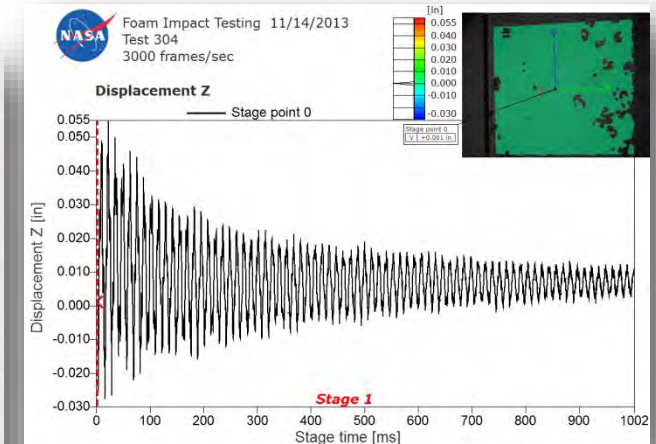
Applications and Development work for Digital Image Correlation at NASA



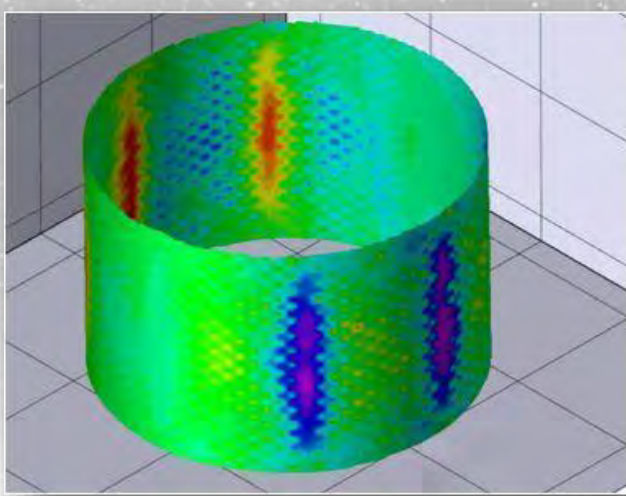
Blast Pressure Wave Tracking at 70,000 fps



Subscale Nozzle Displacements at 1700F

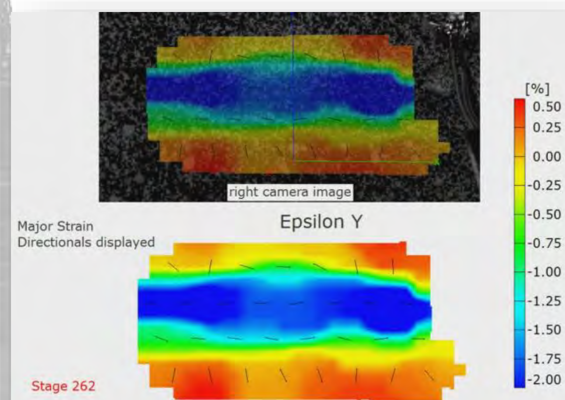


Debris Impact Testing – Eliminated Strain Gages

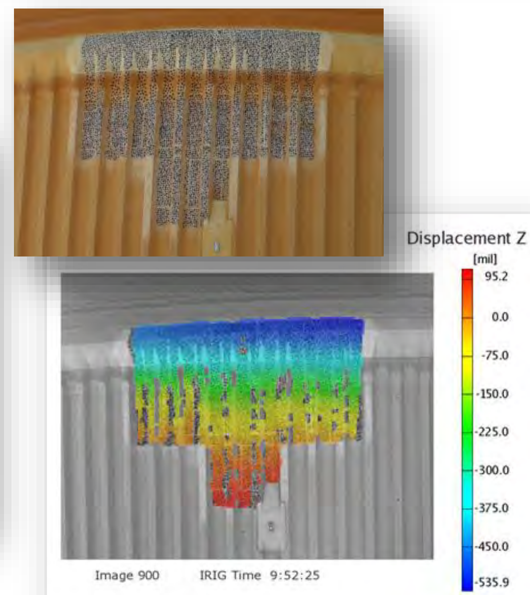


Full-Field Strain and Displacements of 18-ft Dia Tank

Ref: Todd Boles, MSFC/ET30



High Speed Composite Compression – Direct Application of Major Strain

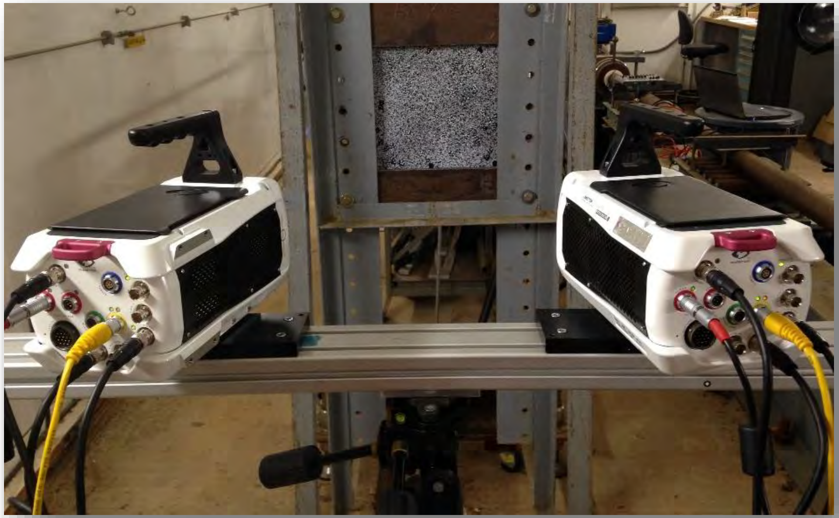


ET (on Pad) Cryo tanking test to observe stringer displacement

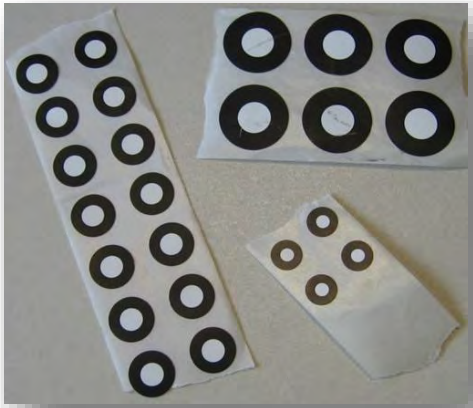
Digital Image Correlation - Overview of Technology

- Uses paired high speed video cameras calibrated to a volume to full field surface data
- Post-processing of paired images to determine **Displacement of surface, strains, acceleration, velocity**
- High Speed cameras can provide high frame rate although frame rate limited by duration of test and current post-processing techniques (tremendous amounts of data)

Photos by: Paul Gradl and Gilbert Handley

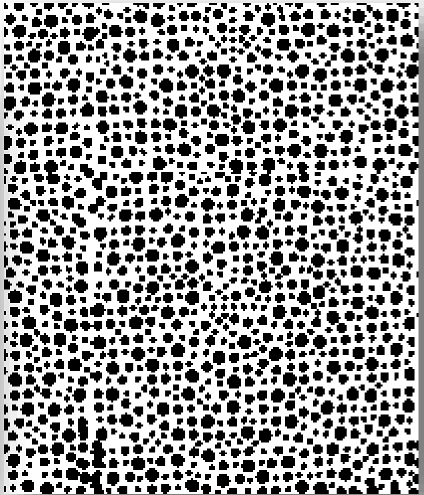


PONTOS



Discrete Point Setup

ARAMIS



Full Surface Setup

What is Digital Image Correlation?

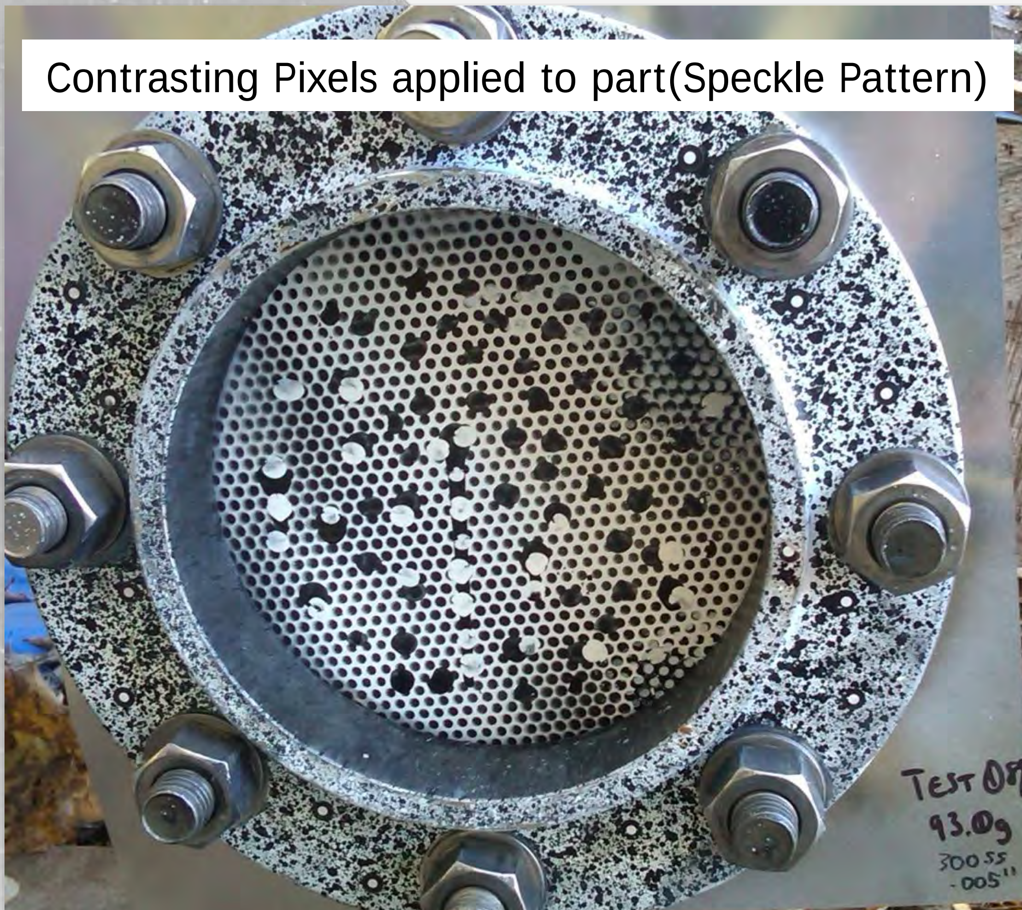


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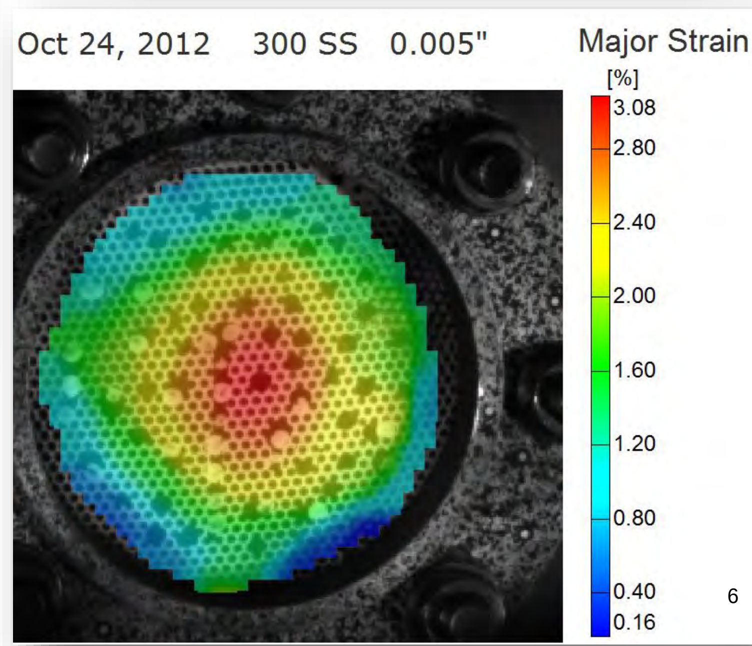
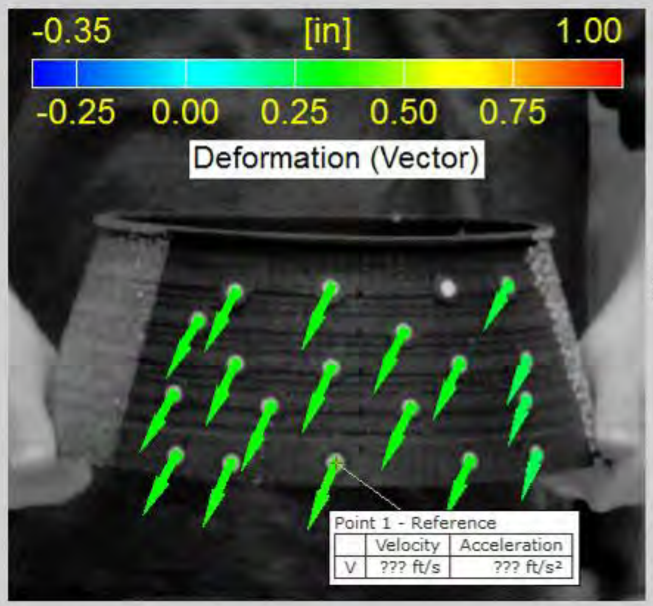
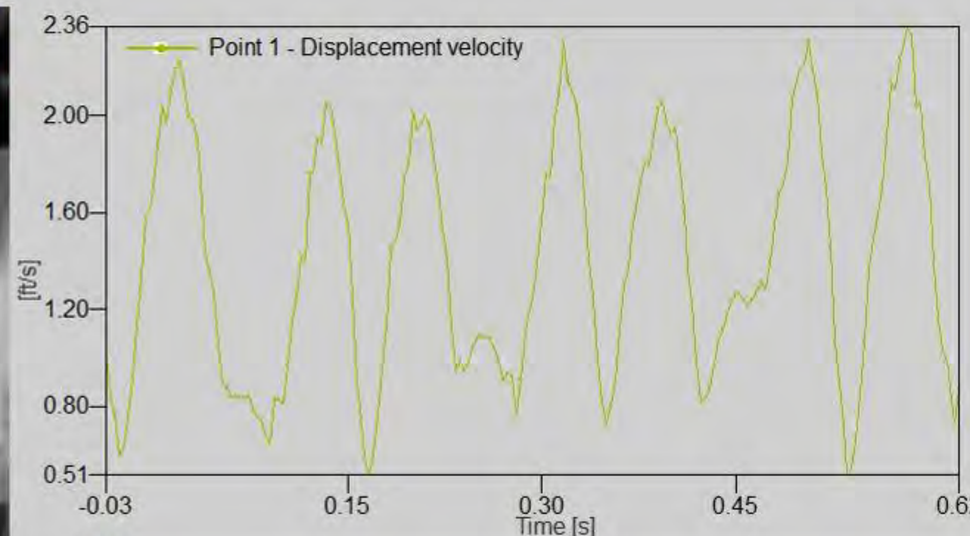
Photo Provided by: Tim Schmidt / Trilion



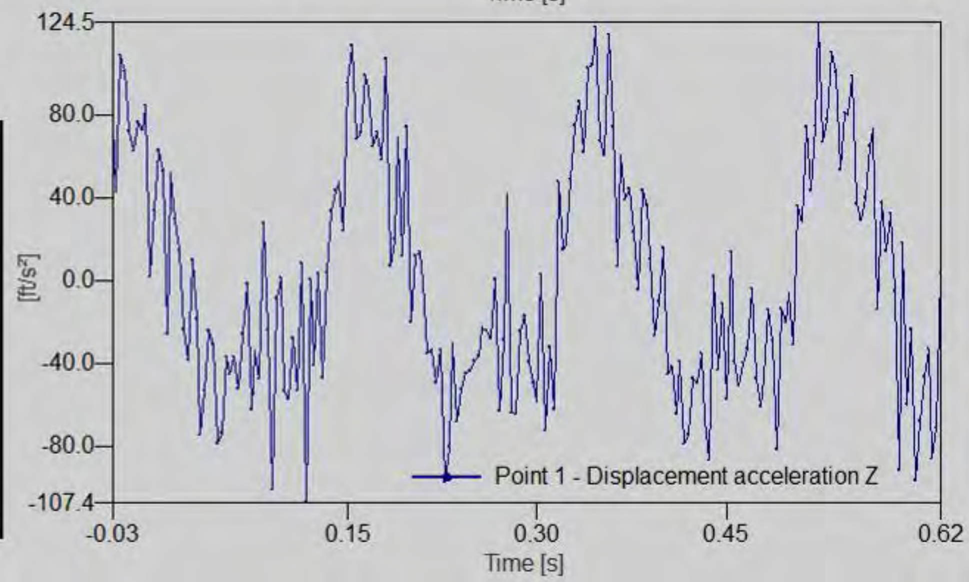
= Full Field Displacement and Strain Measurements

PONTOS Lab Experiments



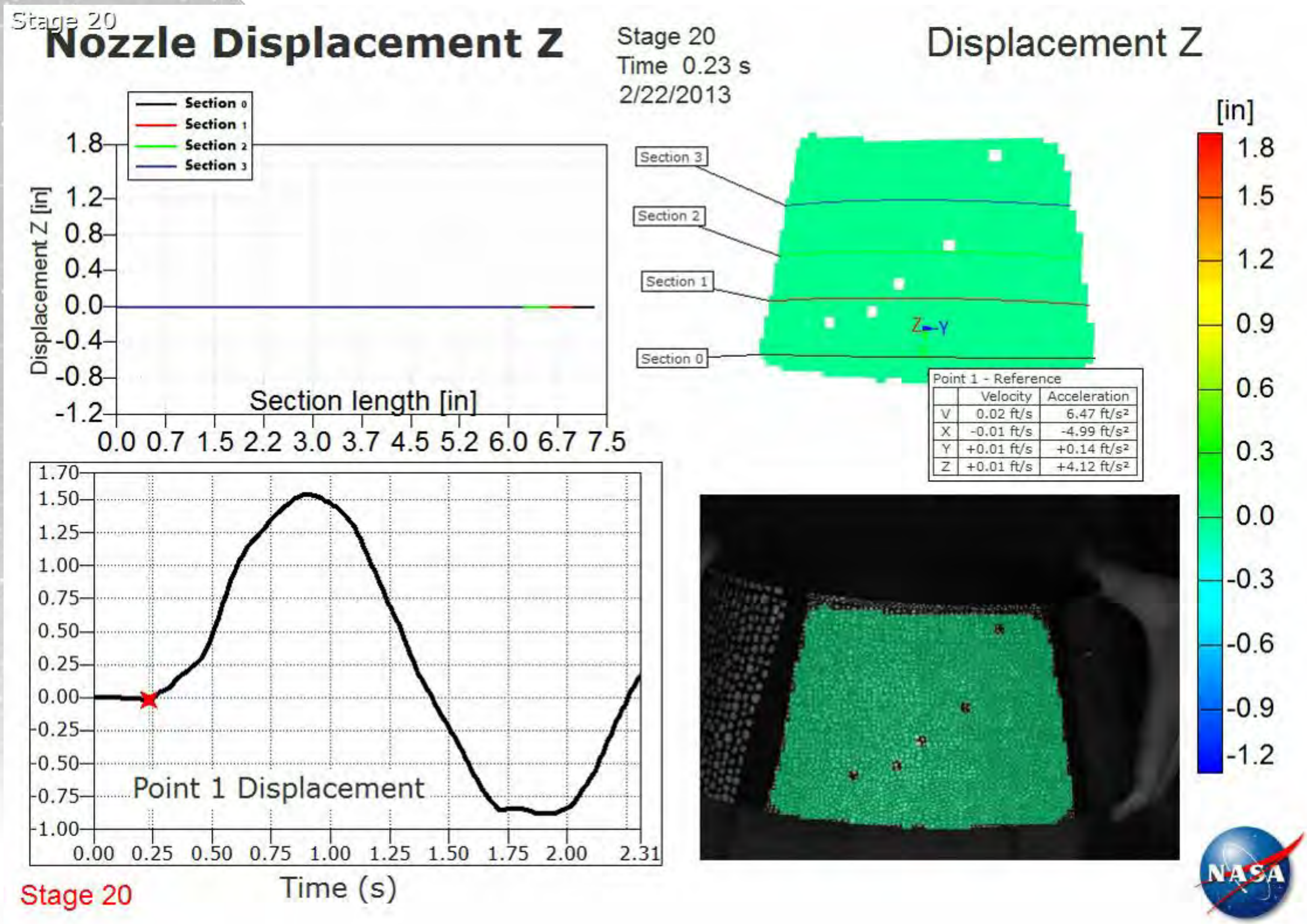


Nozzle Deformation
Date: 4/2/2013
0.000000 sec
Phantom 7.1M HS
50mm lenses

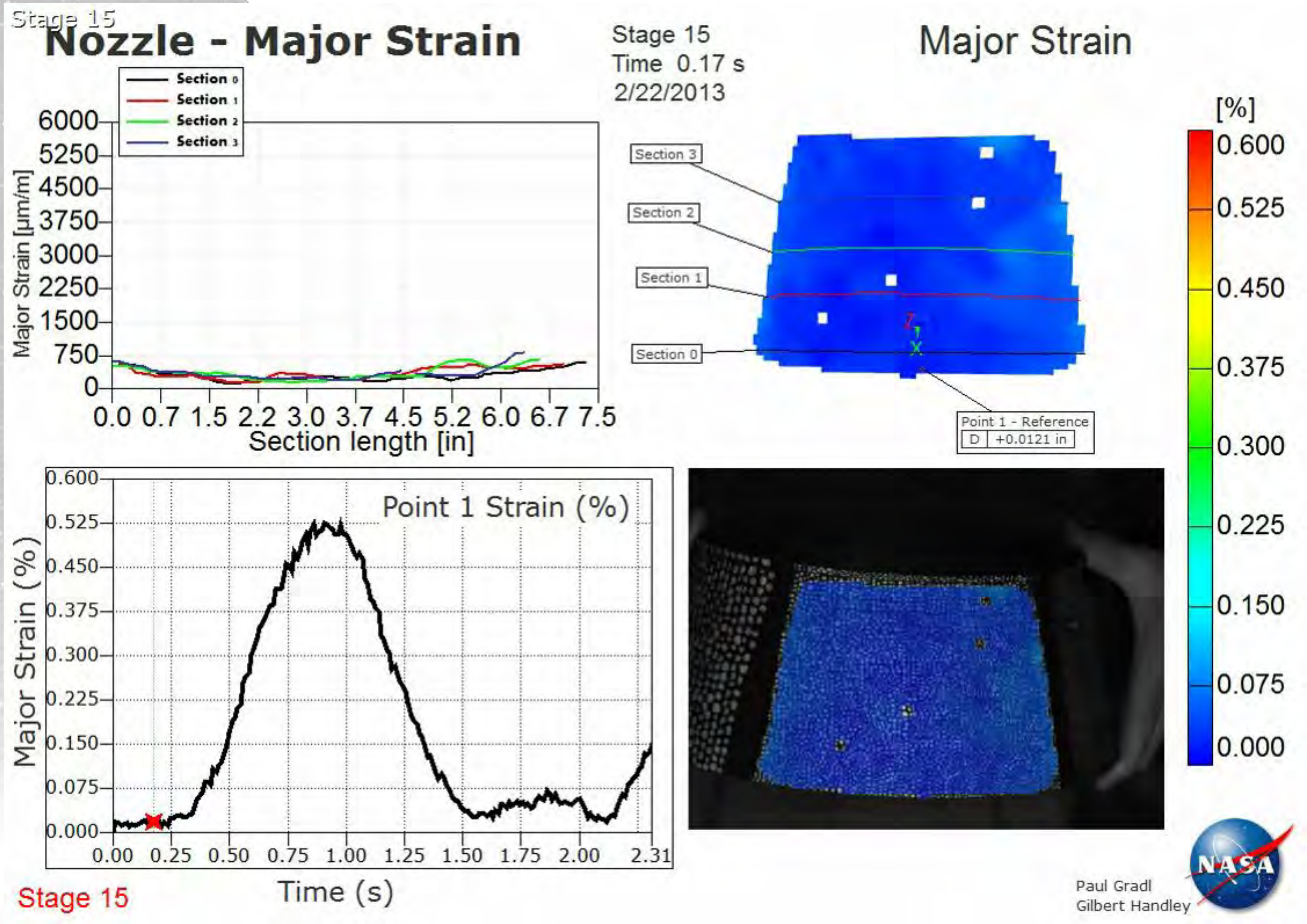


Paul Gradl
Gilbert Handley

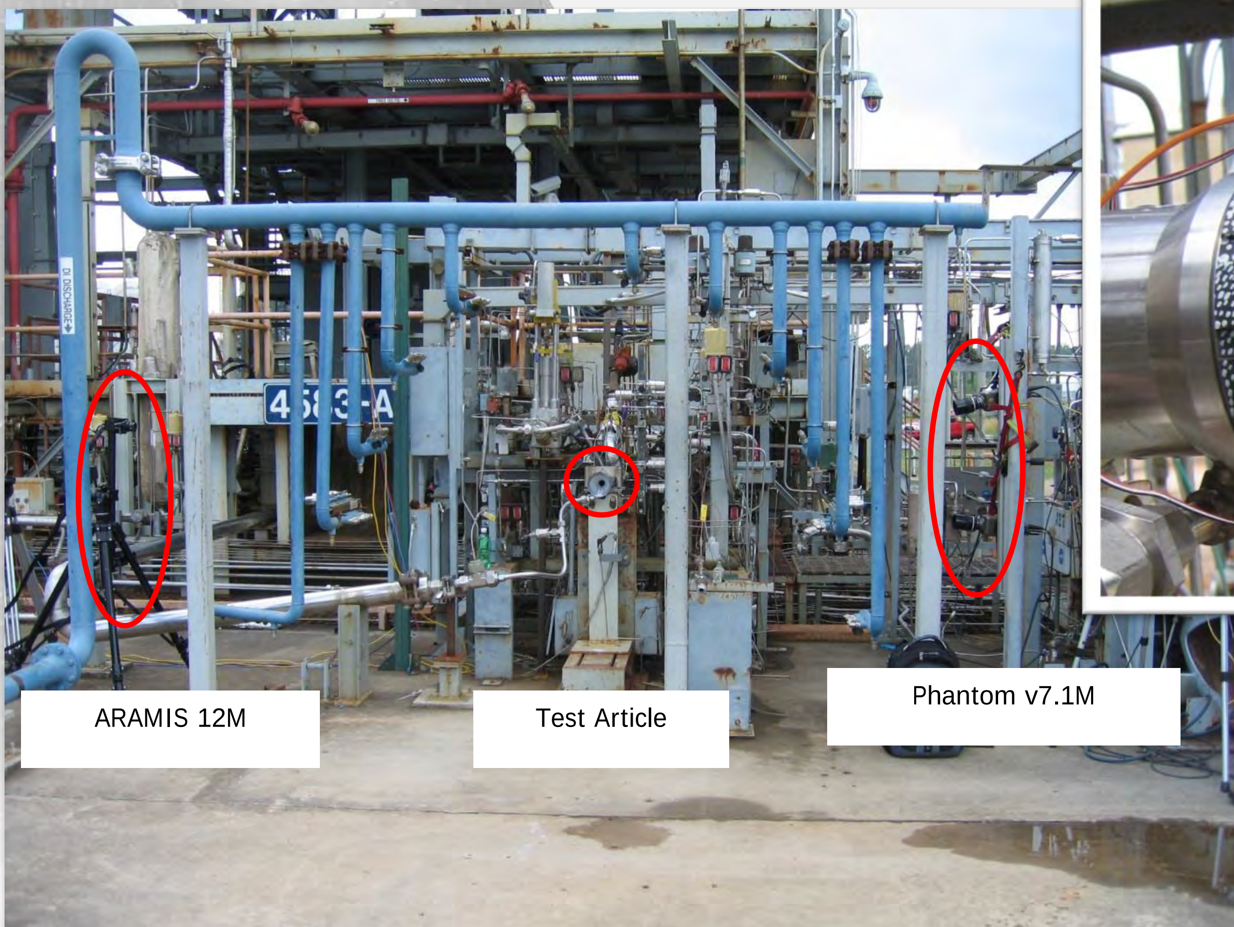
ARAMIS Lab Experiments – Displacement

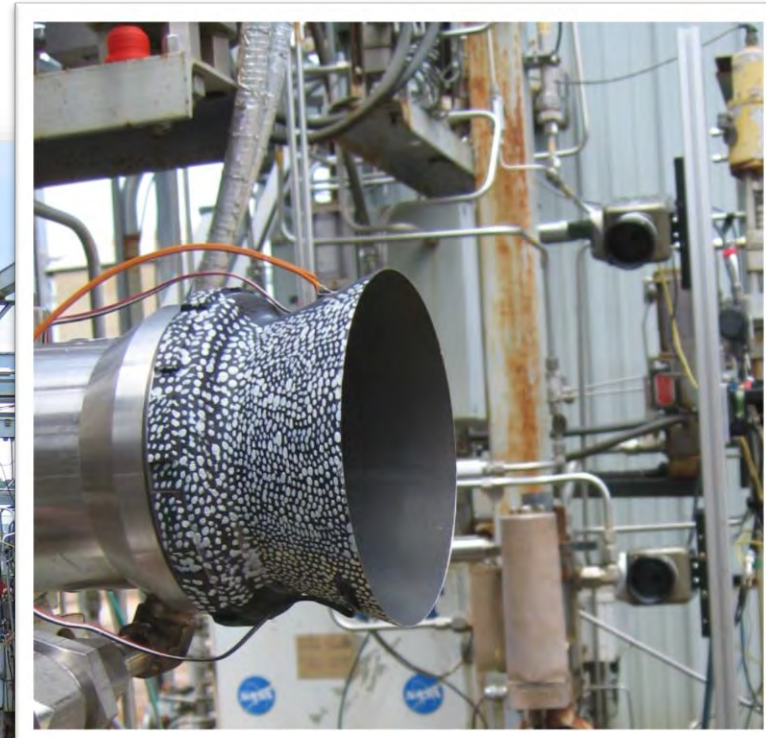


ARAMIS Lab Experiments – Principal Strain



Subscale Hot-fire Nozzle Testing

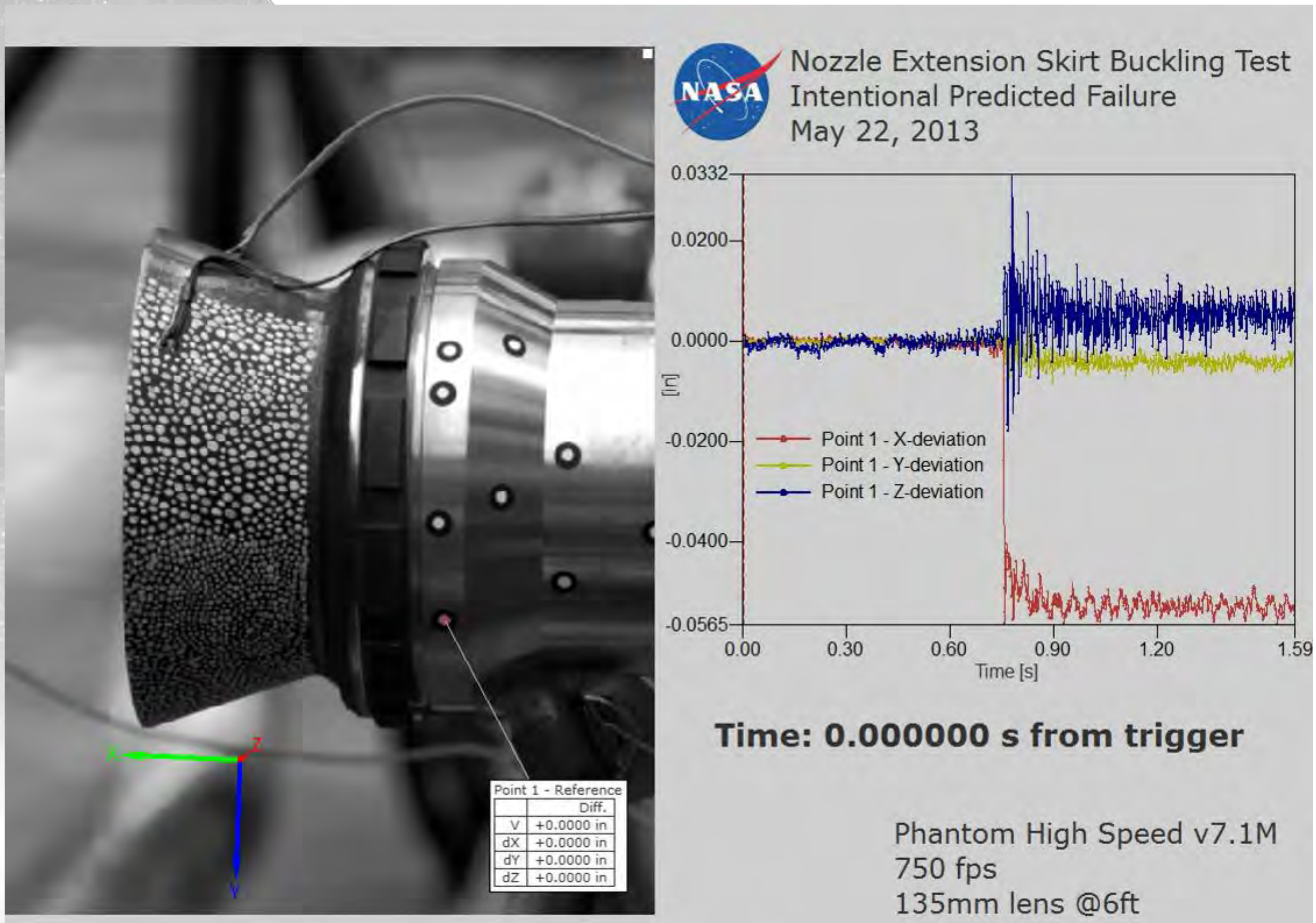




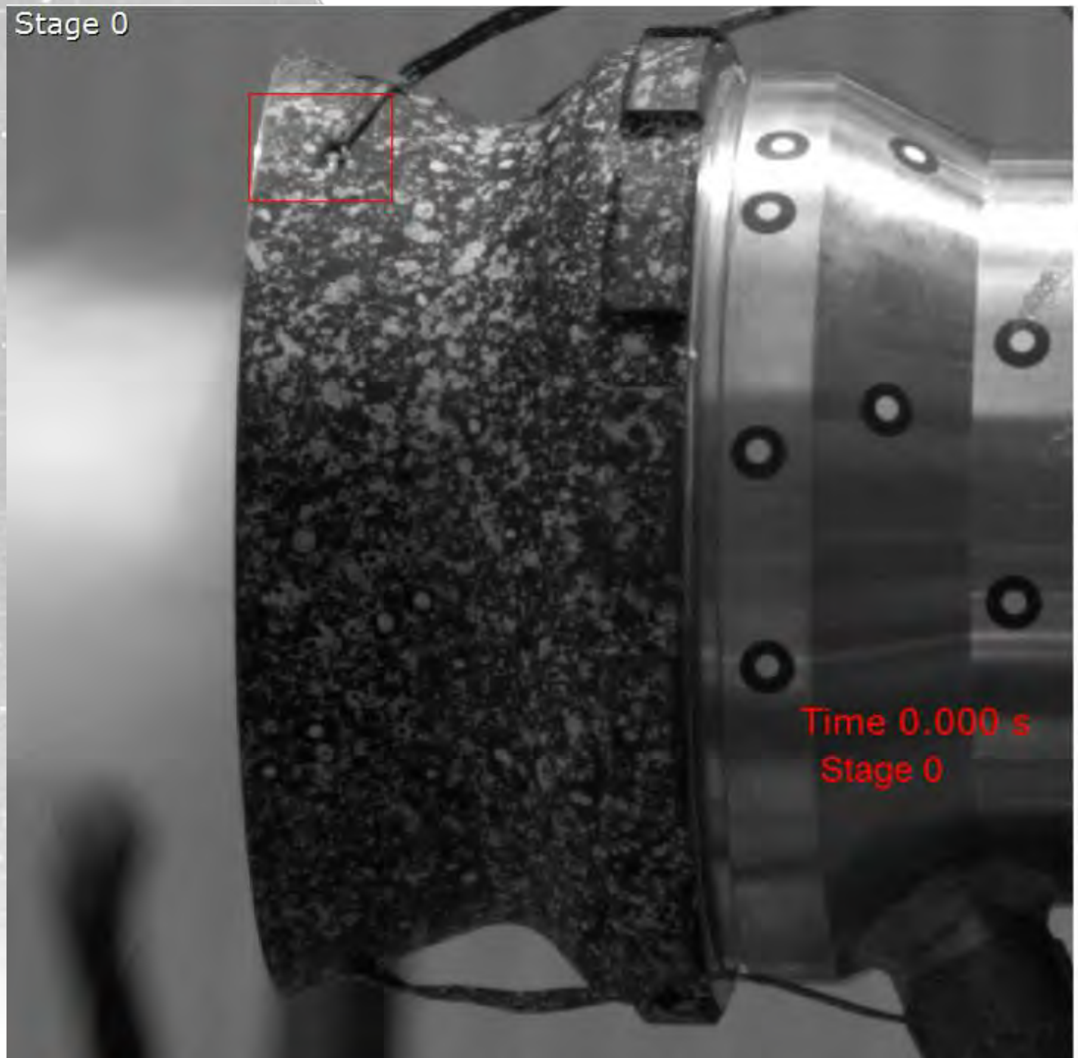
Additive Manufactured Radiative Cooled Nozzle Extension

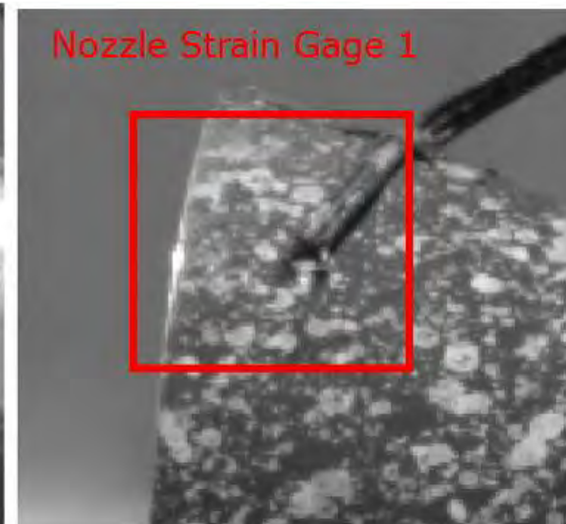
Test Photos and Data Collection:
Paul Gradl
Gilbert Handley
Sandy Elam Greene

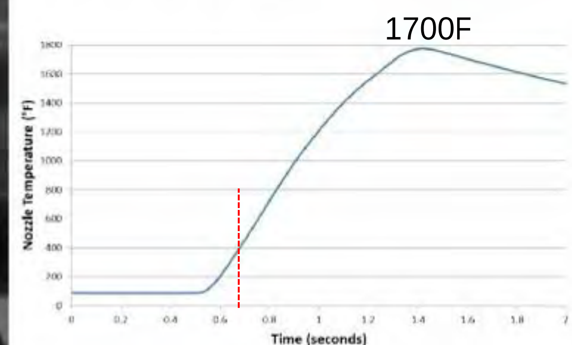
Bench Testing Doesn’t Always Translate into the Field…



Motivation to Develop Technique







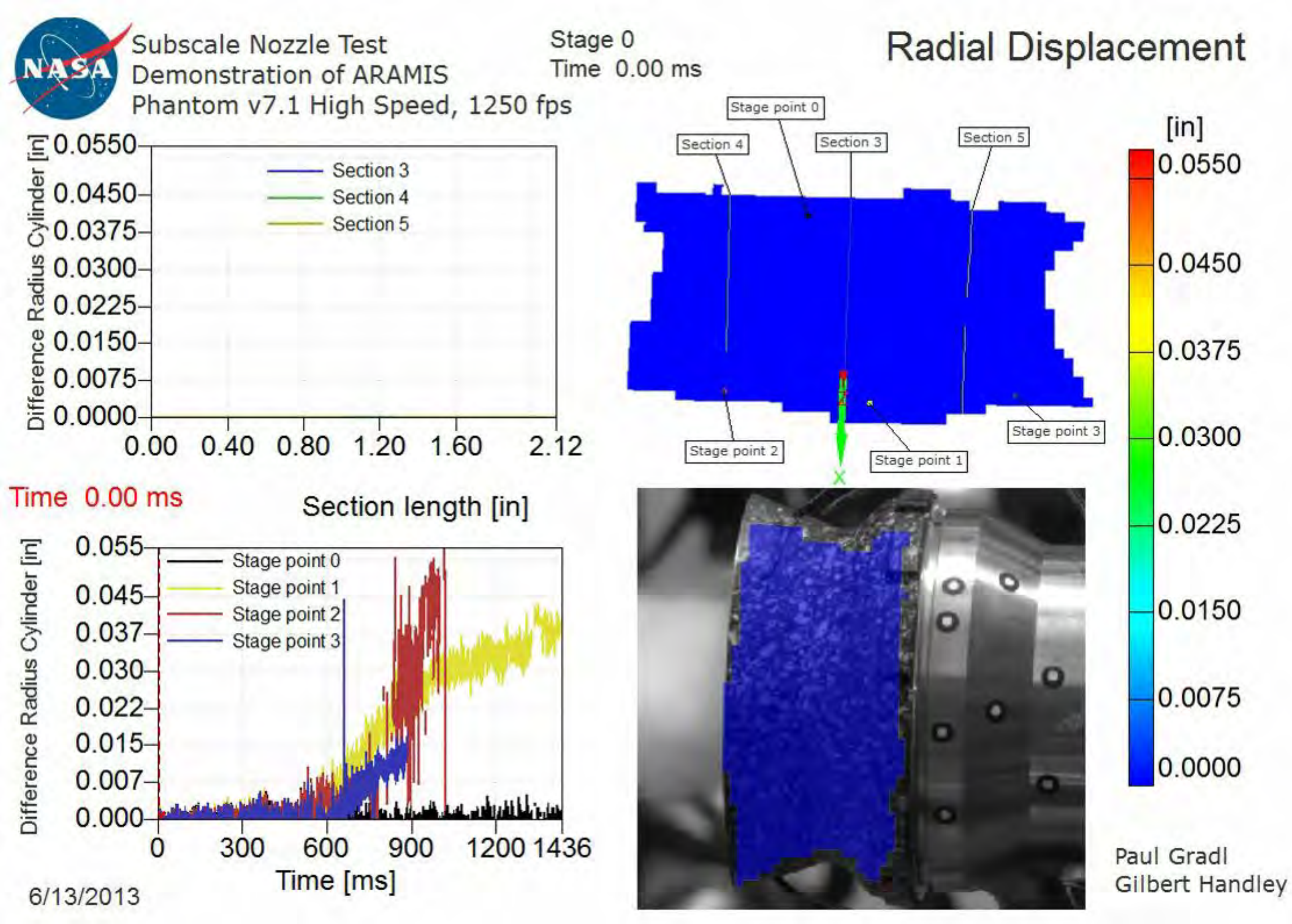
Strain Gage Failure at ~400F

Subscale Nozzle Hotfire Demonstration
Phantom v7.1 M, 1250 fps

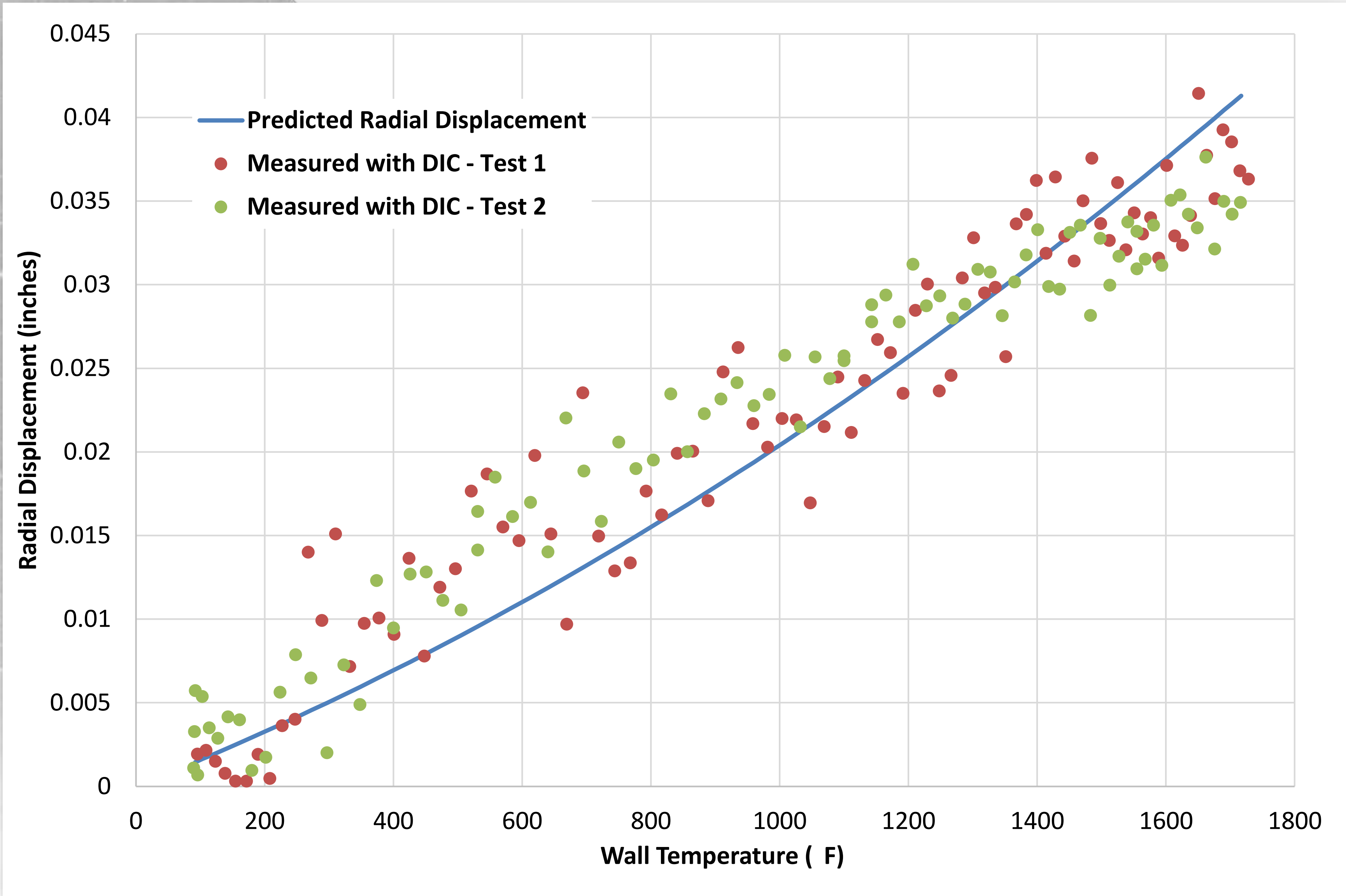
6/13/2013

Paul Gradl
Gilbert Handley

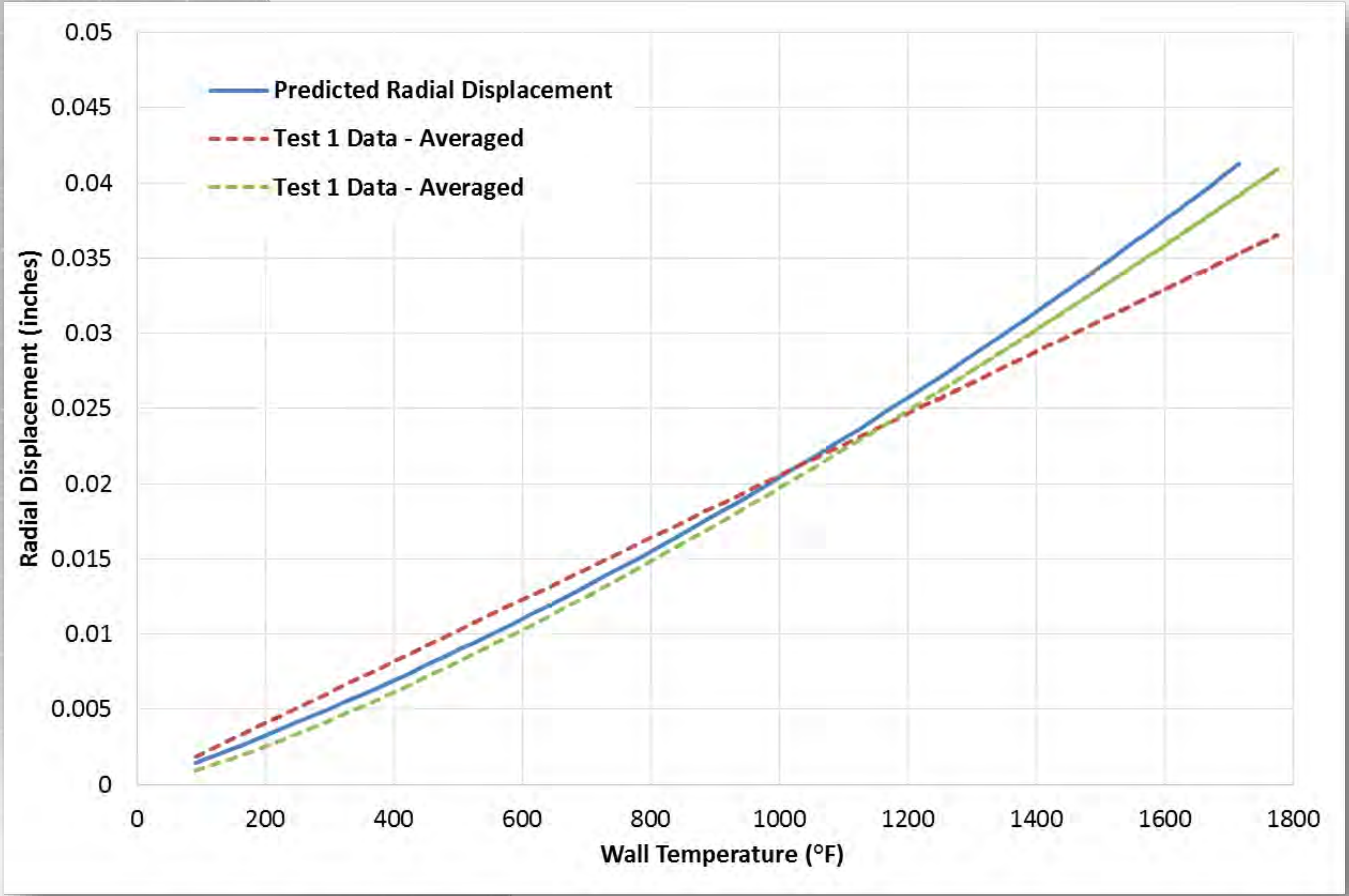
Subscale Hotfire Testing on Nozzle



Subscale Hotfire Testing – Data Analysis



Subscale Hotfire Testing – Averaged Data



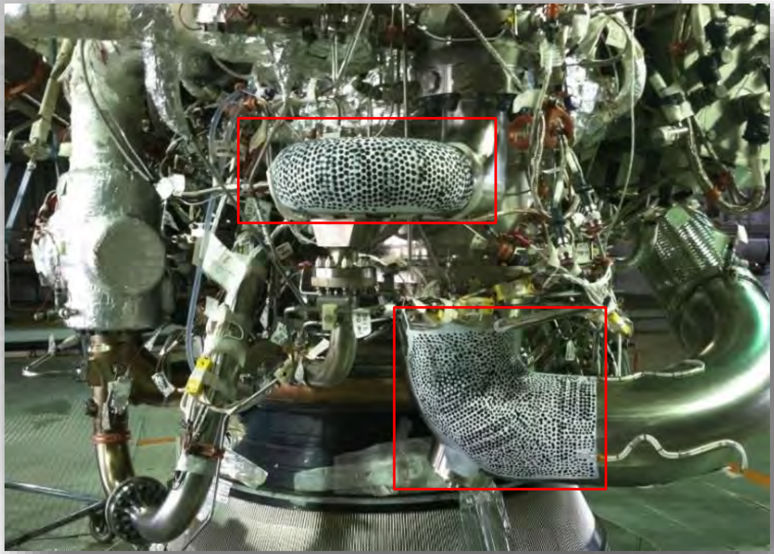
Optical test data tracking closely with predictions; error grows at elevated temperatures

Large Scale D.I.C. for Engine Hotfire Testing

MSFC has developed new optical measurement techniques to augment or replace traditional gages in harsh environment engine testing or manufacturing operations

Stereo high-speed cameras measure full-surface displacements and strains using "speckle pattern" (calibrated triangulation)

- Leveraged basic techniques from NESC Shell Buckling Test and NASA & industry experts
- Developed speckle pattern and initial vibration damping in subscale hotfire testing at MSFC
- J-2X provided the test-bed environment to develop camera stability damping
- Industry-first attempt for high temperature, high vibration environments where traditional gages do not operate reliably



Stereo Cameras installed and Speckle Pattern Applied at Stennis A1 Stand

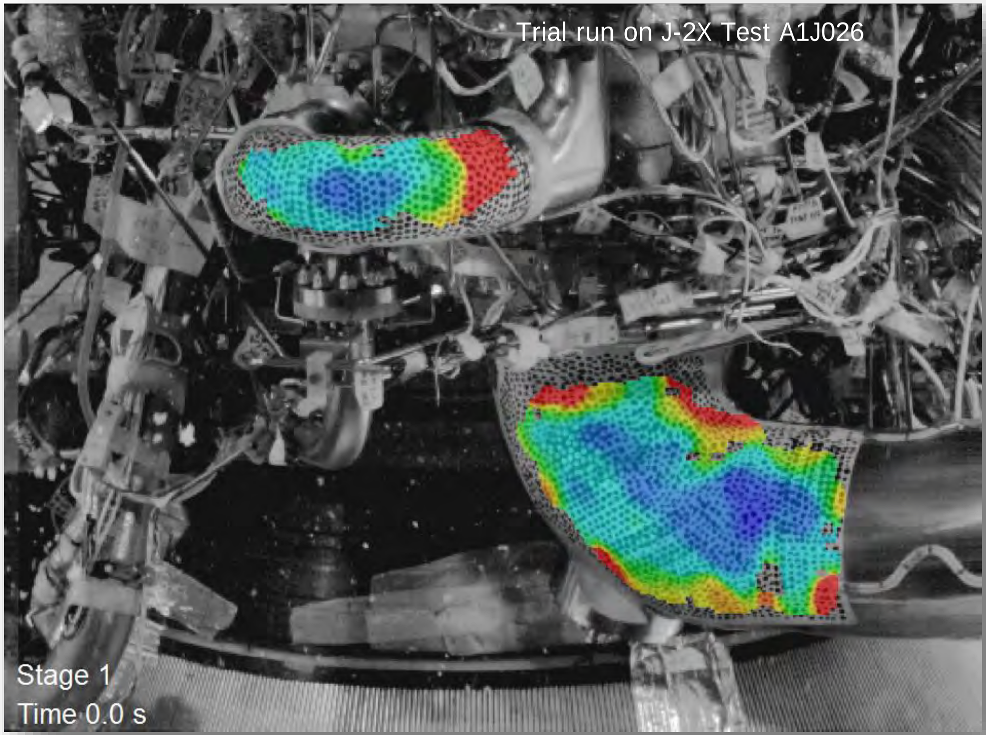
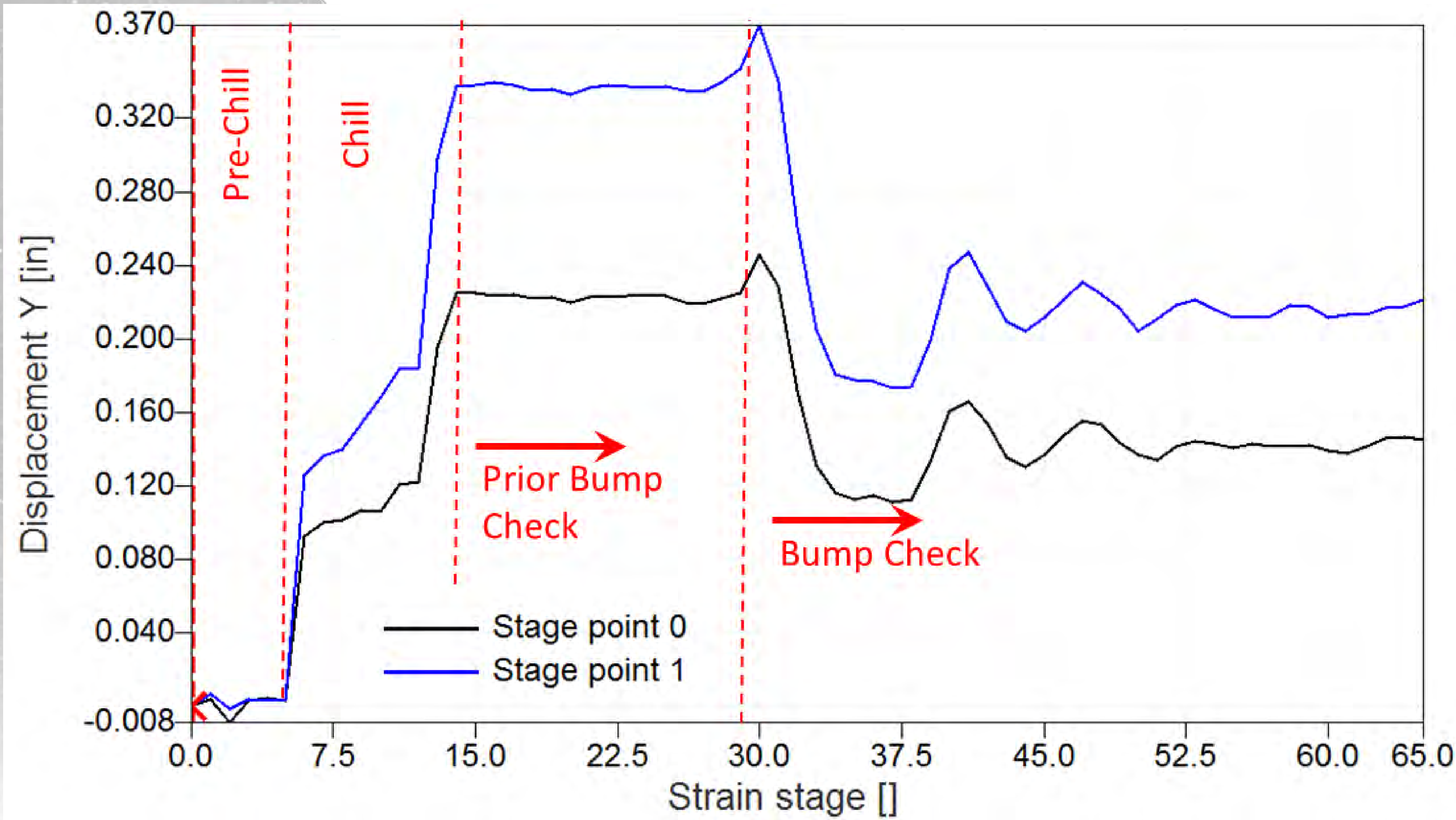


Photo Credit: Dan Goade

Test Data Collection:
Paul Gradl, Gilbert Handley, Brian West

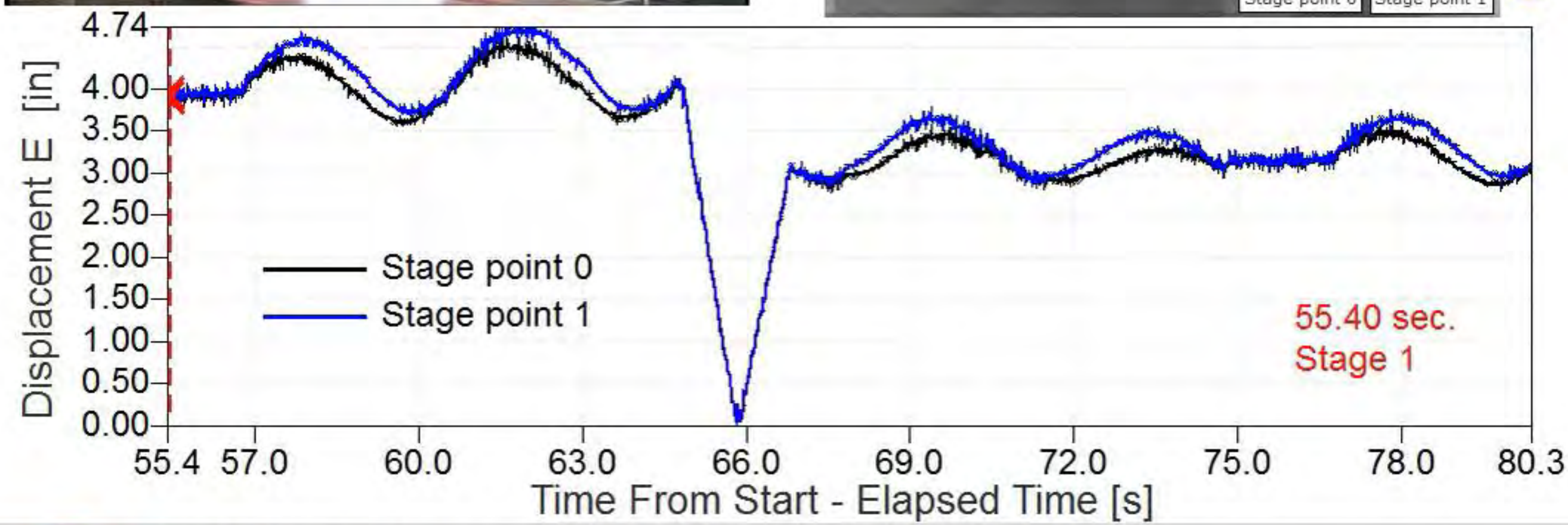
ARAMIS high speed cameras

Engine Movement and Strains during Pre-test Ops



Ability to track engine during all chill and gimbal checkout operations

ARAMIS Full Surface Strain Measurement Proof of Concept Displacement during A1J028 Test

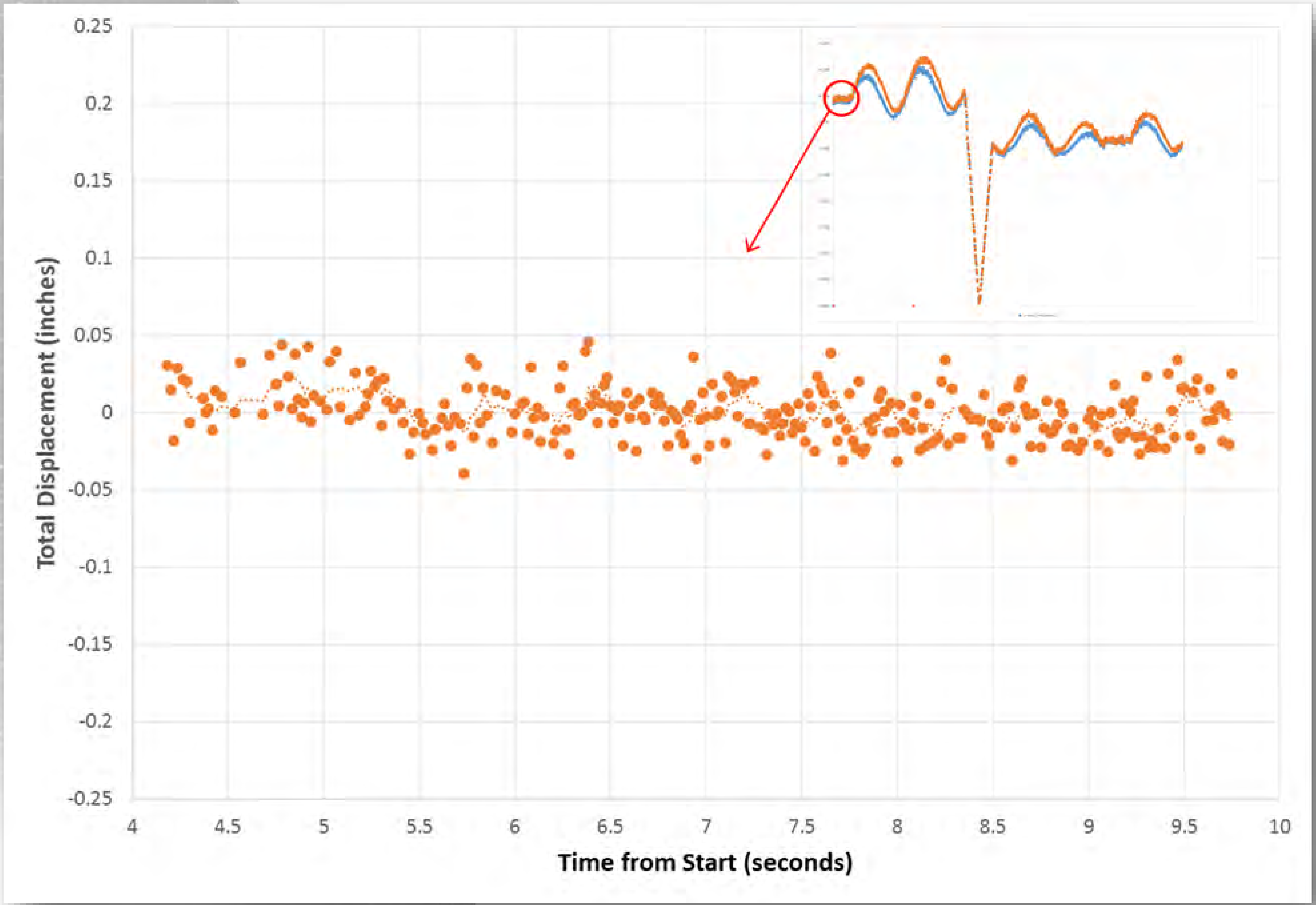


ARAMIS Trial on J-2X A1J028

Paul Gradl
Gilbert Handley

Displacement E (Total X, Y, Z)

Error Associated With Measurements During Hotfire



2.75" Hydra Testing Demo

Test Support: Paul Gradl/MSFC, Cory Medina/MSFC, John Tyson/Trilion, John "*Yanni*" Psilopolous/Trilion

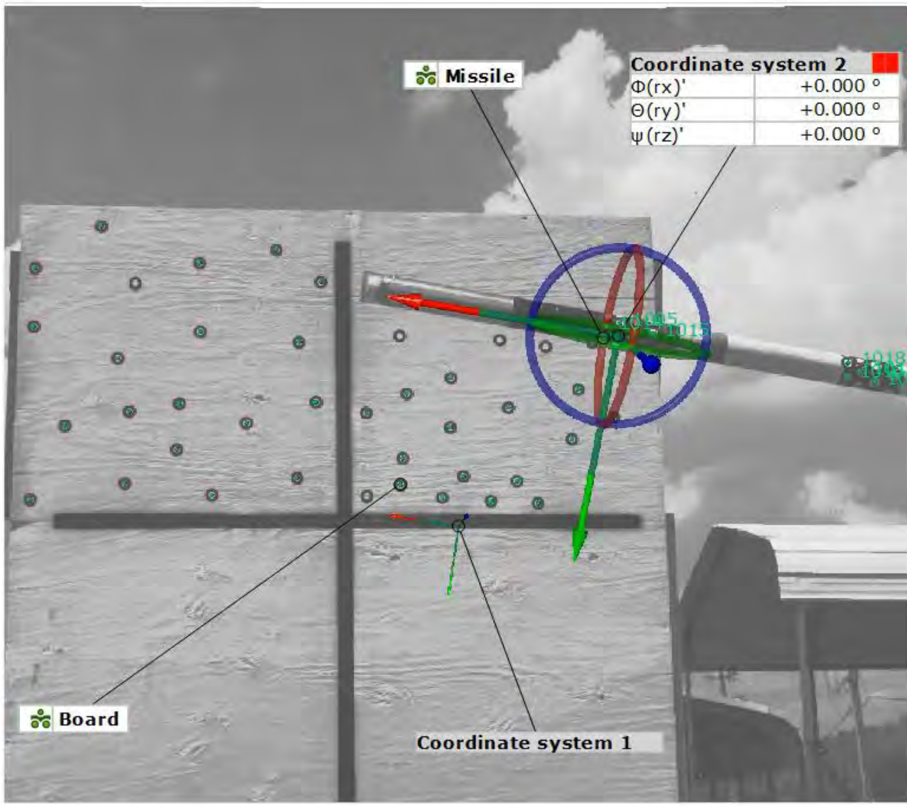
Demonstrated initial feasibility of using photogrammetry and digital image correlation for range testing of missile burst testing.

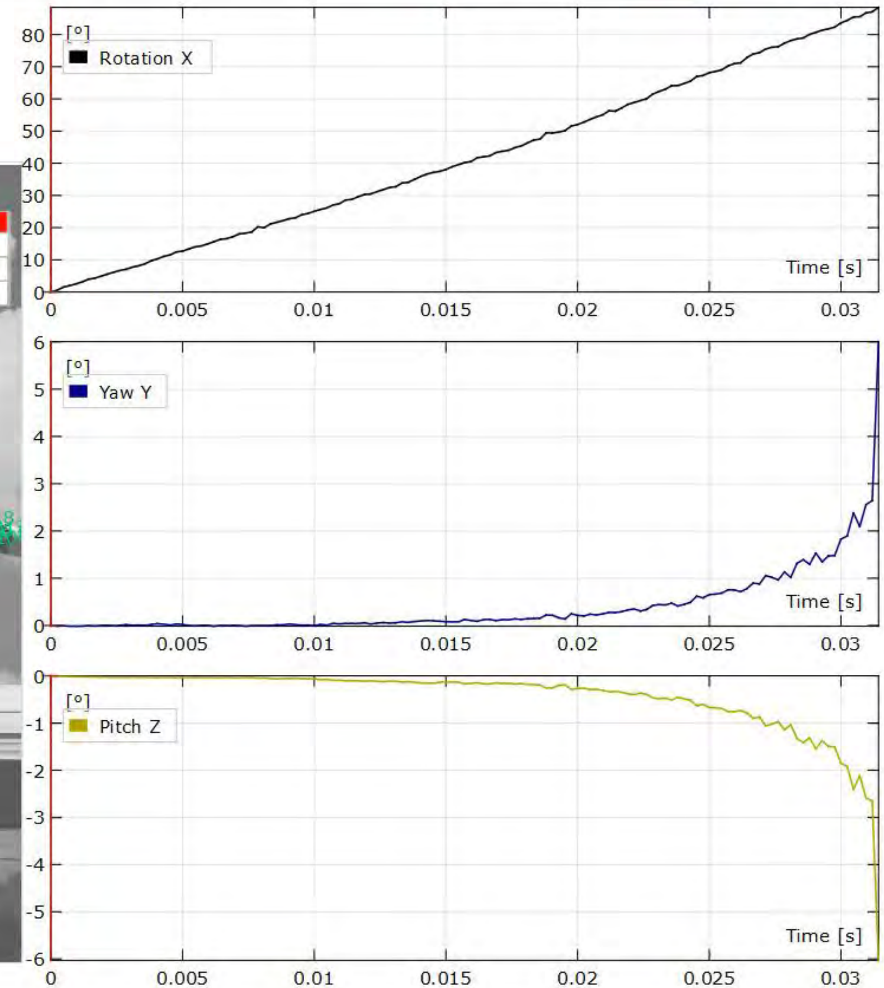
Feasibility of 6-dof Analysis of Missile Testing

Report - PONTOS Testing

Test 62 - TM1 Hydra Missile Testing

Test Data provided:
Paul Gradl and Cory Medina





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Conclusions and Future Work

NASA MSFC has advanced a series of dynamic digital image correlation techniques for use during hotfire engine testing

- Subscale and full scale testing and analysis has demonstrated feasibility to accurately determine local and global displacements and surface strains

NASA will continue to advance this technology for rocket engine testing, subscale testing, component testing and bench top testing

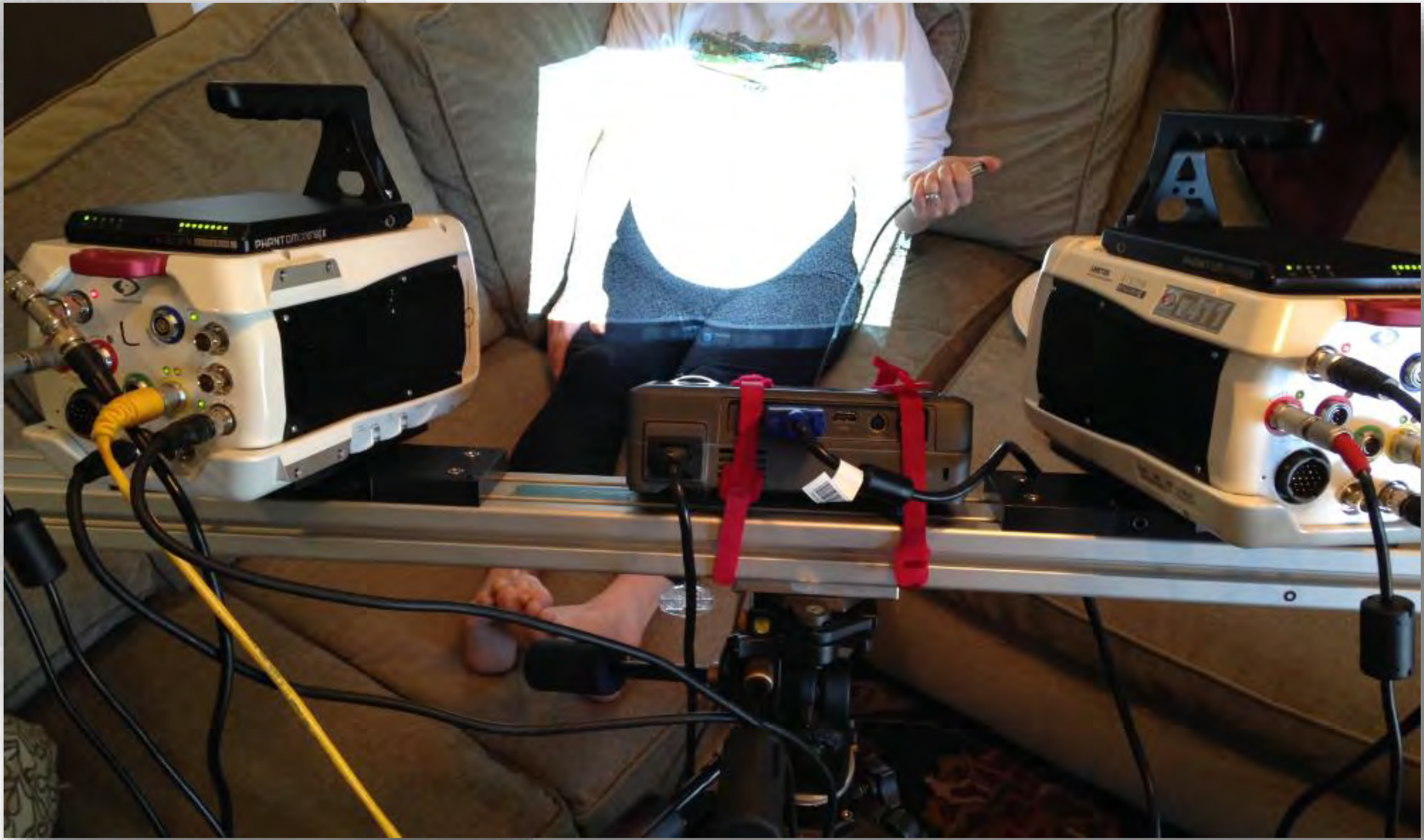
- Replace traditional measurement systems
- Integrate with modern analysis tools
- Combine advanced techniques such as IR thermography and digital image correlation
- Continue to research and advance techniques for elevated temperature applications

Share lessons learned with industry and government through technical papers and presentations

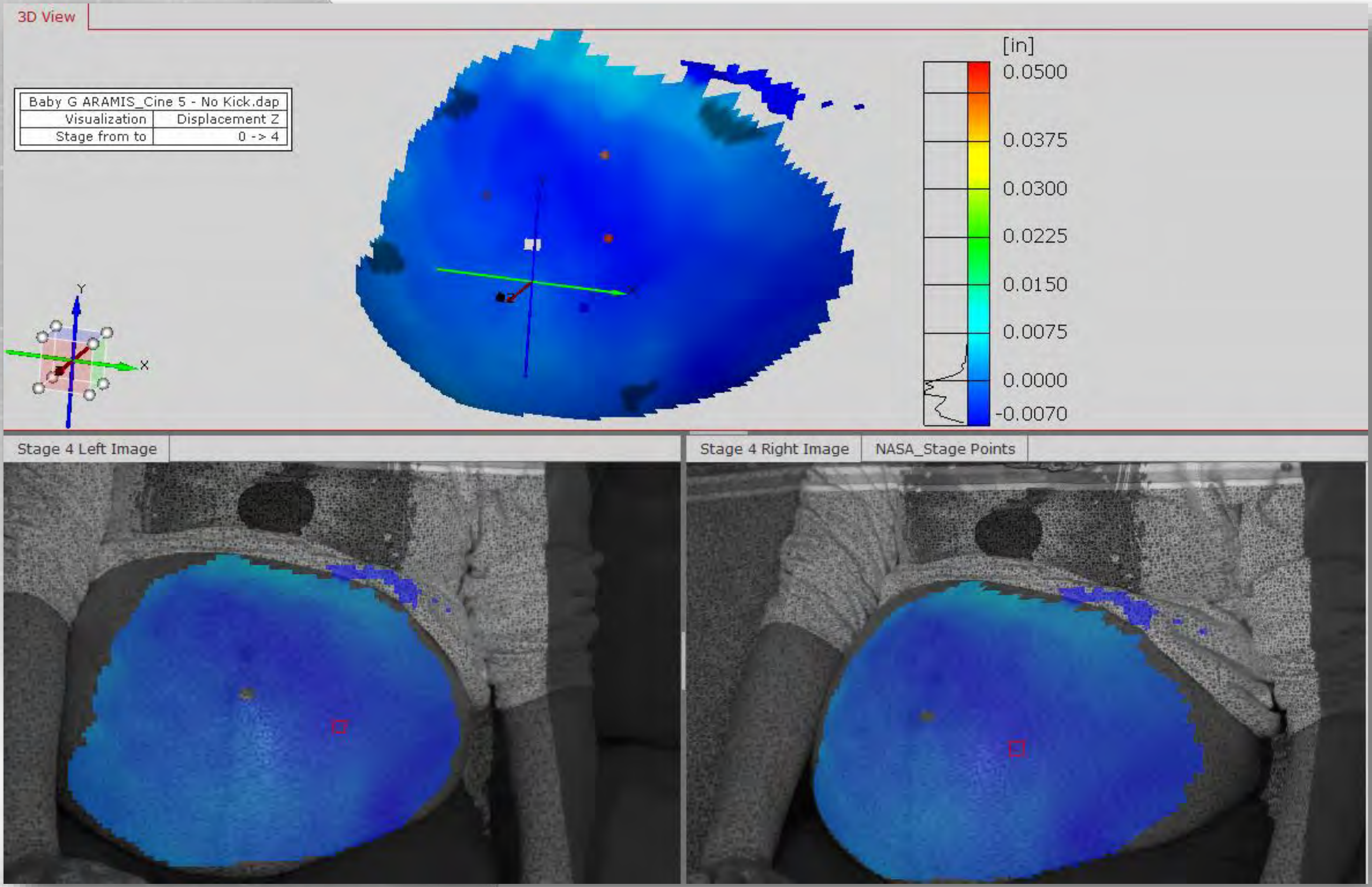
The possibilities of dynamic data collection are endless…

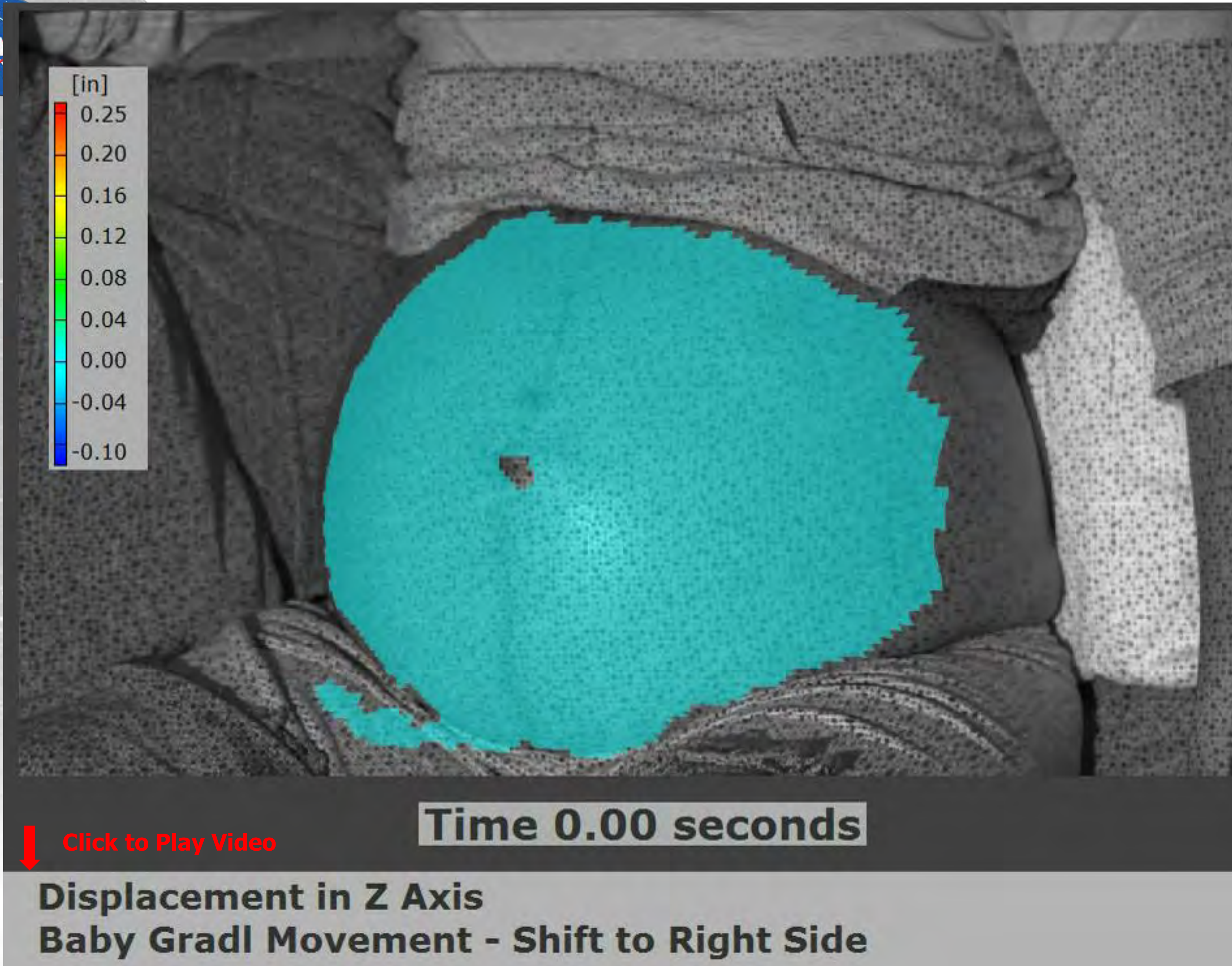
Dynamic responses require an input to excite the system…

Images were collected using a projected pattern instead of painting a speckle pattern on her belly…
High Speed cameras were post triggered after movements felt.

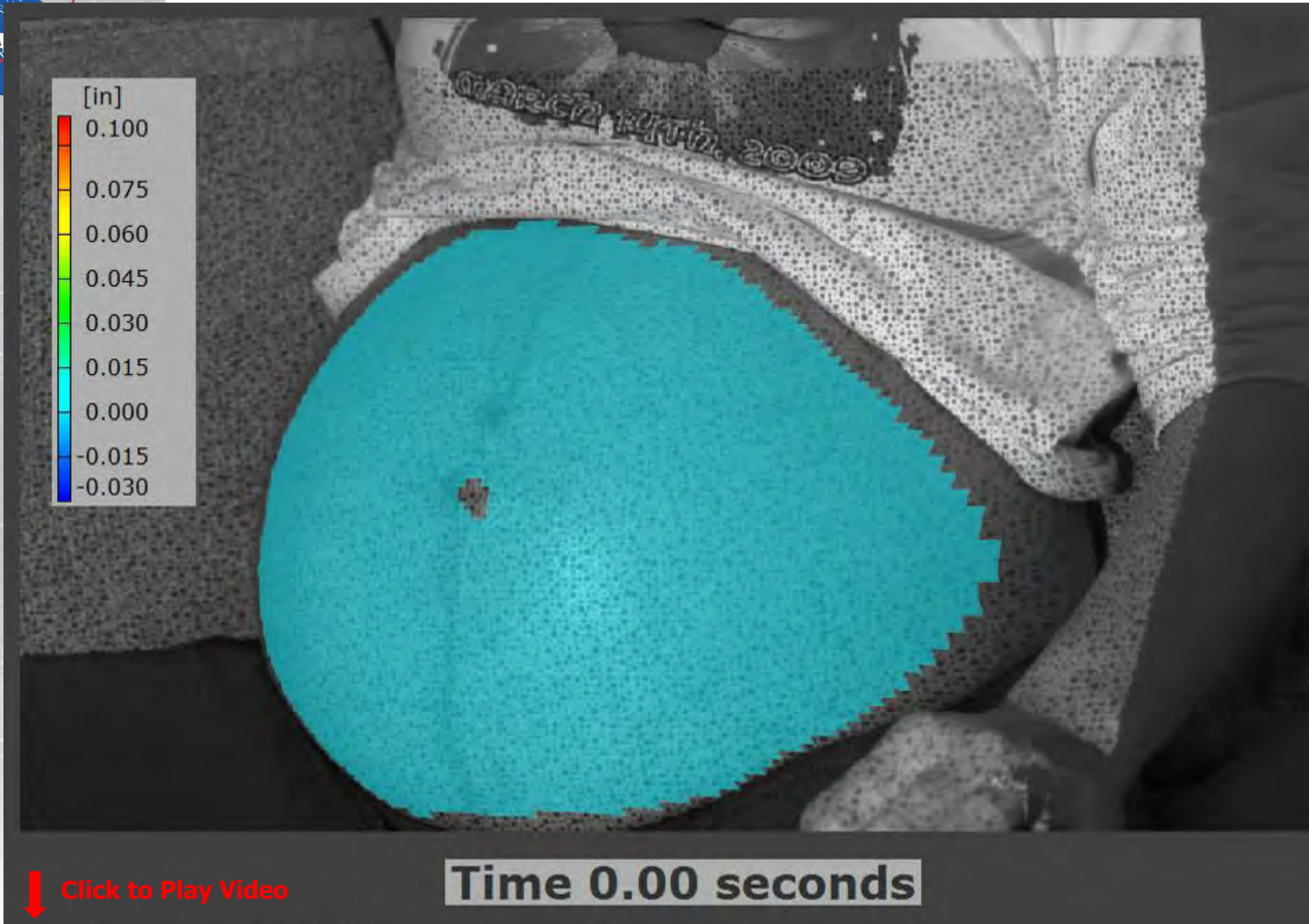


To ensure that kicks and movement data was real a background test was conducted with no baby movement (to correct for breathing and body motion)




[in]
0.25
0.20
0.16
0.12
0.08
0.04
0.00
-0.04
-0.10
Time 0.00 seconds
Click to Play Video
Displacement in Z Axis
Baby Gradl Movement - Shift to Right Side

Gradl/MSFC



Displacement in Z Axis
Baby Gradl Movement - Baby Kicking

Contact: Paul Gradl
NASA MSFC
256.544.2455
Paul.R.Gradl@nasa.gov

BACKUP

References

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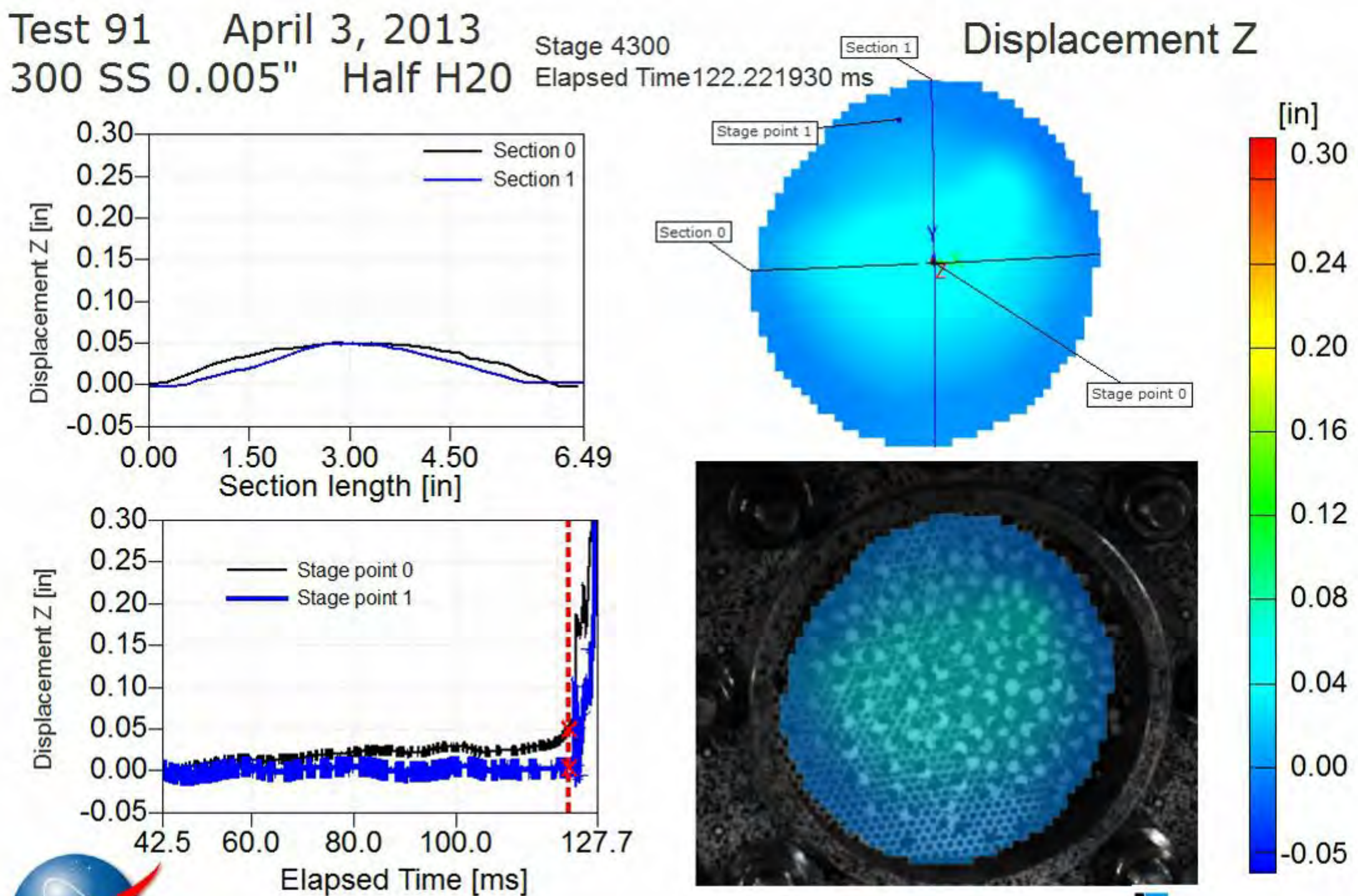
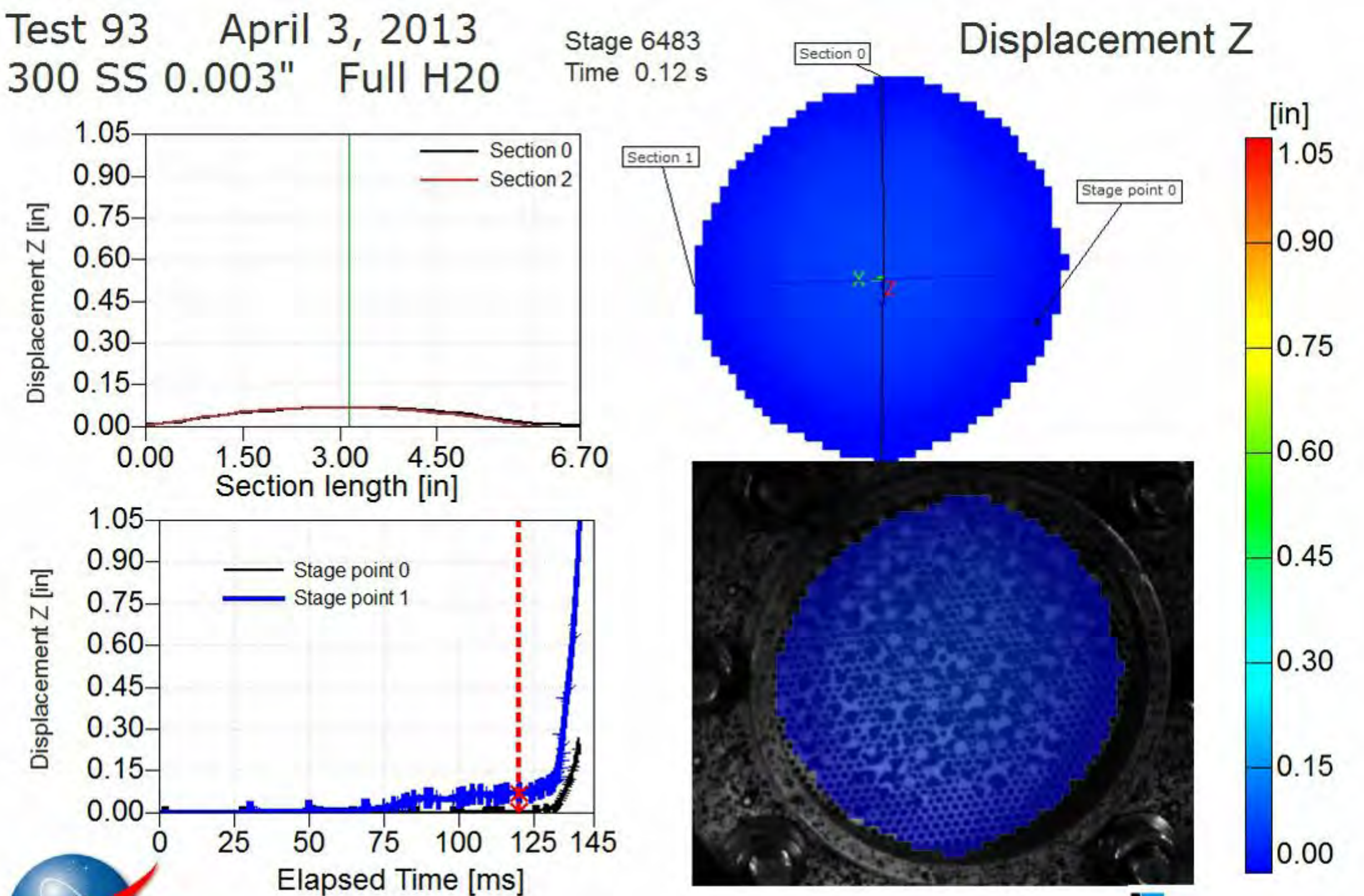
Gradl, P. “Digital Image Correlation Techniques Applied to Large Scale Rocket Engine Testing.” AIAA-2016-4977 Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 26, 2016. Salt Lake City, UT.

High Speed Fragmentation Testing

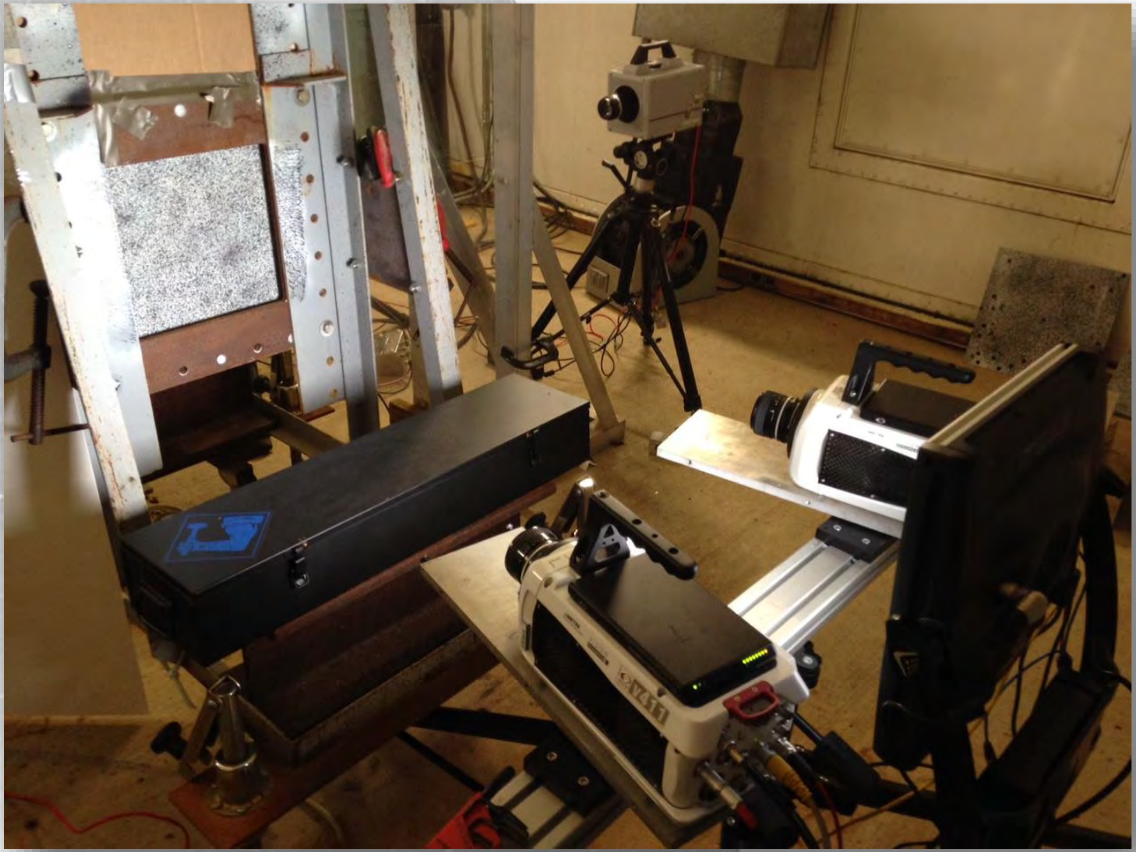


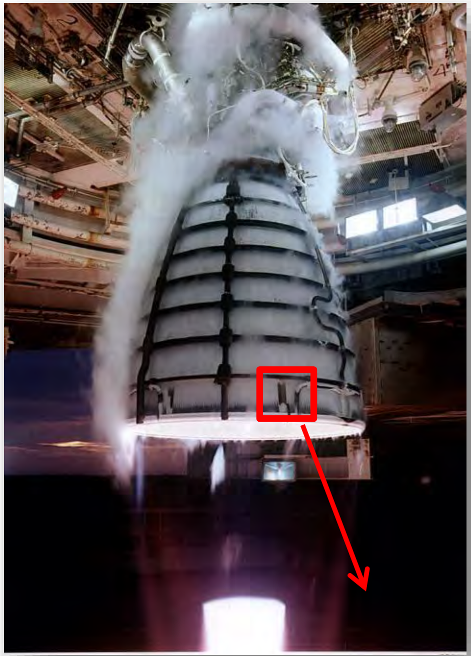
Bangham ENGINEERING INC.

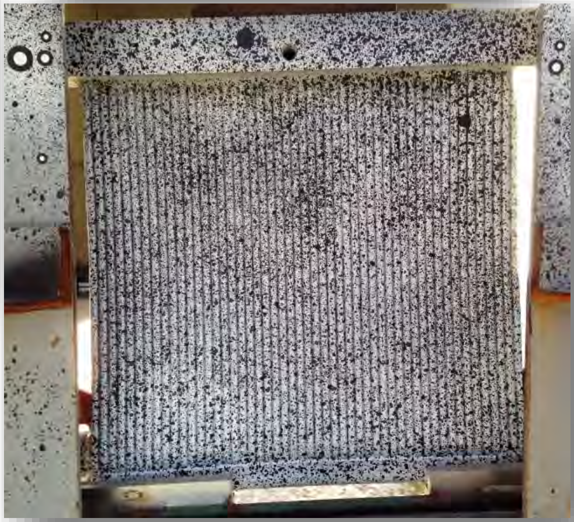
High Speed Fragmentation Testing (cont)



Space Launch System (SLS) Debris Impact Testing



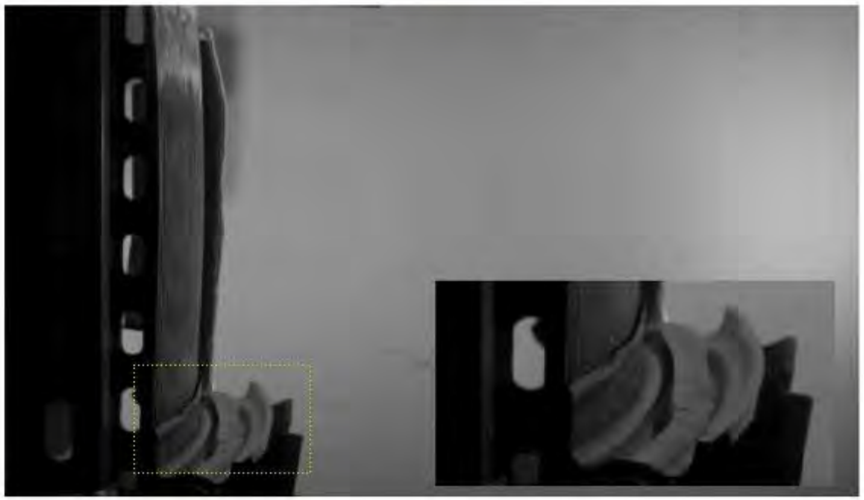


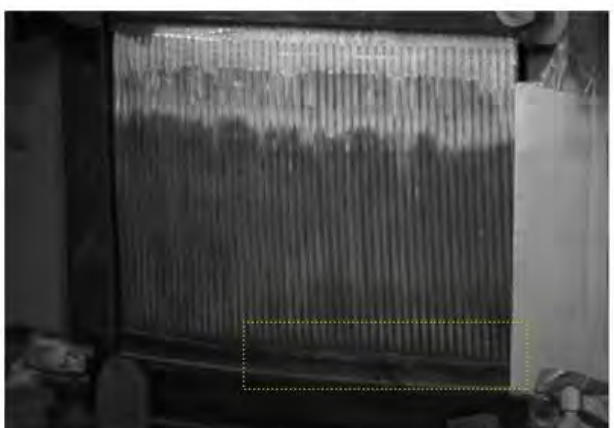


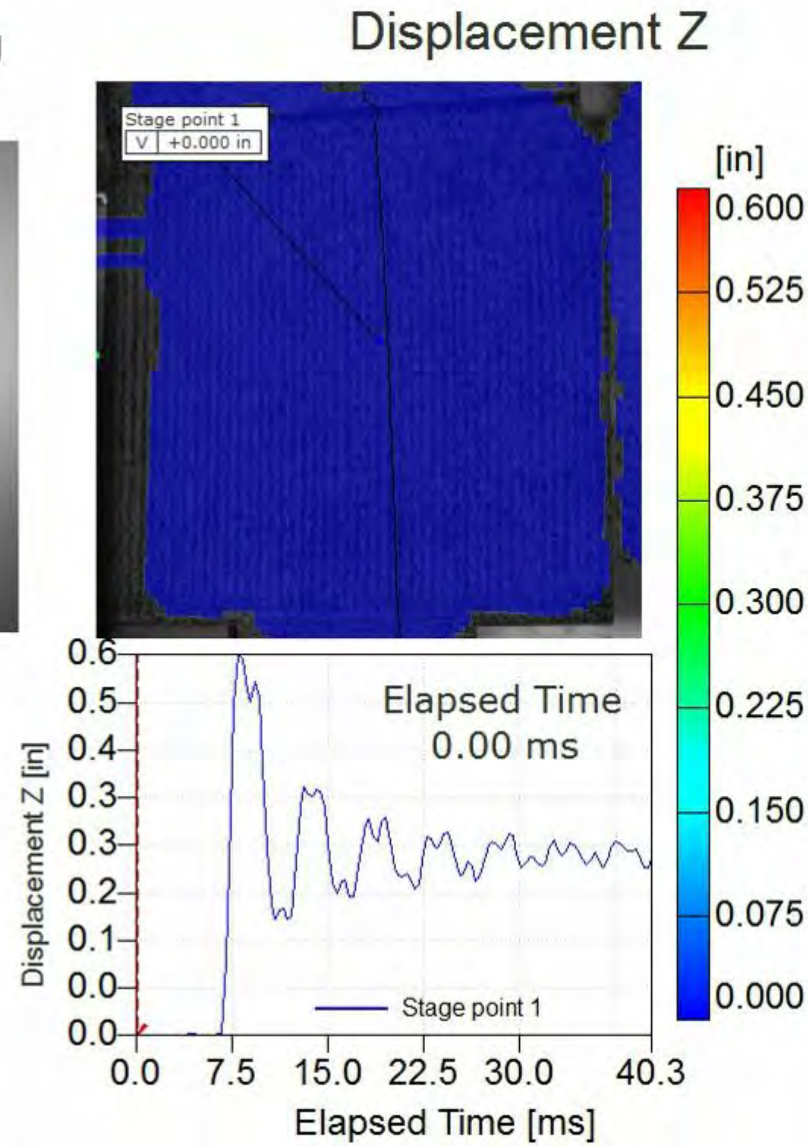
Test provided by: Paul Gradl and Cory Medina
Chip Kopicz, Perry Gray, Bart Suggs

SLS RS25 Nozzle Pressurized Panel

SLS RS25 Pressurized Panel Testing
13 Nov 2015; 6# Foam







Paul Gradl Cory Medina Chip Kopicz