# Modeling and Simulation to Advance Test and Evaluation

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# Acknowledgments

- Authors are privileged to give an overview of the work of many individuals
  - Test and Evaluation
    - Experimental infrastructure support
    - Conduct of experiments
  - Modeling and Simulation
    - Numerical infrastructure support
    - Conduct of simulations

# Presentation Outline

- Two examples showing M&S and T&E synergy will be given
  - – Structural example – Steve Attaway
  - – Thermal example – Sheldon Tieszen
- General comments will be given on the cost of a combined approach.

# Synergy

- Both M&S and T&E have strengths, both have weaknesses
  - Experiment: The full truth partially exposed
    - If you cannot measure the key phenomena, no amount of testing will give you the understanding of margin
    - Some things are too costly to test with existing technology
  - Simulation: The partial truth fully exposed
    - If your model does not contain the key phenomena, no amount of simulation will give you the understanding of margin
    - Some things are too costly to model with existing technology
- Combination of M&S and T&E is stronger than individual components
  - Information content (T&E strength, M&S weakness)
  - Information diagnostics (T&E weakness, M&S strength)

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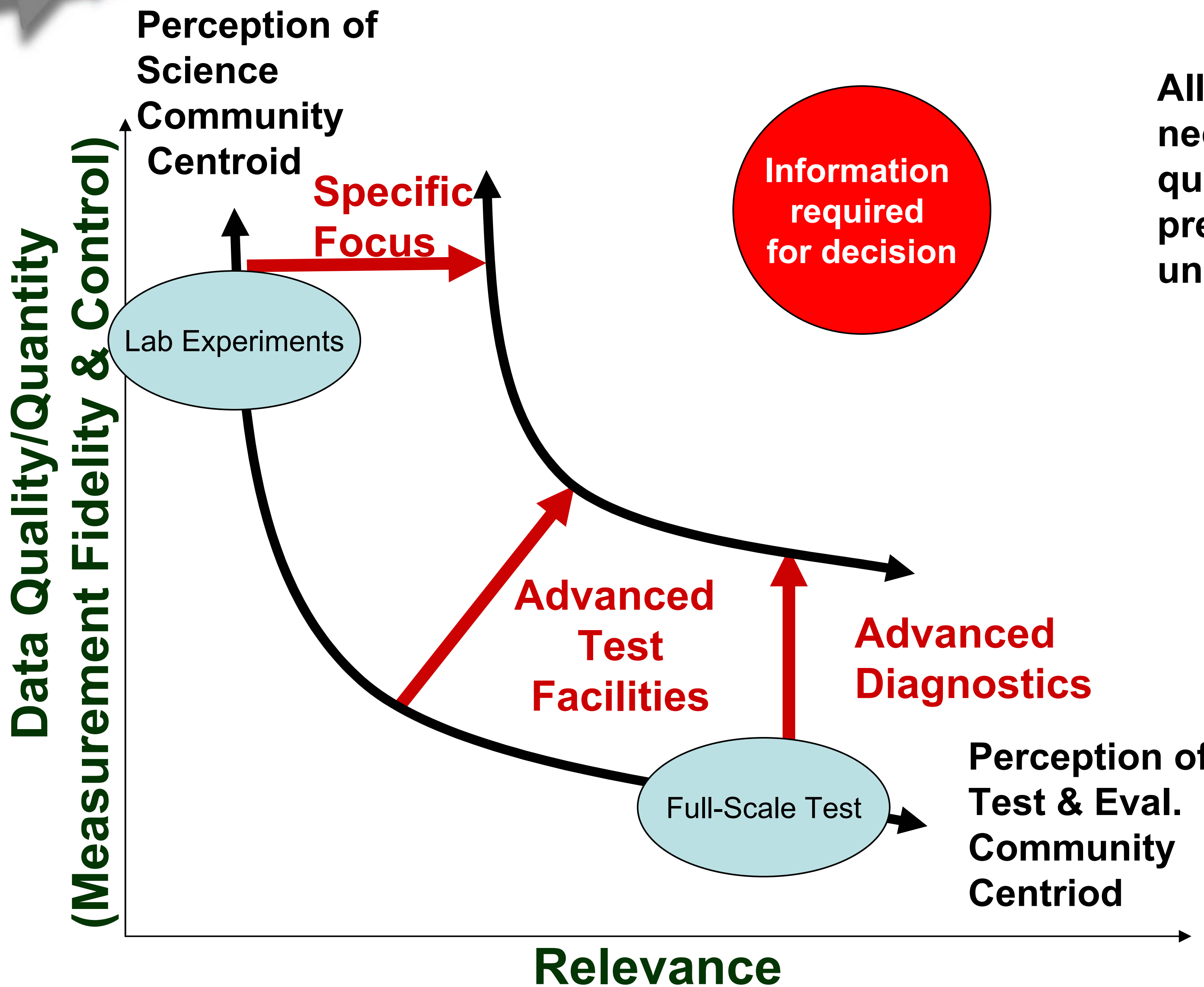
# Goal and Approach

- Our goal is to
  - Provide the technical basis for high-consequence decisions relative to system safety and performance margins

- Our approach is to
  - Combine *Modeling and Simulation* with *Test and Evaluation*
  - Use a Verification, Validation & Accreditation framework to establish that our physical understanding is sufficient
  - Make risk-informed decisions with respect to system safety or performance failure margins

# Test and Evaluation is Science in Relevant Conditions




**All data are necessary to quantify prediction uncertainty!**

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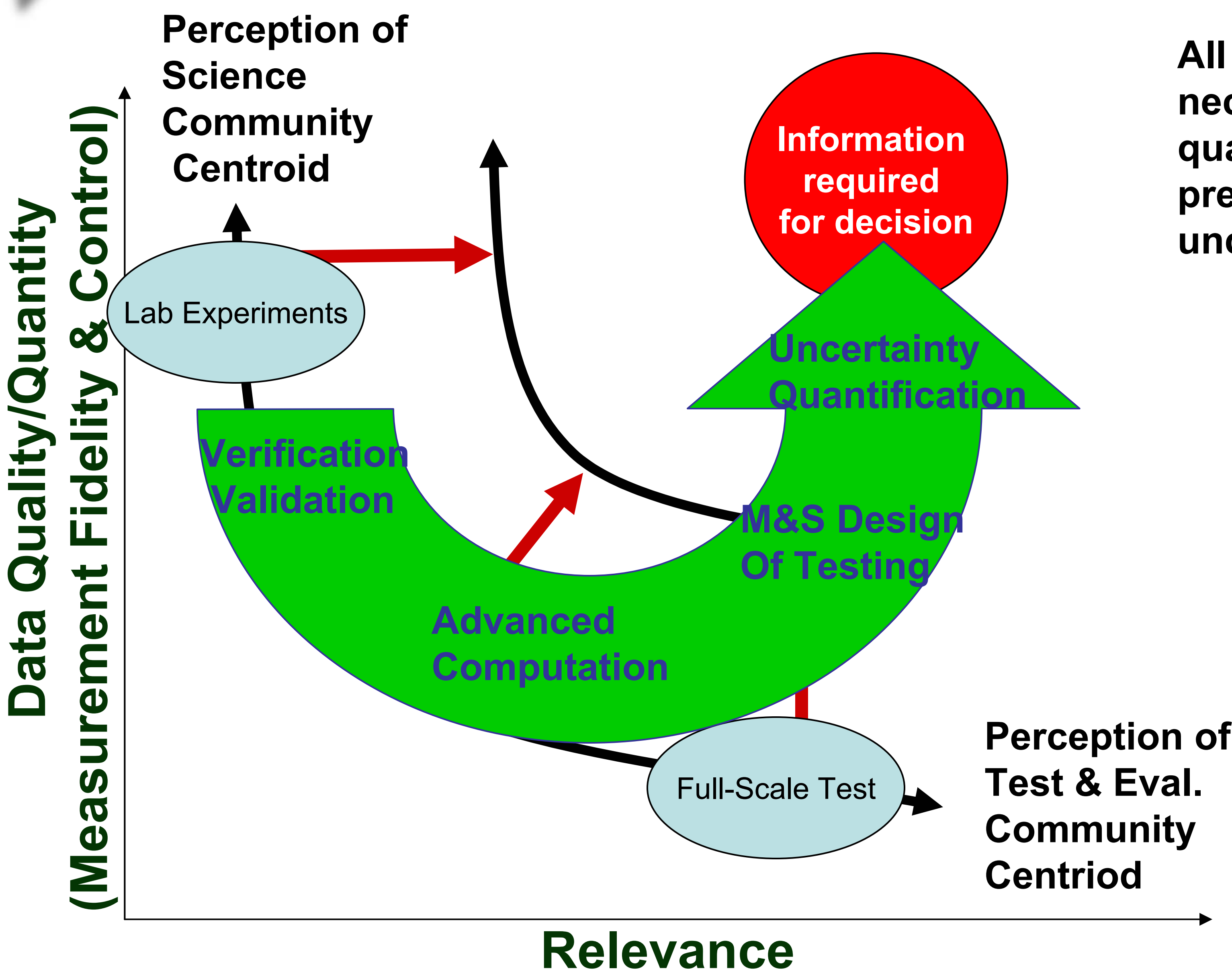
# M&S Advances T&E to Decision Goal

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# Example #1
# Validation Test of Concrete Simulations

Testing was used to validate our ability to simulate heavy damage to reinforced concrete

How does this test/analysis combination improve the prediction of behavior for defense and homeland security systems?

- Validated computational tools for modeling collapse of concrete
- Knowledge gained from modeling reinforced concrete will benefit many programs
- Provides more accurate input to risk based decisions

Critical to understanding concrete behavior and quantifying design margins

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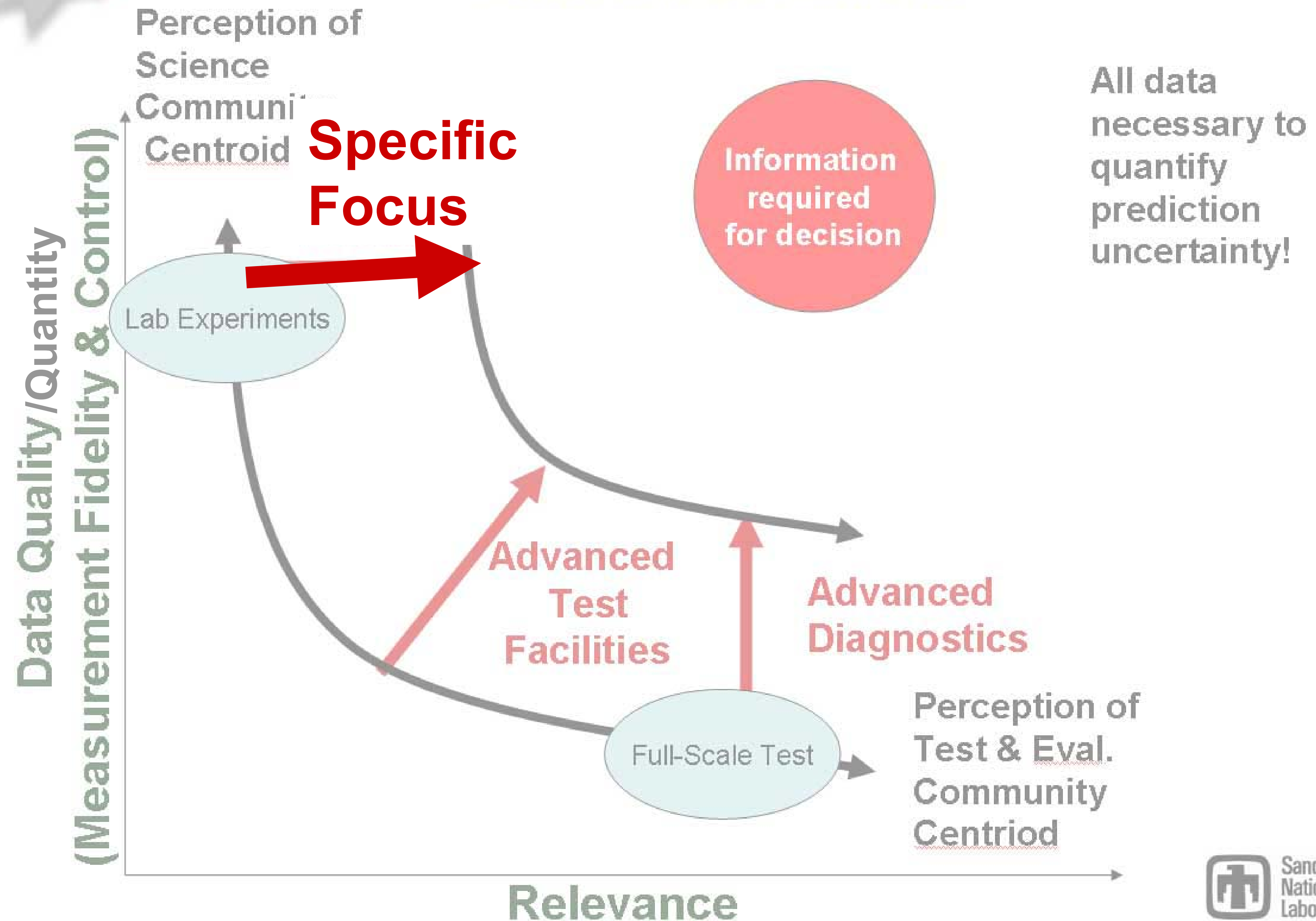
# Test and Evaluation is Science in Relevant Conditions



# Test goals

Capture the response of a reinforced concrete structure in the process of collapse.

Quantify the load deflection curve defined in Uniform Facility Criteria (UFC 3-340-01)

Quantify how the membrane response contributes to the energy absorbing ability of the structure

Measure the deflections of the wall as a function of load

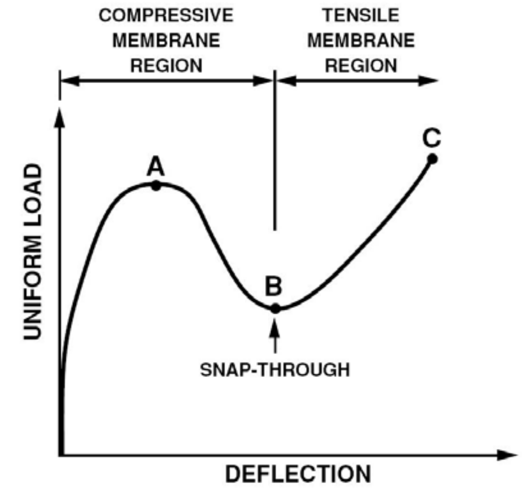



Figure 10-7. Typical Membrane-Enhanced Flexural Resistance Function.

10-18

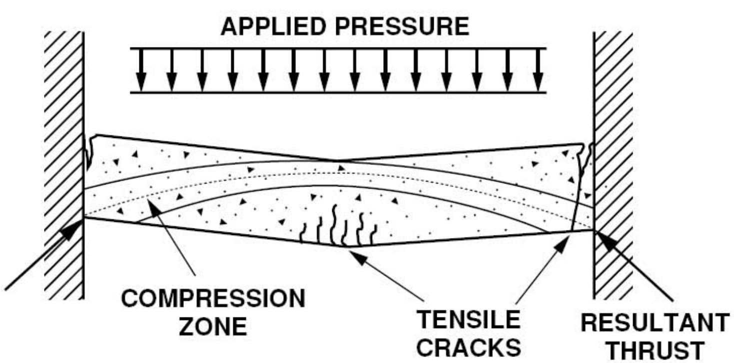



Figure 10-9. Compressive Membrane Action.

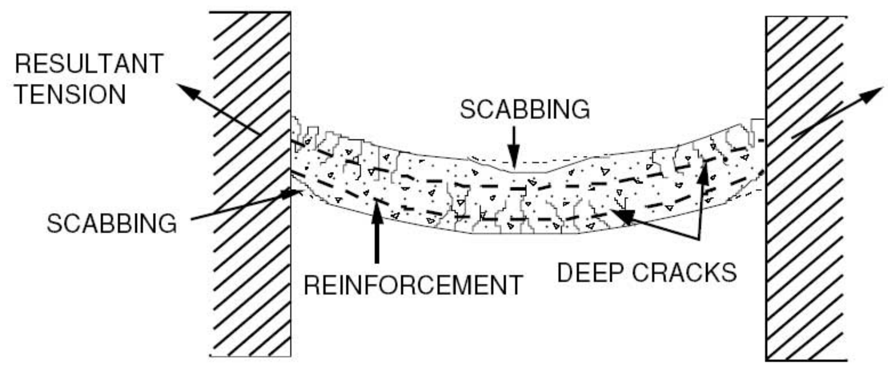
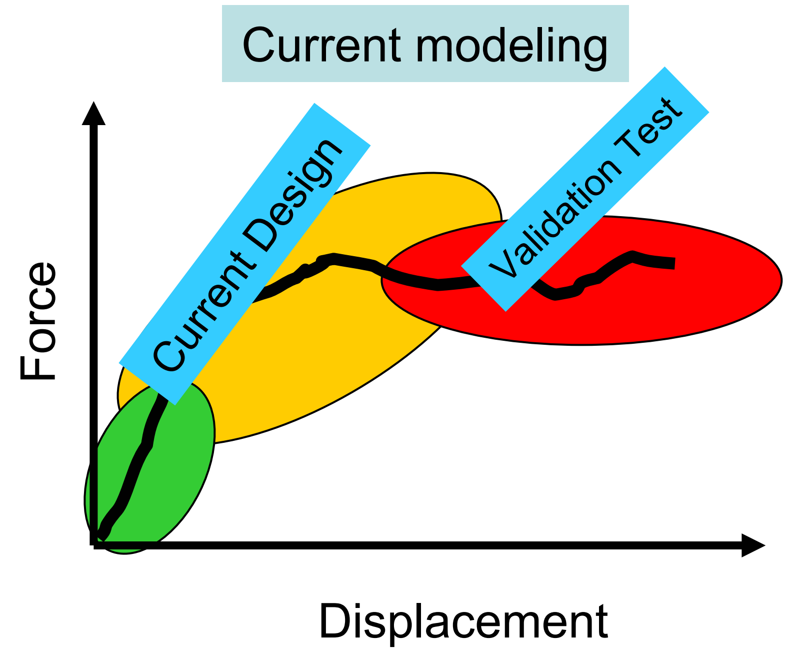



Figure 10-12. Tensile Membrane Action

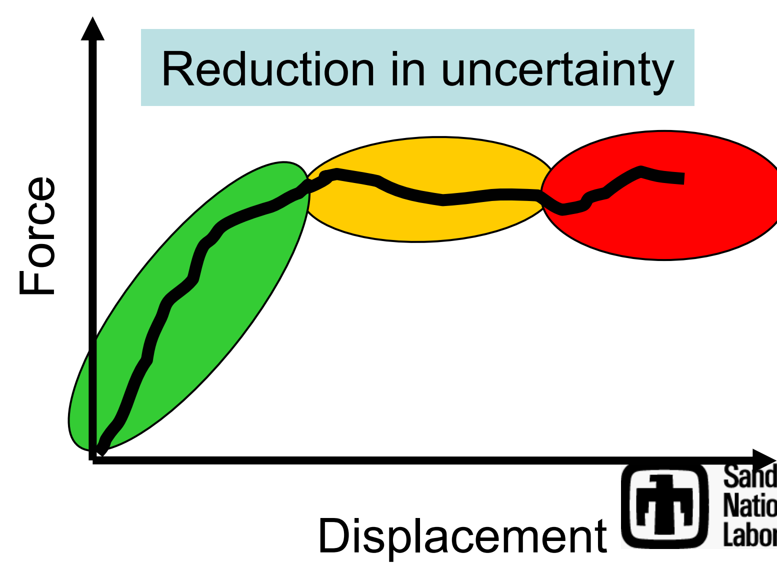
# Uncertainty Quantification

Large uncertainty may result in facilities being over designed

Reduction in uncertainty equals reduction in cost




- Validation test was designed to produce a response in in the yellow/red zone
- Current design point is in the green/yellow zone.

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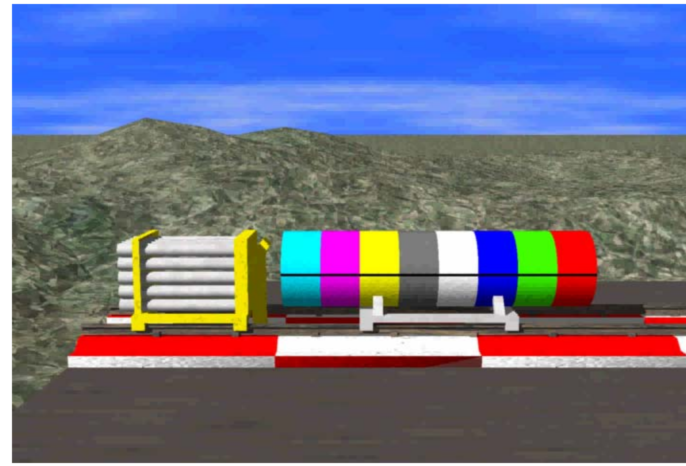
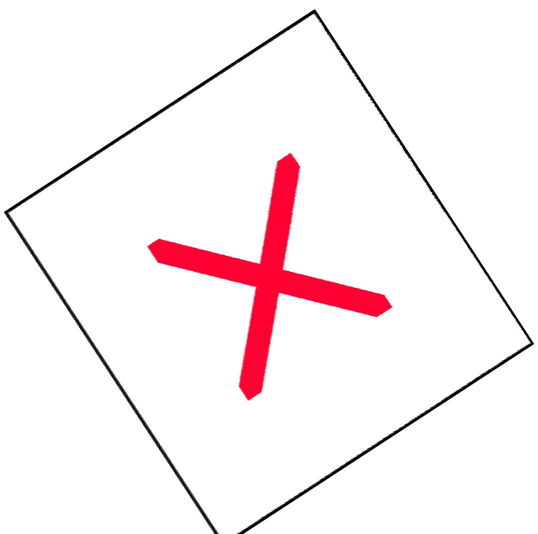
# Surrogate Load

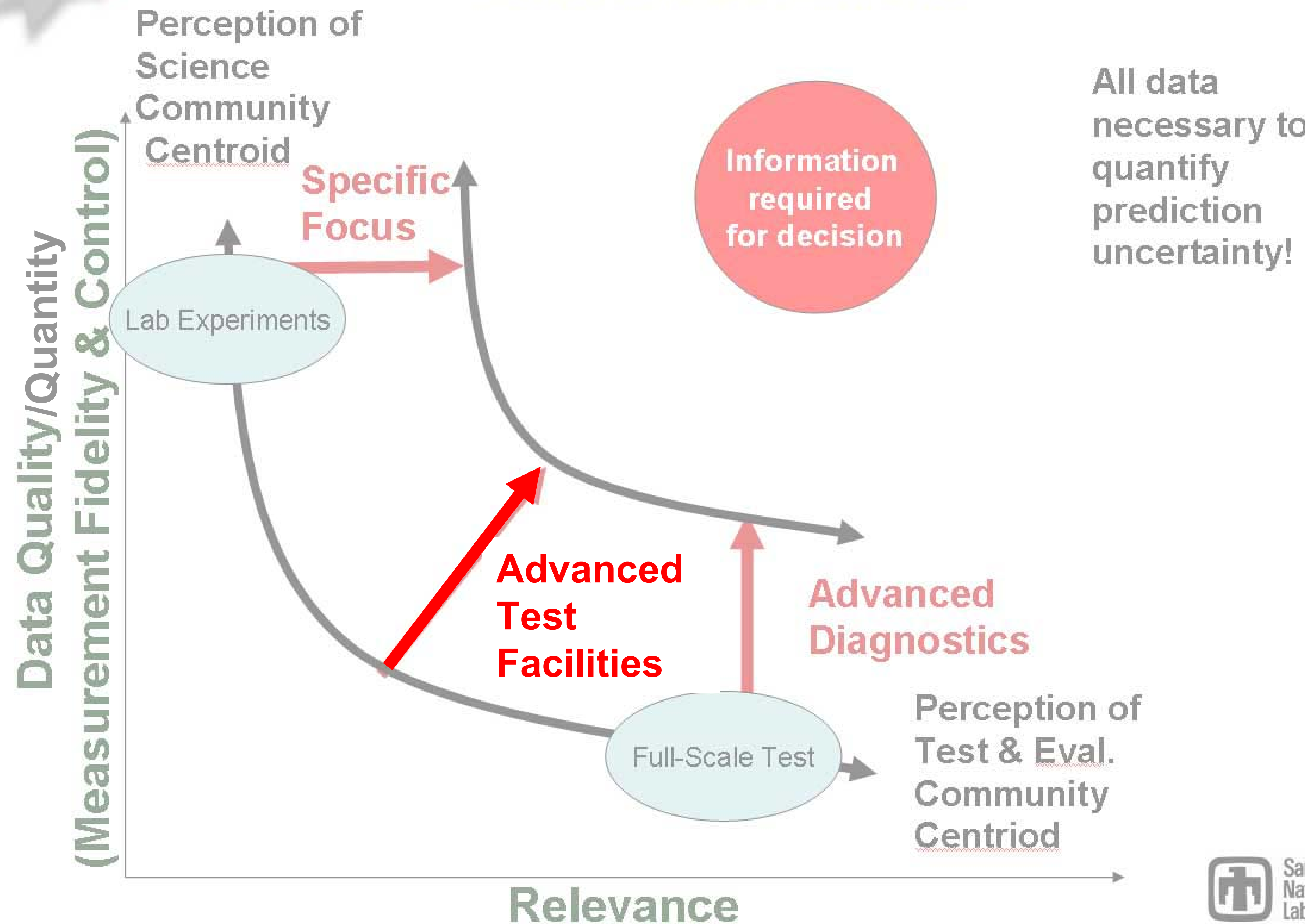
- A water slug was used to drive the structure response

- Water was slug accelerated to 600.1 ft/sec on high speed sled track using 48 rocket motors





# Test and Evaluation is Science in Relevant Conditions

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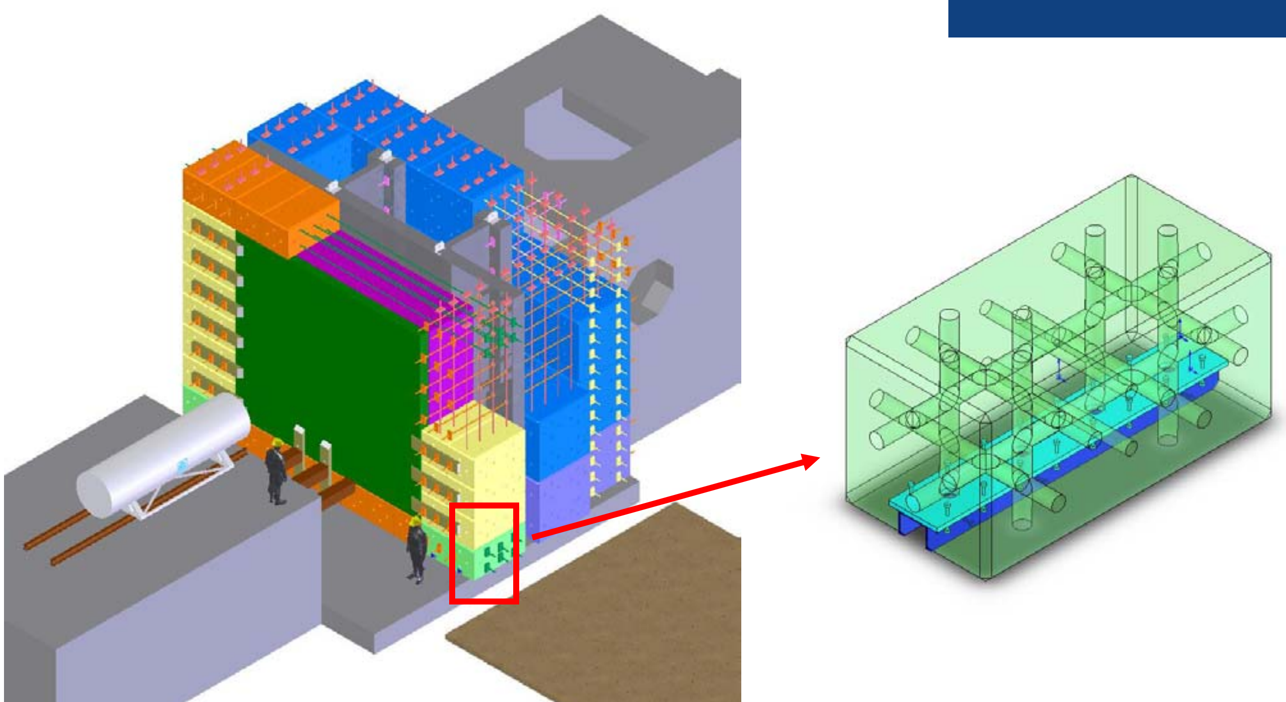
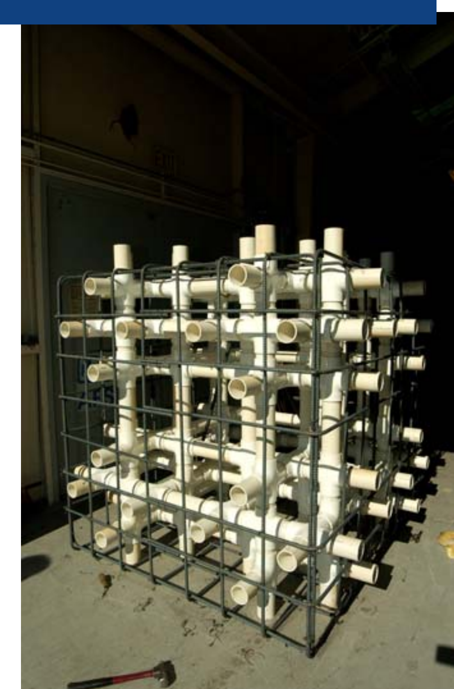
# Agile Reaction Frame

- Re-usable post-tension reaction frame used to confine soil, support slab, and support wall section



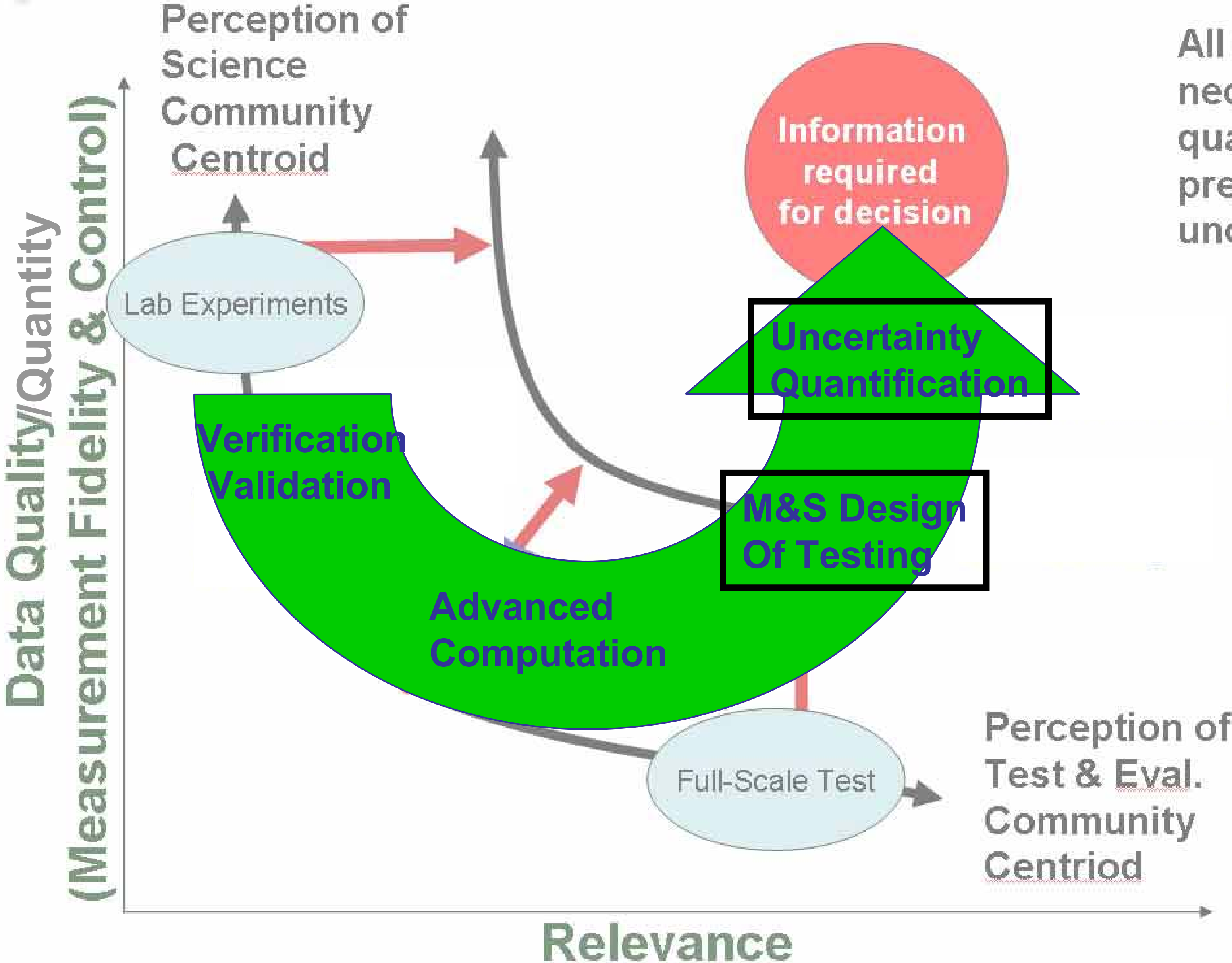



3-5


4N52V

# Time lapse video

# M&S Advances T&E to Decision Goal




All data necessary to quantify prediction uncertainty!

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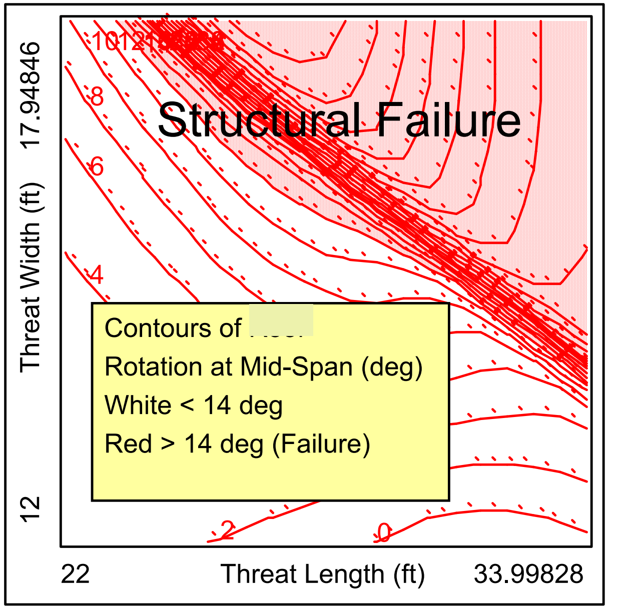
# Test Design Parameters

- Test parameters were based on statistics-based multi-dimensional sampling
  - Thousands of 2D simulations were used to define a failure surface
  - 3D high fidelity simulations were used to define specific test parameters

- Design parameters:
  - Load magnitude
  - Soil cover
  - Soil strength
  - Structure Span
  - Concrete strength

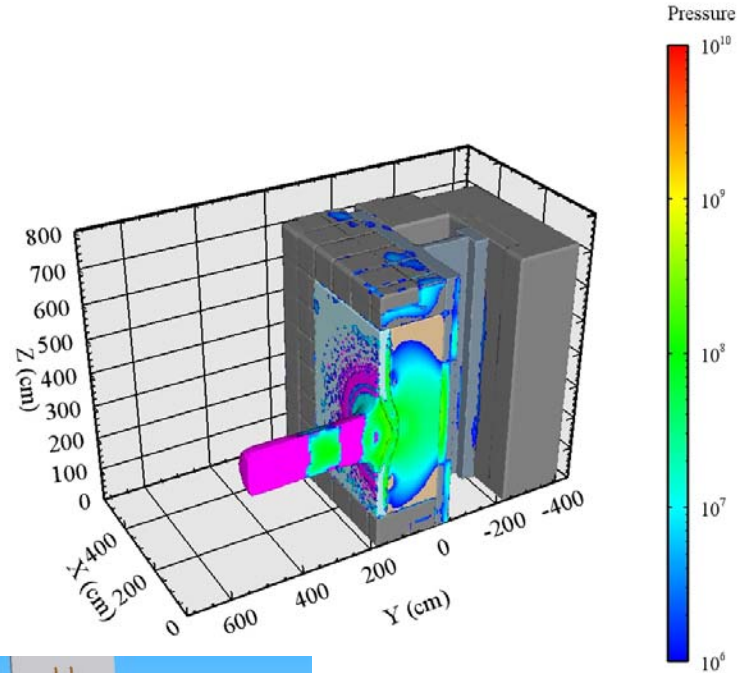


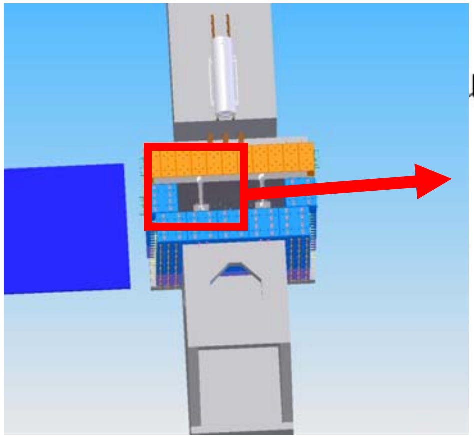
# 3D Pre-Test Prediction

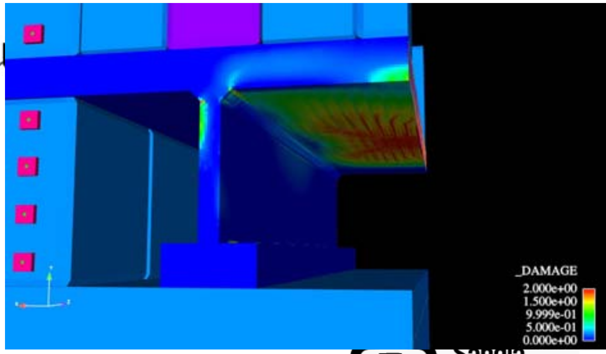
Eulerian model of water slug, soil, and target structure

One-way coupling between Eulerian model and FEM model

FEM model included explicit treatment of reinforcing steel, post tensioning, gravity pre-load and contact between blocks.



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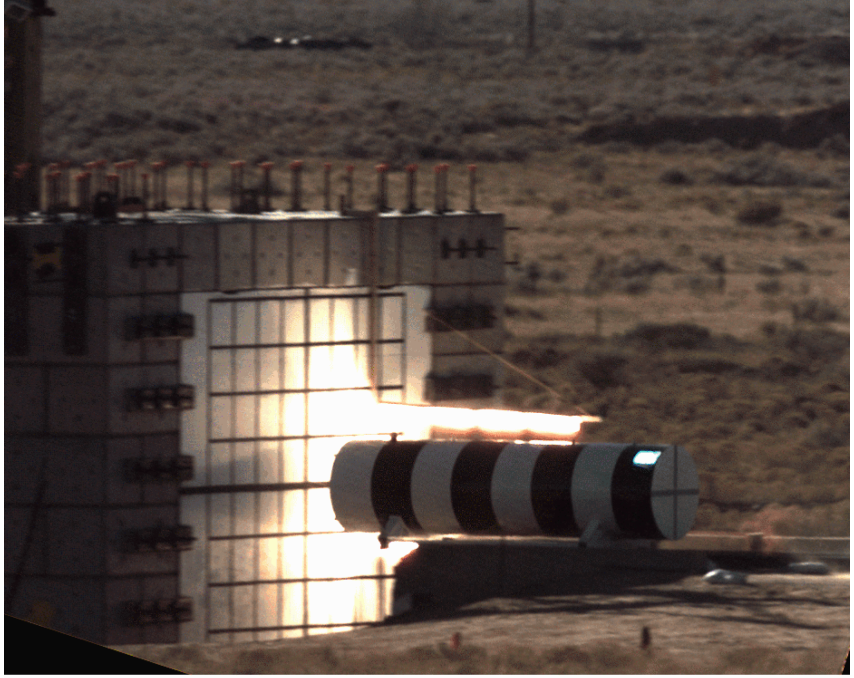
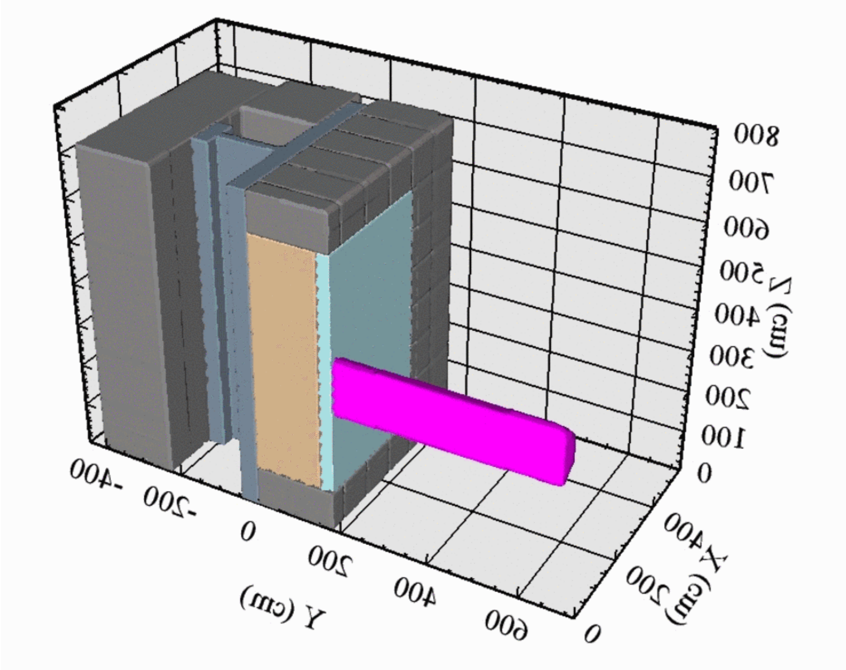
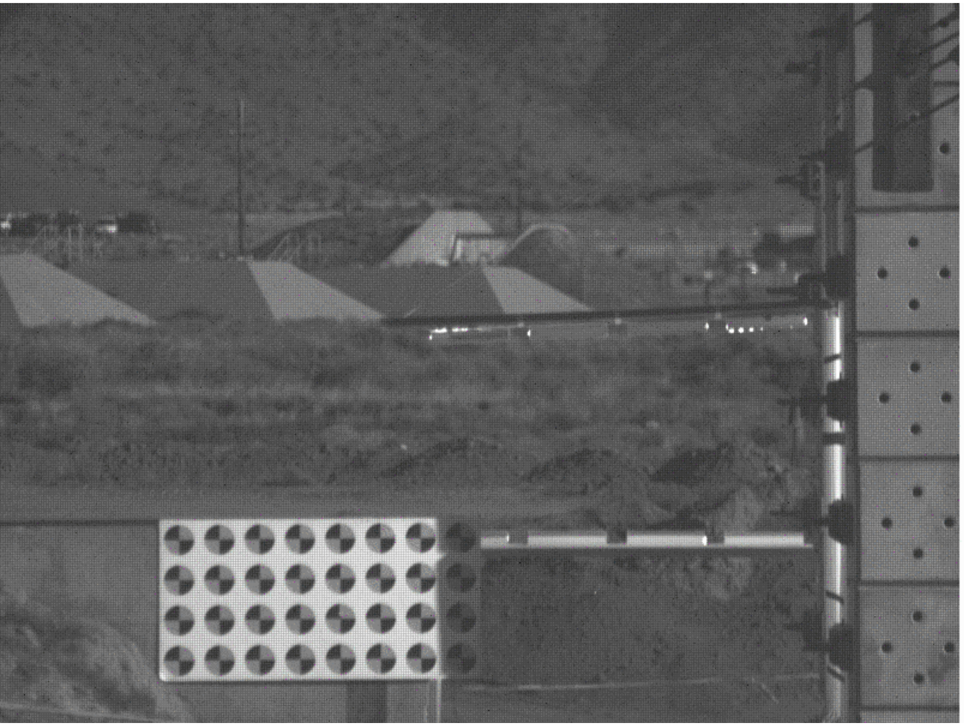
# Test Results

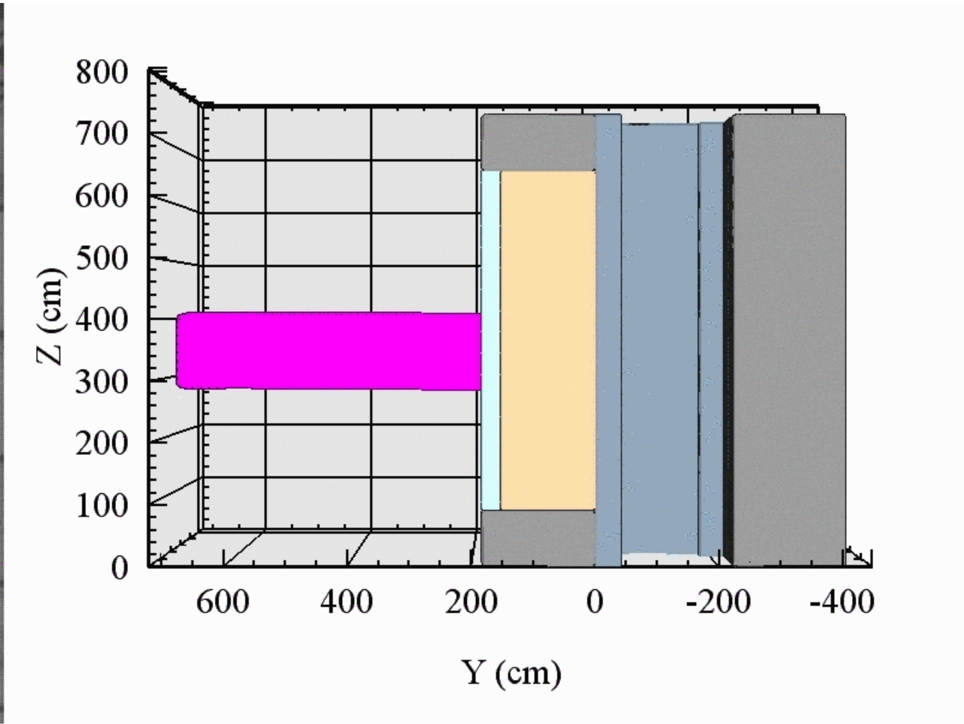
- 100% success on instrumentation
- Pressures measured at soil/concrete interface
- Three independent displacement measurements
- Excellent high speed video
- New “speckle correlation” displacement measurement technique provided full-field displacements and velocities for back wall surface





# Side view of impact

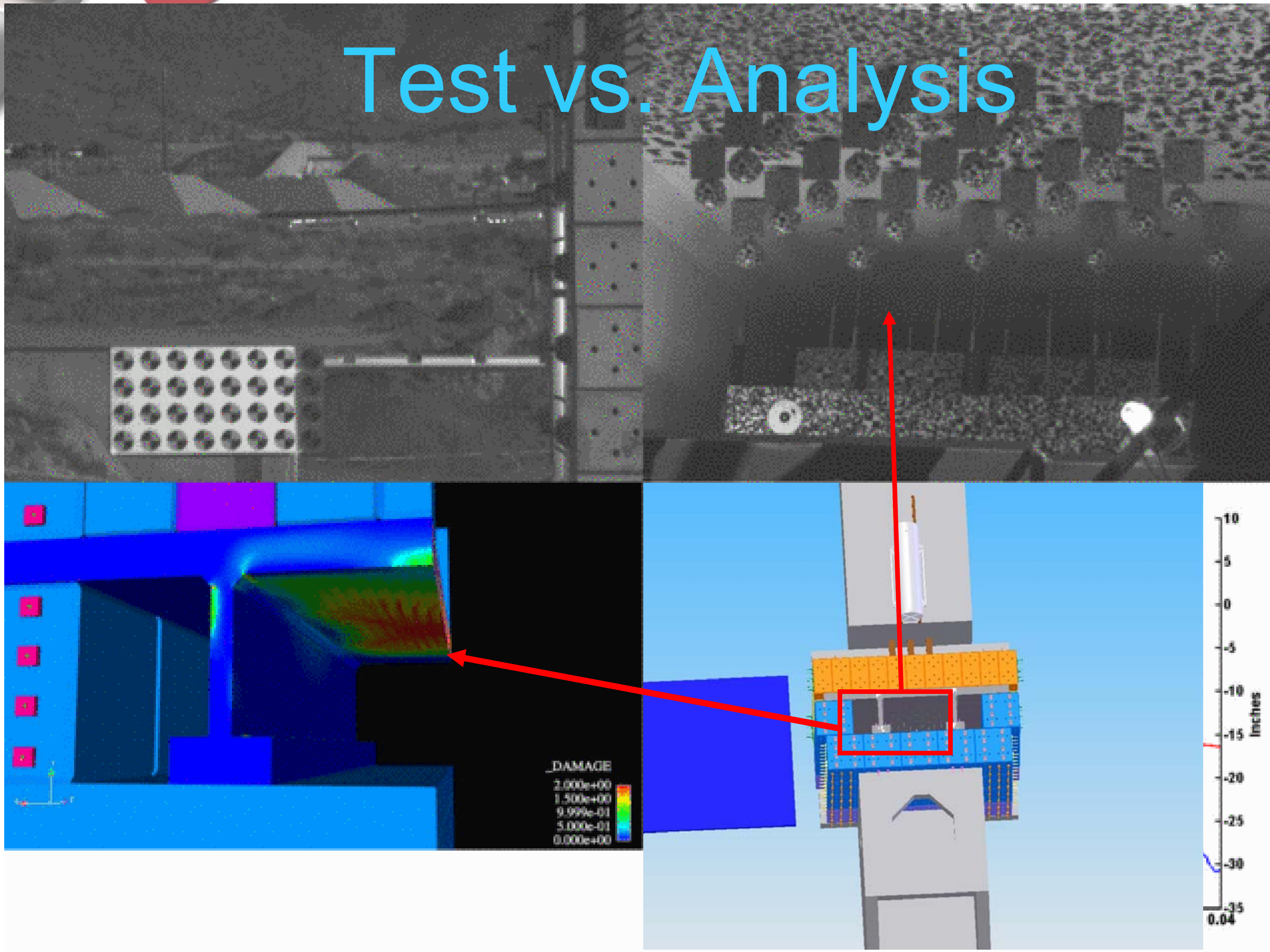





CTH simulation

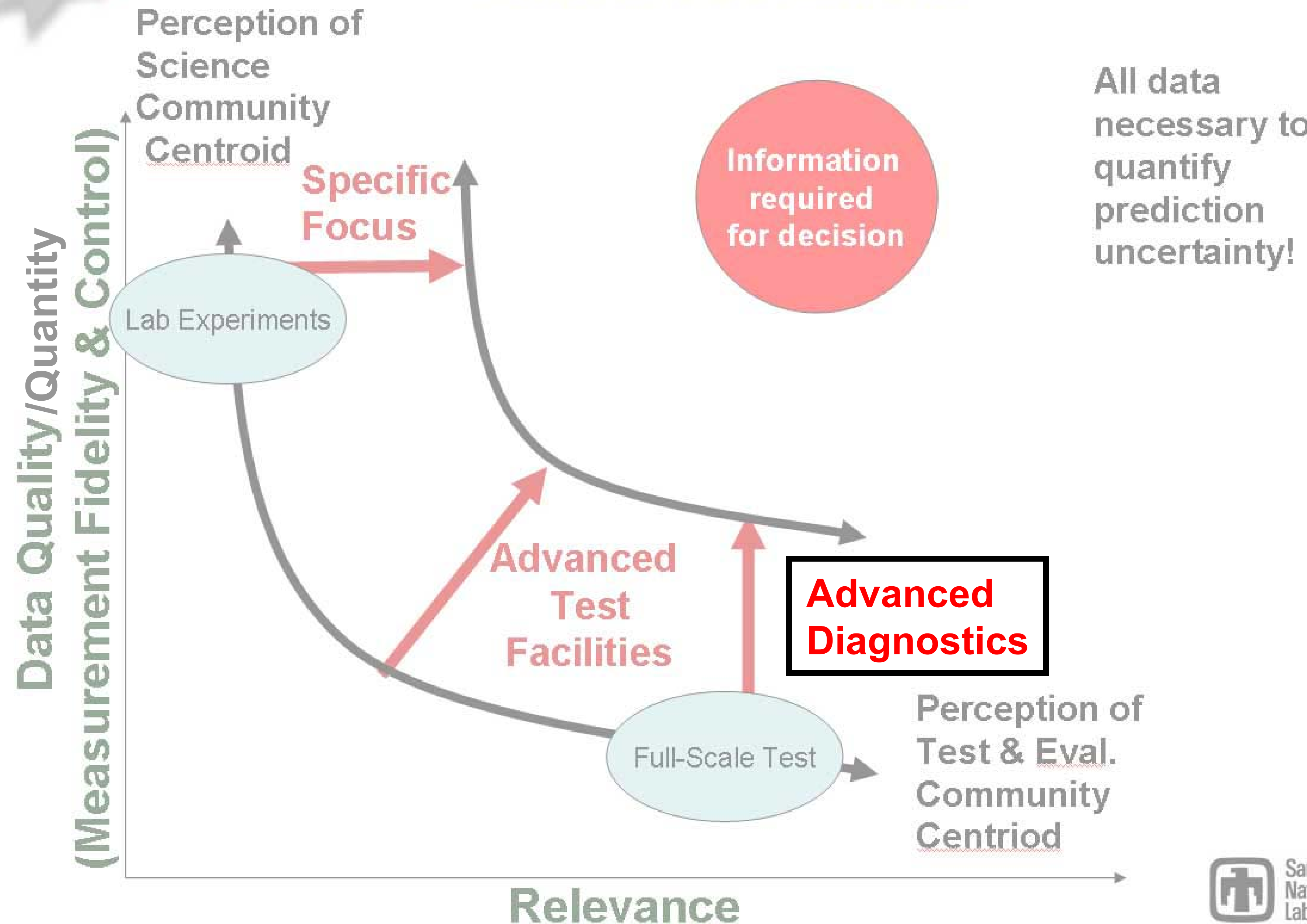
4x16 ft water slug moving
at 600 ft/sec

# Test vs. Analysis



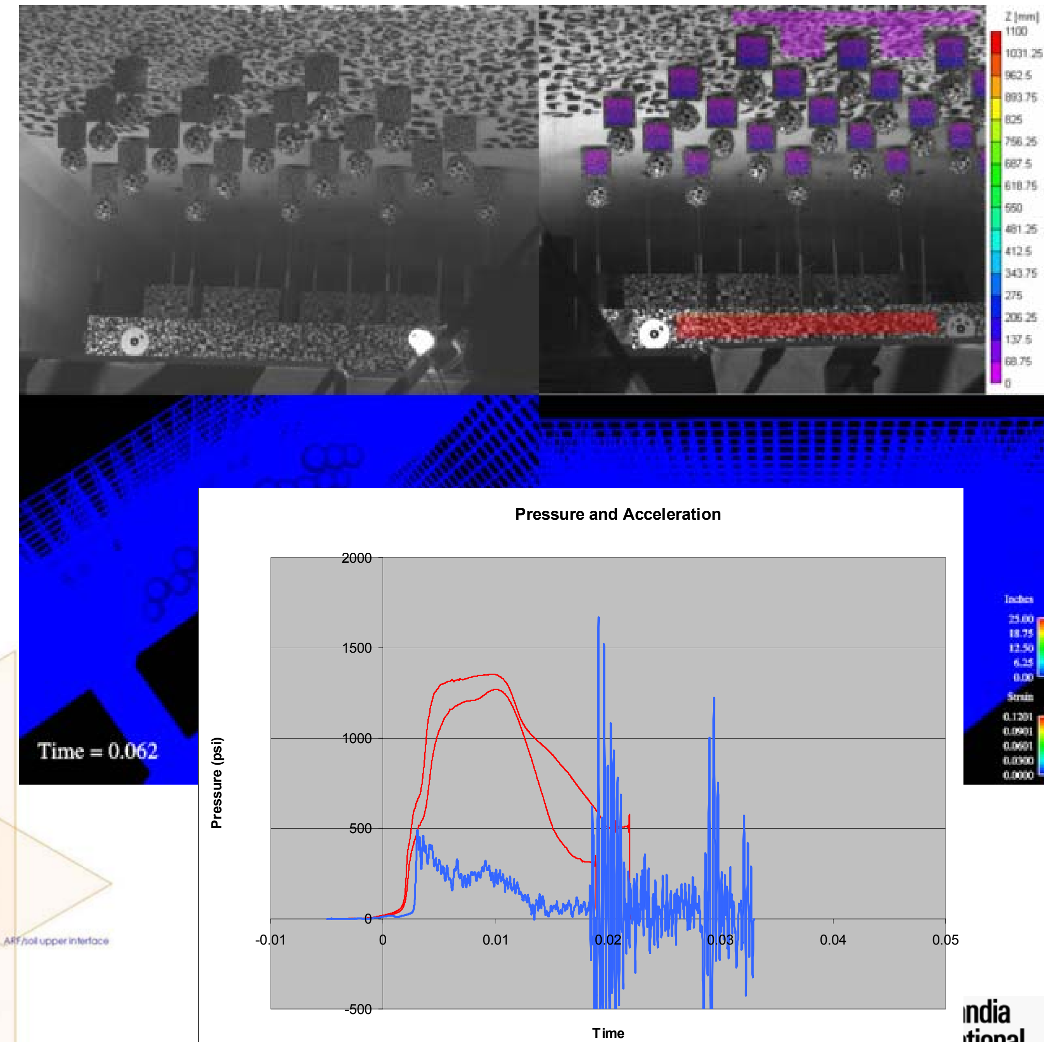

**Simulation** **Test Data**

# Test and Evaluation is Science in Relevant Conditions

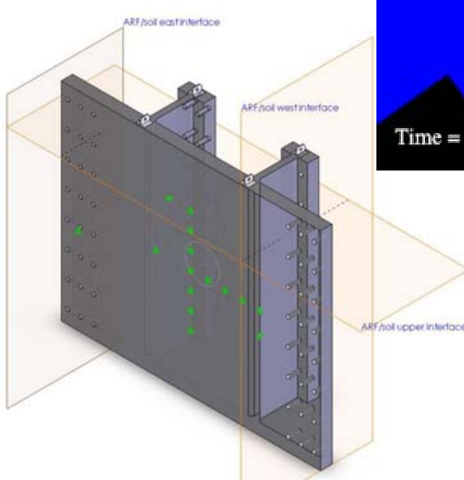


# New diagnostic technology demonstrated

- New testing method: “Speckle correlation”
- Provides 3-D full field displacement measurement of structure as it collapses
- Pressure measured at soil/concrete interface to measure pressure in soil
- Pressures were used to validate soil model
- Balls on simulation colored by error




Pressure Gauge Location



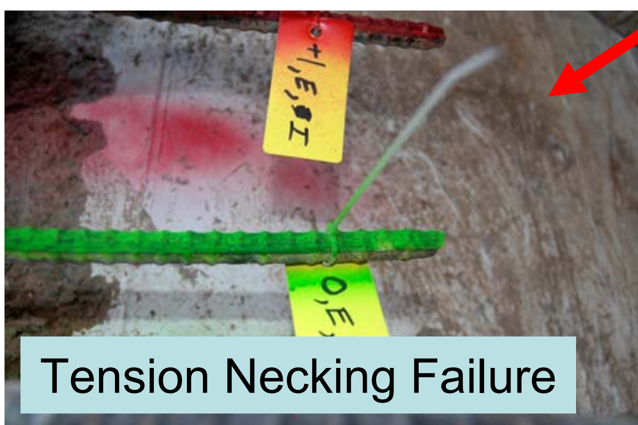
# Rebar failure location and timing

Rebar failure location

- 3D FEM models were predicting failure of rebar in compression
- Many features of the test compared well with the pre-test prediction.

Areas of improvement needed based on comparison of the pre-test analysis with test results:

- Rebar failure needs improvement
- Location of rebar failure in pretest simulations were incorrect
- A fully coupled analysis is needed to correctly capture soil pressure as the structure collapses



Tension Necking Failure

# Structural Example Summary

- Testing challenges
  - Too costly to do full-scale structure test
  - Too costly to explore parameters space with relevant reduced-fidelity tests
- Simulation challenges
  - Too costly to do full physics simulations
  - Too costly to reduce uncertainties without tests
- Combination of M&S with T&E provides only realistic path to solution
  - Simulation optimized the parameter space, designed the test, evaluated results
  - Reduced uncertainty in modeling by testing

# Example #2
# Weapon Systems Qualification in Fire Environments

- Validation of numerical simulation
  - Uncertainty quantification for modeling and simulation requires validation data
- Application of numerical simulation
  - Examples showing modeling and simulation greatly aids test and evaluation

- General comments on cost

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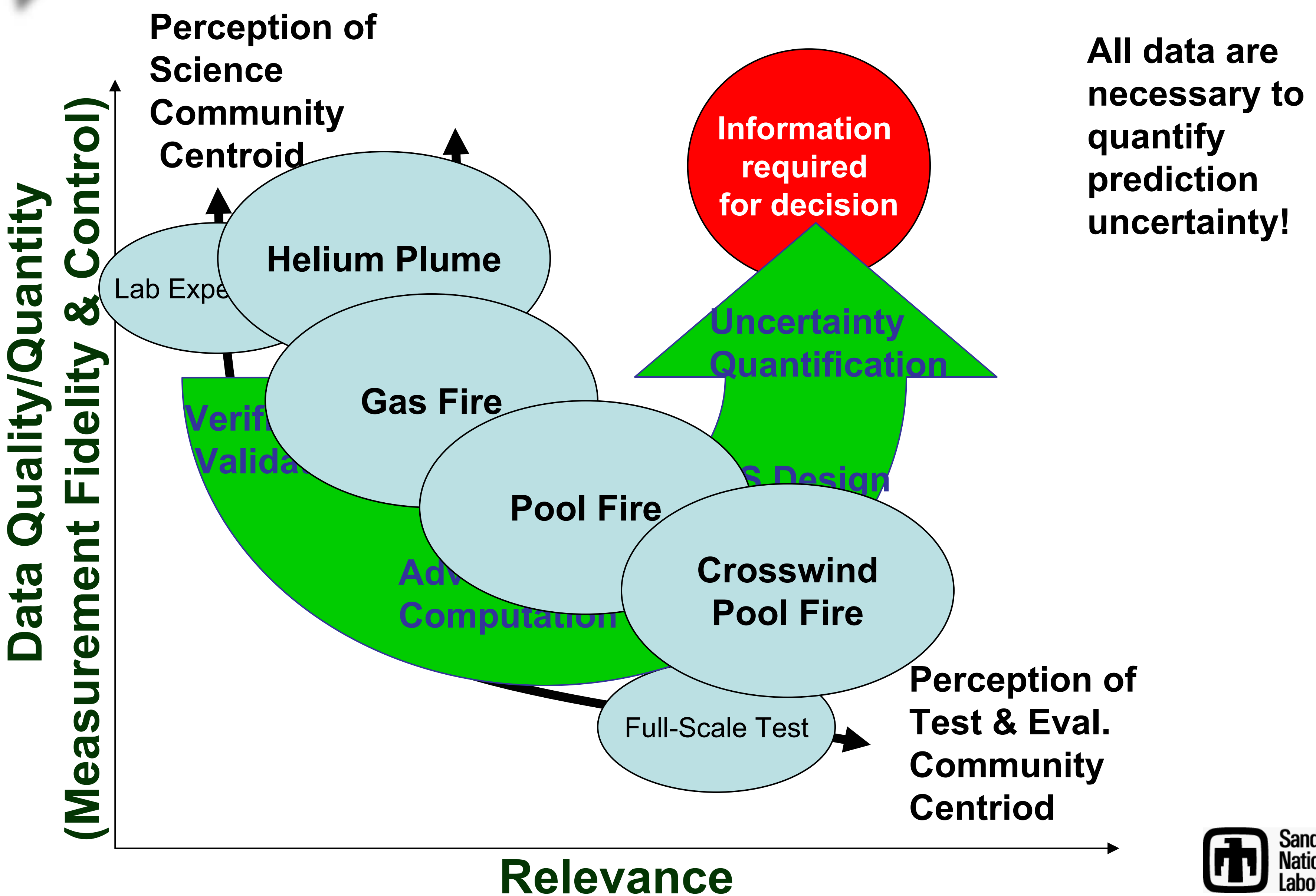
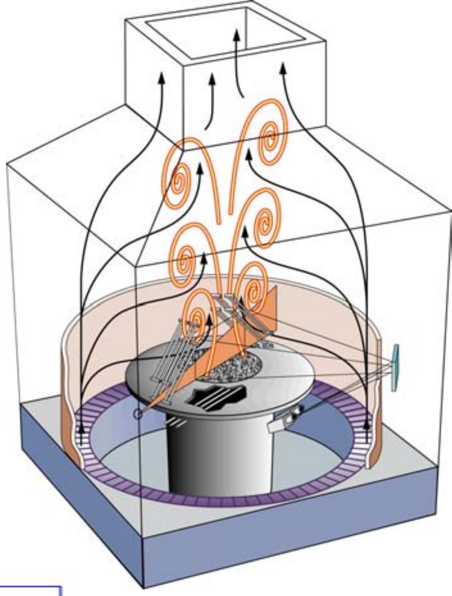
# Example of validation for fire



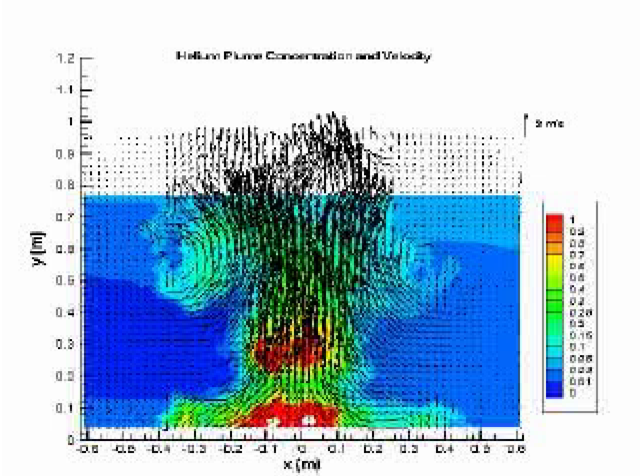
# Test data establishes prediction uncertainty in plumes



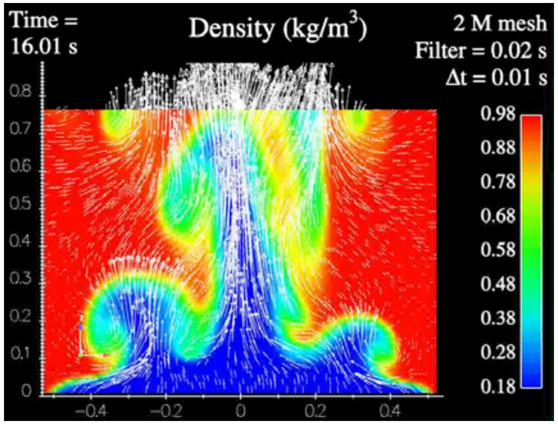
Helium plume - First pair wise momentum/scalar coupling

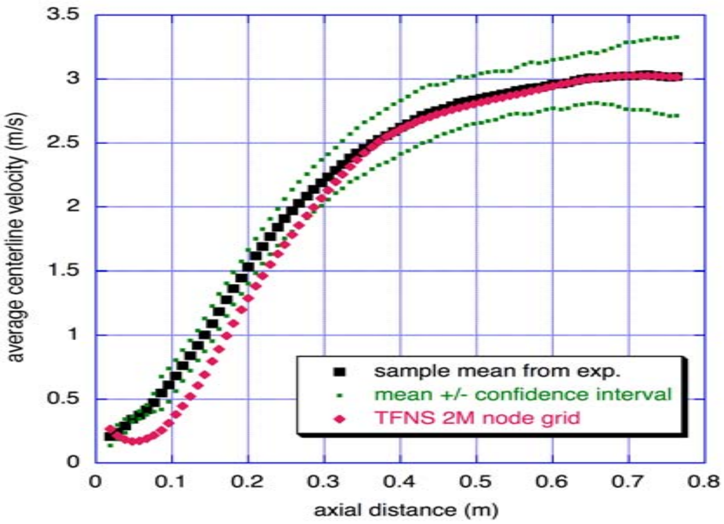
- 2-D density, velocity and turbulent statistics.

**Test Data**




**Fuego – 2M node simulation**




- Developing quantitative comparison statistics

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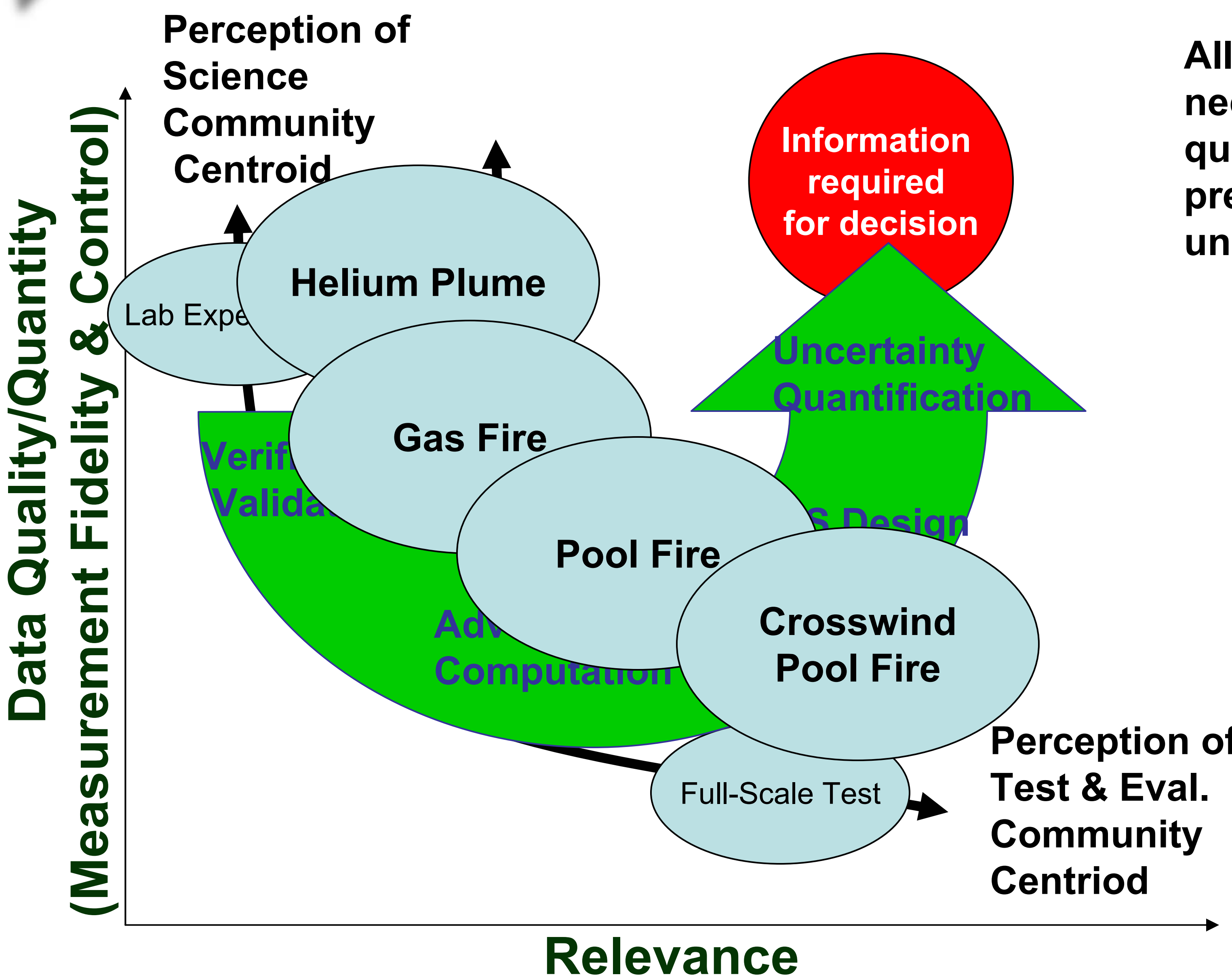
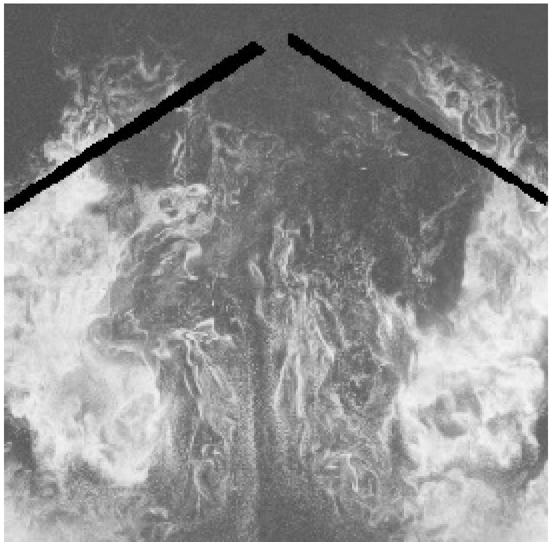
# Example of validation for fire



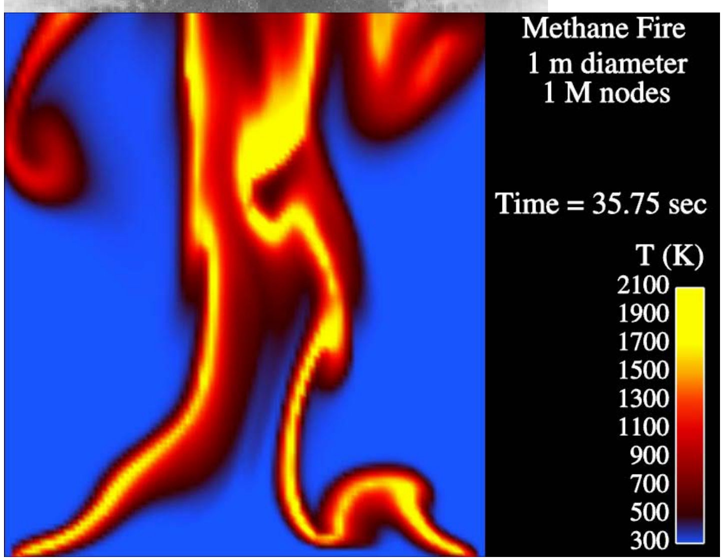

**All data are necessary to quantify prediction uncertainty!**

# Test data establishes prediction uncertainty in gas fires

- Combusting, non-sooting & sooting gas fires

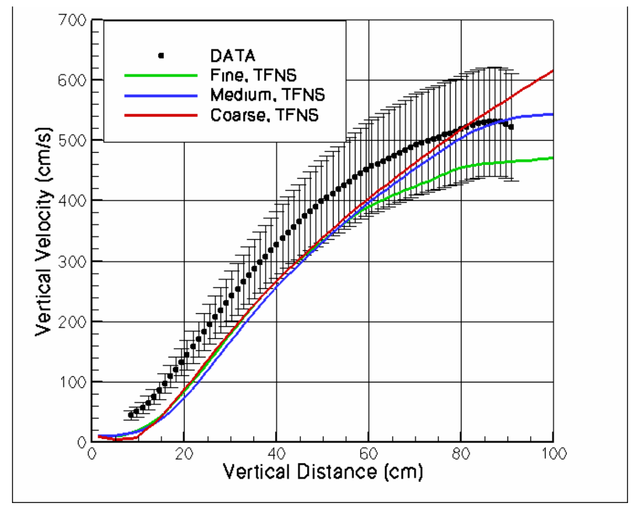


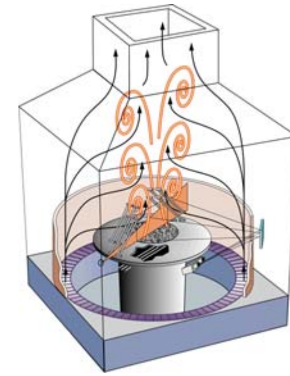
Raw Data



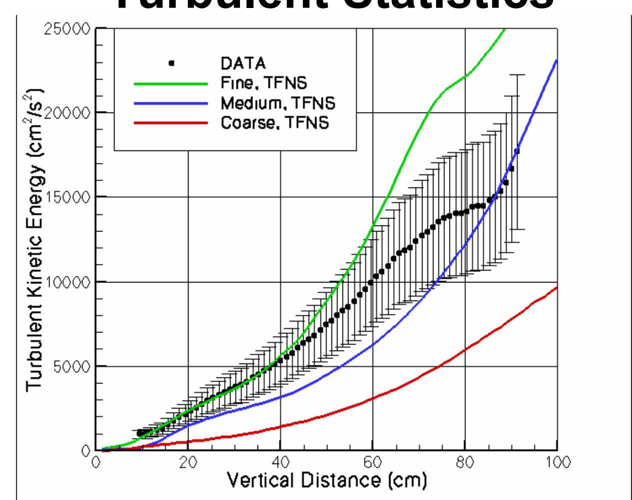

Fuego Simulation

**Velocity**

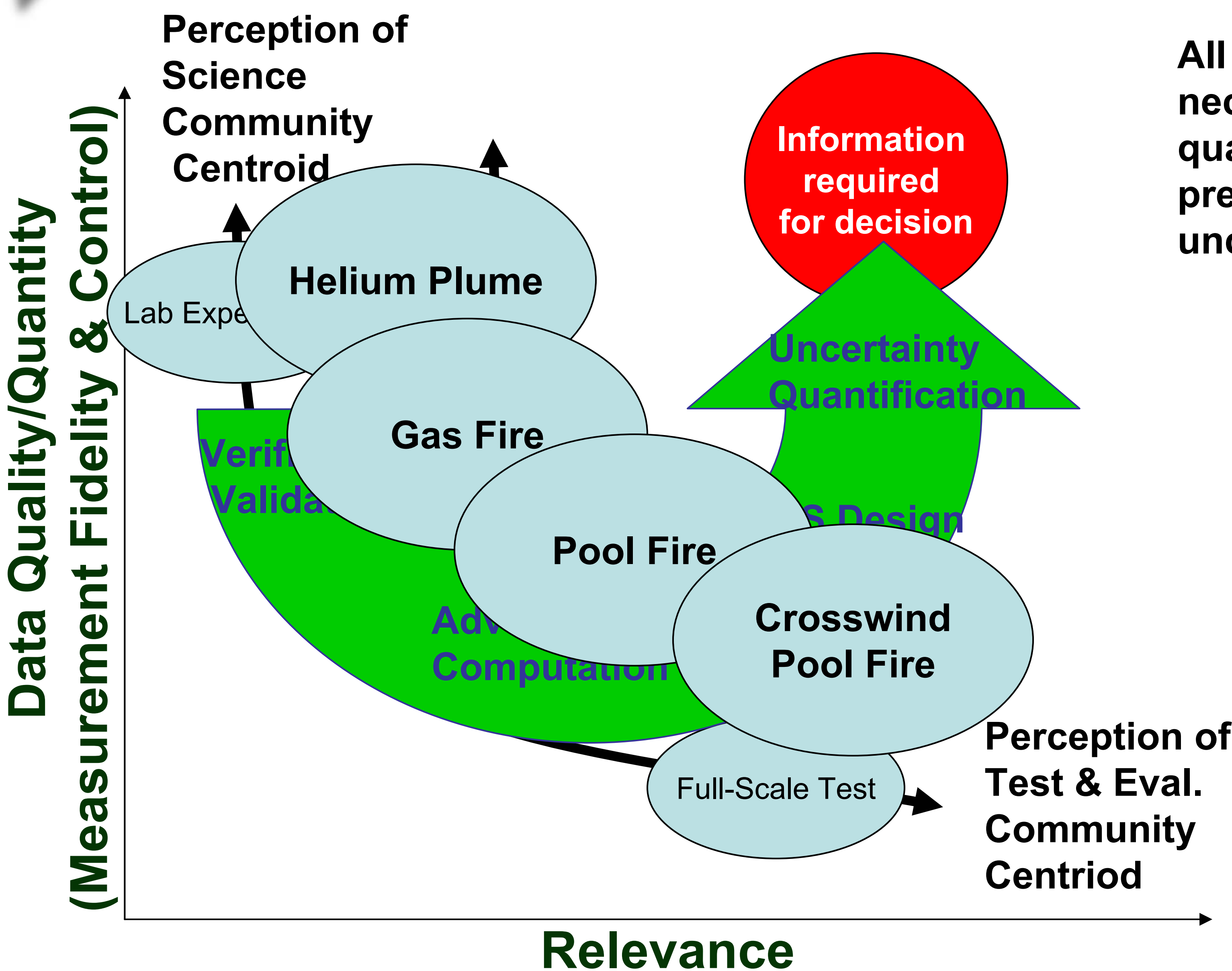


**Turbulent Statistics**

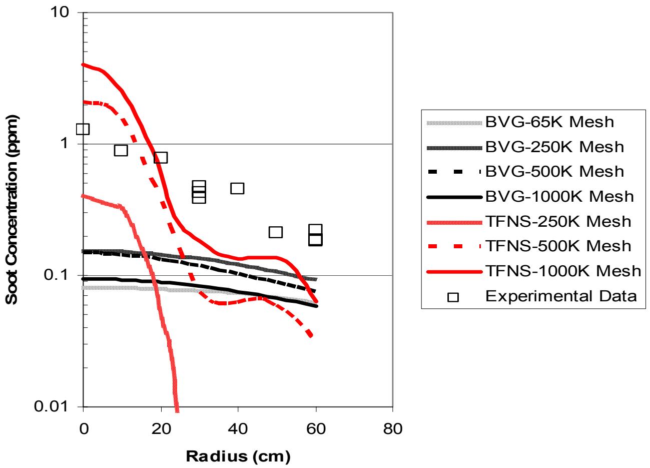


# Example of validation for fire



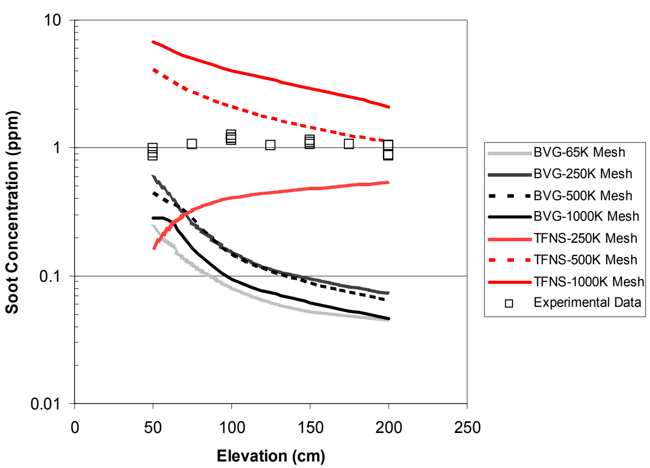

All data are necessary to quantify prediction uncertainty!

# Test data establishes - prediction uncertainty in quiescent pool fires




**Radius at 1 m elevation**

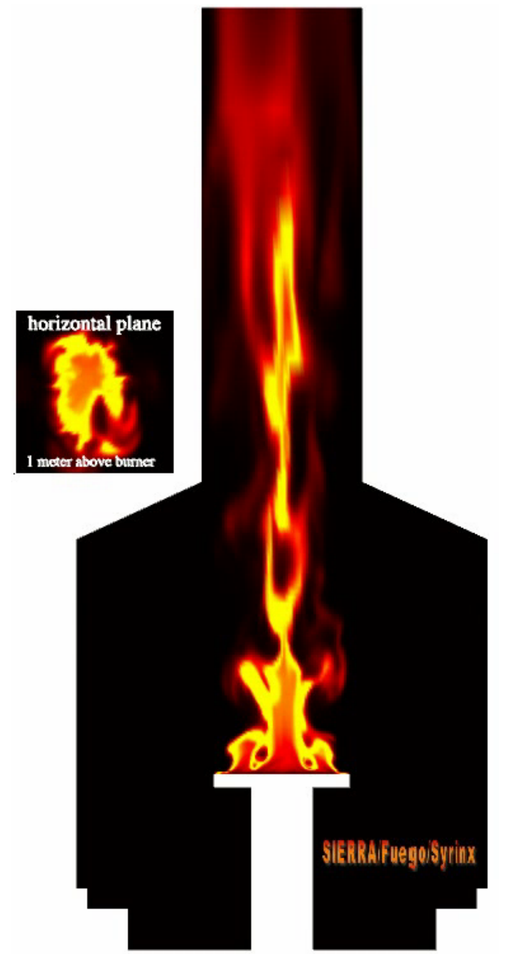
**Soot Concentration**




**Centerline**

- **JP-8 2m Dia. quiescent Fire**
- **Soot concentration, a modeled quantity, is not accurately predicted.**

**1.2 M node Fuego sim.**

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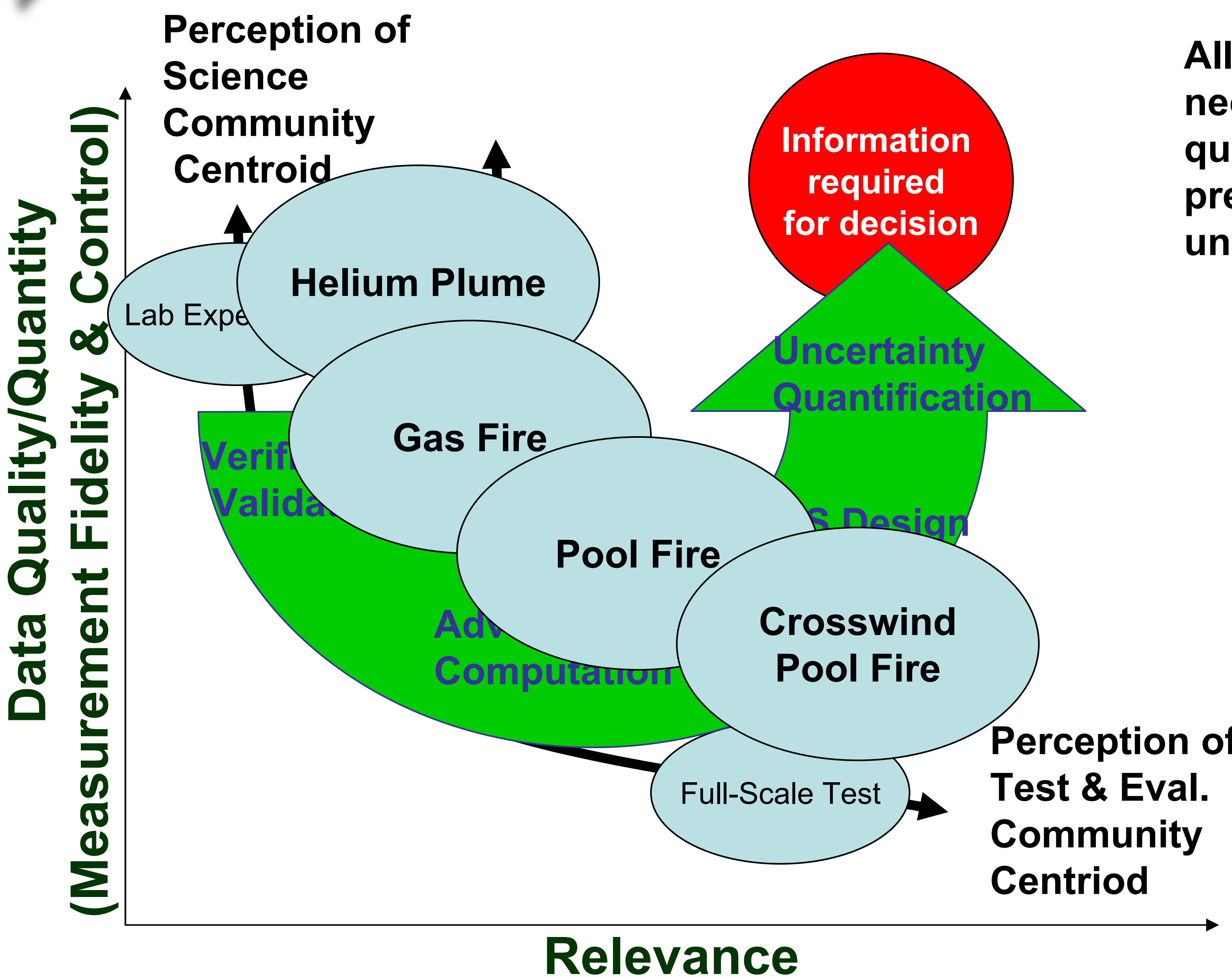
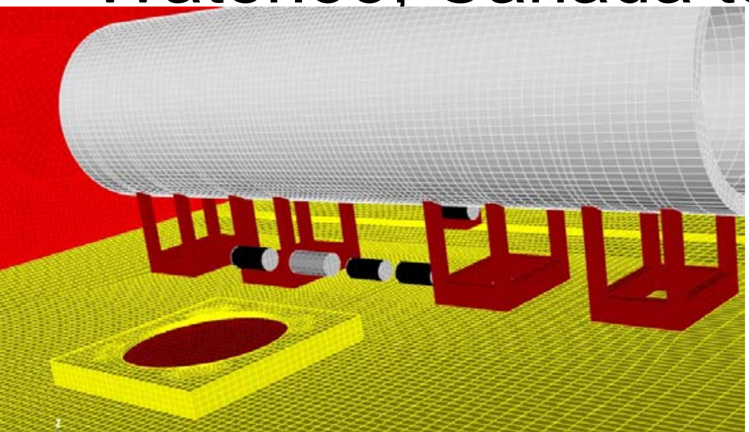
# Example of validation for fire

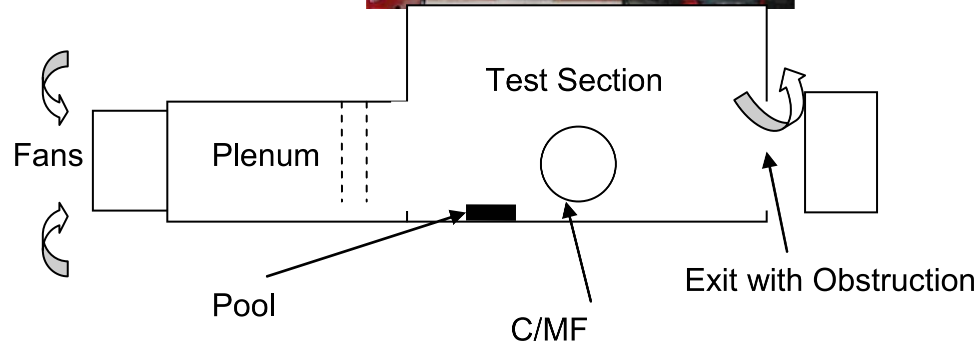


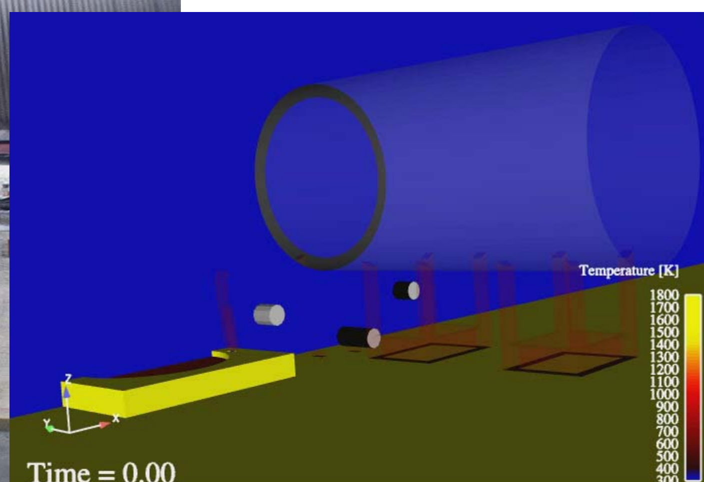

**All data are necessary to quantify prediction uncertainty!**

# Test data establishes - prediction uncertainty in cross wind pool fires

- JP-8 2m Dia. Cross-Wind Fire Waterloo, Canada test facility







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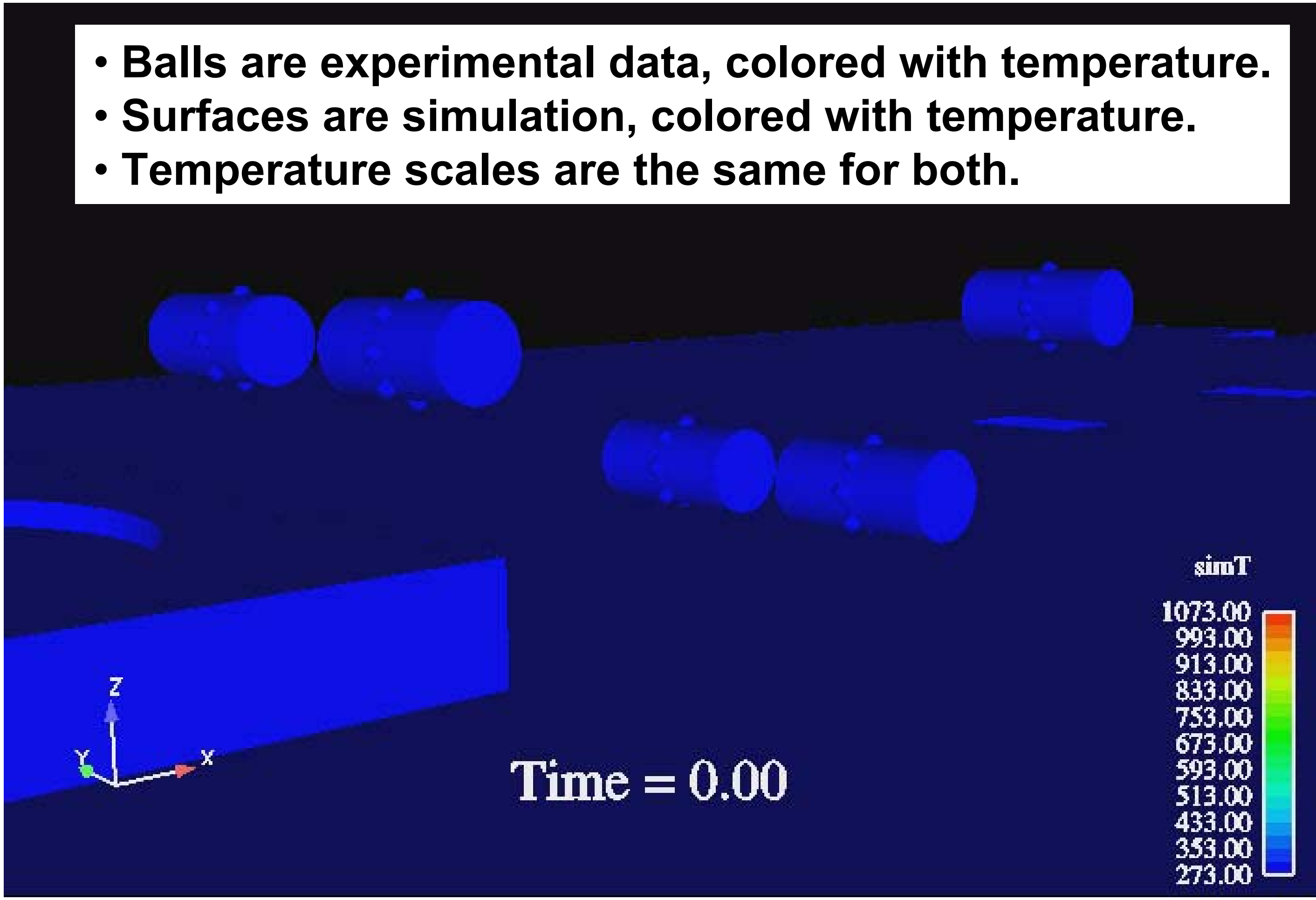
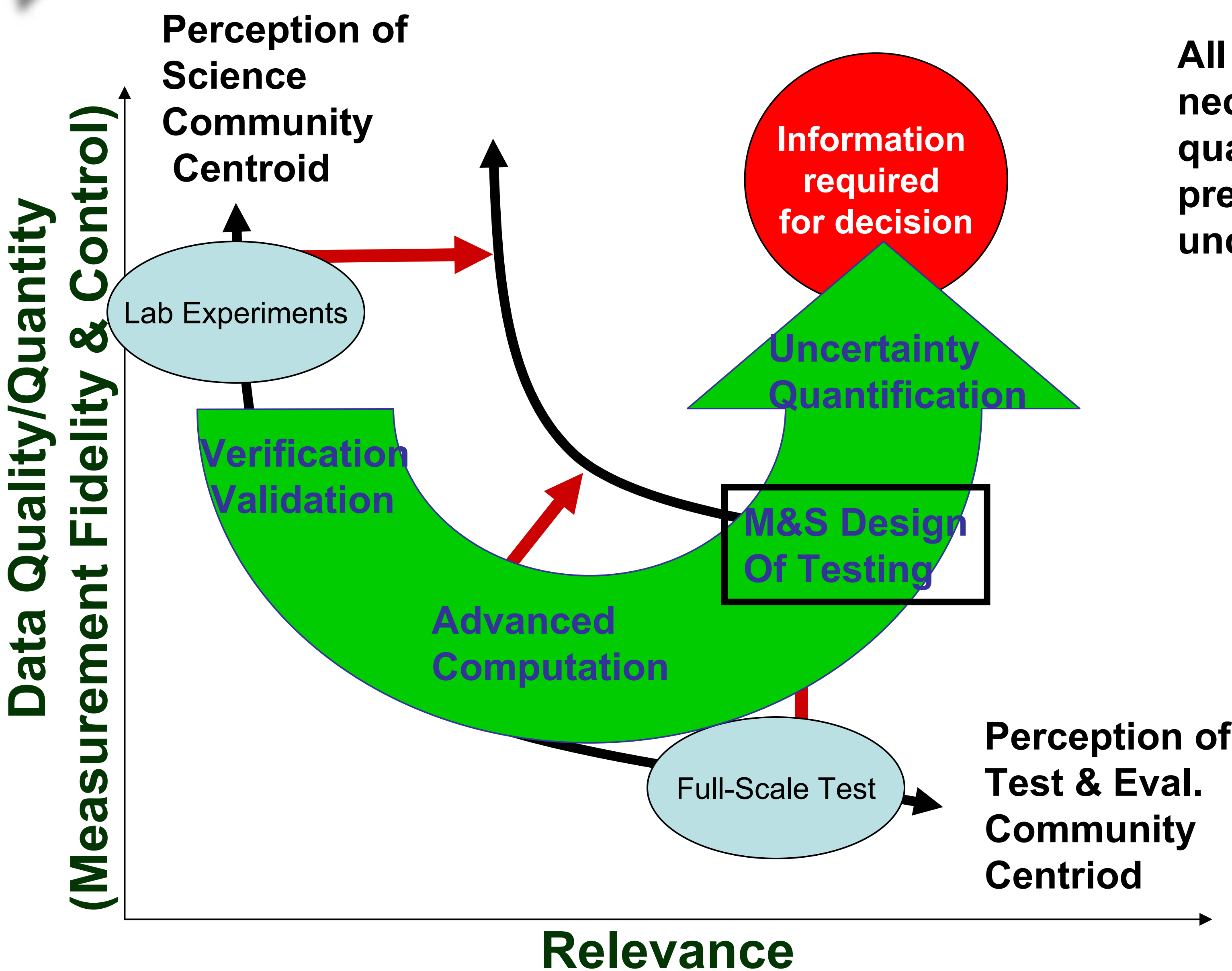
# The Challenge of Non-linear Physics Prediction in Relevant Geometries

- Predicting thermal response from fire.
- One calorimeter is thermal response is well predicted, the second is not.
- Sensitivity studies show that fire is predicted strongest on the centerline while test is shifted right.




**In this and every example we have run of relevant test problems, the results have given us insight into parameter sensitivities. Quantifying uncertainty in relevant geometries with relevant physics is challenging.**

# M&S Advances T&E to Decision Goal




**All data are necessary to quantify prediction uncertainty!**

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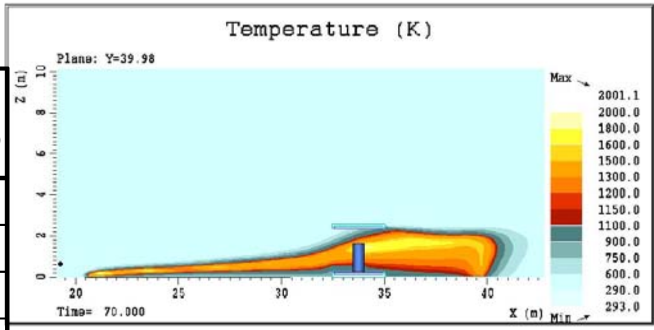
# Modeling & Simulation in Support of Weapon System Qualification

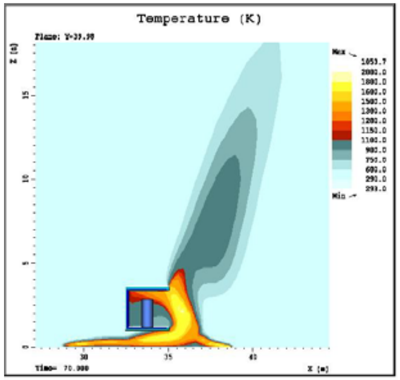
- Challenges
  - Infinite number of accident/incident environments
    - Large parameter space
  - Complex systems have multiple response modes
    - Different loads challenge different modes
  - Different safety & security philosophies
    - Different levels of acceptable outcome

# Modeling and Simulation of Large Parameter Spaces

– **M&S strength: Hundreds to thousands of low resolution simulations can conducted**

| Case # | Hole Size ($m^2$) | Fuel Pool Location (m) | Object | Enclosure Height (m) | Pool Size (m) | # of Holes | Wind Speed (m/s) | Peak Heat Flux ($kW/m^2$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.47 | 0 | No | 1 | 10 | 1 | 2-10 | 99 |
| 2 | 5.57 | 0 | No | 1 | 10 | 1 | 2-10 | 175 |
| 3 | 3.0 | 1.85 | No | 1 | 10 | 1 | 2-10 | 235 |
| 4 | 0.47 | 3.7 | No | 1 | 10 | 1 | 2-10 | 80 |
| 5 | 5.57 | 3.7 | No | 1 | 10 | 1 | 2-10 | 247 |
| 6 | 3.0 | 1.85 | Yes | 1 | 10 | 1 | 2-10 | 175 |
| 7 | 0.47 | 3.7 | Yes | 1 | 10 | 1 | 2-10 | 72 |
| 8 | 5.57 | 3.7 | Yes | 1 | 10 | 1 | 2-10 | 255 |
| 9 | 5.57 | Wind Side | No | 0 | 10 | 1 | 2-10 | 34 |
| 10 | 5.57 | Wind Side | No | 1 | 10 | 2 | 2-10 | 200 |
| 11a (Case 5) | 5.57 | 3.7 | No | 1 | 5 | 1 | 2-10 | 133 |
| 11b (Case 13) | 5.57 | Wind Side (2m up) | No | 0 | 5 | 2 | 2-10 | 266 |
| 12 | 5.57 | Wind Side (2m up) | No | 1 | 10 | 2 | 2-10 | 171 |
| 13 | 5.57 | Wind Side (2m up) | No | 0 | 10 | 2 | 2-10 | 254 |



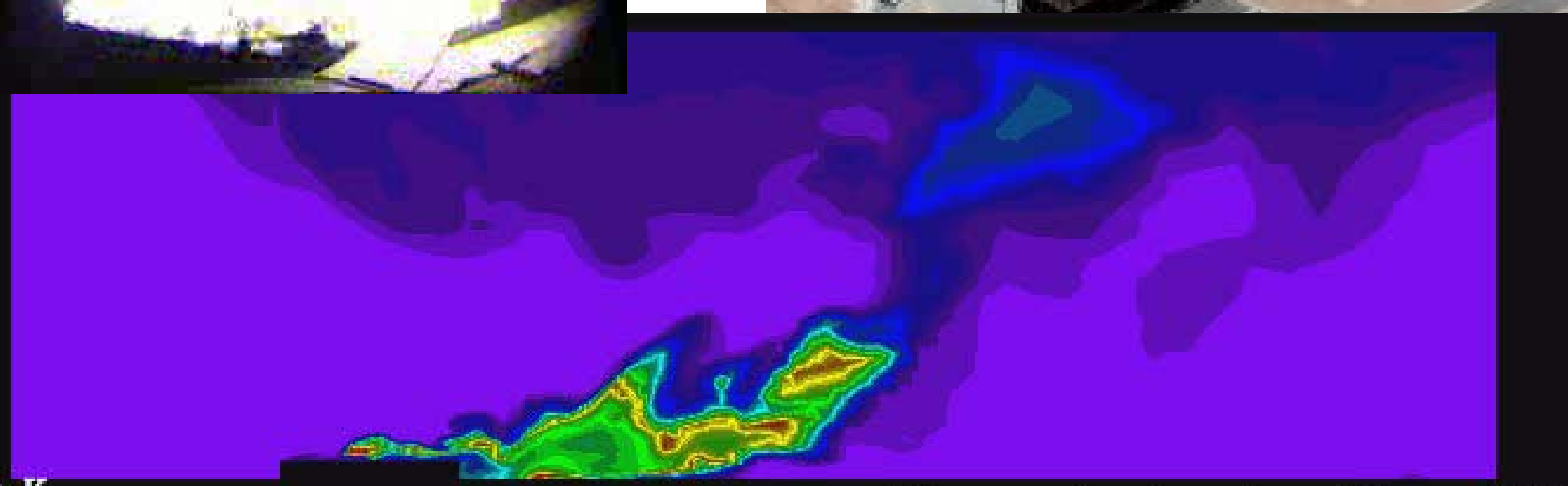
# Testing the Selected Scenario

- Test results showed
  - Thermal loads for specified scenario
  - Steady simulations predicted peak heat flux levels but average levels were ~ 50% lower than prediction
  - In spite of our best efforts to control boundary conditions outdoors, wind effects too much to reproduce test for expensive hardware
  - We have very recently moved indoors

# Designing a Wind Tunnel for Fires

- Desire to reproduce outdoor fires indoors to control boundary conditions.
- Simulations used to design and commission cross-wind test facility

**Cross Wind Fire Test Facility**



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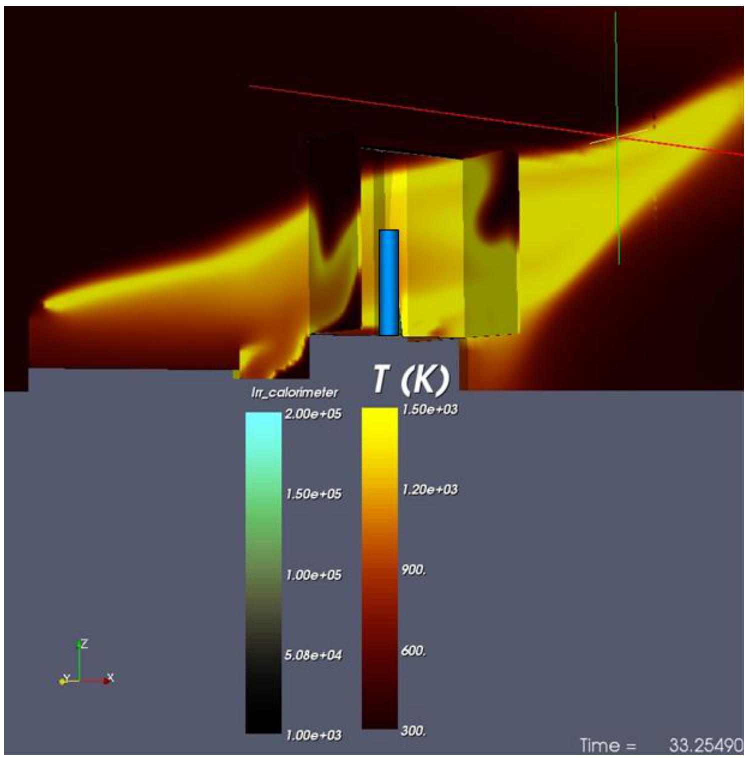
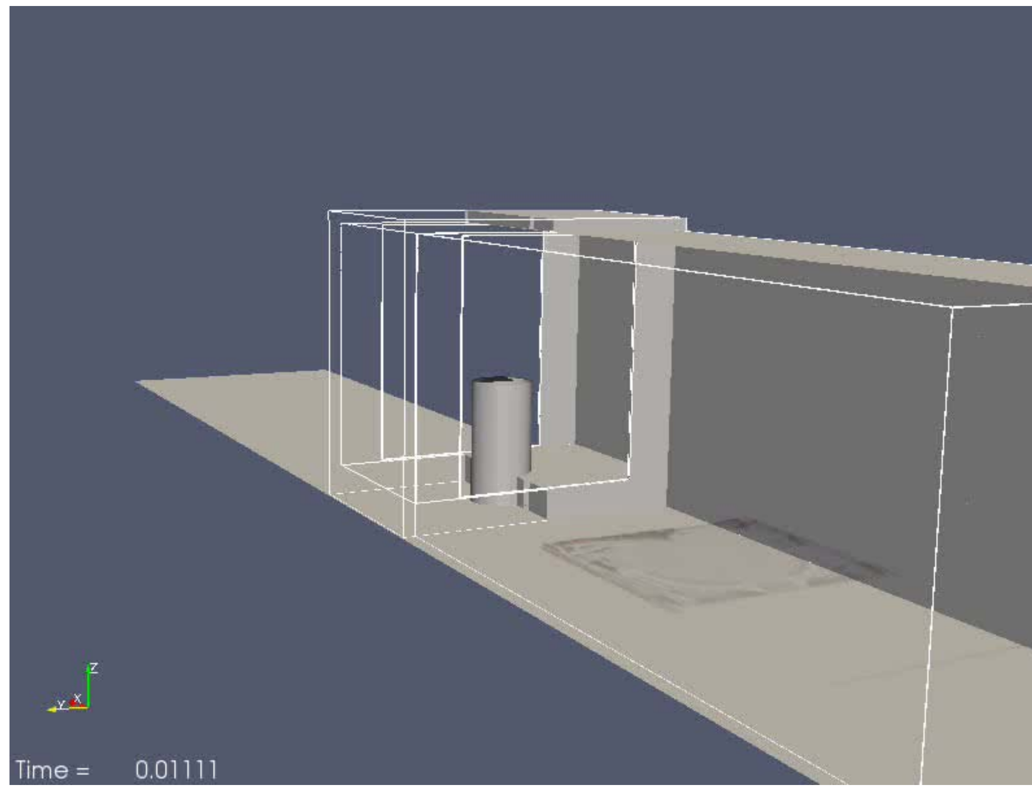
# Designing the Indoor Test

- Design with M&S to reproduce the heat flux levels in the outdoor fire.
- Current status: Design is locked and testing is imminent.



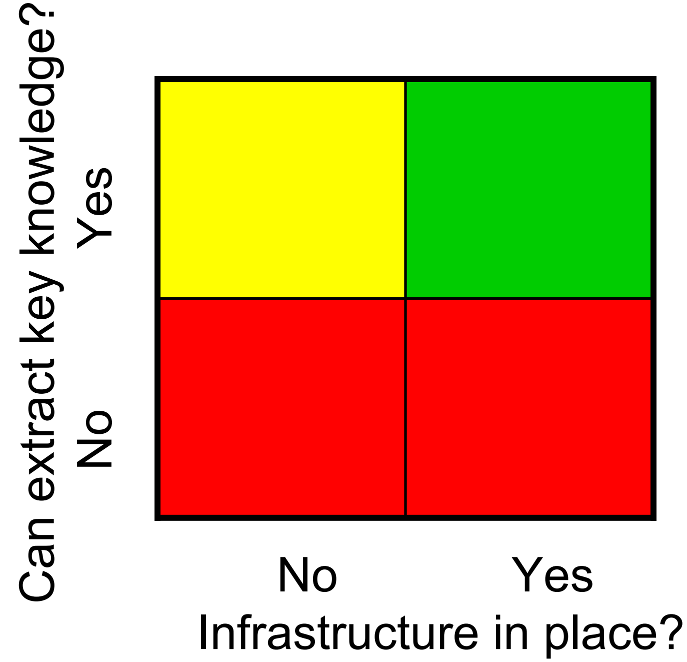



# Fire Example Summary

- Testing challenges
  - Too costly to explore parameters space with relevant reduced-fidelity tests
  - Full-scale structure tests are too costly to design with trial and error empirical learning approaches
- Simulation challenges
  - Tests are required for validation to establish uncertainties
  - Uncertainty for complex non-linear physics problems in real geometries is not easy to establish
- Combination of M&S with T&E provides only realistic path to solution
  - Simulation optimized the parameter space and designed the tests
  - Reduced uncertainty in modeling by testing

# General Comments on Cost

- Which is cheaper Modeling and Simulation or Test and Evaluation?
  - Both have infrastructure costs, both have use costs
    - In general infrastructure costs are high relative to use costs




  - Either approach can be cheaper
    - Do you have the requisite infrastructure in place?
      - Relatively easy to answer
    - Can you extract the key knowledge?
      - Relatively hard to answer

# General Comments on Cost

- Is the combination of M&S and T&E cheaper?
  - In general, no.
    - Infrastructure costs are high and not shared so *cost effectively doubles relative to the cost if the key knowledge can be obtained by single approach*
  - Can the combination be cheaper? Yes
    - With an unknown unknown, what approach will yield the necessary knowledge?
    - Dual track approaches are commonly used to minimize risk when a given approach can fail, but the combination is likely to succeed
      - Optimum dual track approach is one which minimizes common mode failure and maximizes synergy
    - M&S in combination with T&E has highest likelihood to succeed for supporting high-consequence decisions involving system margins
      - The authors contend that neither example given would have been successful with the combination of modeling and simulation

# Summary Experience to Date

- The combination of M&S and T&E  is analogous to the well established scientific method.
  - M&S is the current codification of theory.
  - T&E is experimentation under realistic conditions.
- The goal is to have sufficient understanding of the truth to make high-consequence decisions with respect to failure margins.
  - Our experience is that the M&S/T&E combination has yielded much more confidence in our decisions that would be obtained by either approach alone.
  - The approach in the examples is generic and broadly applicable.
- Cost/benefit demonstration for dual track approaches will remain challenging
  - Difficult to establish savings – combined costs appear high if failures are avoided – hard to prove we avoided failure by this approach.