# Advanced Instrumentation, Information, and Control Systems Technologies

Light Water Reactor Sustainability

## Online Monitoring of Material Aging and Degradation

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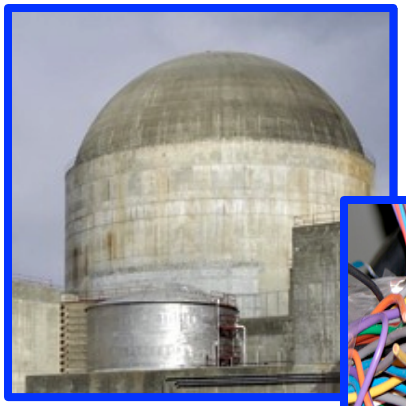
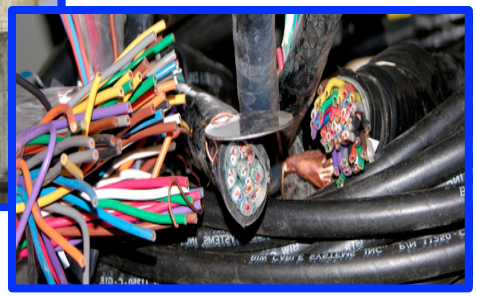
Light Water Reactor Sustainability R&D Program

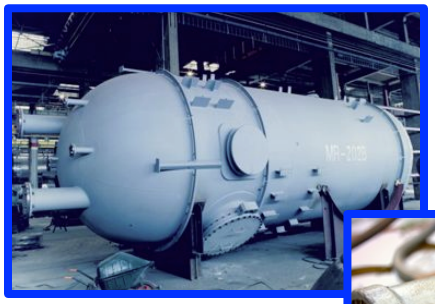
# Passive Structures in Nuclear Power Plants



Concrete



Cables



Reactor Pressure Vessel

Piping

- The Advanced Instrumentation, Information, and Control Technologies Pathway under the LWRS program conducts research to address
  - Aging and reliability concerns within the current operating fleet of light water reactors
  - Enhance operational and maintenance (O&M) efficiency
  - Improved reliability, productivity, and safety
- Capability to determine the “remaining useful life” of a component to justify its continued operation over an extended plant life

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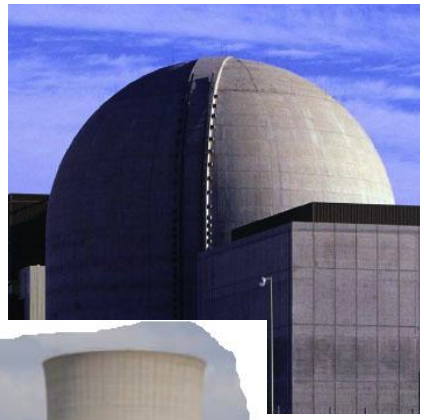
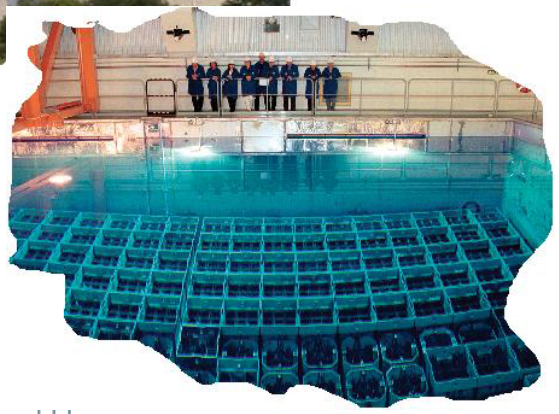
# Concrete Structures in Nuclear Power Plants





- All nuclear power plants contain concrete structures
  - Primary containment
  - Containment internal structures
  - Secondary containments/reactor buildings
  - Spent fuel pools and Cooling towers
- Concrete structures provide important foundation, support, shielding, and containment functions
- Assessment and management of aging concrete structures is essential for plant long-term operation

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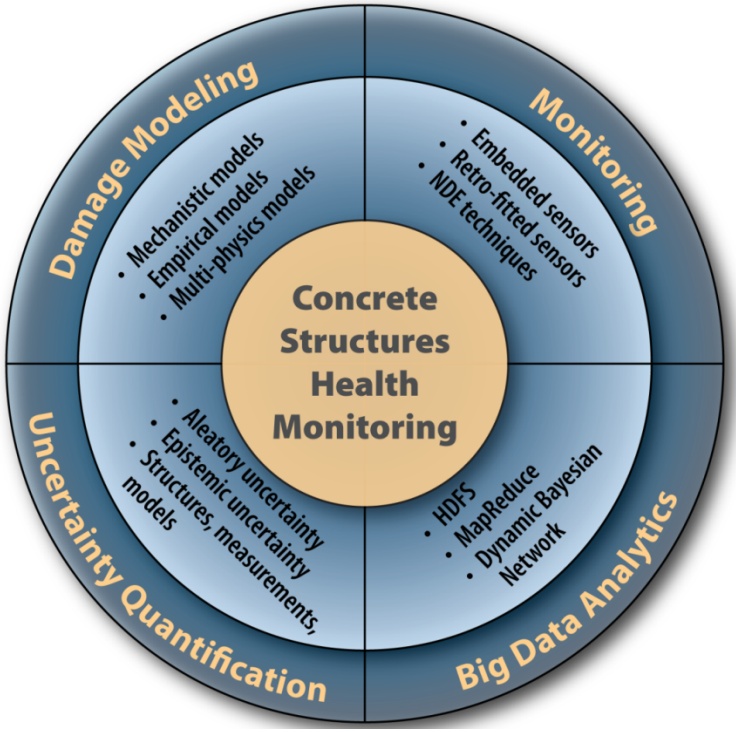
# Concrete Prognostics and Health Management Framework




- **Damage Modeling:**
  - Utilize ASR degradation models to develop fault signatures that can be used for monitoring of damage interface
- **Monitoring:**
  - Investigating full field imaging techniques – optical, thermal, and acoustic
- **Big Data Analytics:**
  - Heterogeneous (structured, unstructured, and binary) data need to be stored, processed, and analyzed to develop diagnostic and prognostic models
- **Uncertainty Quantification:**
  - Quantification of Aleatory and Epistemic sources of uncertainties is essential for making risk-informed decision

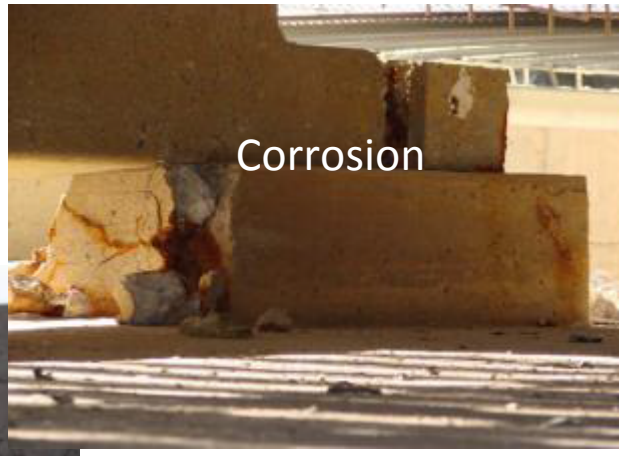
# Some Current Concrete Concerns

- **Alkali-Silica Reaction** (ASR) in reinforced concrete structures (Seabrook)
- **Delamination cracking** in tendons (Crystal River and Davis-Besse)
- **Seismic impact** on aged concrete structures

Source: U.S. Nuclear Regulatory Commission (NRC)

# Other Degradation Modes

- Besides ASR, other degradation modes exist





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# Degradation: Alkali-Silica Reaction (ASR)

- ASR is an intrinsic chemical reaction that forms a gel in concrete pores, expands, and causes stress and cracking of concrete
- Can be associated with corrosion of steel reinforcement bars and other steel structures embedded in the concrete
- Water containing sulfate or chloride causes ASR

**Challenges**

- Extent of ASR occurrence
  - location throughout the plant
  - position within the thickness of the concrete wall
- Extent to which ASR has reduced mechanical properties of concrete

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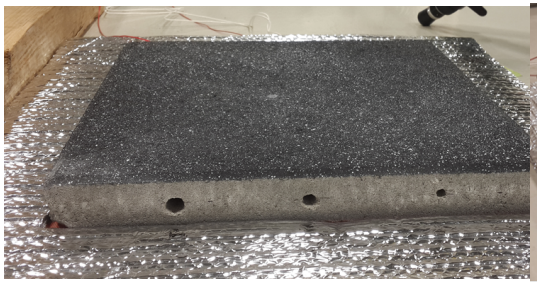
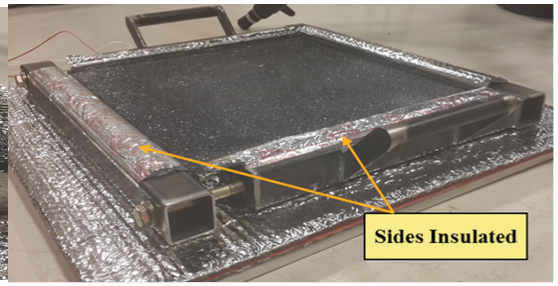
# Monitoring

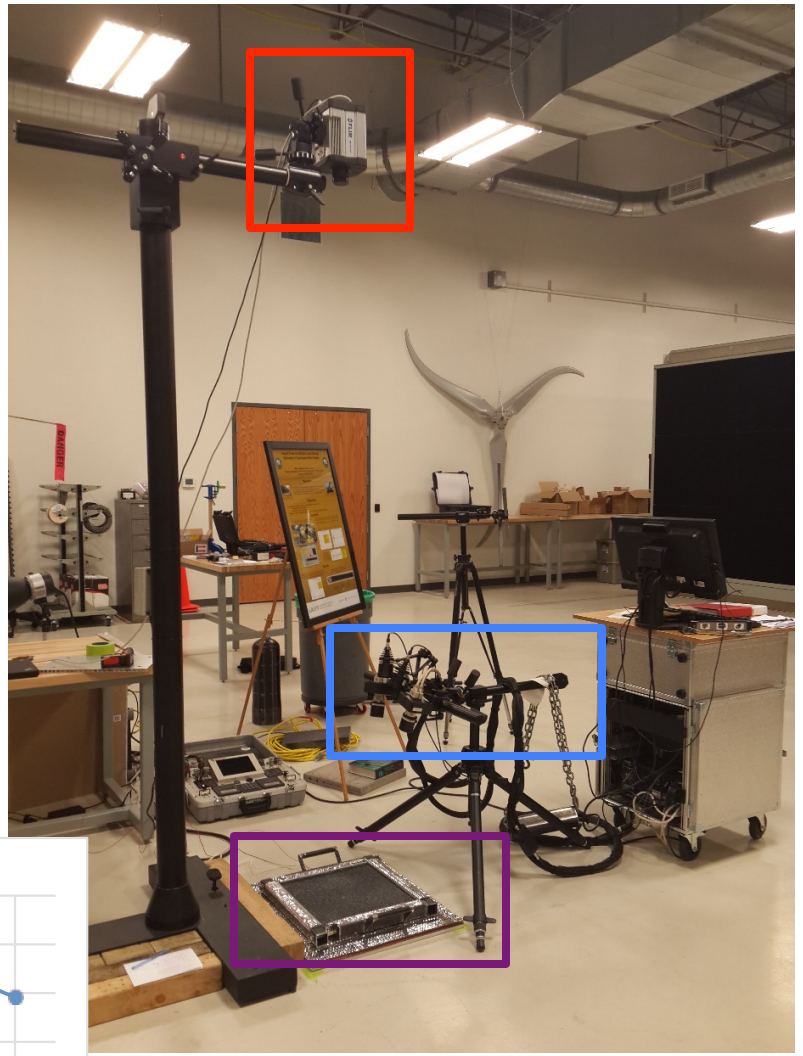
**Infrared Thermographic Camera**

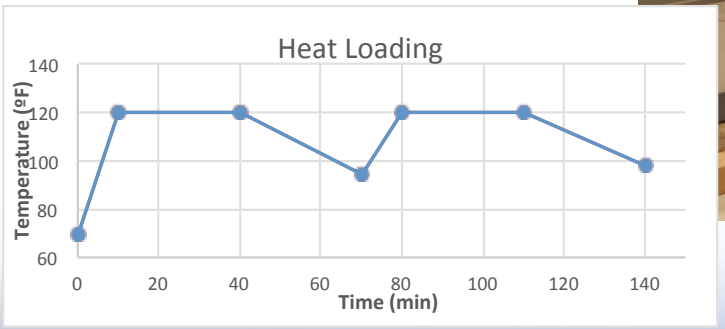

**Digital Image Correlation Camera**

**Concrete Sample**





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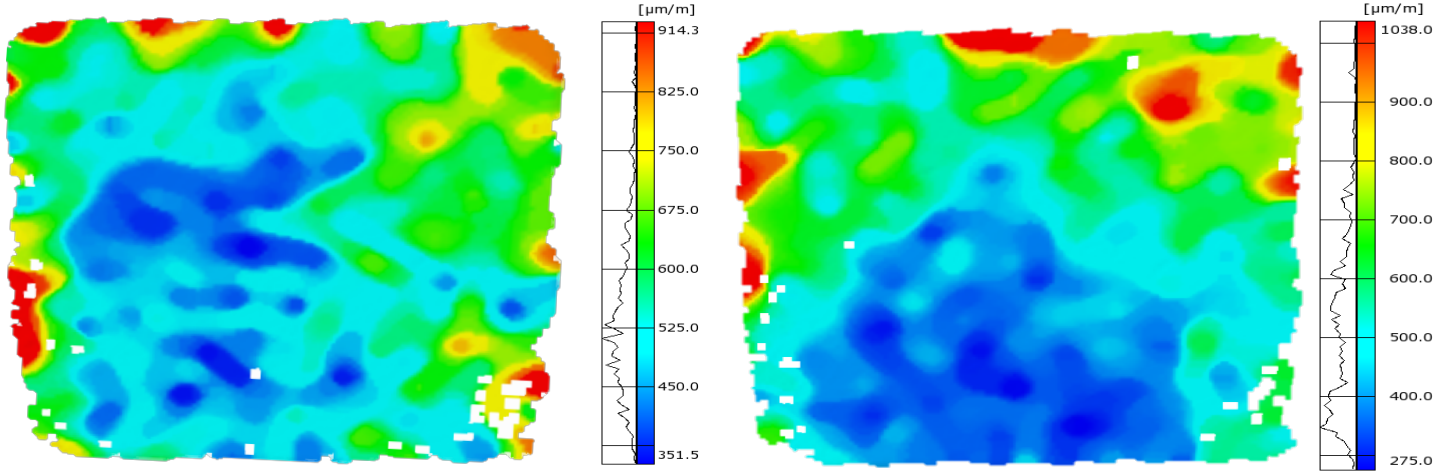
# Monitoring

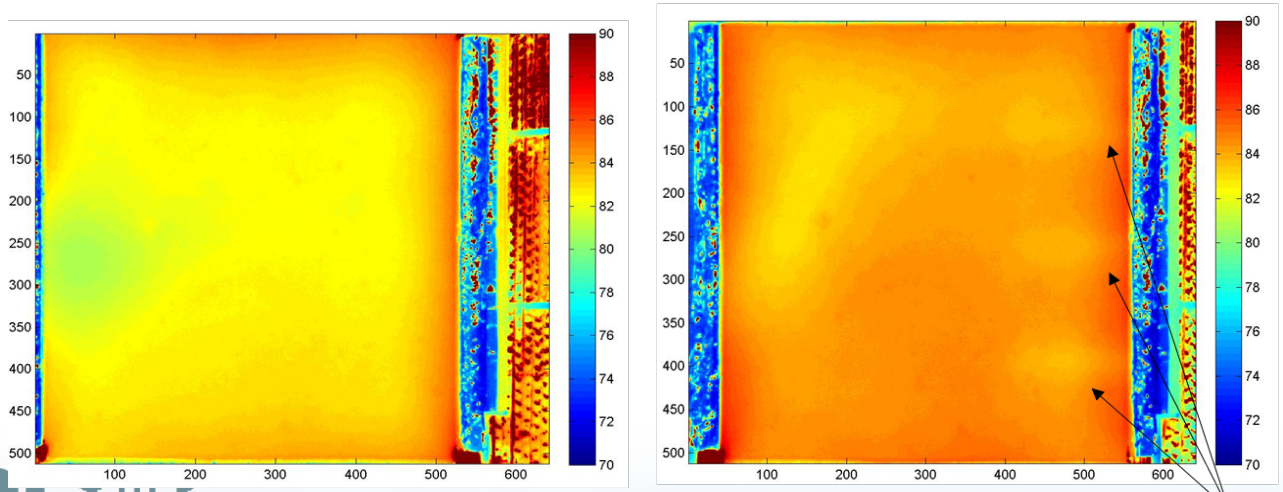
**Healthy Slab**




**Slab with holes**

**DIC image at minute 24 of loading**

**Healthy Slab**

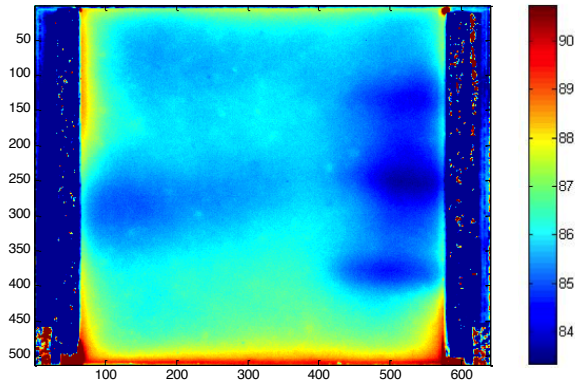



**Slab with holes**

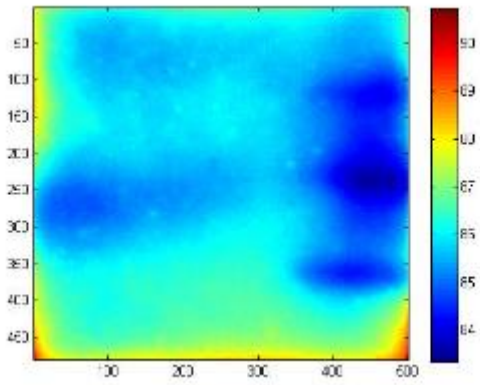
**Thermographic image at minute 24 of loading**

# Data Analysis and Diagnosis


- Diagnosis based on processed monitoring data is subjected to uncertainties
  - Due to processing parameters
  - Measurement errors
- Uncertainties are quantified



Raw acoustic image



Cropped image

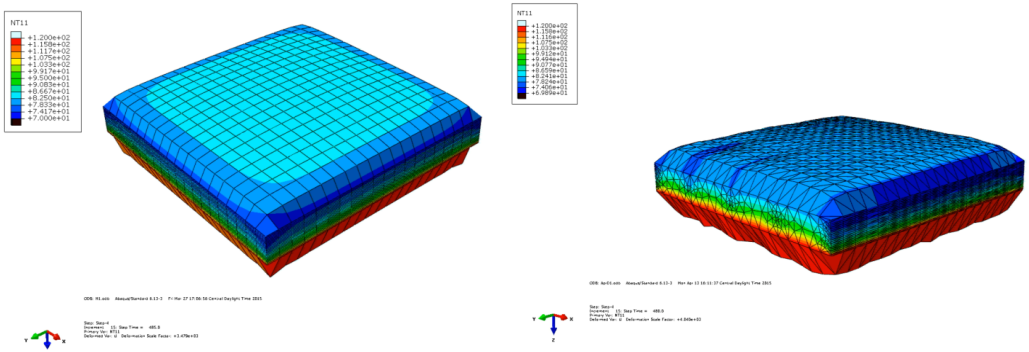
Sobel filtered image

Diagnosis

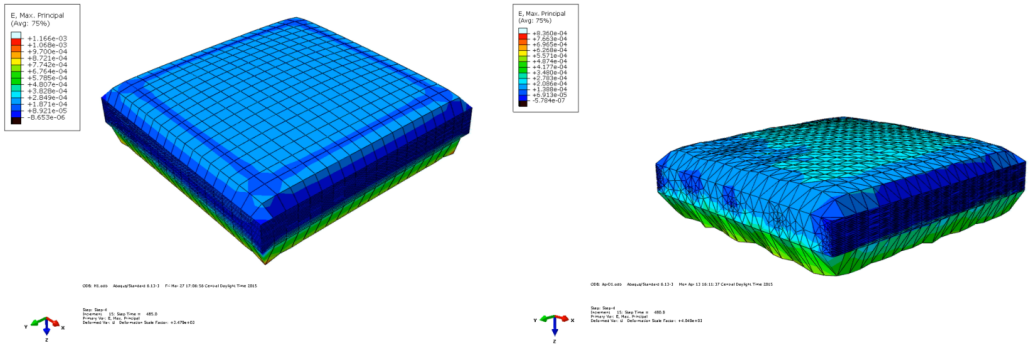
# Damage Modeling

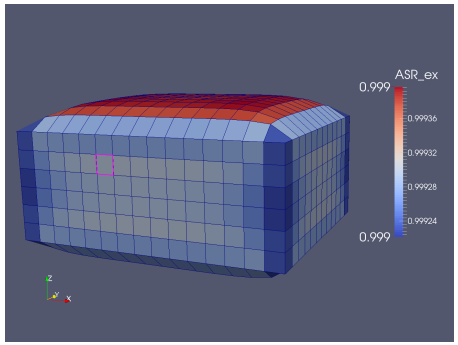
## Finite Element Analysis

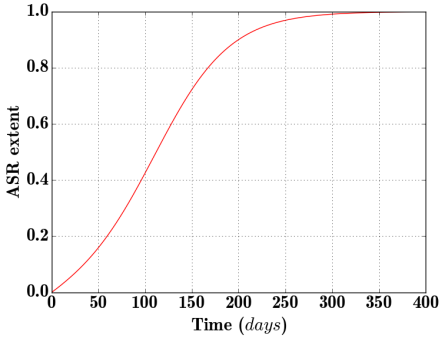
**Temperature Contour**



**Strain Contour**






ASR extent at t=400 days.

## MOOSE Framework for ASR Modeling

- GRIZZLY
- Isotropic and Anisotropic stress distribution

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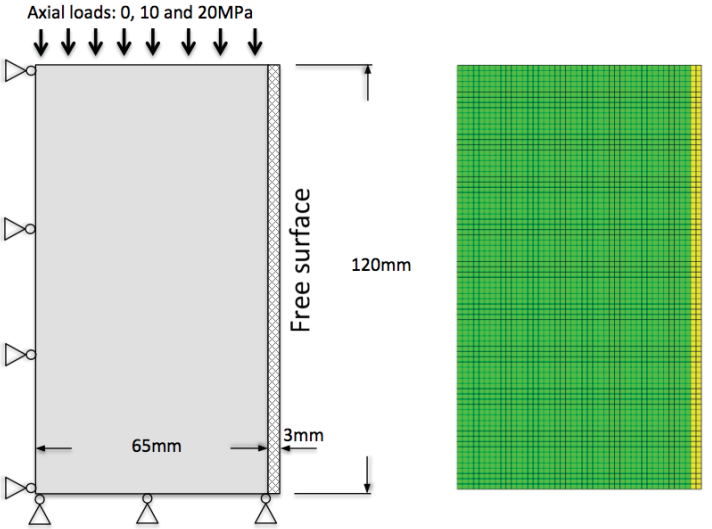
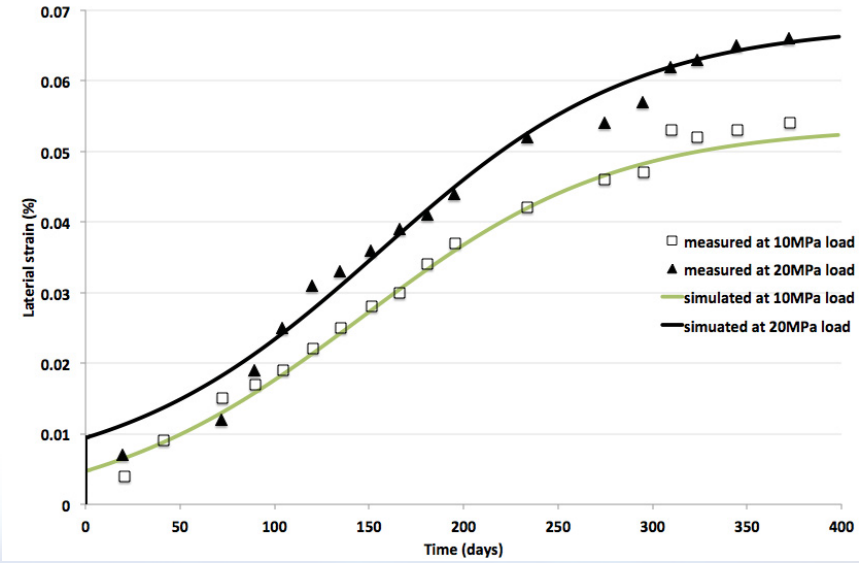
# Simulation Results in GRIZZLY

- ASR expansion test with 3 mm thick steel ring confinement
- Measured lateral strains of the specimen when subjected to 10MPa axial load was used to calibrate model parameters
- Anisotropic ASR swelling model[1] shows better agreement with experiment data



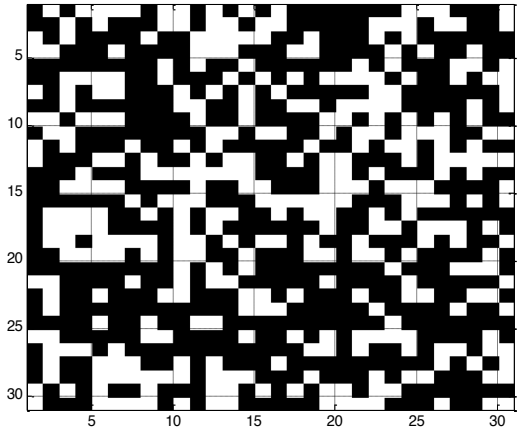

[1]Saouma and Perotti (2006): Constitutive Model for Alkali-Aggregate Reactions. ACI Materials Journal, pp. 194-202.

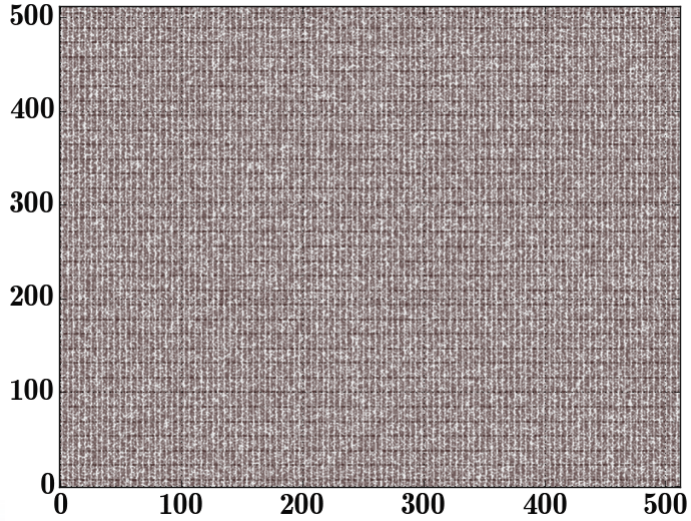


Huang et al. Grizzly Model of Multi-Species Reactive Diffusion, Moisture/Heat Transfer, and ASR in Concrete. INL/EXT-15-36425, September.

# Percolation Theory for Modeling ASR

- Percolation theory describes the behavior of connected clusters in a random graph
- Percolation models are
  - viable models for ASR propagation in existing concrete structures
  - computationally less expensive than high-fidelity physical models

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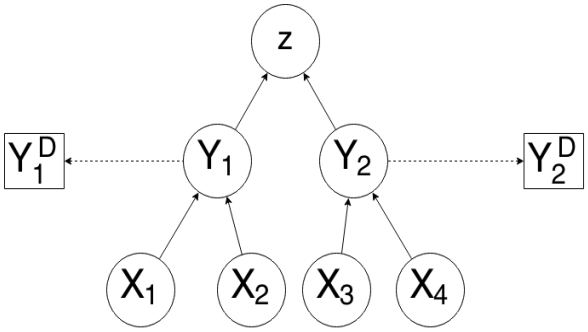
# Uncertainty Quantification

Bayesian Network (BN) – Integrates all available information

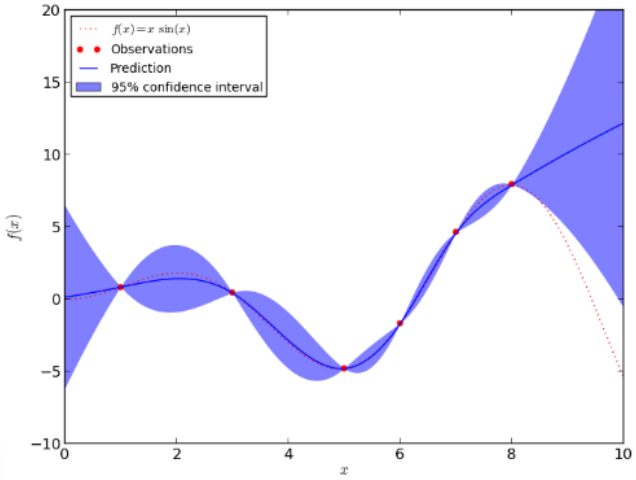
- Bayesian calibration
  - Markov Chain Monte Carlo (MCMC)
- Diagnosis
  - Damage identification, localization and quantification
- Prognosis
  - Monte Carlo Sampling

Gaussian process (GP) surrogate model

- FE model is expensive to do MCMC
- The surrogate model is trained with original model runs at selected training points
- Prediction of surrogate model has uncertainty → Normal distribution with mean and standard deviation




**Example of DBN**



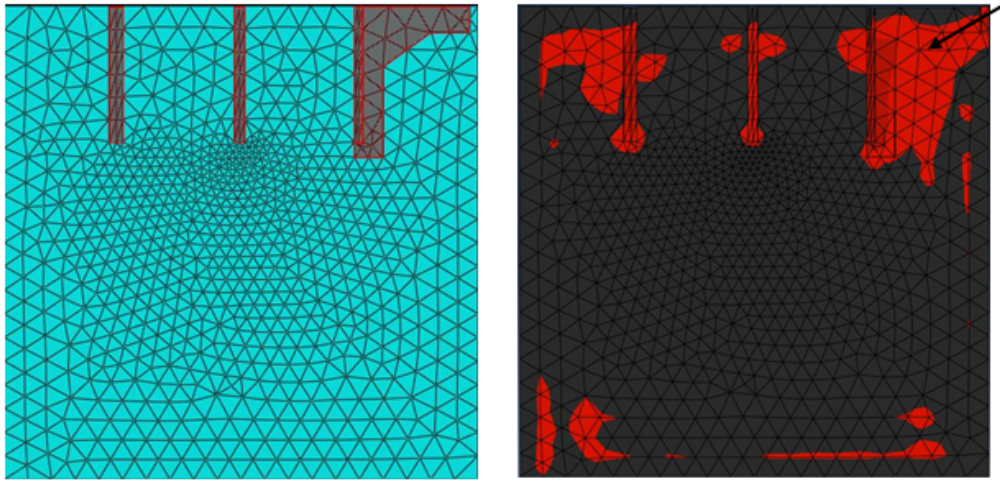

**Example of GP surrogate model**

# Damage Prognosis & Uncertainty Quantification

- The cracks diagnosed by monitoring were incorporated in the finite element model
- The finite element model is used for prognosis
- Crack areas predicted for six sets of crack diagnoses using different data analytic features are used for uncertainty quantification of crack growth

<u>Diagnosis UQ</u>
Mean = 9.44 sq. in.
Stdev = 2.11 sq. in.

<u>Prognosis UQ</u>
Mean = 14.3 sq. in.
Stdev = 3.71 sq. in.



**Finite element modeling for prognosis**

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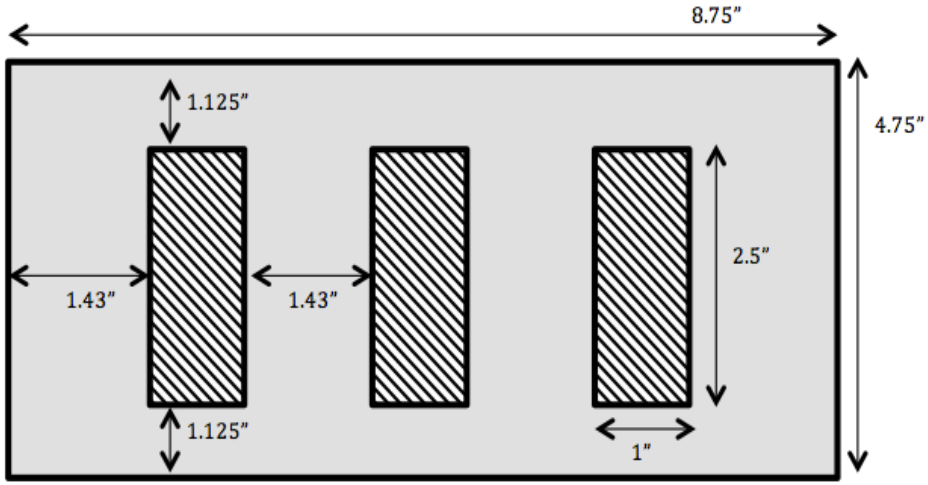
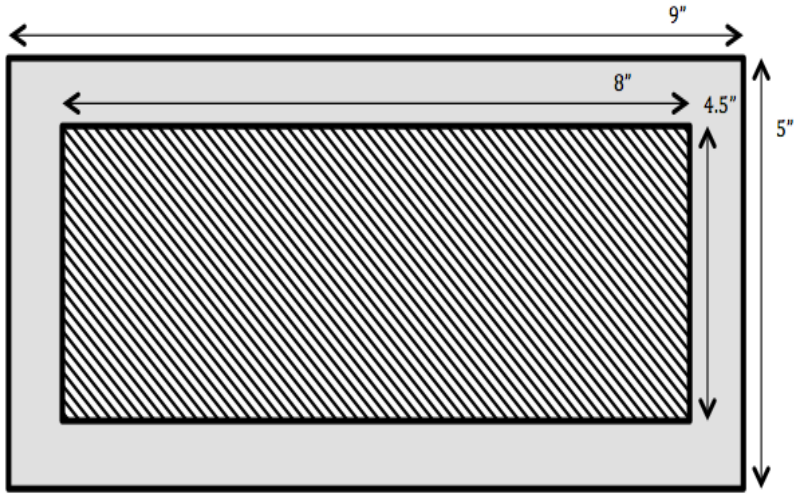
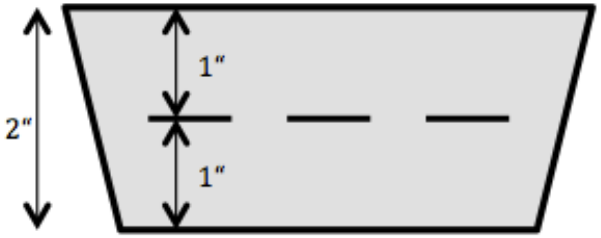
# Concrete Samples with Embedded Glass

Vanderbilt developed 6 samples of dimensions 9 in. x 5 in. x 2 in.

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# Technology Impact

- Innovative and advanced online monitoring technology for passive structures (a.k.a structural health monitoring) in nuclear power plants

- Enables risk-informed decision for
  - license renewal application of existing fleet of light water reactors
  - Mitigation strategies

- Development of a framework that integrates
  - Physics based modeling information
  - Experimental data
  - Diagnosis and prognosis outcomes
  - Uncertainties quantification

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# Summary and Future Research

**Summary**

- Demonstrated proof-of-concept of concrete PHM framework on a small sized concrete sample subjected to thermal loading and stress

- All modeling, experimental, and data analytics results were integrated using Bayesian network
  - Uncertainty in model calibration, diagnosis, and prognosis were calibrated
  - Diagnosis and prognosis uncertainty quantification is valuable for decision-making

- Implemented anisotropic ASR expansion in the GRIZZLY code based on Saouma and Perotti developed model

- Utilized ASR expansion implemented in the GRIZZLY code to study the percolation aspects of concrete

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# Summary and Future Research

**Future Research**

- Vanderbilt University will develop medium-sized concrete samples with ASR degradation using reactive aggregates with and without steel reinforcement

- INL will collaborate with Material Aging and Degradation Pathway on development of large scale concrete sample with ASR

- A data analytics and visualization framework will be developed to analyze and visualize heterogeneous data on a unified and easy-to-use platform