# Concrete Aging and Degradation in NPPs

# LWRS Activities

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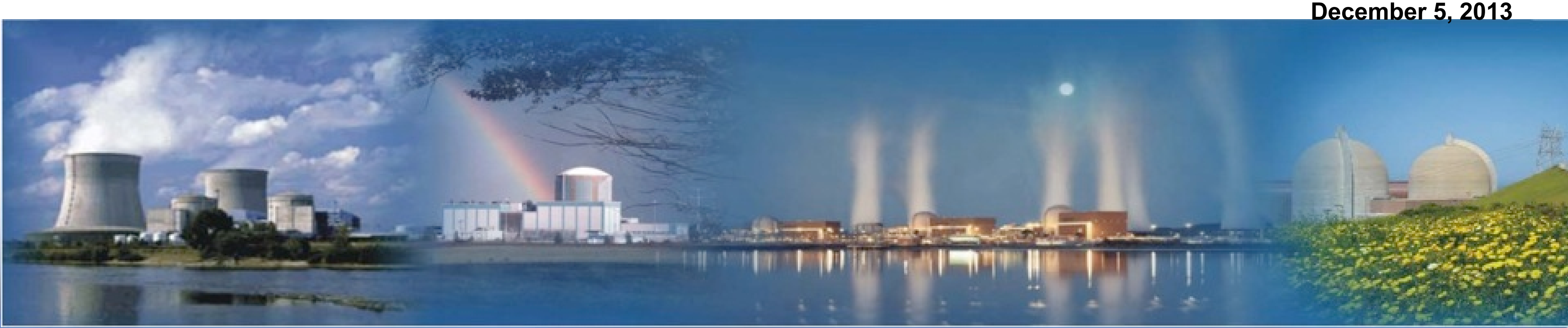
**Oak Ridge National Laboratory**

Light Water Reactor Sustainability R&D Program

**MEETING BETWEEN THE U.S. NUCLEAR REGULATORY COMMISSION STAFF AND INDUSTRY**
**TO DISCUSS SUBSEQUENT LICENSE RENEWAL**
**Concrete and Civil Structures**
**December 5, 2013**



# DOE's LWRS Program

***Materials Aging and Degradation path addresses:***

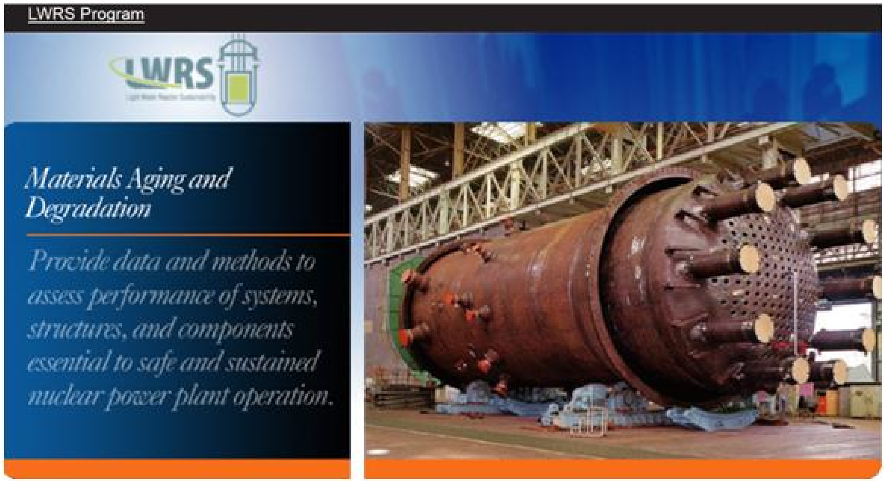
**reactor metals,**

**concrete,**

**cables,**

**buried piping,**

**and mitigation strategies.**




https://inlportal.inl.gov/portal/server.pt/community/lwrs_program/442/introduction

**The strategic goals of the pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of systems, structures, and components essential to safe and sustained nuclear power plant operations.**

# Introduction: motivation

In the last 15 years more than 70 NPPs in the US have undergone a license renewal process to extend their lifetime up to 60 years.

Extensions to 80 years and beyond are being considered to meet the future national energy demands.

Concrete degradation was identified as a *subject of interest* for extended NPPs operation.

Identified priorities for Containment/Shield/Bio-Shield/RPV Supports and buildings:

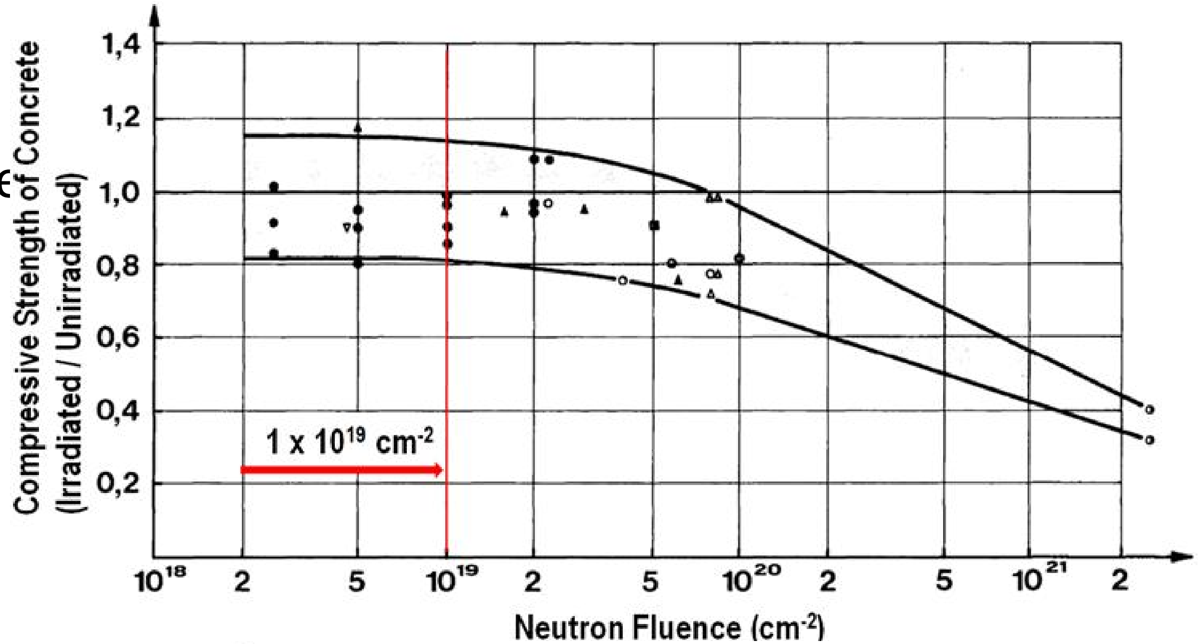
- Radiation (Part I)
- Alkali-Aggregate/Silica Reaction (Part II)
- Creep/creep-fracture interaction (Roadmap to be developed)

# Part I- Irradiated Concrete

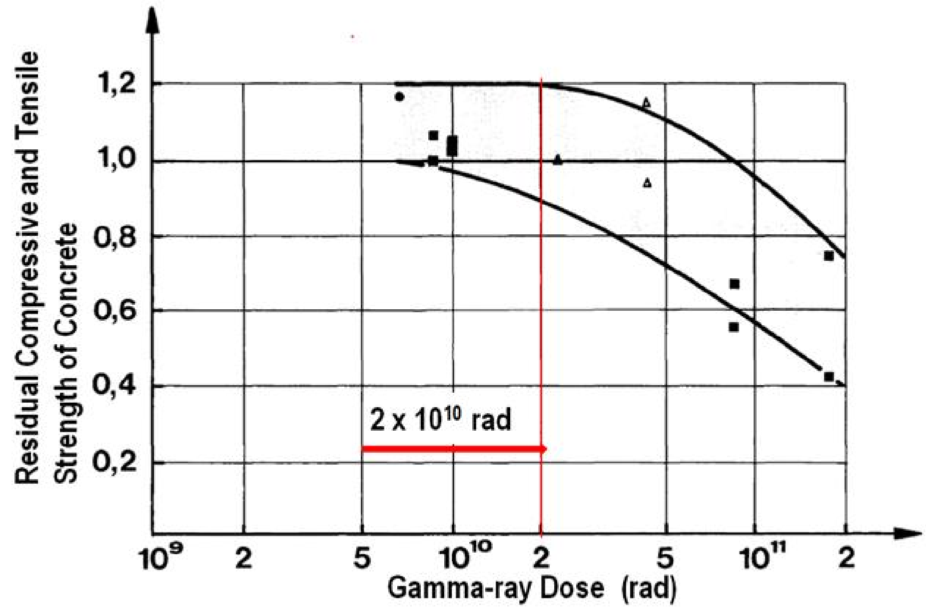
Research results provided: 2012-2016

# Why concrete: the Hilsdorf curve

Current understanding of radiation effects on concrete is largely based on the 'Hilsdorf curve,' dating back to 1978.




**Gaps in information:**
the neutron fluence
cutoff energy,
the composition of concrete,
the irradiation temperature,
gamma-ray dose, etc.




**Therefore:**
**the applicability to NPP concrete is uncertain; more data needed.**

# Project Strategy – Irradiation

- Characterize radiation fields in concrete structures in NPPs and determine the bounding values of neutron fluence and gamma-ray dose in the biological shield concrete at 80 years of operation and beyond.
- Obtain more data on the effects of neutron and gamma irradiation as well as extended time at elevated temperature on concrete.
  - Develop a more exhaustive database including recently unclassified data
  - Irradiate prototypical concrete to levels equal to or greater than expected in extended service (accelerated irradiation studies) and evaluate possible degradation.
  - Harvest and test irradiated concrete from decommissioned plants (US and international).
- Develop a more robust fundamental understanding of the effects of radiation on concrete.
- Establish a collaborative research effort with international partners.

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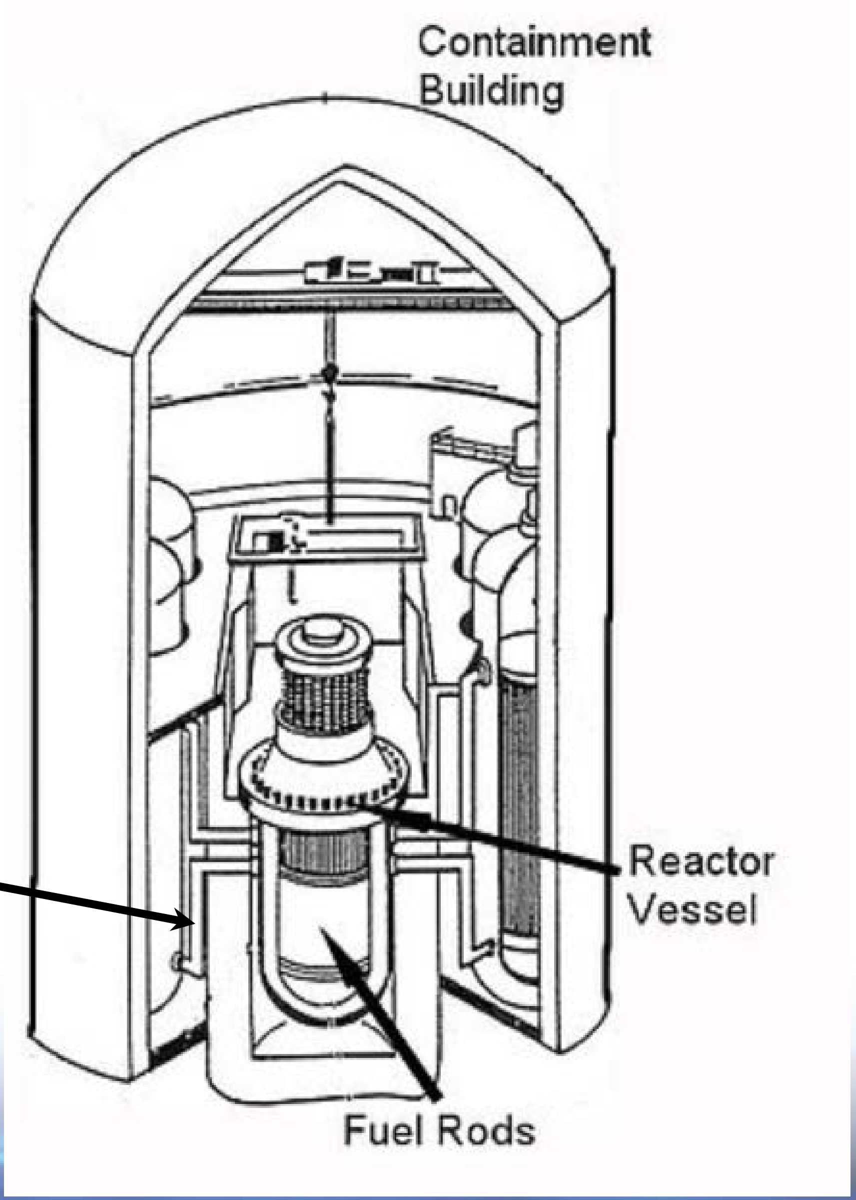
# Characterization of radiation fields in concrete of the biological shields

**Performed coupled neutron and gamma-ray transport calculations for one selected 2-loop and one 3-loop plant**

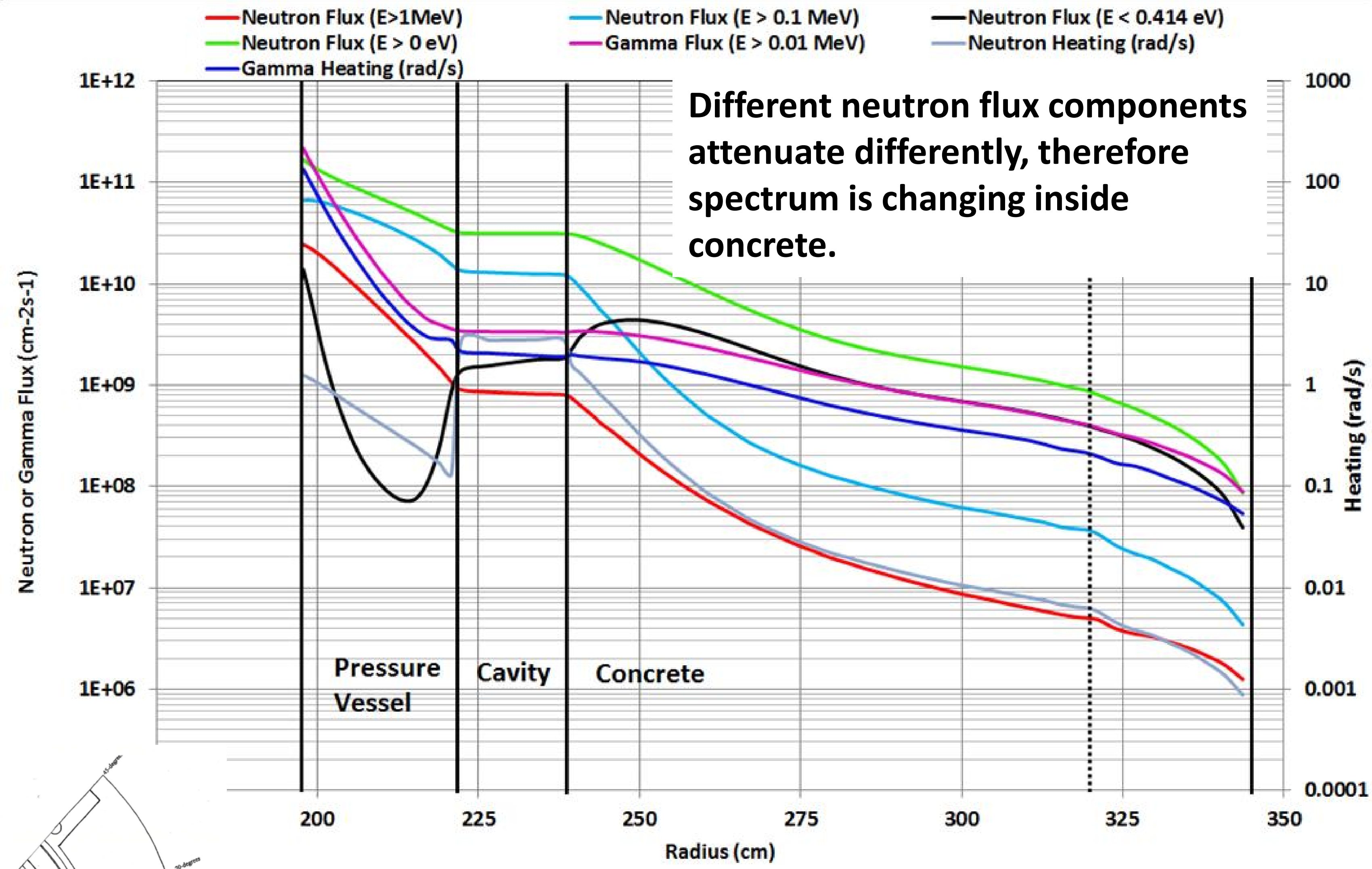
**Reviewed publicly available reactor pressure vessel surveillance reports for relevant data (work in progress)**

**[http://www.nrc.gov/reading-rm/adams.html](http://www.nrc.gov/reading-rm/adams.html)**

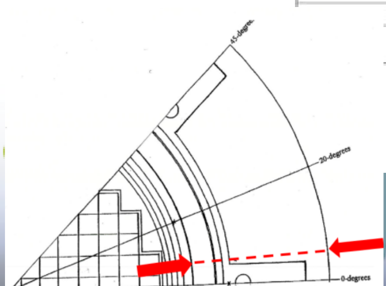
**Biological shield in PWR**



## Radiation environment in concrete biological shields: neutron and gamma flux and heating rates (radial variation, at azimuthal maximum)




**Different neutron flux components attenuate differently, therefore spectrum is changing inside concrete.**



# Neutron fluence and gamma-ray dose in PWRs biological shield

| | | Calendar Years of Operation to Reach Selected Neutron Fluence and Gamma-Ray Dose Rate Levels | | | |
|---|---|---|---|---|---|
| | | Neutron Flux Energy Threshold | | | Gamma-Rays |
| Fluence or Dose | NPP Type | E > 0 eV | E > 0.1 MeV | E > 1MeV | E > 0.01MeV |
| Fluence 1 x $10^{+19}$ $cm^{-2}$ | 2-loop | 5 | 14 | 123 | |
| | 3-loop | 11 | 30 | | |
| Fluence 5 x $10^{+19}$ $cm^{-2}$ | 2-loop | 27 | 71 | | |
| | 3-loop | 56 | 152 | | |
| Fluence 1 x $10^{+20}$ $cm^{-2}$ | 2-loop | 55 | 143 | | |
| | 3-loop | 111 | | | |
| Gamma-Ray Dose 1 x $10^{+10}$ rad | 2-loop | | | | 70 |
| | 3-loop | | | | 172 |

# Accelerated irradiation of prototypical concrete: comparison of PWR, LVR-15, and Halden

| | Neutron Flux ($cm^{-2}$ $s^{-1}$) | | | Heating Rate (W/g) | | |
|---|---|---|---|---|---|---|
| | E > 1MeV | E > 0.1 MeV | E < 0.41 eV | Gamma | Neutron | N + G |
| **2-loop PWR** In Concrete at Maximum | 2.79E+09 | 2.41E+10 | 4.64E+09 | 4.90E-5 | 3.70E-5 | 8.60E-5 |
| **LVR-15,** Czech Republic Ratio to 2-loop PWR | 4.99E+11 179 | | | | | 0.44** 5116 |
| **Halden (JEEP-2),** Norway Ratio to 2-loop PWR | 1.6 E+12 570 | 4.1 E+12 170 | 2.1 E+13* 4526 | 0.1 2041 | | |

**LVR-15: 232 days to reach fast fluence (E>1MeV) $1x10^{19}$ $cm^{-2}$ $s^{-1}$, gamma dose $8.8x10^{+11}$ rads.**

**Halden: 72 days to reach fast fluence (E>1MeV) $1x10^{19}$ $cm^{-2}$ $s^{-1}$, gamma dose $6.3x10^{+10}$ rads**

*Flux with E < 0.625 eV

**Not clear if N + G or Gamma-ray only heating

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# Summary

## US reactor fleet bounding fluence:

- Based on estimated fluence levels in biological shields and available data on concrete strength versus fluence, concrete degradation within 80 years of plant operation can not be ruled out.
- Neutron fluence “energy cutoff” (if any) needs to be carefully assessed.
- If the “fluence threshold,” above which the degradation of concrete occurs can be specified in terms of fast neutron fluence (E > 1 MeV), then data from the RPV surveillance programs could be sufficient to bound the conditions of concrete in NPPs.

## Accelerated irradiation experiments:

- Since the relevant irradiation parameter for concrete is not established it is desirable to obtain full neutron and gamma spectra in the samples for the experiment.
- For the concrete irradiation experiments it is desirable to use neutron and gamma spectra similar to those in the actual plants. However, neutron spectrum changes significantly through the biological shield.
- For relatively small concrete samples it may be difficult to obtain gradients similar to those in biological shields. It may be better to try to obtain “uniform” irradiation through the samples.

# Project Strategy

- Characterize radiation fields in concrete structures in NPPs and determine the bounding values of neutron fluence and gamma-ray dose in the biological shield concrete at 80 years of operation and beyond.
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  - Develop a more exhaustive database including recently unclassified data
  - Irradiate prototypical concrete to levels equal to or greater than expected in extended service (accelerated irradiation studies) and evaluate possible degradation.
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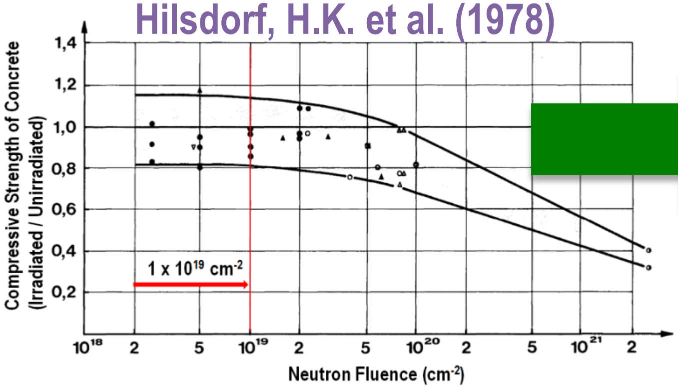
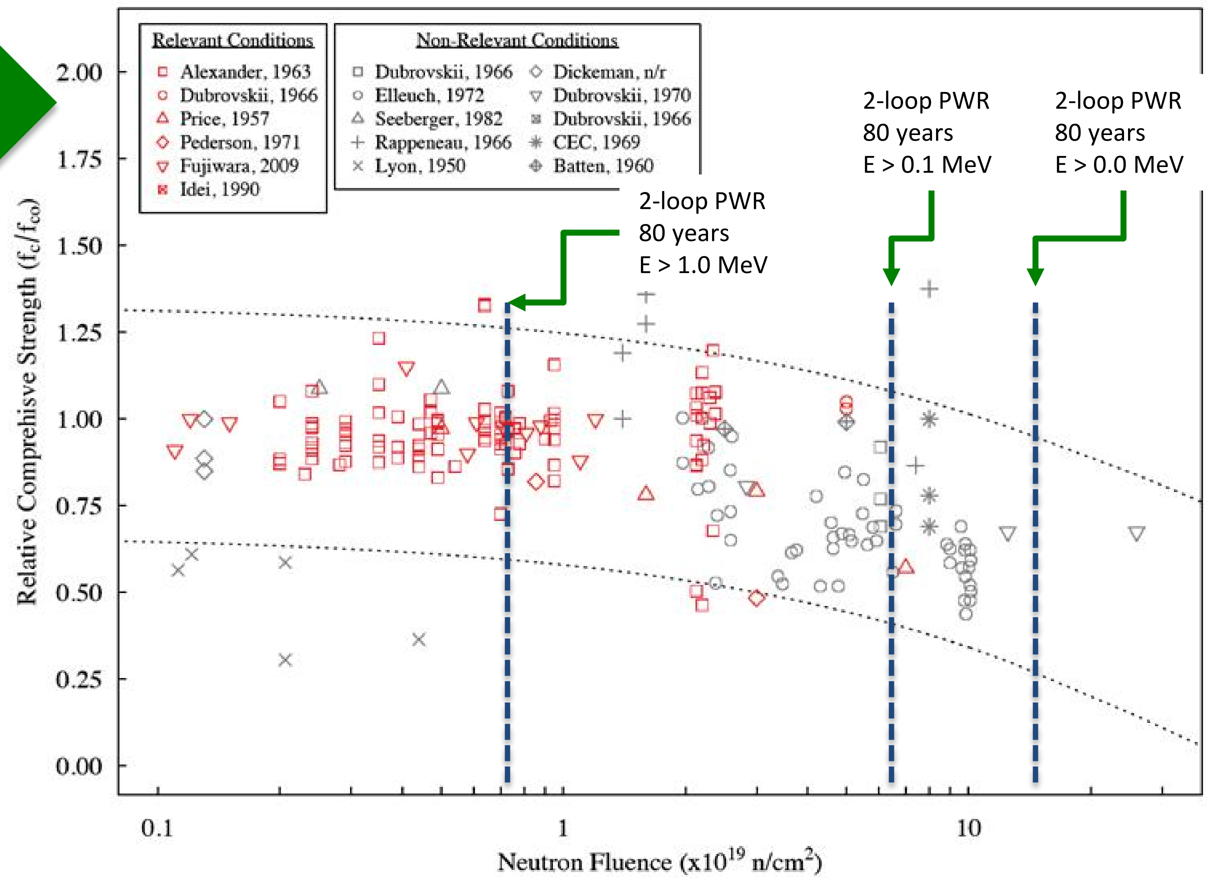
# Literature review of compression strength of irradiated concrete

Hilsdorf, H.K. et al. (1978)




ORNL (2013)




Hilsdorf et al. Upper Bound

Larger dataset supports downward sloping trend in compressive strength but requires filtering for commercial NPP applicability

Most data at high fluence are also at elevated temperatures, >100 °C (grey symbols) or/and with particular shielding concrete

Possible degradation of properties near LWR fleet end-of-life

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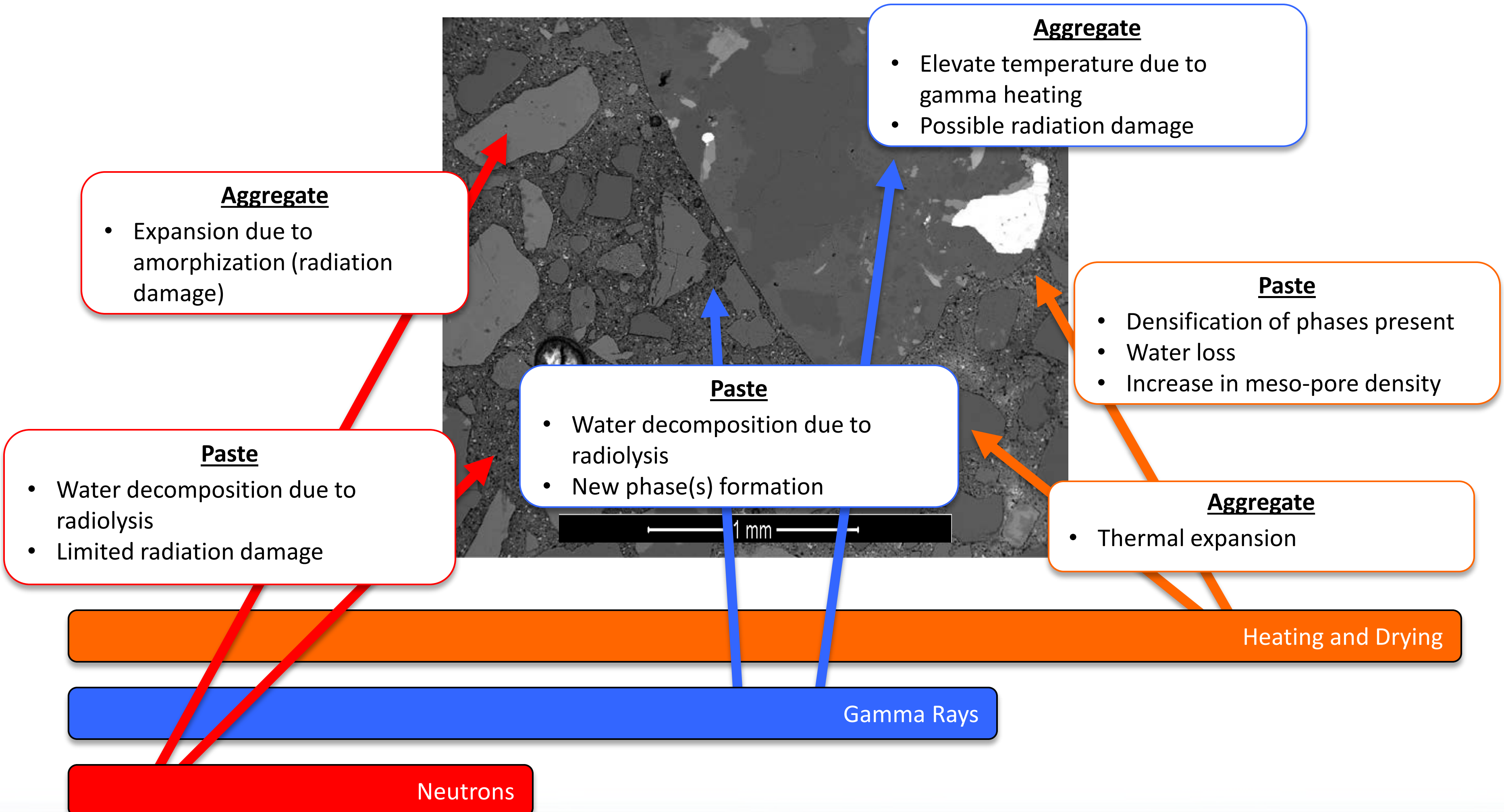
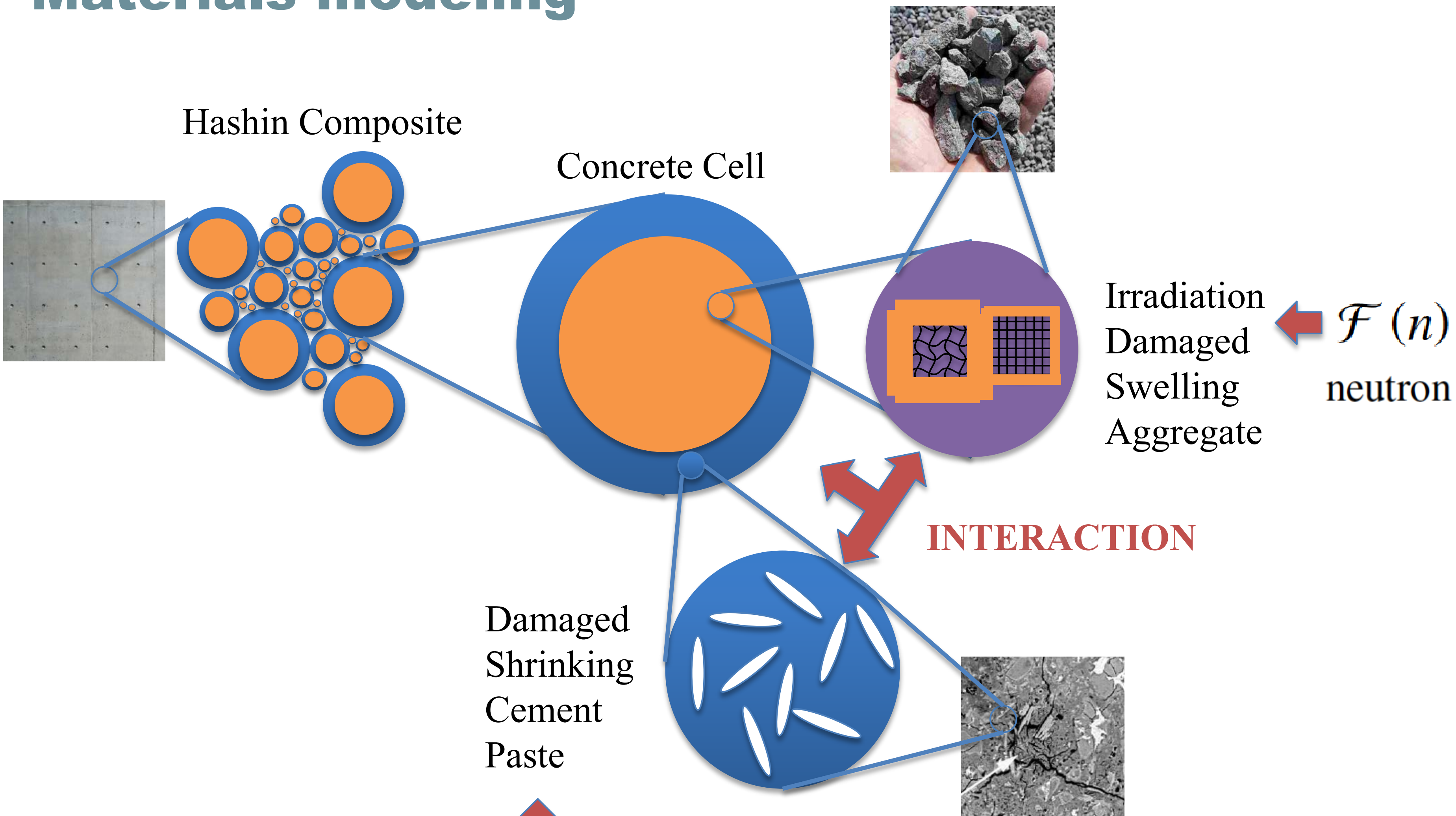
# Summary of possible radiation induced effects on cement and aggregate



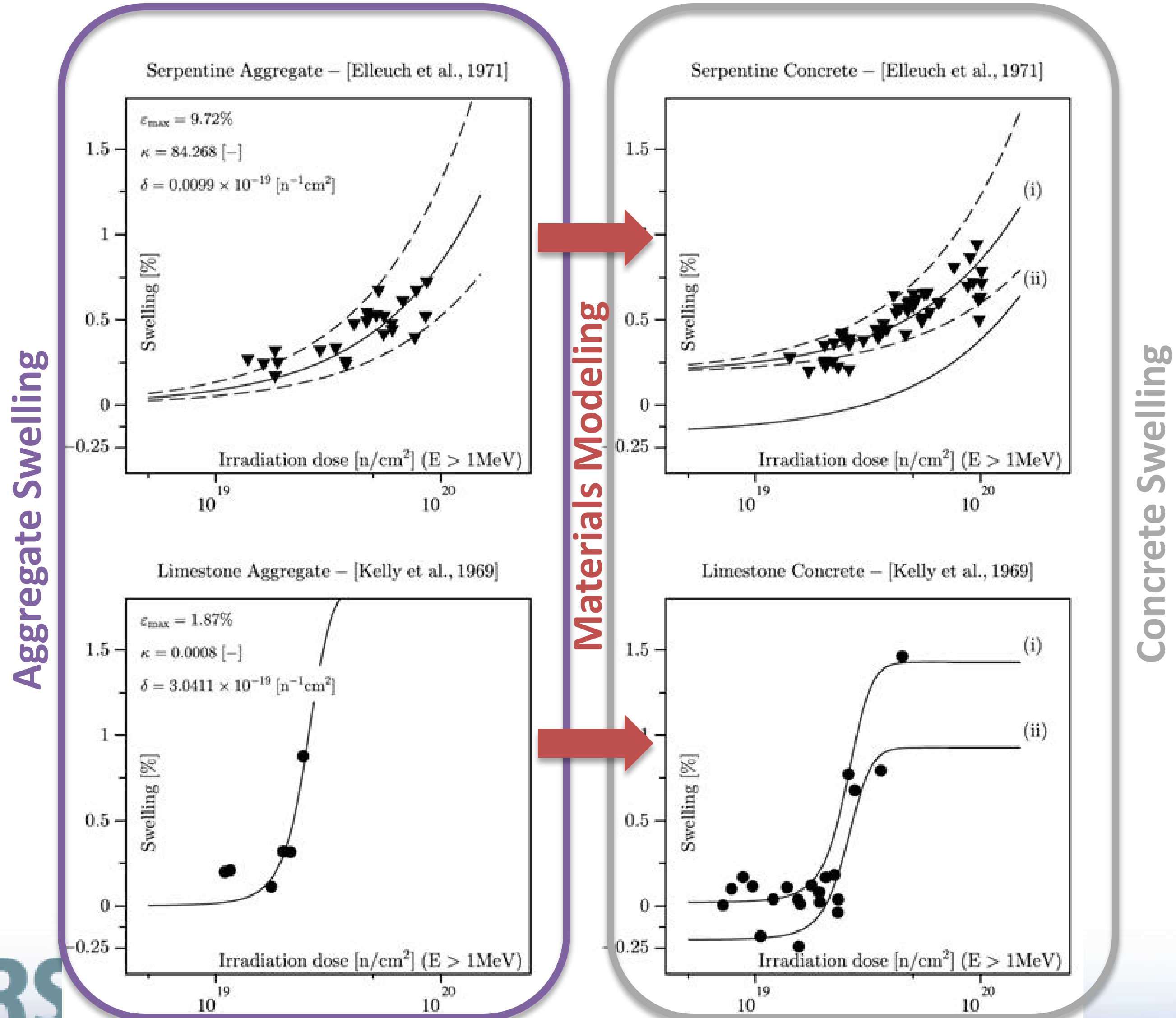

*Slide based on Maruyama, I. "Introduction of Concrete Research in JAMPSS Program" July, 30 2013.

# Materials modeling




$$\mathcal{F}\left(\underbrace{\frac{\Delta m}{m_0}(\gamma,T,HR)}_{\text{Loss of Moisture Content}}\;,\;\overbrace{\Delta\varphi(\gamma)}^{\text{Porosity Change}}\;,\;\underbrace{T}_{\text{Thermal Damage}}\right)$$

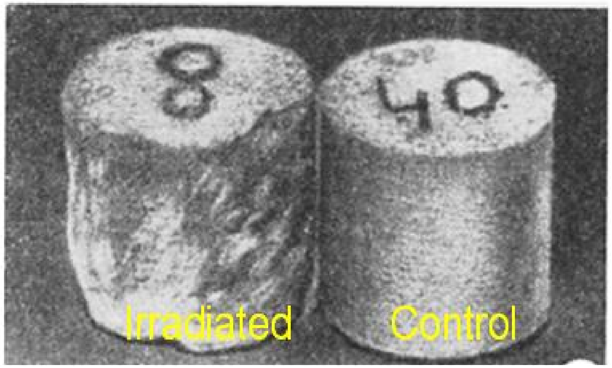
# Development of a micromechanical model for irradiated concrete



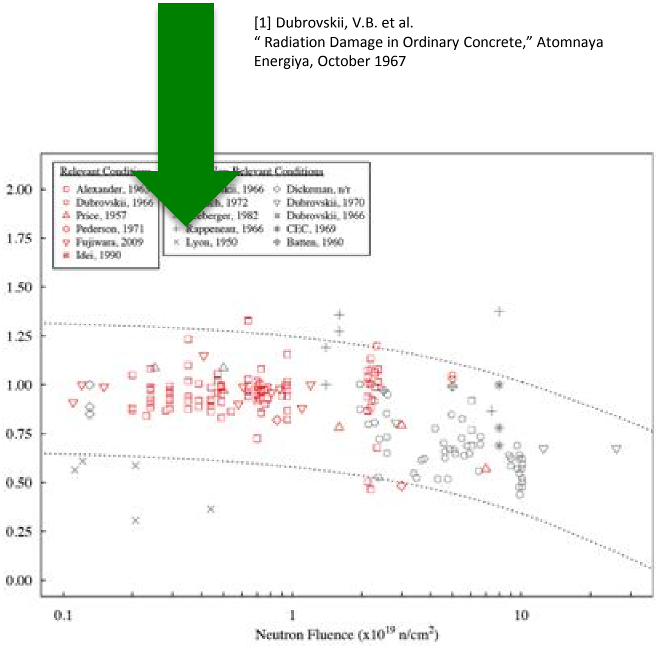
# Summary on radiation effects in concrete

- Expansion is possible for aggregates and concretes exposed to neutrons
  - Different aggregate types swelled at different rates
  - Expansion ∝ % silicate amorphization
- Mechanical properties (elastic modulus, tensile strength, compressive strength) are all changed at fluences above $1 \times 10^{19}$ n/cm$^2$
  - Close to bounding fluence for all PWR reactor types at 80+ years operation
- Future experiments are needed to answer open questions on irradiated concrete
  - Future experiments require several important variables to be evaluated for the aggregate, paste, and concrete separately (Mass change, length change/swelling, strength, elastic modulus, % amorphization, aggregate phase volume fraction)
- Structural significance to be investigated
  - Combine simulation/experiment to determine change of properties
  - Account for neutron, gamma, temperature, humidity gradients

Irradiation: **~6.1x10$^{19}$ n/cm$^2$** E>0.1 MeV
Temp: 100-150 °C, OPC w/ **River Sand**+Sandstone[1]




[1] Dubrovskii, V.B. et al. " Radiation Damage in Ordinary Concrete," Atomnaya Energiya, October 1967



# Part II- Alkali-Silica Reaction

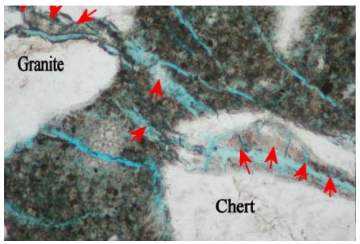
Research results provided: 2014-2017

# Alkali-Silica Reaction in a Nutshell 1/2


www.chaneyenterprises.com

cement alkali

+ *Reacts with*



www.cmc-concrete.com

reactive silica

+ *And absorbs*


www.borealwater.com

water

=

www.fhwa.dot.gov

expensive gel
resulting from the
**alkali-silica reaction**

Thermal activation

(accelerated test 100°F)

Need at least ~70%
of moisture content

# Alkali-Silica Reaction in a Nutshell 2/2

- Expansion of Concrete resulting from the reaction between alkali (generally from cement), reactive aggregate (like amorphous silica) and water absorption
  - Causes expansion, cracking, loss mechanical properties
  - Common mechanisms for dams (age, high moisture content)
  - One recent occurrence at a nuclear power plant in the U.S.
  - DOT study showed more than 70% of the states have experienced ASR related issues of their infrastructures
- Questions:
  - Likelihood of occurrence
  - Significance for Safety-Related Structures (containment bldg, reactor cavity, SFP…)

# Project Strategy – Alkali-Silica Reaction

- Characterize temperature and moisture fields in concrete structures in NPPs at 80 years of operation and beyond.
- Develop a solid assessment of the structural significance of ASR .
  - Investigate the role of stress confinement on the development of ASR in thick reinforced/prestressed structures
  - Investigate the effect of ASR on the residual structural resistance of thick reinforced/prestressed structures
  - Develop innovative means of monitoring
- Establish a collaborative research effort with national/international partners.

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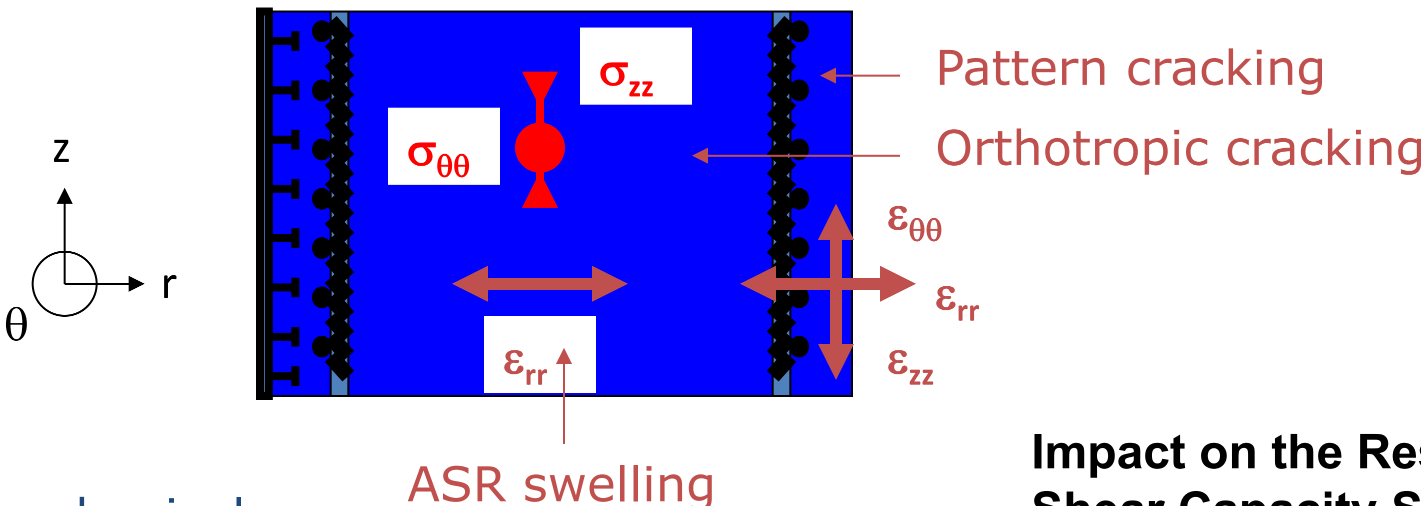
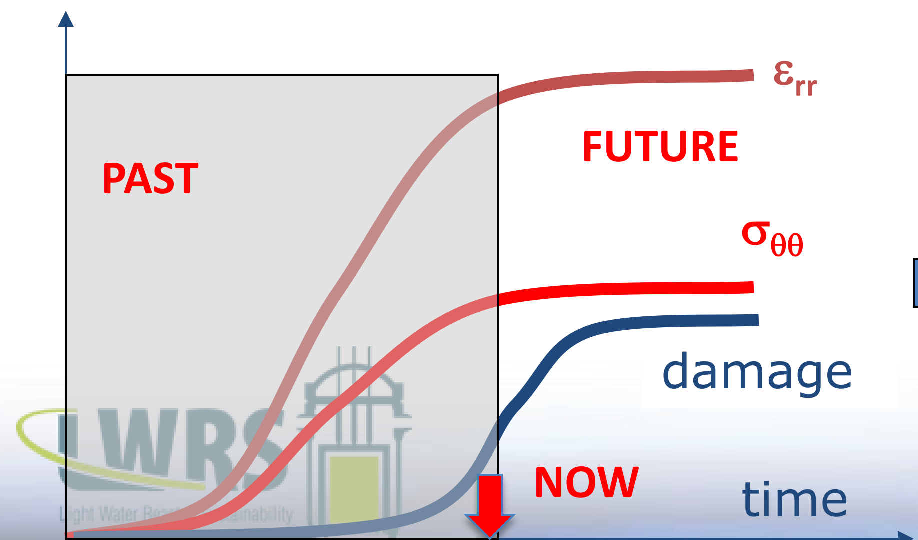
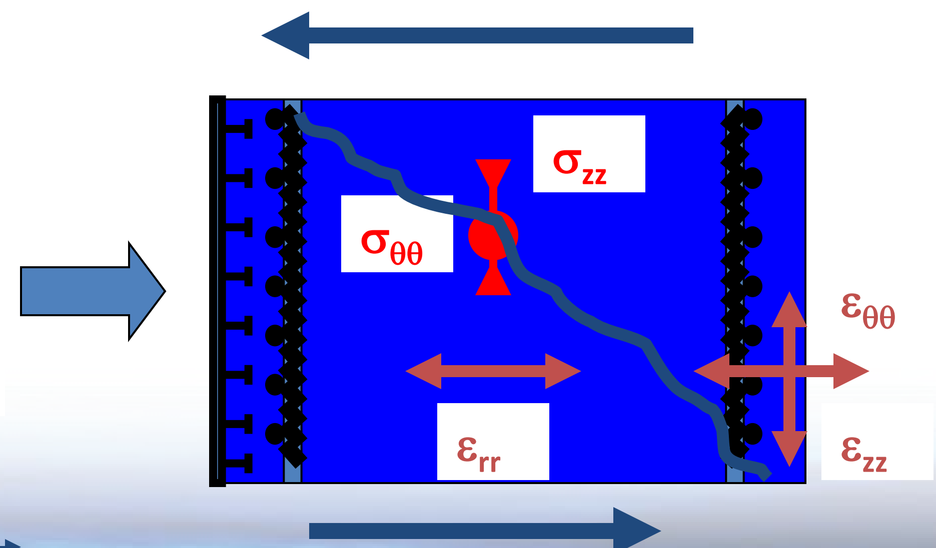
# Structural Significance: Residual Shear Capacity

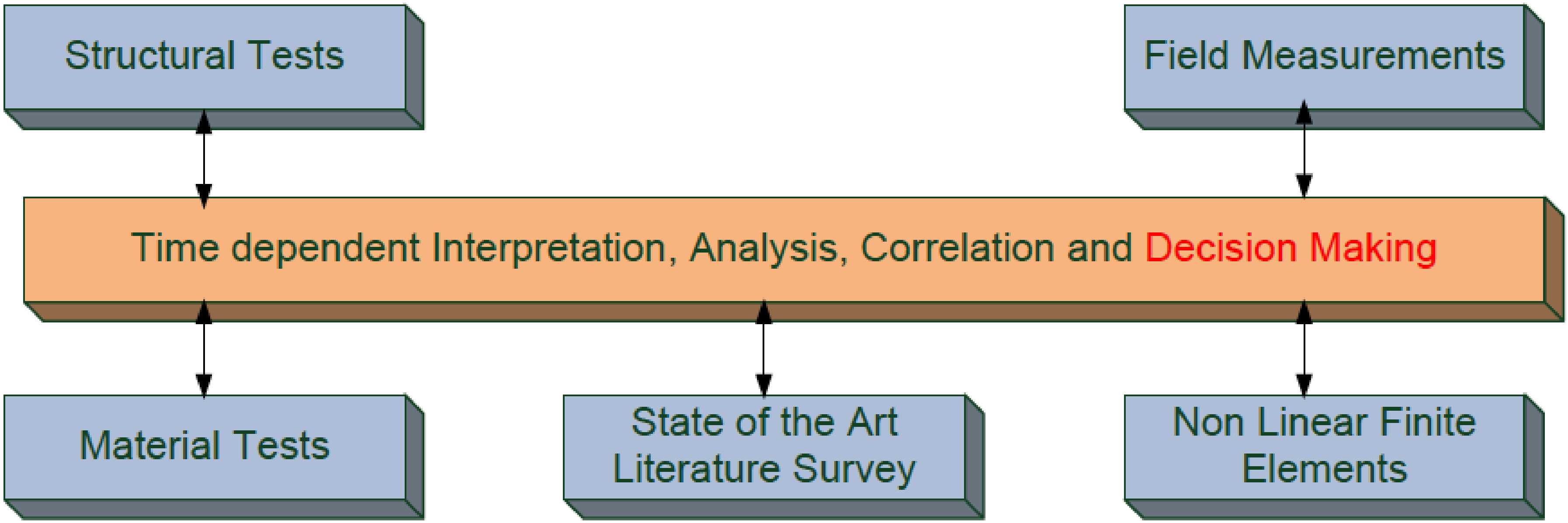



**Impact on the Residual Shear Capacity Safety Margin?**



# Integrated Aging Management




Courtesy of Pr. V. Saouma (U. of Colorado)

# Blending Experimental and Numerical Simulations

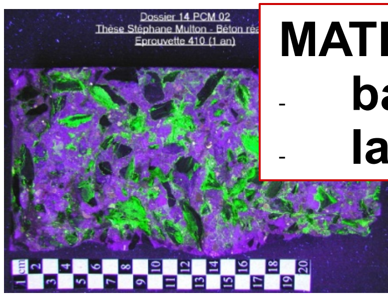
**Objectives**

1. Interpretation of the test results
2. Transposition from the laboratory/simulation to the actual structure
3. Accounting for the uncertainties (unreinforced concrete shear strength exhibits important scattering)

**Pathways**

1. Develop a highly instrumented large-scale mockup including stress confinement
2. Use non linear numerical simulation for understanding the role of anisotropic damage in shear fracture propagation

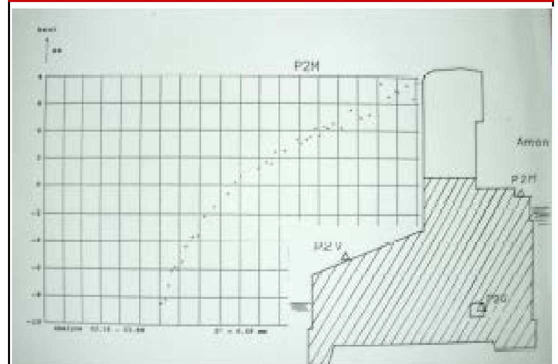
# Simulation of ASR Structural Effects on Dams / EDF experience

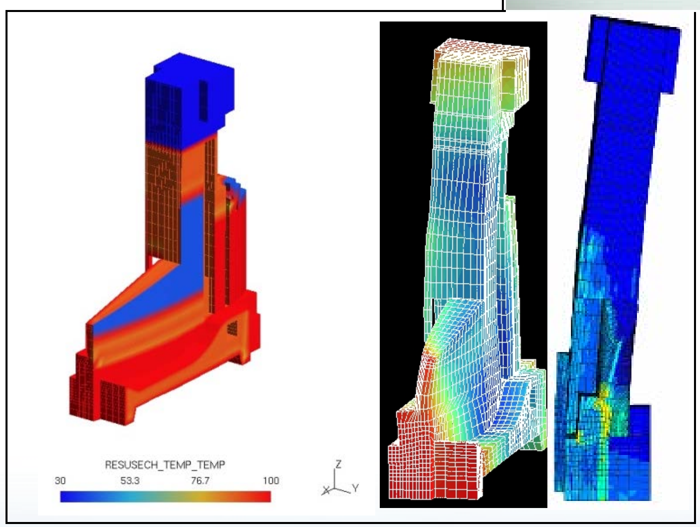




**MATERIALS SCIENCE**
- basic mechanisms
- lab tests

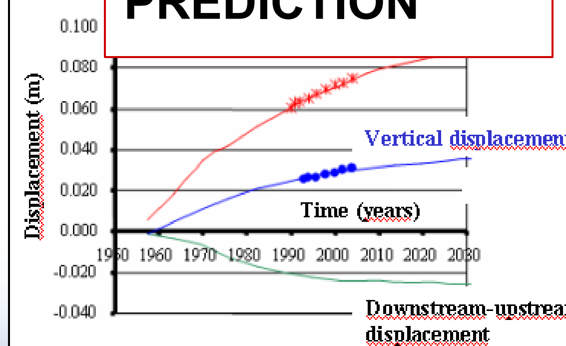
**MONITORING**
- feed-back
- bayesian approach




**COMPUTATION**
**TH-M FEA**

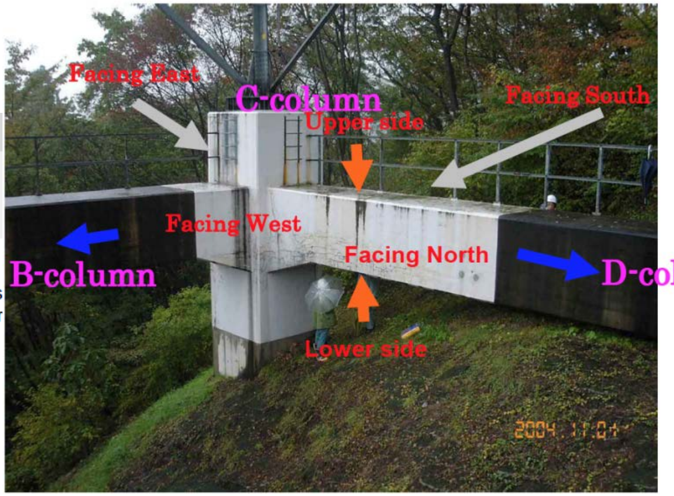
**FEM/MONITORING PREDICTION**

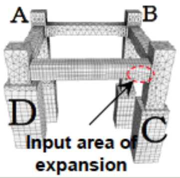


# Simulation of Transmission Towers (TEPCO)

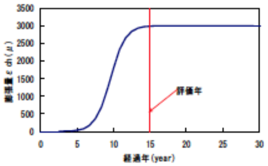


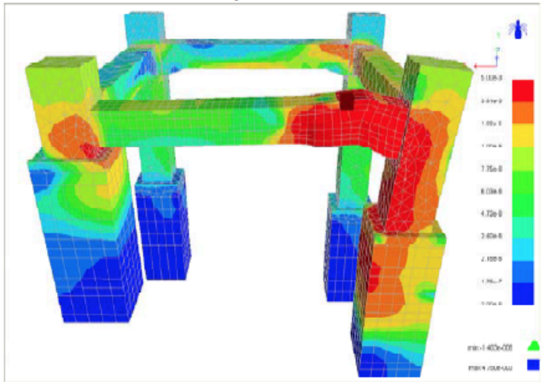
## Finite Element Analysis 4: Entire Frame; AAR in Localized part of C-D



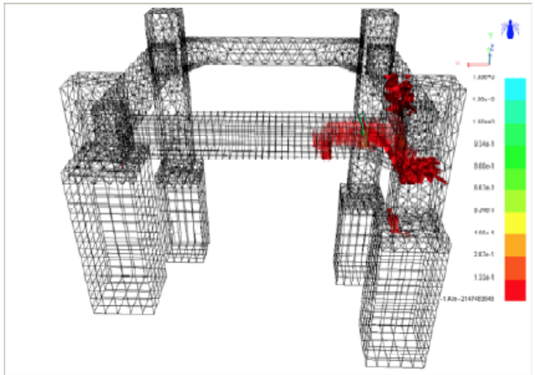




Analysis in 15 years
completion of constr



Maximum principal stress



Crack distribution

- Compute cracking is close to observed one.
- Little cracking in Column C.

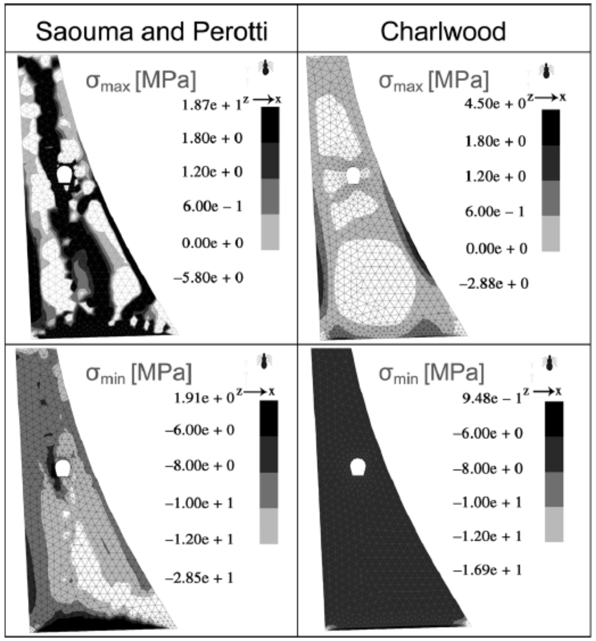


Courtesy of

# Computational Simulation

**Deterministic Modeling**

- Orthotropic damage modeling of ASR damage
  [Capra & Sellier, 2003], [Saouma & Perotti, 2006]
- Propagation of shear fracture in an orthotropic damaged materials




**Structural Reliability Analysis**

[Ellingwood & Mori, 1997], [Enright & Frangopol, 1998]

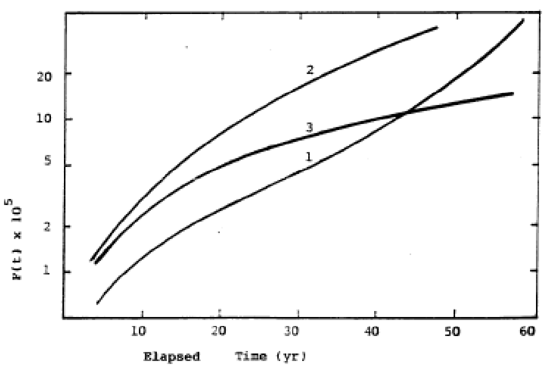



Fig. 2. Failure probability of concrete slab.

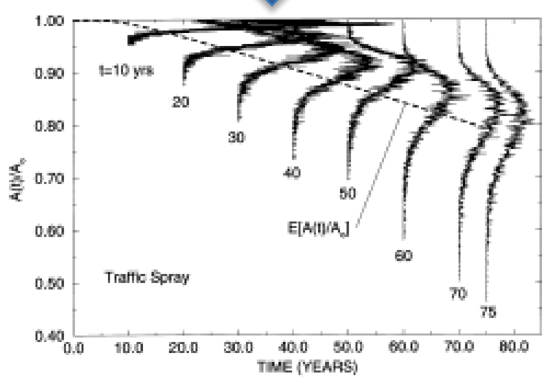



*Figure 13* Distribution of normalized time-variant area of bending reinforcement

# Testing Mockups Plans

**Scope**

- ASR subjected specimen block:
  - Dimension relevant for nuclear 'thick' concrete structures
  - Relevant reinforcement ratio and placement
  - Relevant boundary condition (temperature, moisture transport, mechanical confinement)
- Acceleration of ASR for obtaining results in a decent time frame
  - Concrete mix design
  - Temperature, moisture ingress.

**Objective**

- Evolution of the expansion in all directions (monitoring displacement, moisture content, temperature…)
- Evolution of the damage on the surface and in the bulk (NDE)
- Evolution of the mechanical properties (destructive testing, standard and non standard)
- Residual structural shear capacity
- Residual expansion tests…

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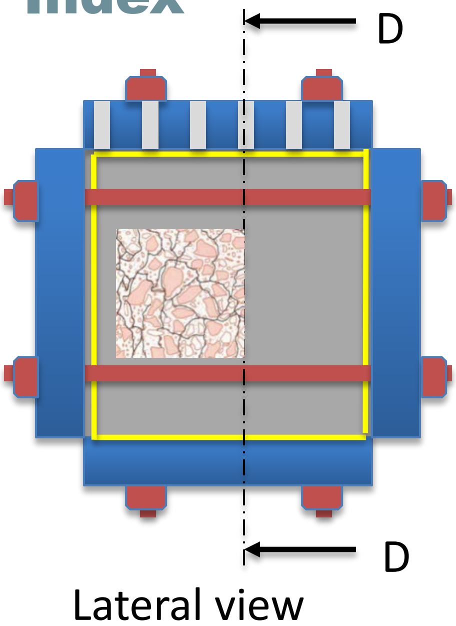
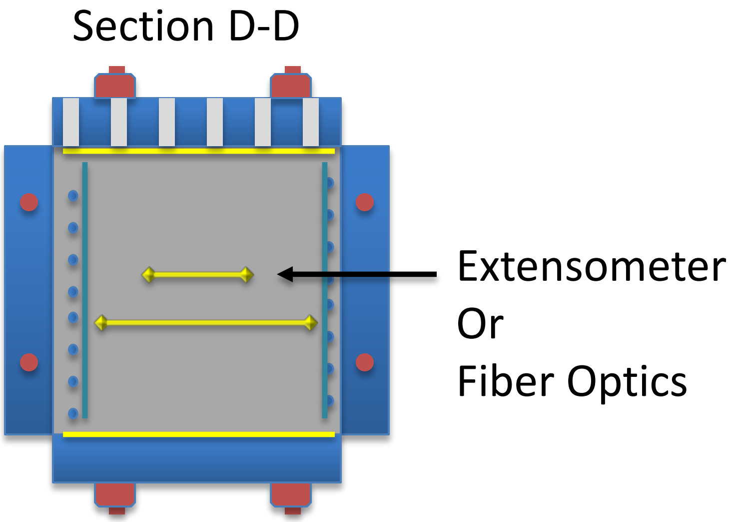
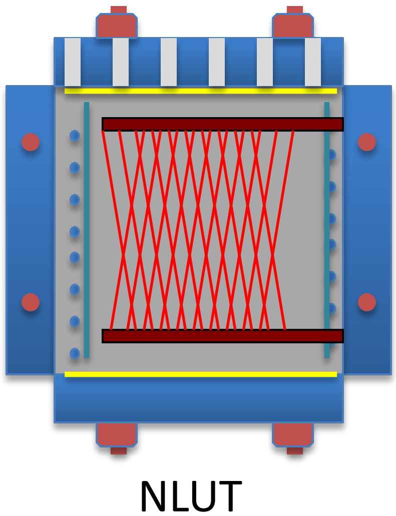
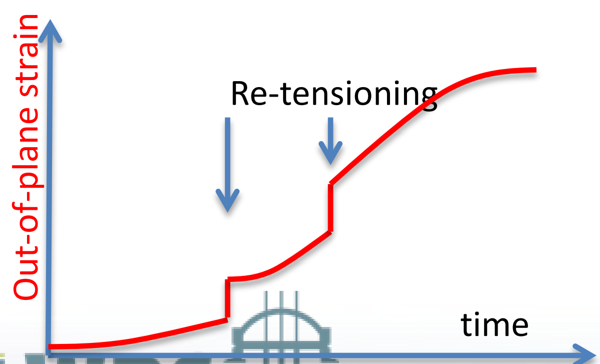
# A First Preliminary/Conceptual Design

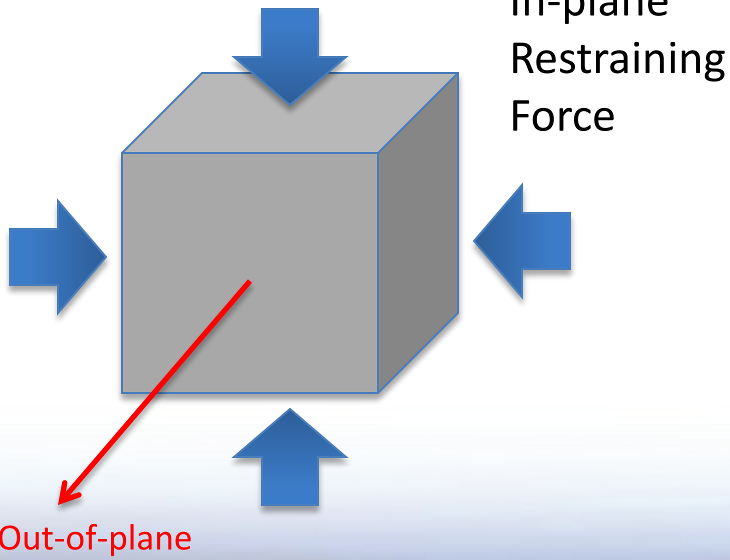
## Monitoring the 'Out-of-Plane' Deformation and the Cracking Index



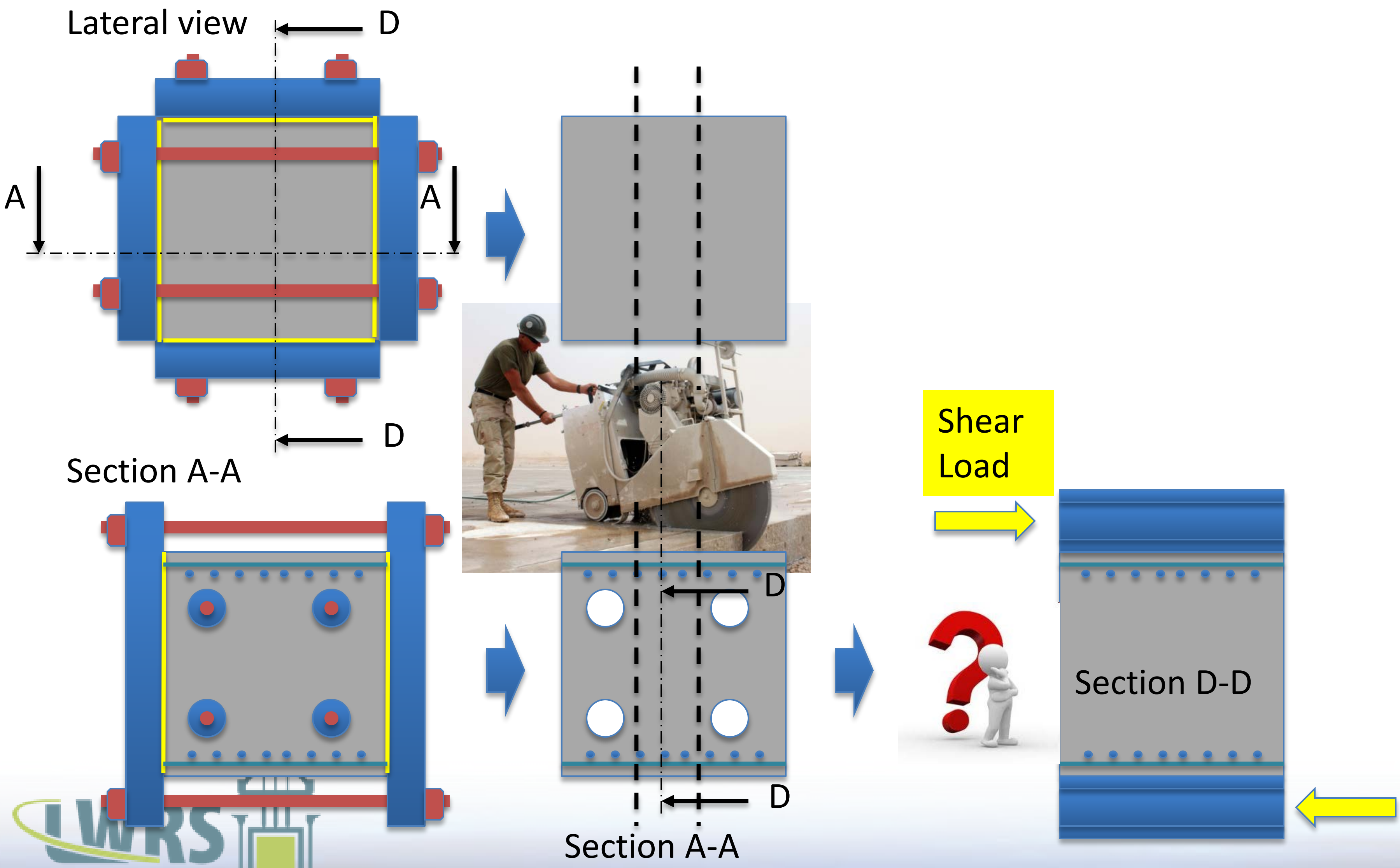



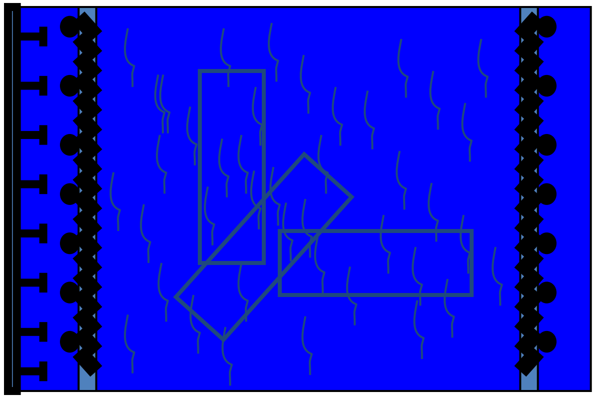



# Post-ASR Structural Testing

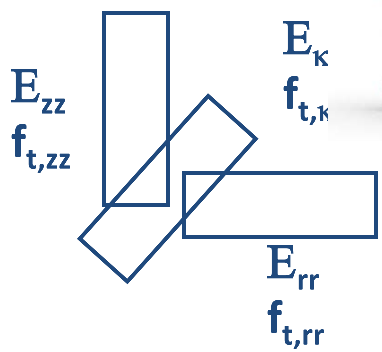


# NDE Development

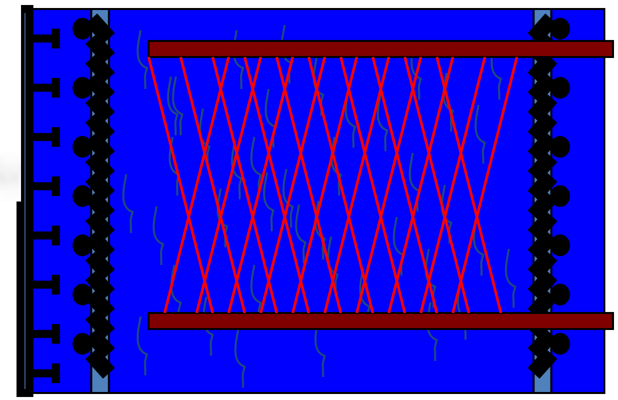
1. Evaluation of the Damage



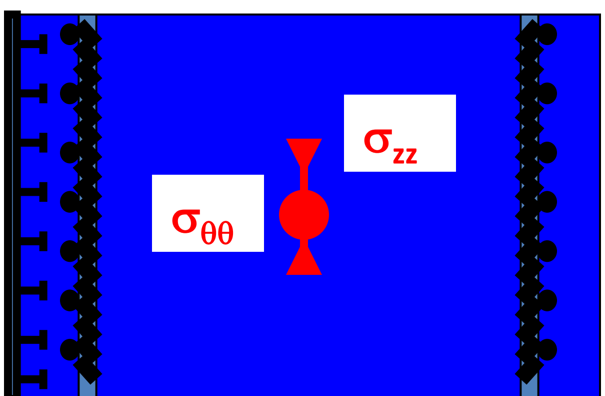
'virtual coring'



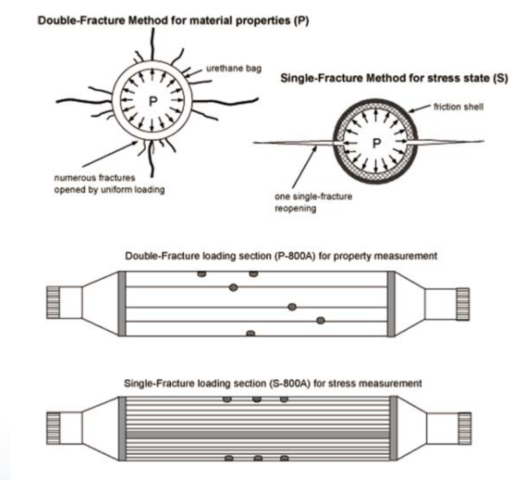

deep cross hole strategy, NLUT



2. Evaluation of the Internal Stresses




Pressure probe



# Summary of LWRS On-going ASR Program

- Investigate the residual shear capacity of massive concrete structures using numerical simulation
- Design/fabrication of a large test ASR mock-up
  - Confinement system (replication of actual condition in service)
  - Monitoring
  - Study of the damage evolution (including coring in different directions)
- Organization of a Workshop on ASR simulation

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# Quick Note on Concrete Creep and Creep Fracture

Research efforts starting in 2015

# Concrete Creep/Creep-fracture 1/2

- Mechanisms in a nutshell
  - Sustained loading (prestressing)/moisture content driven mechanism
  - At constant internal relative humidity, creep amplitude/kinetics function of the initial w/c and aggregate elasticity primarily
  - Moisture gradient results in stress gradient in thick structures
- Structural Significance for Prestressed Concrete Containment
  - Possible delamination (similar to CR3)
  - Possible delayed local fracture in complex sustained 3D-stress state
  - Concrete fracture interaction (accidental loading)
    - Fracture can occur at a sustained loading above approx. 70% of the strength
    - Creep-induced micro-cracking interaction with fracture

# Concrete Creep/Creep-fracture 2/2

- Existing Knowledge
  - Concrete creep database (Northwestern/RILEM).
  - Important recent progress in the understanding of the fundamental creep mechanisms
  - literature on creep/creep fracture
  - Large-scale mockups
    - BARCOM 1/4th scale mockup (India) Early 2000's
    - EDF 1/4th scale mockup (France) 2014-2024
    - Several structural test on reinforced/prestressed containments (Sizewell B 1989, Civaux , NRC 1987, CTL/EPRI tests, Sandia…)
- Knowledge Gaps (preliminary list)
  - Creep-fracture interaction after principal stress rotation
  - Structural significance on concrete containment
  - Monitoring?

# Thank You for Your Attention

# Discussion?

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