USC Nuclear Engineering Education and Research

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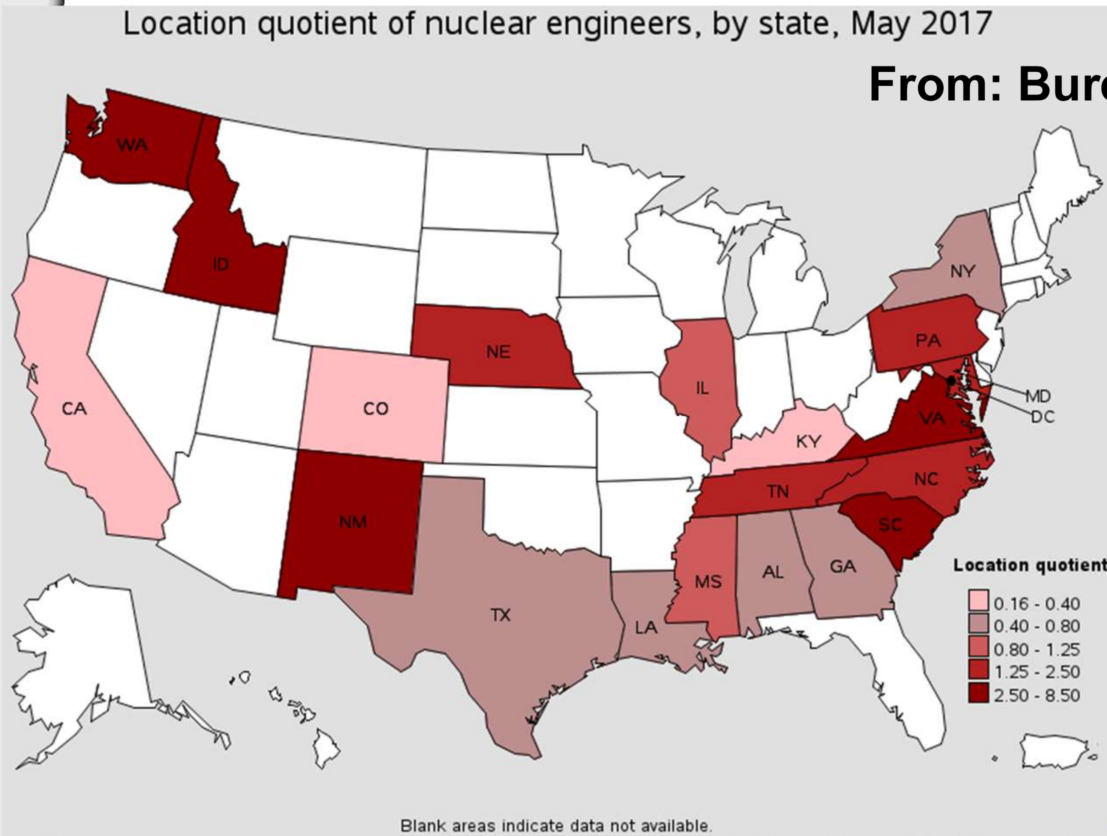
USC Nuclear Engineering Milestones

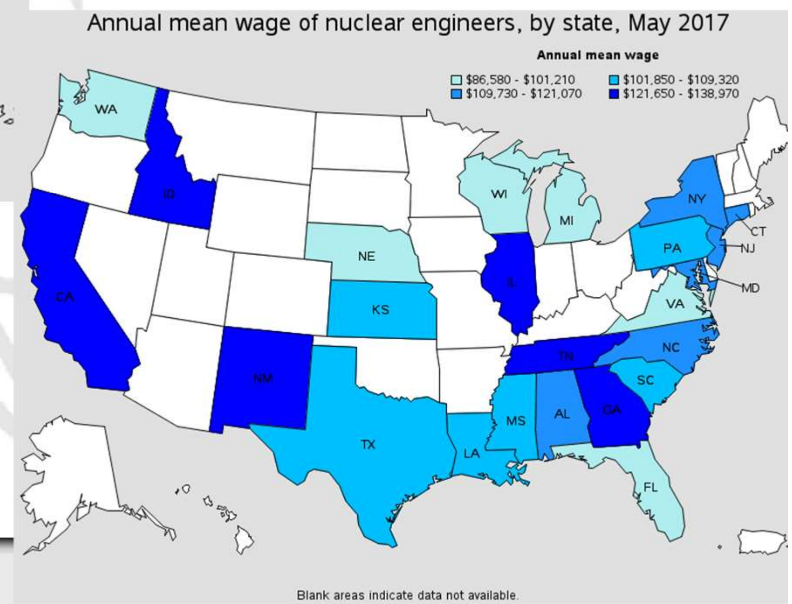
- USC began graduate nuclear engineering program (MS, PhD) in Fall 2003 in Mechanical Engineering Department
  - On campus and distance learning
- Fall 2004 hired two new tenure track faculty in addition to Mechanical Engineering faculty and adjunct faculty.
- May 2005, graduated first MS students
- December 2007, graduated first PhD
- Began an undergraduate minor in Fall 2008
- Center of Economic Excellence in Nuclear Science and Engineering awarded in 2008 by SC Research Centers of Economic Excellence
  - **Endowed Chair, Dr. Dan Cacuci, hired Jan. 2012**
- Additional tenure track faculty began in Fall 2009
- Center of Economic Excellence in Nuclear Science Strategies awarded in 2009 by SC Research Centers of Economic Excellence
  - **Endowed Chair, Dr. Ted Besmann, hired Nov. 2014**
- New Junior Faculty hired Fall 2015
- More than 100 MS and PhD graduates – Summer 2017

South Carolina - Nuclear Engineering

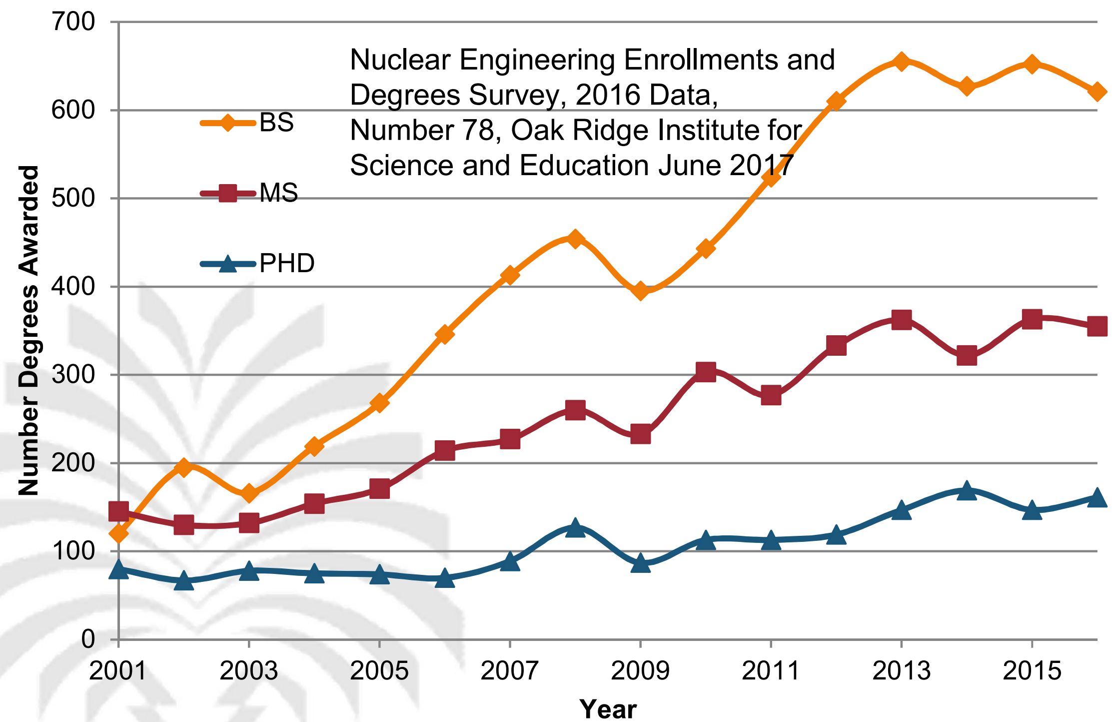


From: Bureau of Labor and Statistics

Location quotient (LQ) is a valuable way of quantifying how concentrated a particular industry, cluster, occupation, or demographic group is in a region as compared to the nation.

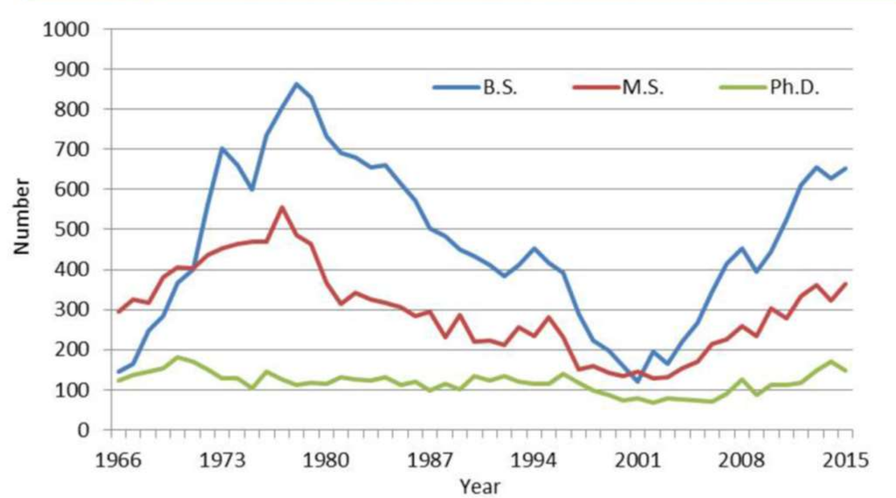


Nuclear Engineering Enrollment and Degrees Awarded



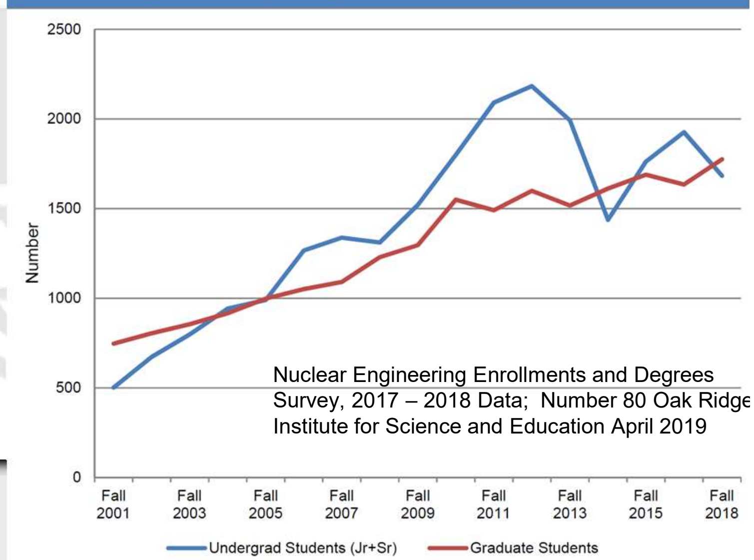
Nuclear Engineering Enrollments & Degrees Survey Data 50-Year Trend Assessment, 1966-2015, March 2017

FIGURE 2 | Nuclear Engineering Degrees, by Degree Level, 1966-2015



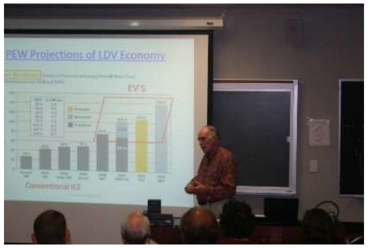
Source: Oak Ridge Institute for Science and Education.

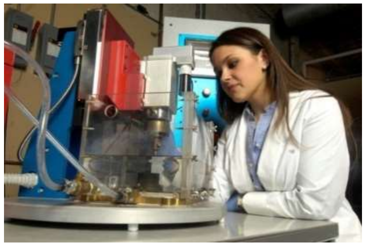
FIGURE 1 | Nuclear Engineering Enrollment Trends, Fall 2001 – Fall 2018

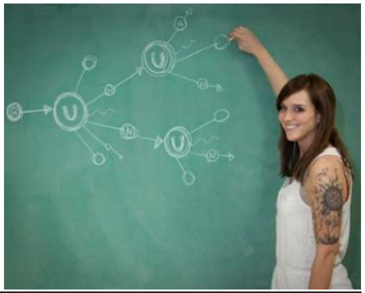


Undergraduate Minor and Graduate Nuclear Engineering Degrees and Requirements

- Undergraduate Minor – 18 credits
  - 6 nuclear engineering courses (4 core courses)
  - Able to utilize 4 undergraduate electives
- Accelerated BS/MS
  - Dual count up to 4 elective classes toward MS degree
  - Obtain MS degree in 1 additional year beyond BS
  - Thesis and Non-Thesis Options
- MS (Master's of Science) - 30 credits total
  - 6 credits from thesis research
  - 24 credits from course work (includes core courses)
- ME (Master of Engineering) - 30 credits from course work
  - includes core courses
- PhD requires additional 30 credits beyond MS/ME (60 credits beyond BS)
  - 12 credits from dissertation research
  - 18 credits from course work







Nuclear Engineering Undergraduate Minor

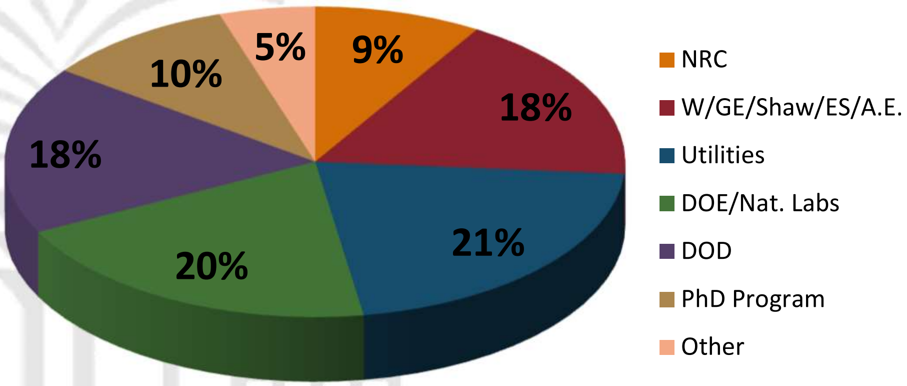
- **A strong emphasis on nuclear science and engineering instruction supporting energy related topics**
- **Required/Core Classes**
  - EMCH 552: Introduction to Nuclear Engineering (Fall)
  - EMCH 553: Nuclear Fuel Cycles (Spring)
  - EMCH 557: Radiation Shielding (Fall)
  - EMCH 558: Nuclear Systems (Spring)
- **Two electives (below regularly offered):**
  - EMCH 556 Introduction to Risk Assessment and Reactor Safety (Fall)
  - EMCH 573 Introduction to Nuclear Materials (Fall)
  - EMCH 550 Introduction to Nuclear Safeguards (Summer)
  - EMCH 753 - Chemical Thermodynamic Calculations and Modeling with Applications (Spring)
  - EMCH 754 Thermal Hydraulic Design of Nuclear Reactors (Fall or Spring)
  - EMCH 770 Predictive Modeling: combining experiments with computations (Spring)
  - EMCH 460* Special Problems (related to NE)
    *requires faculty approval and mentorship
- **Additional elective options outside the College:**
  - PHYS 307: Intro Modern Physics
  - PHYS 511: Nuclear Physics
- **Pre-requisites:**
  - CHEM 111, PHYS 211, MATH 241, MATH 242

Nuclear Engineering Graduate Courses

- **Core Courses Required (4)**
  - EMCH 552 Introduction to Nuclear Engineering (Fall)
  - EMCH 553 Nuclear Fuel Cycles (Spring)
  - EMCH 758 Nuclear Systems (Spring)
  - EMCH 757 Radiation Shielding (Fall)
- **Elective Courses (at least 3 for MS or at least 5 for ME)**
  - EMCH 756 Safety Analysis for Engineering Systems (Fall)
  - EMCH 573 Introduction to Nuclear Materials (Fall)
  - EMCH 753 - Chemical Thermodynamic Calculations and Modeling with Applications (Spring)
  - EMCH 754 Thermal Hydraulic Design of Nuclear Reactors (Fall)
  - EMCH 550 Introduction to Nuclear Safeguards (Summer)
  - EMCH 755 Advanced Nuclear Engineering (Spring)
  - EMCH 770 Predictive Modeling: combining experiments with computations (Spring)
- **Engineering Elective (up to 1)**
  - Any NE elective (from above)
  - Any Engineering course at 500 level or higher.
    - i.e. EMCH 508 Finite Element
  - GEOL 650: Microscopy & Microanalysis

USC Nuclear Engineering Programs – Statistics

- USC NE program includes a strong **distance learning** component to support professionals seeking an advanced degree. Currently professionals at:
  - Utilities (SC, GA, NC), SRNL/SRS, LANL, NRC, U.S. Navy Nuclear Power School (Goose Creek, SC), Army, AFTAC, Others; formerly NASA, KAPL
- **115 graduates** have assumed variety of positions in the nuclear industry (graduates: 57 fulltime/58 part-time) since first graduates in Fall 2005:
  - Utilities, NRC, SRNL, ORNL, A/E (mostly in SC), Vendors, Fed. Gov., Academia
  - PhD=8, MS=39, ME=68
- **Enrolled (active) – 35**
  - PhD=13, MS=8, ME=14
- Undergraduates – **Minor in NE**



Three students placed in academia:
- **Military Academy, West Point (x2)**
- **Virginia Commonwealth University**

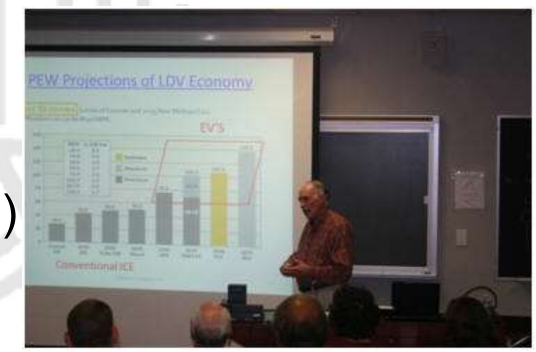
(*)Part-time students only counted if they took a new position in their company or changed companies upon graduation (% of total=80)
(**) students may pursue the minor and declare in their final semester

Nuclear Engineering Faculty

- Tenure Track (Teaching and Research)
  - Ted Besmann (endowed chair)
  - Dan Cacuci (endowed chair)
  - Jamil Khan
  - Travis Knight
  - Anthony Scopatz
- Adjunct and Visiting (Teaching and Research)
  - Larry Hamm (SRNL)
  - Elwyn Roberts (retired Westinghouse)
  - Val Loiselle (retired)
- Affiliated (Research, active, current)
  - Xinyu Huang (ATF cladding tests)
  - Lucy Yu (NDE used fuel canisters, gas detection in piping)
  - Paul Ziehl (concrete degradation, NDE)
- Post-Doctoral Staff
  - 11 currently



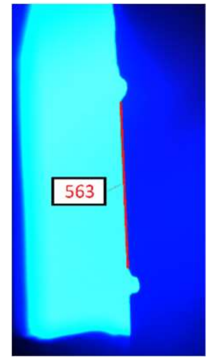


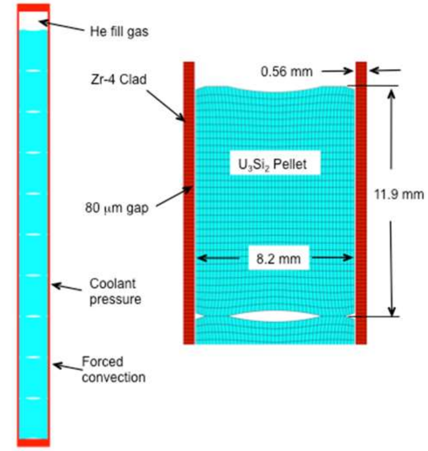


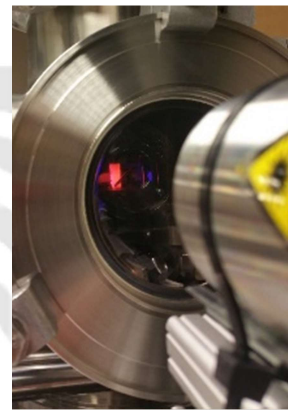
Research Areas - Examples

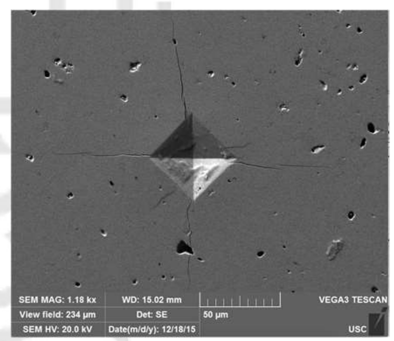
Uranium Silicide – Accident Tolerant Fuel

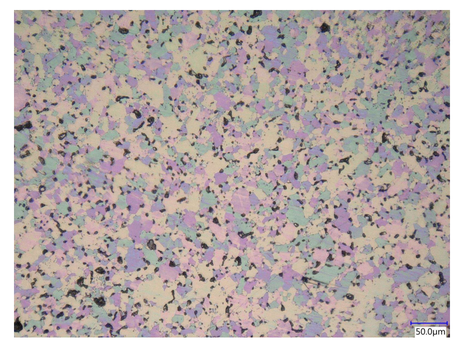
- U_3Si_2 is one of the advanced fuels being considered as an accident tolerant fuel (ATF)
- Changes to the fuel and cladding are being considered.
- Compression creep testing.
- Modeling in BISON, fuel performance code.
- Sponsor: DOE-NEUP





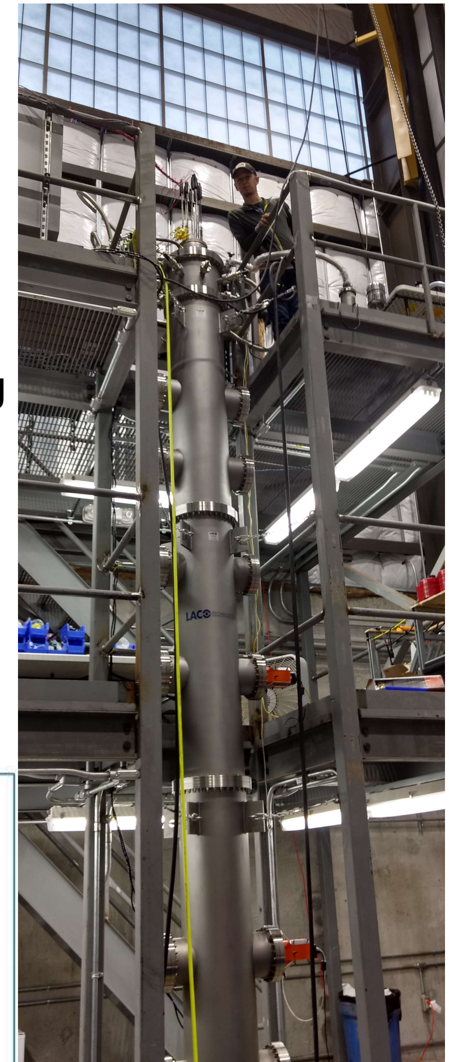


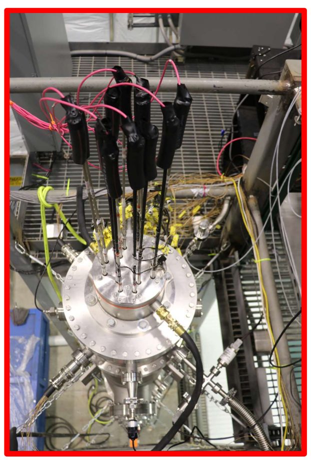


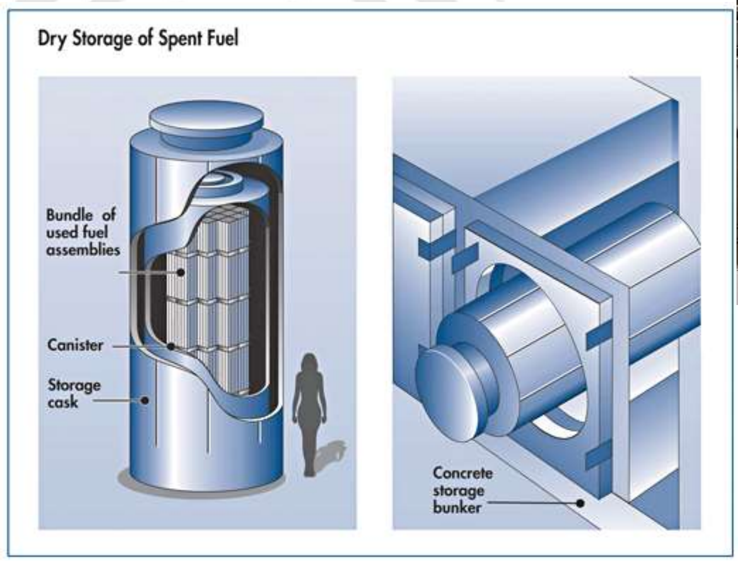


Used Fuel Drying Research

- DOE NEUP - Integrated Research Project (IRP)
- Collaboration: USC, UF, SCSU, Areva (Framatome/Orano)
- Motivation and Goals
  - Quantify water remaining in dry cask after typical industry drying operation
  - Science based understanding of the cask drying process
  - Evaluate range of conditions, features likely to encounter for storage of used fuel
  - Develop modeling tools for utilities, vendors, regulators







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General Atomics Center for Development of Transformational Nuclear Technologies

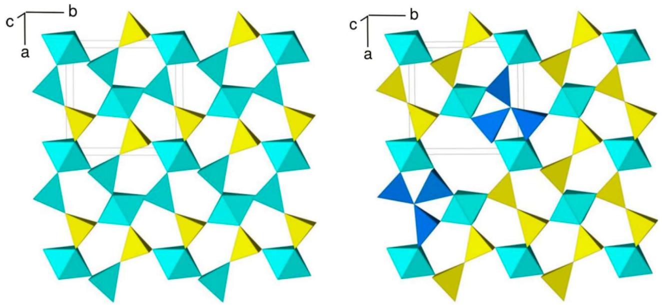
Theodore (Ted) M. Besmann Ph.D.
SmartState Endowed Chair
BESMANN@cec.sc.edu

Research Interests

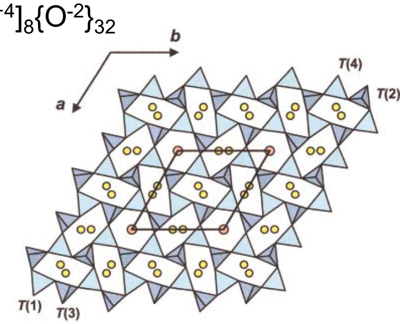
- **Preparation, measurements and analysis of phase formation and thermochemistry of energy materials**
- **First principles modeling and experimental measurement of phase and thermodynamic behavior of energy materials**
- **Predictive thermochemical models for energy materials development and behavior**
- **Creation of computational capability for inclusion of thermochemistry in complex process codes**
- **Energy/electricity policy issues related to sustainability**

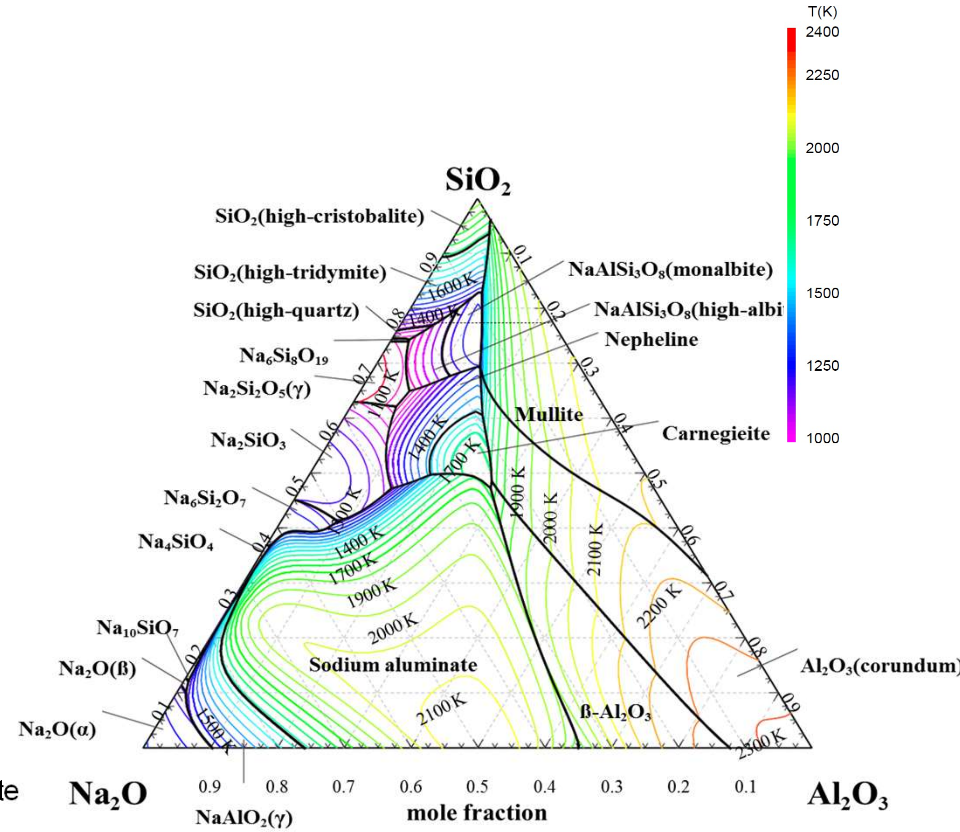
Modeling materials for fuel cells, hydrogen storage, nuclear fuels & wastes…

- Mullite
  - $Al_2(Al_{2+2x}Si_{2-2x})O_{10-x}$, $0 \le x \le 1$
  - Solubility from Al_2SiO_5 to Al_2O_3
  - Substitution of Al^{+3} for Si^{+4}
  - Charge deficiency compensated by formation of oxygen vacancy
  - $(Al^{+3})_2\,[Al^{+3},Si^{+4}]_1\,\{O^{-2},Va\}_5$



- Nepheline
  - Idealized composition $Na_3K(AlSiO_4)_4$
  - $Na_{2-x}Va_xNa_6Al_{8-x}Si_{8+x}O_{32}$, $0 \le x \le 2$
  - Excess SiO_2 results in Si^{+4} replacing Al^{+3}
  - Charge compensated by vacancy formation on cation site
  - $((Na\text{-}Al)^{+4},(Va\text{-}Si)^{+4})_8[Si^{+4}]_8\{O^{-2}\}_{32}$





Liquidus projection of the NAS system

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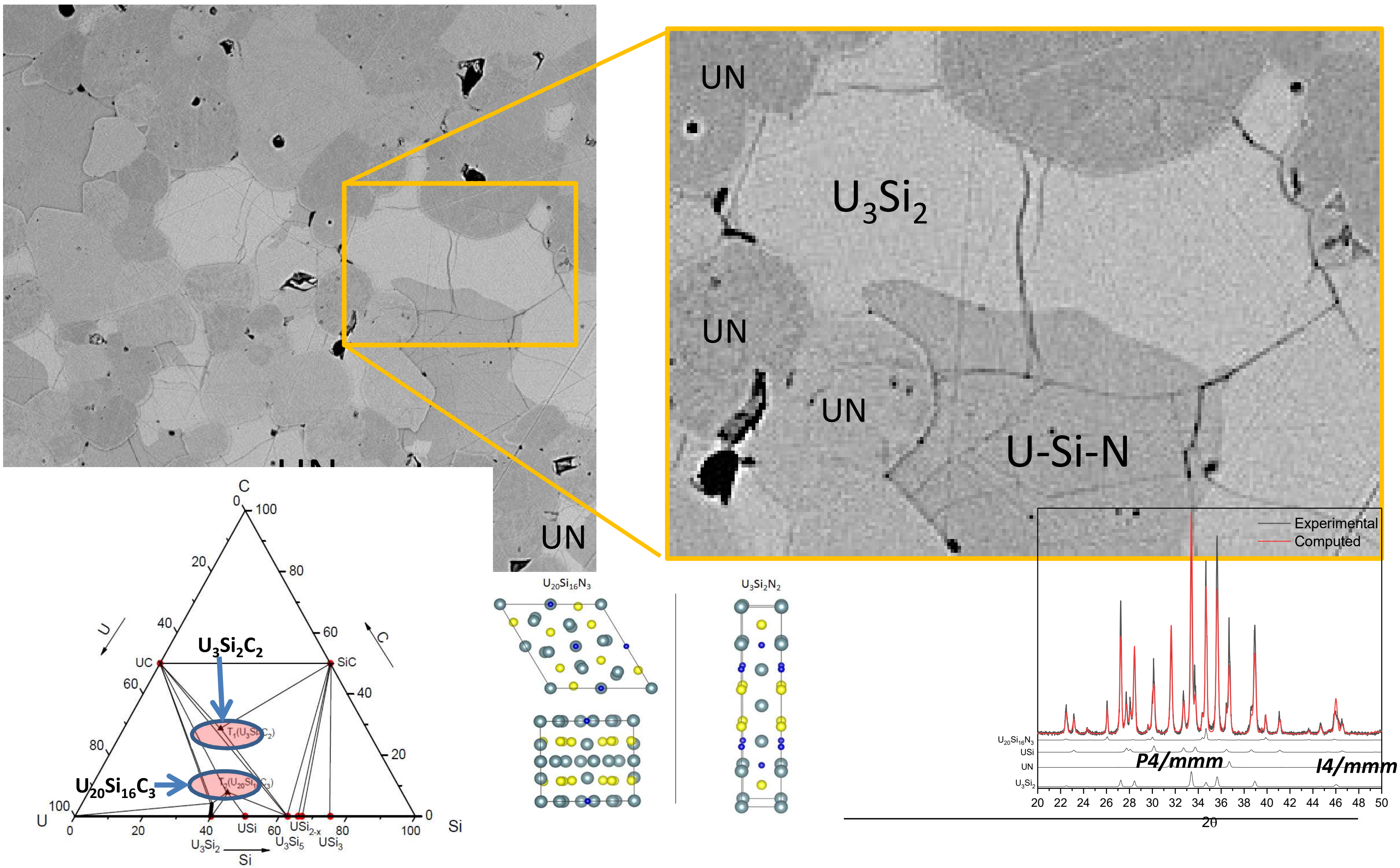
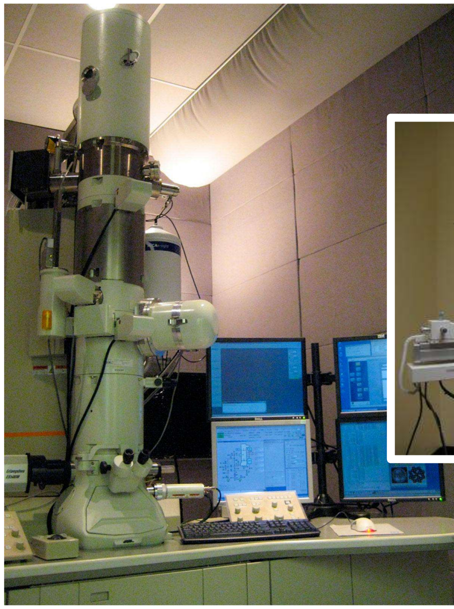
Experimental and Computational Exploration of Multi-Element Systems: Identifying new U-Si-N Phase

Analysis with SEM, neutron and x-ray diffraction, and computational models



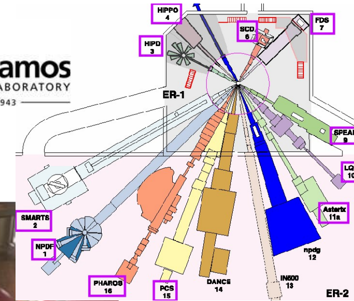
Facilities

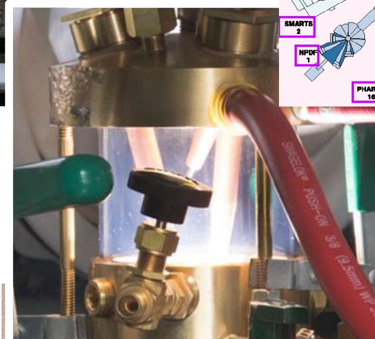
USC
Electron Microscopy Center



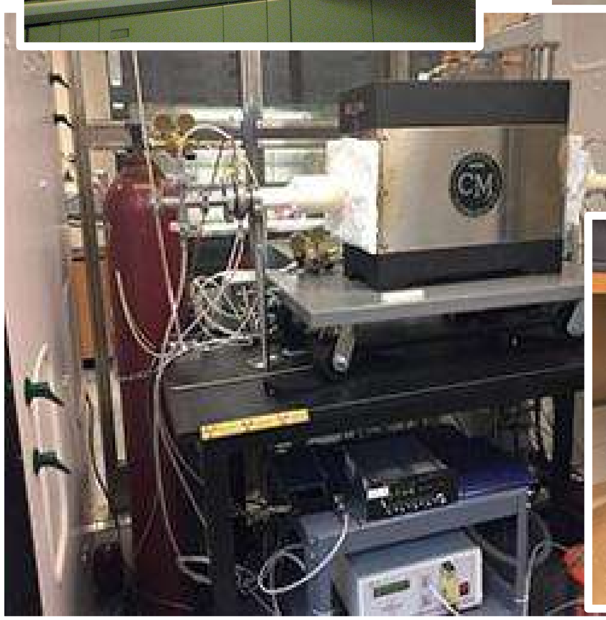
Neutron Diffraction

Los Alamos
NATIONAL LABORATORY
EST.1943





USC X-Ray Diffraction Facility



Currently Funded Project Areas

- First principles and thermochemical modeling of complex oxide phases, salt inclusion materials, metal-organic frameworks
- Experimental preparation and analysis of silicide-nitride materials (nuclear fuels)
  - Arc-melting
  - X-ray and neutron diffraction
  - Electron microscopy
  - Thermal analysis – DSC, TGA
  - First principles and thermochemical modeling of novel systems
- Thermochemical measurements and modeling of molten salts
  - First principles and thermochemical modeling
  - Preparation of complex fluoride and chloride salts
  - Thermal analysis – DSC/TGA
  - High temperature X-ray diffraction
- Hydrogen storage materials
  - Thermochemical modeling of complex compositions
  - Machine learning applied to experimental and computed systems

Remote Condition Assessment for Complex Structural Systems

concordmonitor.com

daily kos

Tampabay.com

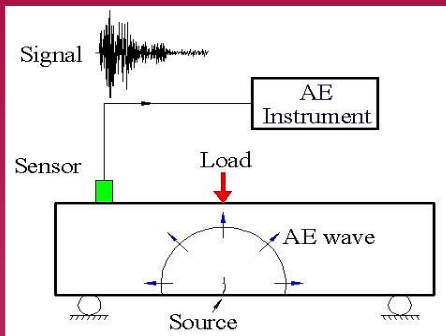
Up and atom
June 11, 2019

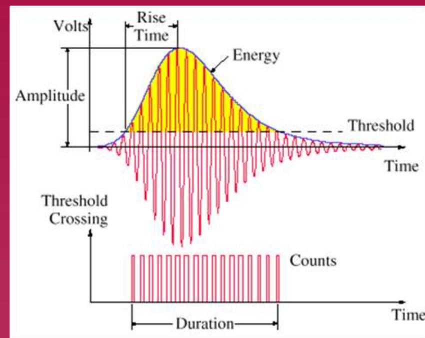
Paul Ziehl
U. South Carolina

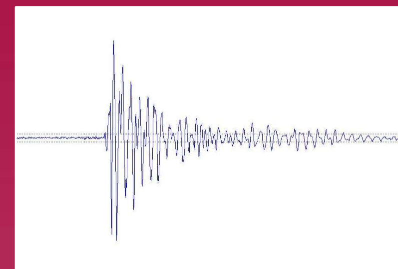
UNIVERSITY OF SOUTH CAROLINA

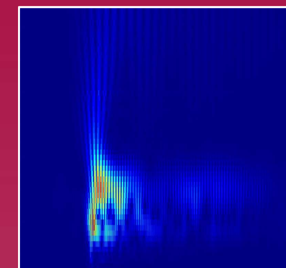
Stress Wave Based Evaluation (Acoustic Emission)

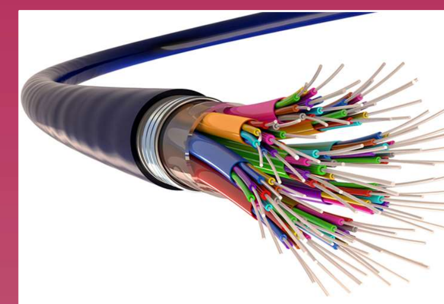
PI: Paul Ziehl



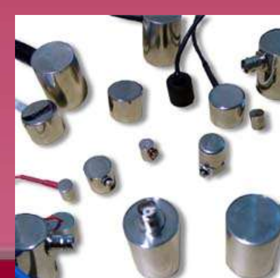








Frequency range ~ 10 to 500 kHz
Sampling frequency ~ 500 MSPS
Data rate ~ 1 TB per hour



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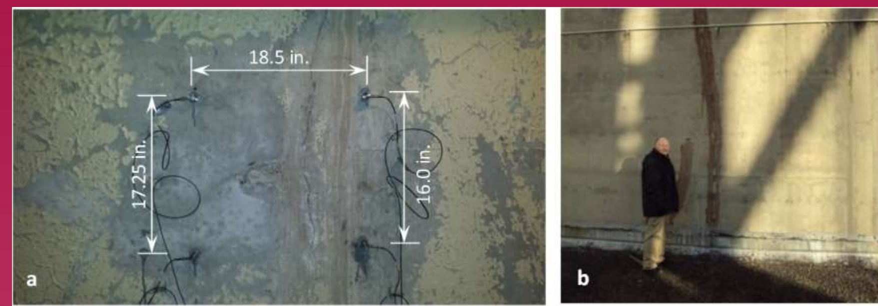
In Situ Decommissioning Sensor Network – Acoustic Emission Sensing System Demonstration at the 105-C Reactor Facility...

PI: Paul Ziehl

Reactor building 105-C at the Savannah River Site.

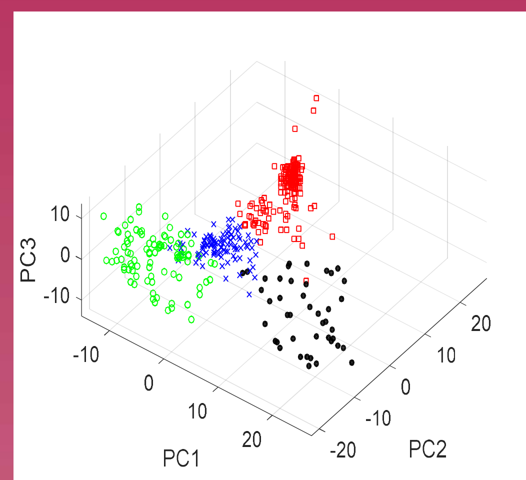


Photographs at +48 level: (a) sensor grid from interior, and (b) vertical crack from exterior.

Photographs of the crane maintenance area: (a) main sensor grid, (b) close-up of sensor on side of column,

EPRI: Nondestructive Evaluation: Investigation of Acoustic Emission Technologies for Monitoring Inaccessible Regions of Dry Fuel Storage Systems (3002007816)

PI: Paul Ziehl



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The Comprehensive Adjoint Sensitivity Analysis Methodology:

Computation of Second-Order Response Sensitivities to Model and Boundary Parameters

Dan G. Cacuci

LANL Review Meeting

Motivation for Computing Higher-Order Sensitivities using C-ASAM

- Variations around nominal values in a physical system can be quantified only if 1st-order response sensitivities (functional derivatives) with respect to model parameters are available;

- Maxima, minima, and distributional asymmetries ("skewness") can be quantified only if 2nd-order response sensitivities are available;

- Reliable quantification of Non-Gaussian features of response distribution requires the computation of 3rd- and 4th-order response sensitivities, to enable incorporation of triple and quadruple parameter correlations;

- Predictive modeling beyond currently achievable accuracy requires computation of 2nd, 3rd- and 4th-order response sensitivities, to enable incorporation of triple and quadruple parameter correlations;

- But…the number of large-scale computations needed by current methods for computing response sensitivities increases exponentially with the order of sensitivities, which I define as the "Curse of Dimensionality in Predictive Modeling" (including "model calibration & validation")…paralleling R.E. Bellman's expression for dynamic optimization;
- C-ASAM aims at overcoming the "Curse of Dimensionality in Predictive Modeling."

Conventional Methods are Doomed by the "Curse of Dimensionality"

- Conventional methods (statistical, finite-differences)…
  - Cannot compute sensitivities exactly;
  - For a model with *N* parameters, require the following number of large-scale computations per response :

1. At least N large-scale computations to obtain approximate 1st-order sensitivities;

2. At least N(N+1)/2 large-scale forward computations to obtain approximate 2nd-order sensitivities;

3. At least N(N+1)(N+2)/6 large-scale forward computations, to obtain approximate 3rd-order sensitivities;

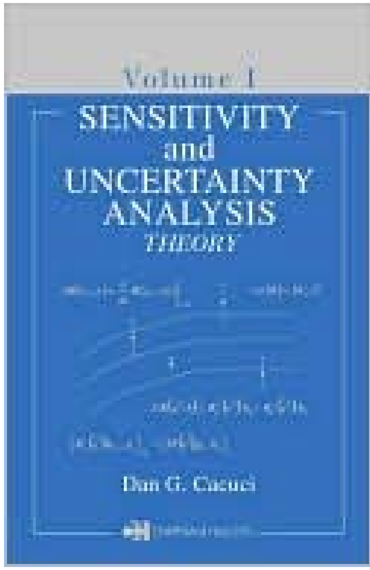
….

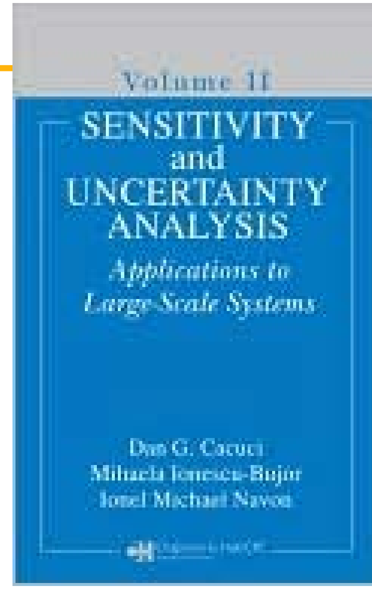
Adjoint Sensitivity Analysis Methodology (ASAM)

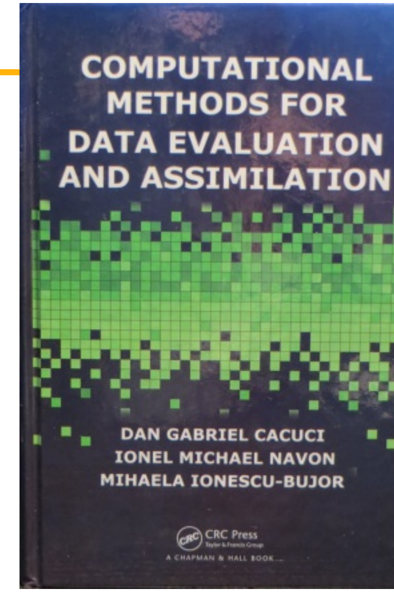
- **E.P. Wigner (1945):** Perturbation method using the adjoint neutron transport equation (linear problem) to compute exactly 1st-order sensitivities of reactor multiplication factor and reaction rates with *N* parameters, using 1 adjoint computation per scalar-valued response.

- **D. G. Cacuci (NSE 1980, JMP 1981): Conceived ASAM for nonlinear systems with operator-valued responses:** 1 large-scale adjoint computation for obtaining exactly 1st-order sensitivities.

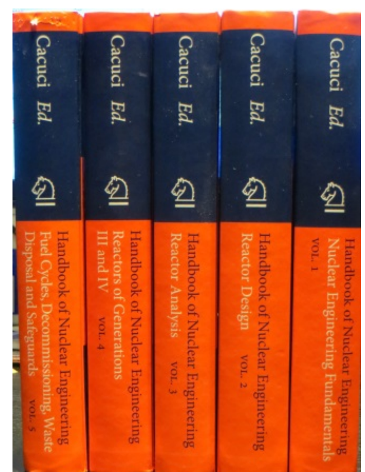
- **D. G. Cacuci (JCP 2015, NSE 2016, CRC Press/T&F 2018): Conceived 2nd-ASAM for nonlinear systems with operator-valued responses:** at most N large-scale adjoint computations for obtaining exactly N(N+1)/2 2nd-order sensitivities.







First-Order Sensitivity Analysis , Uncertainty Quantification, and Data Evaluation and Assimilation (Forward & Adjoint Methods)



Handbook of Nuclear Engineering

Ongoing Work

- The planned implementation of Cacuci's unified framework for sensitivity analysis of multiplying systems into PARTISN, and subsequent extension to computation of 2nd-order sensitivities, is currently "on hold" pending resolution of some LANL-internal considerations;
- Application of C-ASAM to transport of uncollided particles through a two-layered slab benchmark admitting analytical solution (sensitivities to internal & external boundaries).
- Application to a particle diffusion benchmark problem, where the boundary (extrapolation distance) is affected by uncertainties in both material properties (model parameters) and uncertain dimensions (boundary parameter).
- Application to uncollided particle transport in spherically symmetric geometry; a new (yet unpublished) exact & explicit solution indicates that the flux on the sphere's surface w/vacuum is continuous but non-differentiable with respect to the radial coordinate (previously unknown issue ?), as will be discussed in the following.
- Continuation of C-ASAM formalism towards deriving the explicit formulas for computing 3rd- and 4th-order response sensitivities, using 3rd- and 4th-level Adjoint Sensitivity Systems.

Thank You