USC Nuclear Engineering Education and Research

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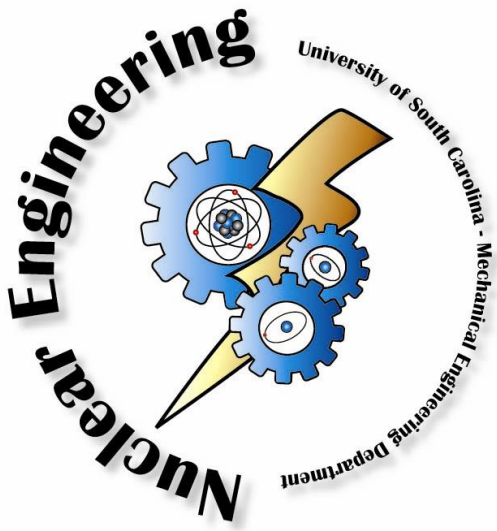
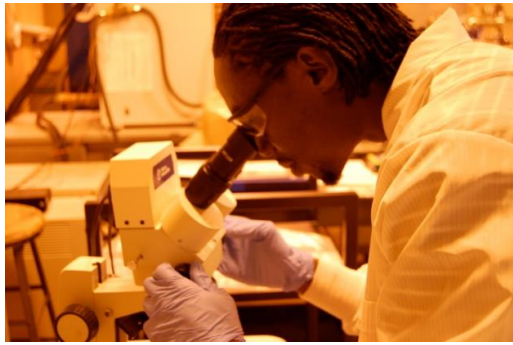


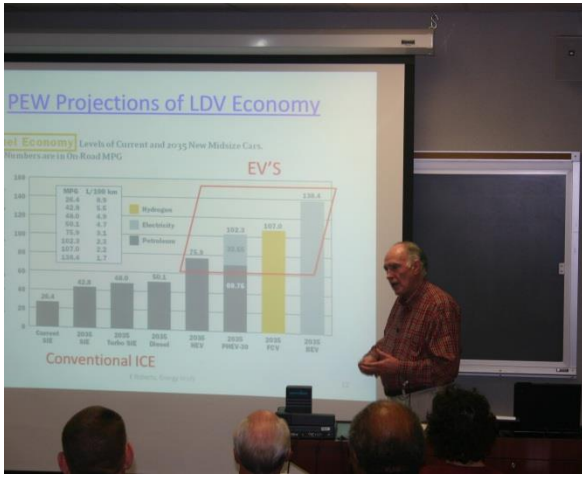
USC Nuclear Engineering Milestones

- 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 M.S. students
- December 2007, graduated first Ph.D.
- 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 and junior faculty hire to start Fall 2014.**



Undergraduate Minor and Graduate Nuclear Engineering Degrees and Requirements

- Undergraduate Minor – 18 credits
  - 6 nuclear engineering courses (4 core courses)
- MS (Master's of Science) - 30 credits
  - 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
  - 12 credits from dissertation research
  - 18 credits from course work



Nuclear Engineering Graduate Courses

- **Core Courses Required (5)**
  - EMCH 552 Introduction to Nuclear Engineering
  - EMCH 755 Advanced Nuclear Engineering
  - EMCH 553 Nuclear Fuel Cycles
  - EMCH 758 Nuclear Systems
  - EMCH 757 Radiation Shielding
- **Elective Courses (at least 2 for MS or at least 4 for ME)**
  - EMCH 556 Introduction to Risk Assessment and Reactor Safety
  - EMCH 756 Safety Analysis for Engineering Systems
  - EMCH 573 Introduction to Nuclear Materials
  - EMCH 774 Radiation Damage in Materials
  - EMCH 754 Thermal Hydraulic Design of Nuclear Reactors
  - EMCH 759 Waste Management in the Nuclear Industry
  - EMCH 555 Radiation Detection and Instrumentation
  - EMCH 561N Nuclear Chemical Engineering
  - EMCH 561-003 Introduction to Nuclear Safeguards
  - EMCH 770 Predictive Modeling: combining experiments with computations

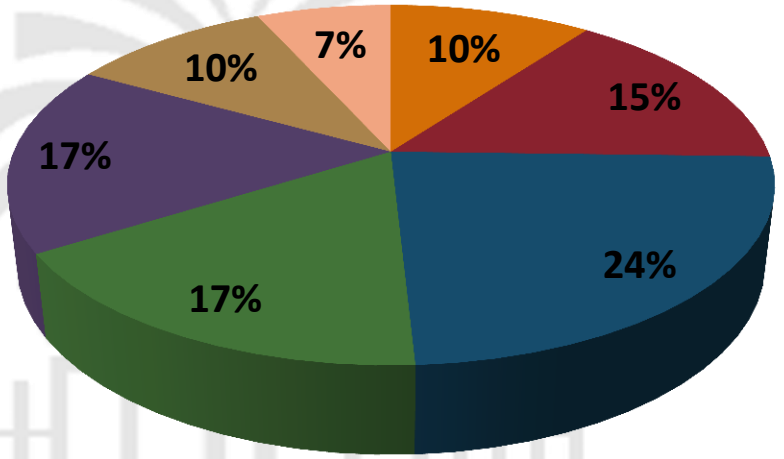
- **Engineering Elective (up to 1)**
  - Any NE elective (from above)
  - A math course (should be advised as which would be most appropriate)
  - Any Engineering course at 500 level or higher.
  - GEOL 650: Microscopy & Microanalysis

USC Graduate Nuclear Engineering Program & Distance Learning

- USC NE program includes a strong distance learning component to support professionals seeking an advanced degree. Currently professionals at:
  - Utilities, SRNL, ORNL, NRC, Naval Nuclear Power School, NASA, KAPL, Other
- All courses offered through distance learning:
  - Streaming of lectures on internet; also live two-way audio interaction
  - Remotely operated nuclear instrumentation laboratory
  - Online tools for managing course notes, homework, quizzes, etc.
  - Online and real time collaboration between on campus and distance ed. students

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, SRNL, ORNL, NRC, Naval Nuclear Power School, NASA, Other
- 79 graduates have assumed variety of positions in the nuclear industry (graduates: 40 fulltime/39 part-time):
  - Utilities, NRC, SRNL, ORNL, A/E, Vendors, Fed. Gov., Academia
  - PhD=4, MS=30, ME=45
  - Women - 7%
  - African American - 6%
  - Asian American - 6%
  - Foreign national - 9%



*Part-time students only counted if they took a new position in their company or changed companies upon graduation (% of total=59)

Two additional PhD students to finish this December 2014.

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

- Enrolled (active) - 55
  - Women – 14%
  - African American – 10%
  - Asian American – 4%
  - Foreign national – 2%
- Undergraduates – Minor in NE
  - 25 completed NE minor
  - 24(**) officially enrolled in NE minor
  - 8 enrolled accelerated BS-ME/MS-NE

(**) students may pursue the minor and declare in their final semester

NE Student Achievements and Recognition

- Robert Maher scholarship, $5000, given by CNTA to undergraduates
  - Matthew Presson, 2007; Andrew Petrarca, 2008; Dillon Inabinett, 2011
- SEMA Scholarship, $3000 (undergraduate)
  - Michael Dulude, 2009
- 2007 Student Literary Award, Materials Science and Technology Division of ANS
  - Gokul Vasudevamurthy, Ph.D. graduate Dec. 2007 - for work published on ZrC-UC composite fuels
- DOE Innovations in Fuel Cycle Research Award
  - Ken Allen, Ph.D. (2010, 3rd Place, $2,000)-for work published on fast reactor transmutation
  - Carey "Mac" Read (2011, $1500, universities under $600M) – for modifications of CINDER90
- 2011 Best Presenter Awards at the ANS Student Conference, Atlanta, GA
  - Mac Read (Reactor Physics Track), Daniell Tincher (Fuel Cycle and Waste Management)
- NANT Fellowship – given by Institute of Nuclear Power Operations (industry supported)
  - Awarded six years: 2005-2009, 2011-2014
- DOE-NEUP and NRC Scholarships for undergraduates (2009-2011, $85k)
- DOE-NEUP and NRC Fellowships
  - Kallie Metzger, NEUP Fellowship – 2012-2016, $155k
  - NRC Fellowship Program (2 Fellows, 4 years, 2010-2014, $380k)
- Local ANS (Columbia Section) Scholarship, $1000 to $1500
  - 1 in 2010; 2 in 2011, 1 in 2012, 3 in 2013
- National Women In Nuclear Conference Scholarship (travel)
  - Julianne Goddard, 2010; Kallie Metzger, 2011

Primary Nuclear Engineering Faculty

- **Travis W. Knight**
  - Advanced nuclear fuels and materials
  - Nuclear safeguards
  - Advanced fuel cycles
  - Space nuclear power

- **Elwyn Roberts**
  - Nuclear fuels
  - Nuclear materials
  - Product Design

- **Jeff Morehouse**
  - Nuclear systems and operations
  - Instrumentation and control
  - Thermal sciences and energy systems

- **Val Loiselle**
  - Waste management
  - Nuclear power
  - Environmental remediation

- **Two open positions: 1 Junior Faculty and 1 Senior Faculty**
- **Ten other adjunct faculty**

- **Dan G. Cacuci**
  - Predictive best-estimate analysis of large-scale physical and engineering systems,
  - large scale scientific computations and nuclear engineering (reactor multi-physics, dynamics, and safety).

- **Djamel Kaoumi**
  - Radiation Damage in Materials
  - High temperature alloys
  - Materials Characterization
  - In-situ TEM techniques

- **Jamil Khan**
  - Thermal hydraulic design of nuclear reactors
  - Computational fluid dynamics

- **Abdel Bayoumi**
  - Preventive and condition based maintenance
  - Materials Characterization

Service, Outreach, Engagement

- Engineering Week
  - NE exhibits and talks
  - Energy Panel 2013
- Sparkleberry Fair 2012
- Media interviews
- Letters to the editor
- Science Cafés (2011,2013)
- Public talks
- Formal seminars
- Local ANS
- ANS: ETWDD, MSTD
- Editor: Nuclear Science and Engineering

- Plant tours
- CASE, visit by Dr. Patrick Moore, May 2012
- Clean Energy America, scheduled for Nov. 8th 2012
- Carolinas' Nuclear Cluster (CNC) and also E4 Carolinas
- NuHub
- CNTA
- SUNRISE
- Edison Lecture Series
- Energy Forum, Engineering Week 2013

Carolinas' Nuclear Cluster

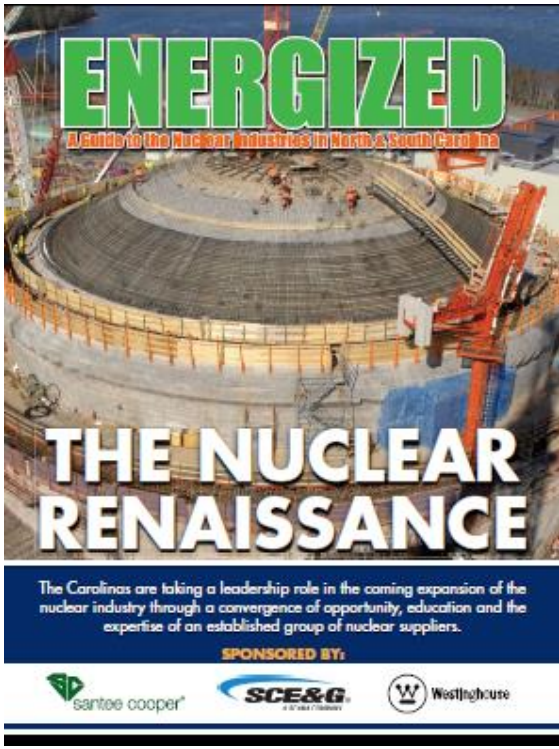
- **USC Nuclear Engineering Program is supporting activities to grow jobs and economic development in the nuclear industry**

Overview/Mission

- The Carolinas' Nuclear Cluster collaboratively strengthens workforce, services, products, and policies to capture and extend our global leadership in nuclear energy capabilities.

- The Carolina's are a hub of nuclear expertise, supplying more than 11% of the nation's nuclear power production, and we can build on that tradition. As the need for electricity increases, our solid energy expertise can provide the Carolinas with environmentally-friendly, safe and plentiful power. In fact, talented Carolinians can help develop energy infrastructure around the globe.

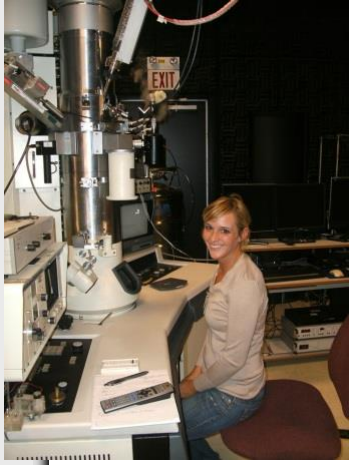
- New Carolina has created a consortium of industry, higher education and nonprofit organizations working in unison to support our energy and economic development – The Carolinas Nuclear Cluster.



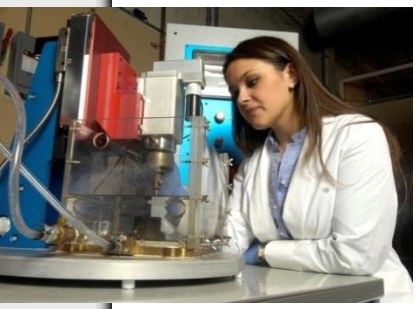
37,000 jobs in SC/NC and $20B economic impact

Research Programs

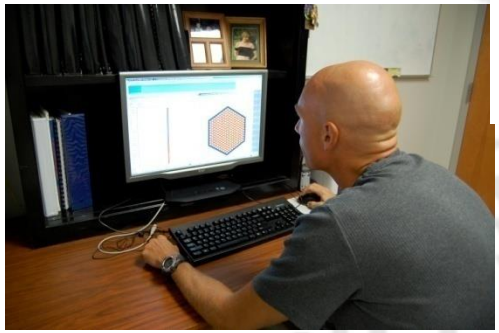
nuclear fuels and materials, predictive best-estimate analysis of large-scale physical and engineering systems, thermal hydraulics, condition based maintenance, radiation detection, nuclear safeguards, and more



graduate students researching radiation damage in ODS steels at Argonne Nat. Lab. using TEM with in situ ion irradiation

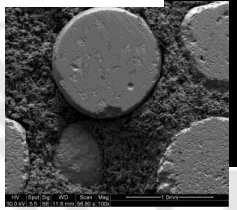


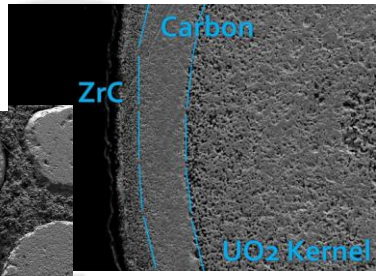
fuel kernel fabrication and testing



small modular fast reactor

composite UC-ZrC fuels for GFR





advanced coated particle fuels for VHTR

graduate students researching composite fuels fabrication and testing

- Advanced nuclear fuels for light-water and gas-cooled reactors
- Advanced alloys for structural and cladding applications in Gen-IV fission reactors and fusion reactors
- High temperature membranes and getters for tritium removal in NGNP (Mech. Eng.)
- Advanced (Helium-3 replacement), room temperature neutron detectors for nuclear safeguard applications (Elect. Eng.)

Nuclear power related research is diverse and interdisciplinary – crossing many departments and programs

Nuclear Materials Laboratory – University of South Carolina

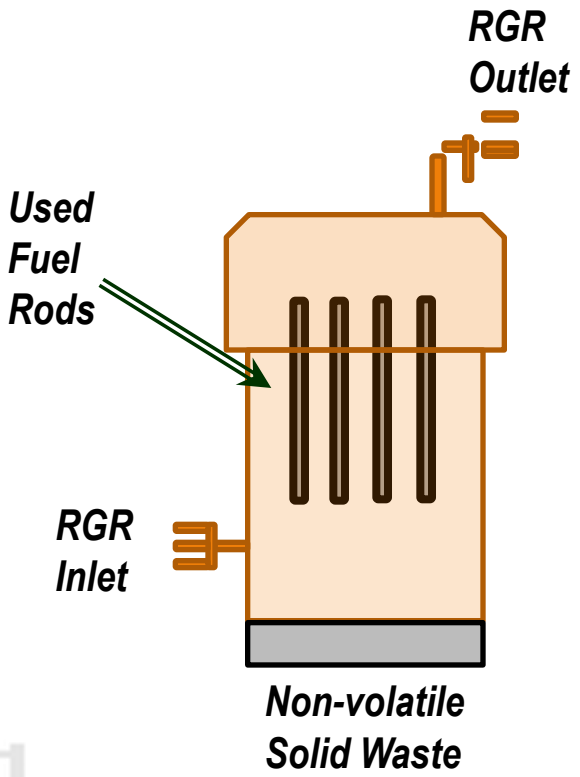
• hold

Recent Research Awards in NE

- **Prof. Dan Cacuci from Los Alamos National Security, LLC/DOE, “Facility Modeling for Separations and Safeguards”, three years for a total of $ 900,000, Mar. 2014**
- **Profs. Dan Cacuci, from Gen4 Energy, Inc./DOE, “USC- G4M LBE Natural Circulation Experimental Facility”, $420,932.00 for two years, November 2013**
- **Prof. Djamel Kaoumi, from DoE NEUP, "Developing Ultra-Small Scale Mechanical Testing Methods and Microstructural Investigation Procedures for Irradiated Materials “, $800,000 for three years with University of Berkley, Prof. Kaoumi his share $270,000, Sep. 2013**
- **Prof. Djamel Kaoumi, from DoE NEUP “High Fidelity Ion Beam Simulation of High Dose Neutron”, $500,000 for three years with University of Michigan, Prof. Kaoumi, his share is $375,000, Sep. 2013**
- **Prof. Travis Knight, DoE NEUP “U3Si2 Fabrication and Testing for Implementation into BISON Fuel Performance Code”, $800,000 for three years, Prof. Xinyu Huang, CoPI, Sep. 2013**
- **Prof. Lingyu (Lucy) Yu DoE NEUP "Structural Health Monitoring of Nuclear Spent Fuel Storage Facilities“, $800,000 for three years, Profs. Knight and Giurgiutiu, CoPIs, Sep. 2013**
- **Profs. Xinyu Huang, from General Atomics, "Experimental Study and Validation of Thermo-Mechanical Robustness of SiC-SiC Composite Cladding “, Prof Knight is the CoPI of this $200,000 for two years, March 2013**
- **Curriculum development grant from NNSA with SRNL for a course on Introduction to Nuclear Safeguards, 2013-2015**

Reactive Gas Recycle of Used Nuclear Fuel

- Overarching Technical Objective – Explore the viability of chemical gas-phase separation processes for UNF
  - Stretch Target: Fully gas-phase separation process
  - Development of gas-phase component processes that may function as stand-alone or as head-end for other separation techniques
- Identification of gas phase reactions that facilitate separation and recycle of UNF via volatility or similar phase separation
  - Thermodynamic screening
  - Experimental verification and kinetic measurements
- Development of prototype process flowsheet incorporating experimental data and theoretical evaluations



J. Gray, R. Torres, M. Martinez-Rodriguez, P. Korinko, S. Sherman, B. Garcia-Diaz, A. Visser and T. Adams,
- Savannah River National Laboratory

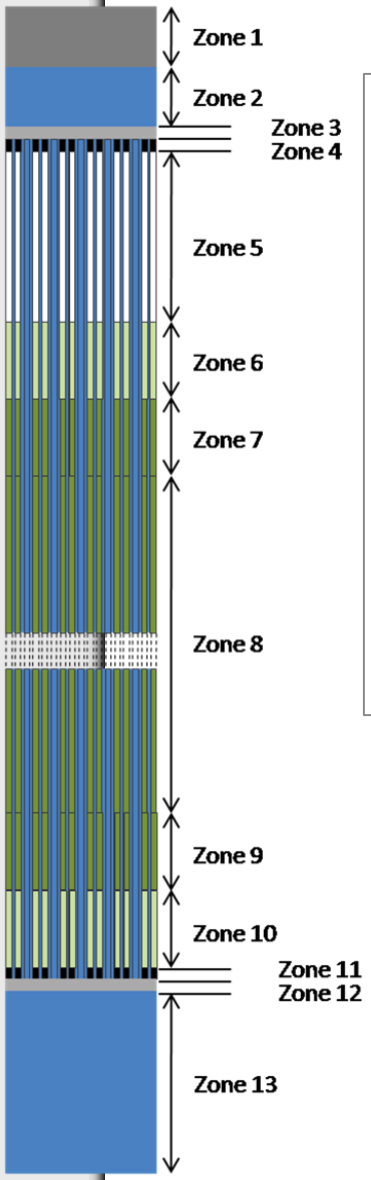
T. Knight, D. Inabinett (grad. Student),
- University of South Carolina

*Inabinett, D., G. Cerefice, T. Knight, T. Adams, and J. Gray, Alternate Fluorination Approaches for Reactive Gas Recycle of Used Nuclear Fuel", *Transactions Of the American Nuclear Society 2012 Winter Meeting*, San Diego, CA, Nov. 11-Nov. 15, 2012

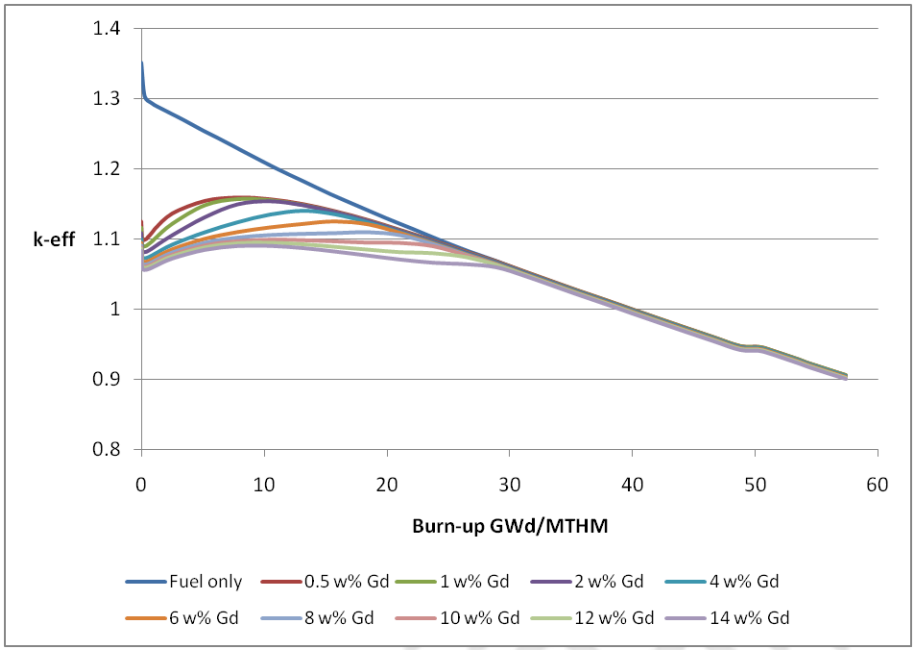
Funding provided by:
- Department of Energy – Nuclear Energy Fuel Cycle Research and Development Campaign
- Savannah River National Laboratory through the Laboratory Directed Research and Development Program

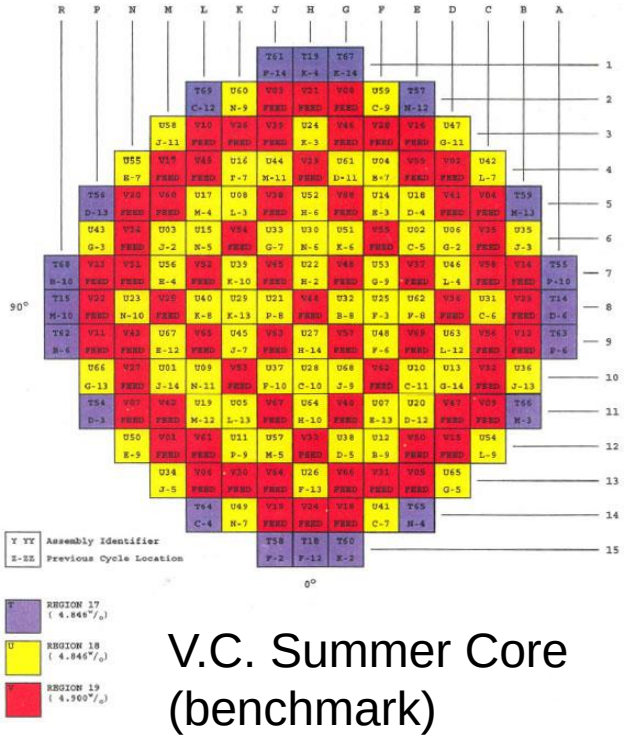
***Strategic Objective* – Development of technologies for RGR leading to a pilot-scale demonstration at SRS – potentially in H canyon**

Innovations in Fuel Management



Typical Assembly



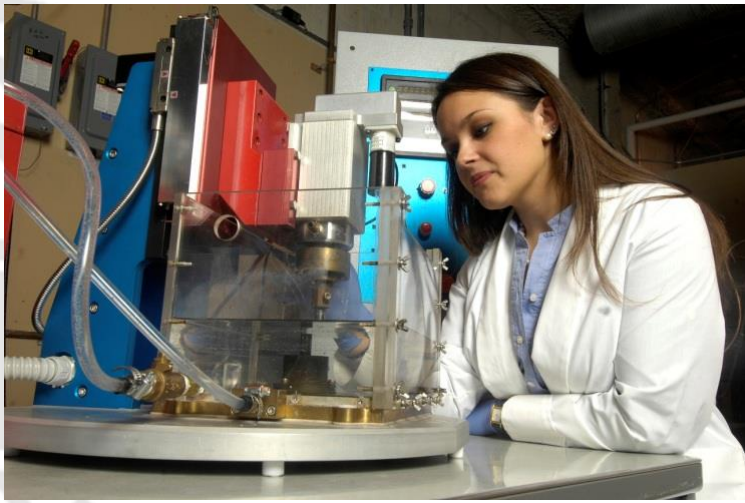


V.C. Summer Core (benchmark)

- Hybrid assembly design of ZrB_2 coated pellets and gadolinia IFBA
- Reduce critical boron “hump”
  - Maintain lower moderator temperature coefficients
  - Improved performance and safety margin
- Collaboration: Westinghouse

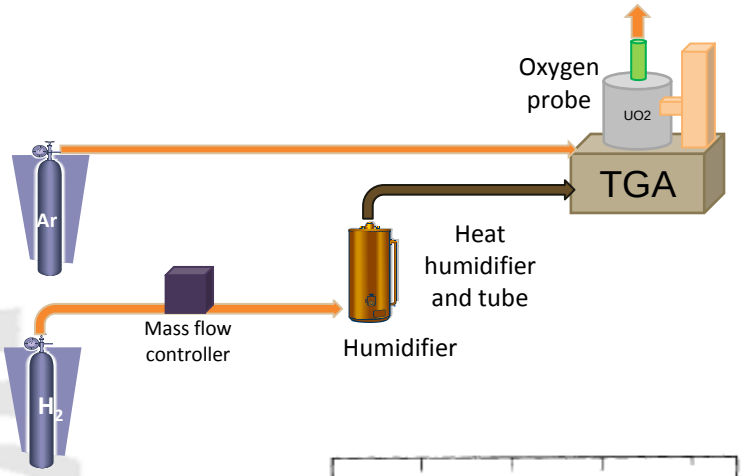
Other projects

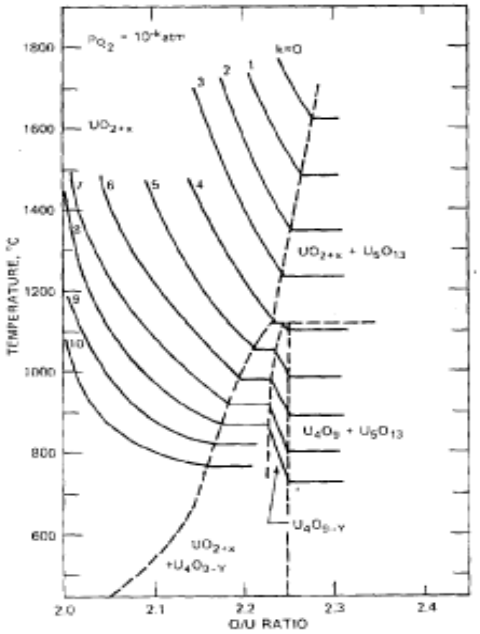
- "Nuclear battery" to address Station Blackout (Fukushima type events) - Westinghouse
- Fuel kernel production and characterization for W-UO_2 Cermet fuel for nuclear thermal propulsion - NASA and Idaho National Laboratory
- Accident tolerant fuels – General Atomics, Westinghouse, and Idaho National Laboratory
- Coupling thermal hydraulic (TRACE) and fuel performance (FRAPCON, FRAPTRAN) for better understanding of fuel condition in accidents i.e. LOCA – collaboration with NRC



Thermochemical Study U-Ln-O

- Fuel designs for higher burnup require better understanding of phenomena such as Fuel Clad Chemical Interaction (FCCI).
  - Fission product transport from the fuel to the cladding surface is governed by thermochemistry and phase equilibria which are controlled by oxygen potential which is set by the stoichiometry of the as-fabricated fuel.
- Measurement of oxygen potential versus temperature versus O:M using TGA.
- Thermochemical modeling with FACT-SAGE software.
- Collaboration of USC and ORNL



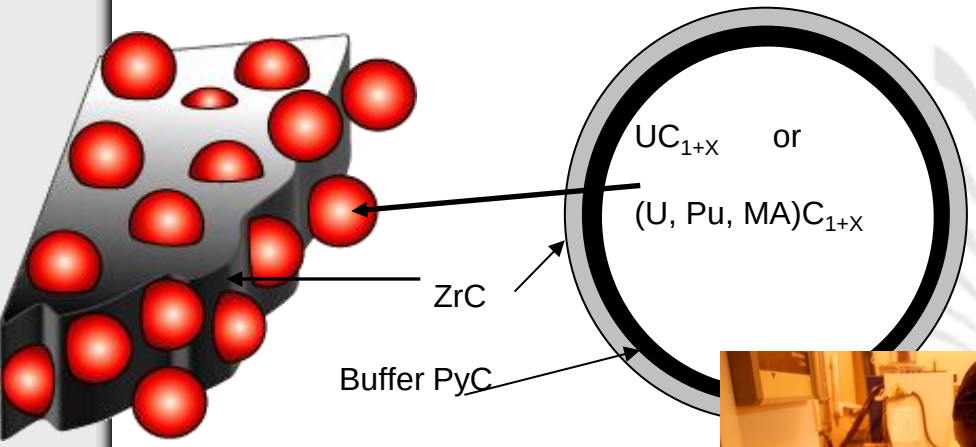


From:Olander

Analysis and Development of A Robust Fuel for Gas-Cooled Fast Reactors

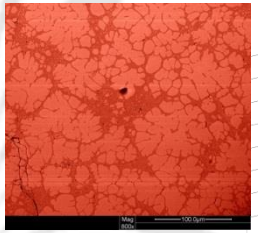
PI: Dr. Travis W. Knight, twknight@sc.edu

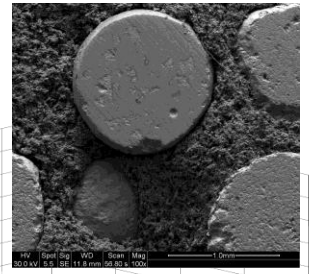
Fuel Form: Composite fuel with kernels of uranium carbide or a mixed carbide of uranium and recycled transuranics (TRU) including minor actinides (MA) in a zirconium carbide matrix



Potential Impacts: 1) recycle TRU including MA to reduce high-level waste; 2) enable more than 80 fold increase in resource utilization; 3) high temperature process heat for hydrogen production, greater thermal efficiency

From L to R: kernel microstructure, composite porosity, and ZrC-UC composite





Challenge: higher vapor pressure of minor actinides leads to significant loses using traditional powder metallurgy; methods developed to reduce time at high temperature during fabrication

Characterization: carbide kernel dendritic microstructure, porosity distribution of the composite

Uranium carbide kernels fabricated at USC using the rotating electrode method

Accomplishments: developed methods for fabrication and characterization of 30vol% fuel ZrC-UC composite (GenIV - GFR goal)

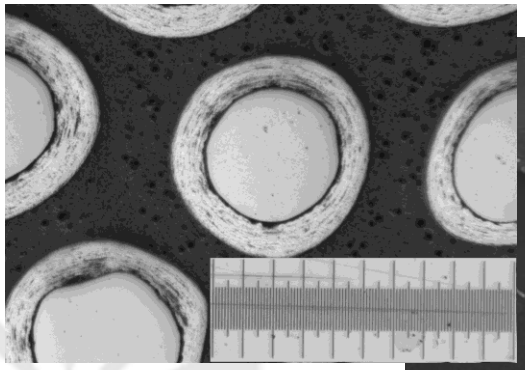
Collaboration: **Savannah River National Laboratory**

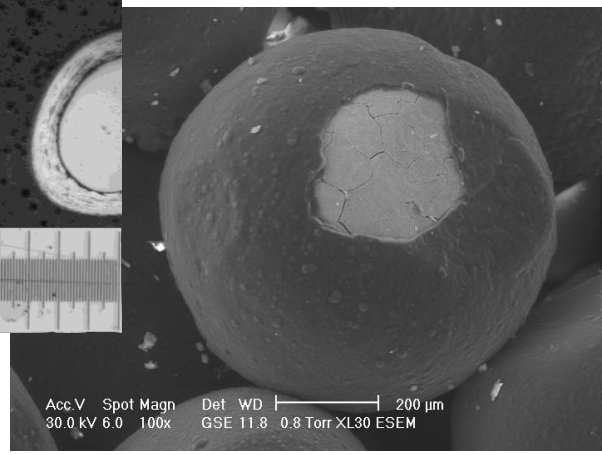
Support: DOE EPSCoR DE-FG02-06ER46270

1. Vasudevamurthy, G., T. W. Knight, T. M. Adams, and E. Roberts, "Production and Characterization of ZrC-UC Inert Matrix Composite Fuel for Gas Fast Reactors", *Nuclear Technology*, 173, 2, February 2011
2. Vasudevamurthy, G., T. W. Knight, E. Roberts, and T. Adams, *Journal of Nuclear Materials*, 347, 1-2, 2008, pp. 241-247
3. Vasudevamurthy, G., T. W. Knight, "Production of High Density Uranium Carbide compacts for use in Composite Nuclear Fuels", *Nuclear Technology*, 163, 2, August 2008, pp. 321-327
4. Vasudevamurthy, G. and T. W. Knight, *Materials Letters*, 61, 27, Nov 2007

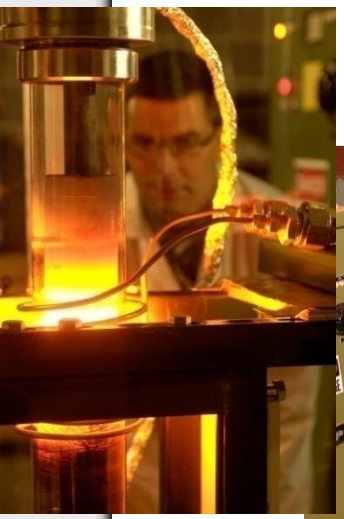
Research Program: Advanced Coated Particle Fuels

- UO_2 Fuel kernel
  - Lots of experience
  - Easier to fabricate
- ZrC kernel coating
  - Oxygen getter, reduce CO formation and pressure buildup
  - Reduce kernel swelling
  - Prevent kernel migration (amoeba effect)
- Collaboration
  - Nuclear Fuel Services

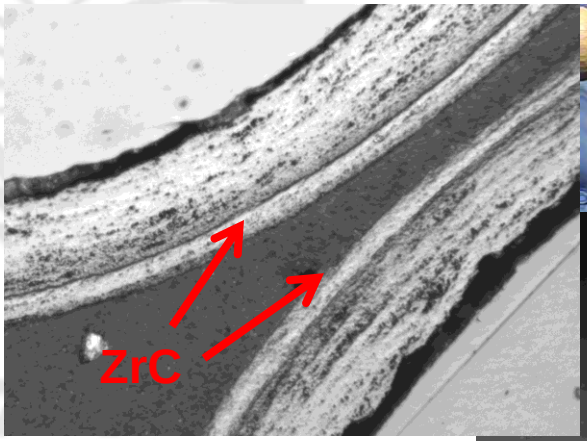


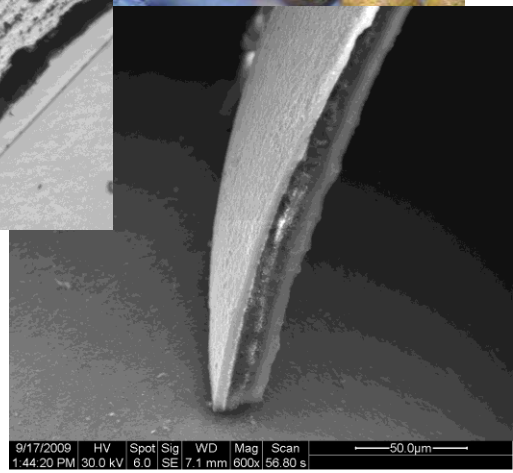


Coated particles produced at USC



Fluidized-bed CVD Coater built at USC

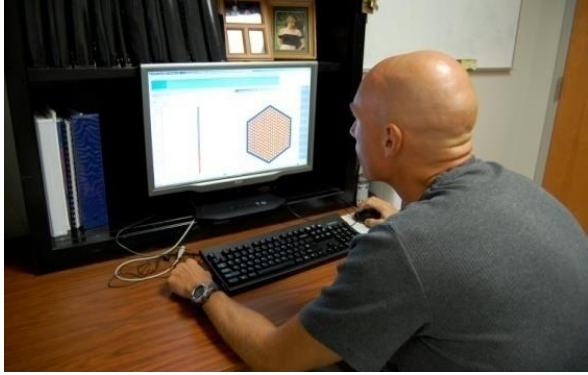




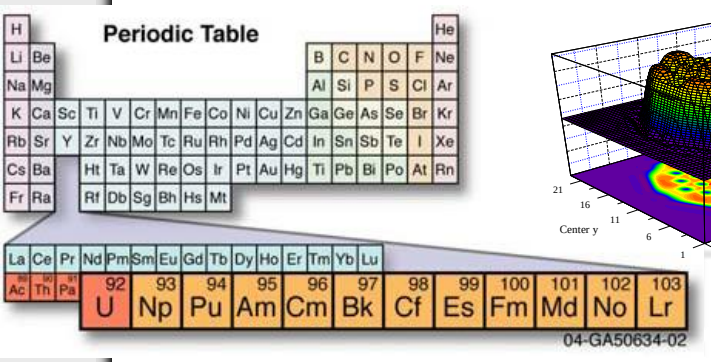
PyC and ZrC layers (early results)

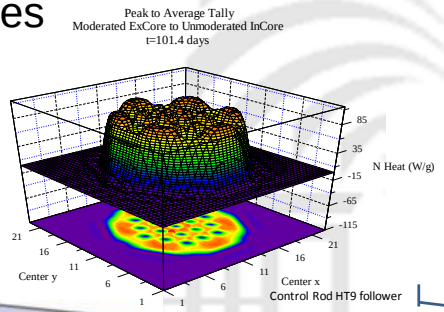
Porter, I. E., T. W. Knight, M. C. Dulude, E. Roberts, J. Hobbs, Advanced TRISO Fuels with Zirconium Carbide for Very High Temperature Reactors, Nuclear Engineering and Design, submitted Sept. 2012

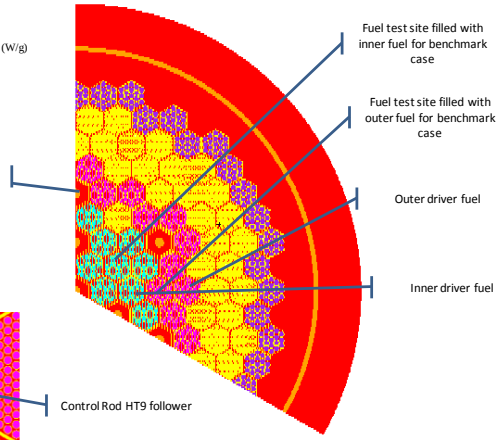
Fast Reactor Design and Fuel Cycle Modeling



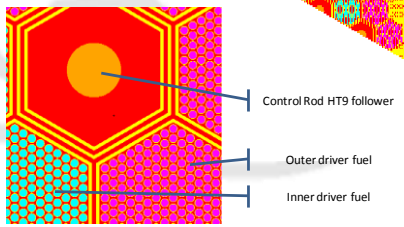
- **SCHIBR** - Sodium-Cooled Heterogeneous Innovative Burner Reactor
  - Reduce stockpiles of plutonium and legacy used fuel
  - Advanced Burner Reactor (ABR) – small size – flexible core design
  - Innovative strategy with heterogeneous moderated targets
  - Shift from thermal to fast spectrum to limit production of higher actinides





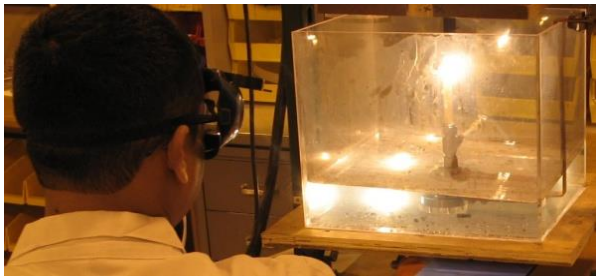


- **DOE Innovations in Fuel Cycle Research Awards 2010 & 2011**



- *Read, Jr., C. M., T. W. Knight, K. S. Allen, "Development of a Multi-Tiered Recycling Strategy with a Sodium-Cooled Heterogeneous Innovative Burner Reactor," Progress in Nuclear Energy, (accepted Sept. 2012
- *Allen, K.S.; T. W. Knight, C. M. Read Jr., "Design of an Equilibrium Core 1000 MWt Sodium-Cooled Heterogeneous Innovative Burner Reactor," *Nuclear Engineering and Design,* 242, January 2012, pp. 108–114
- *Read, Jr., C. M., T. W. Knight, K. S. Allen, "Using a Modified CINDER90 Routine in MCNPX 2.6.0 for the Prediction of Helium Production in Minor Actinide Targets," *Nuclear Engineering and Design,* 241, 12, December 2011, pp. 5033-5038
- *Allen, K. S. and T. W. Knight, S. E. Bays, Benchmark of Advanced Burner Test Reactor Using MCNPX and ERANOS 2.1, *Progress in Nuclear Energy*, 53, 6, August 2011, pp. 633-644
- *Allen, K. S., T. W. Knight, and S. E. Bays, "Actinide Destruction and Power Peaking Analysis in a 1000 MWt Advanced Burner Reactor Using Moderated Heterogeneous Target Assemblies", *Progress in Nuclear Energy*, 53, 4, May 2011, pp. 375-394
- *Allen, K. S. and T. W. Knight, "Destruction Rate Analysis of Transuranic Targets in SFR Assemblies Using MCNPX and SCALE 6.0", *Progress in Nuclear Energy*, 52, 4, May 2010, pp. 387-394

Center of Economic Excellence in Nuclear Science and Energy

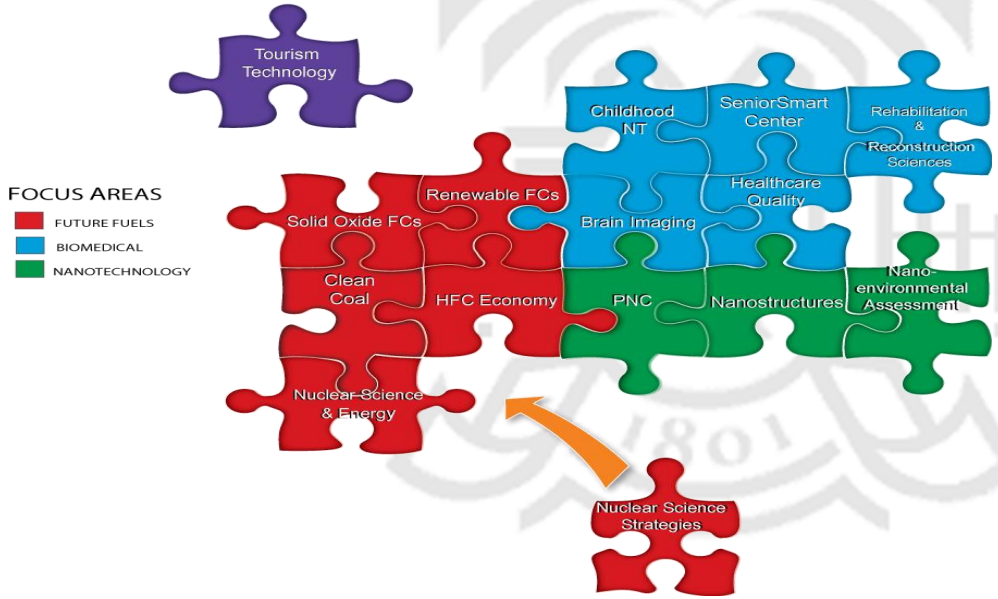


- Selected by SC COEE in 2008
- Endowed Chair in Nuclear Science and Energy
  - Dr. Dan Cacuci, hired Jan. 2012
- Supported by State of SC - $3M endowment
  - Matching funds - endowment, non-endowment for infrastructure and seed projects
- "Research and development on performance, efficiency, and maintenance issues related to existing and power plants "

UNIVERSITY OF SOUTH CAROLINA
RESEARCH

Center of Economic Excellence in Nuclear Science Strategies

- Endowed Chair in Energy and Nuclear Security
  - Endowed chair search underway
- Supported by State of SC - $3M endowment
  - Matching funds - endowment, non-endowment for infrastructure and seed projects



UNIVERSITY OF SOUTH CAROLINA
RESEARCH

Center of Economic Excellence Nuclear Science Strategies

- **Education and Research**
  - Address critical need for professionals in industry and DOE complex in key skill areas
- **Energy Security** – support for nuclear power industry
  - Project management – planning, scheduling, quality control, budgeting, risk management (critical skills for graduates entering workforce).
  - Risk assessment – focus resources on safety significant systems, structures, and components.
  - Advanced reactor concepts and advanced fuel cycles for sustainable nuclear power (recycling of used fuel, resource utilization, reduced waste)
- **Nuclear Security and Safeguards** – support for DOE related programs
  - Advanced analytical techniques and instrumentation
  - Risk assessment of fuel cycle facilities, surplus stockpiles, and facilities for dispositioning of recycled materials
  - Advanced fuel cycles and proliferation resistant fuels
  - Advanced radiation detection materials, detector design

Summary for Nuclear Engineering

- Research focus areas:
  - Advanced Nuclear Fuels and Materials
  - Modeling and Simulation
  - Reactor Safety
  - Nuclear Safeguards
- Funding and Support:
  - Research, infrastructure, and student support
  - Investment by industry, federal gov., state, university
- Sixty graduates have assumed variety of positions in the nuclear industry:
  - Utilities, NRC, SRNL, ORNL, A/E, Vendors, Fed. Gov.
- Furthering education and training of existing professionals through distance education:
  - Utilities, SRNL, ORNL, NRC, Naval Nuclear Power School, NASA, KAPL, Other
- USC nuclear related education contributing to the next generation workforce needed to maintain and grow nuclear power
- USC nuclear related research contributing to the sustainability of nuclear power