UCB NE Overview + Innovation Bootcamp

Prof. Rachel Slaybaugh

April 7, 2016

Tri Alpha Visit

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What are we going to talk about?

- What does Prof. Slaybaugh do?
- What About the Rest of the Department?
- So, I Hear There's a Nuclear Innovation Bootcamp…
- What are the Opportunities for Involvement?

UCB Computational Neutronics Group

Led by Rachel Slaybaugh

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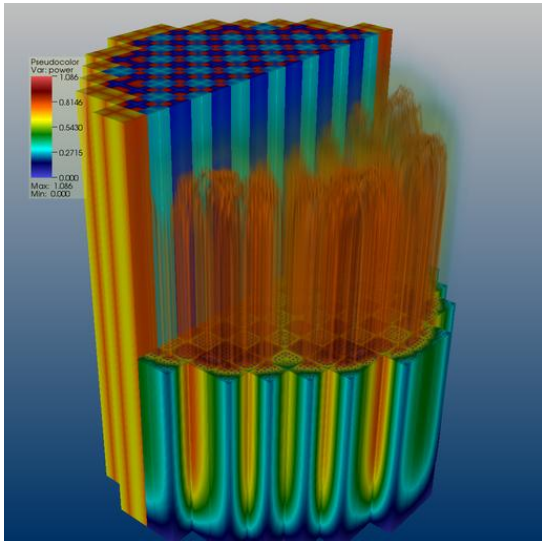
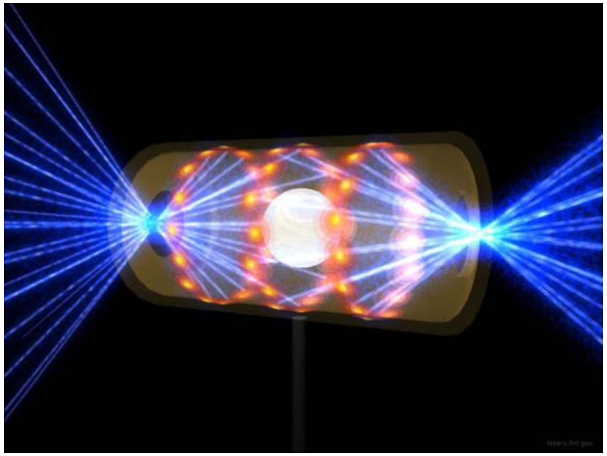
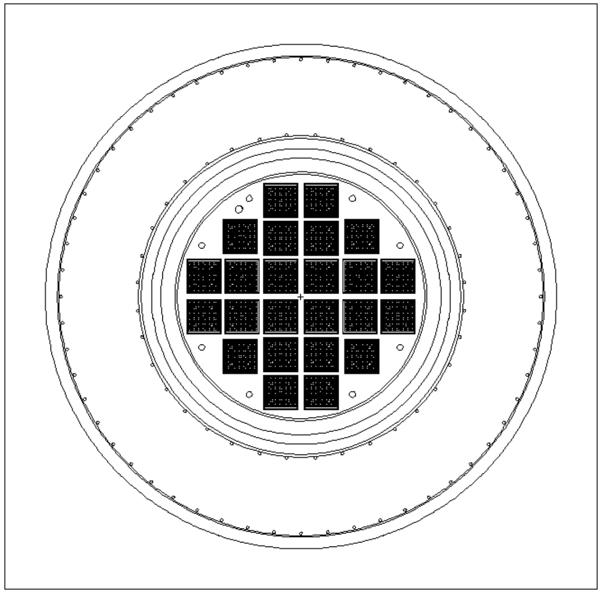
What exactly do you do?

$$
\begin{aligned}
&[\hat{\Omega} \cdot \nabla + \Sigma(\vec{r}, E)]\psi(\vec{r}, \hat{\Omega}, E) = \\
&\quad \int dE' \int d\hat{\Omega}' \, \Sigma_s(\vec{r}, E' \to E, \hat{\Omega}' \cdot \hat{\Omega})\psi(\vec{r}, \hat{\Omega}', E') \\
&\quad + \frac{\chi(E)}{k} \int dE' \, \nu\Sigma_f(\vec{r}, E') \int d\hat{\Omega}' \, \psi(\vec{r}, \hat{\Omega}', E')
\end{aligned}
$$



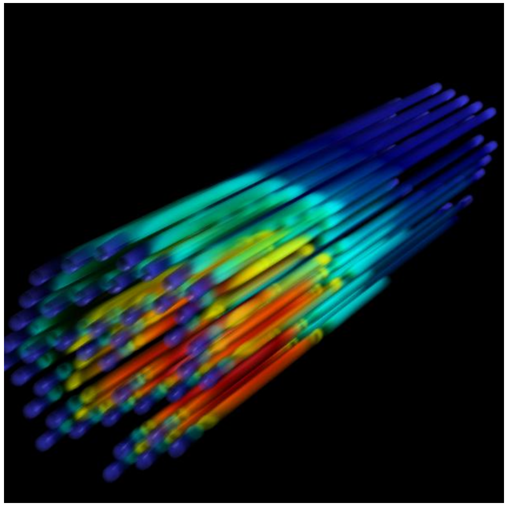


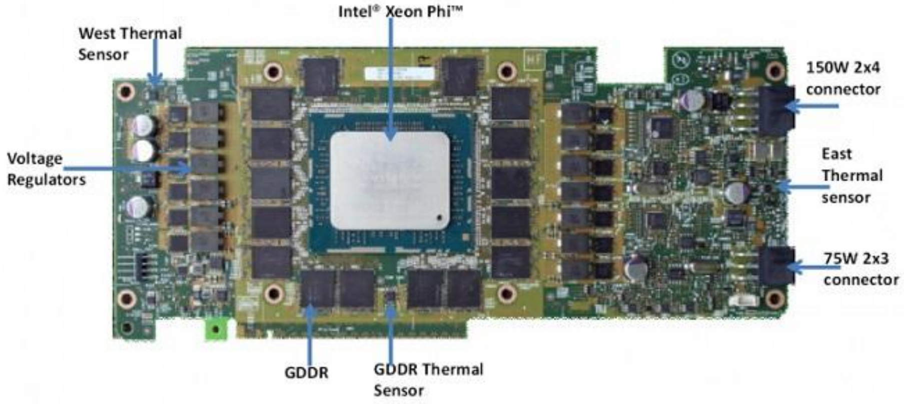


How do you do it?

- Deterministic methods require discretization of phase space
  - discretize more finely to improve solution quality
  - use advanced solvers to converge solution more quickly
- Monte Carlo (MC) treats phase space continuously
  - accuracy depends on number of particles simulated
  - often requires variance reduction (VR)
- Hybrid methods: create MC VR parameters using deterministic solutions

algorithms = physics + architecture





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Quick Brief: deterministic methods

- Discretize phase space; represent as a matrix; apply linear algebra-type solvers
  - Space: mesh (think finite difference/volume)
  - Energy: break into multiple groups
  - Angle: capture with a quadrature set
- Quality of solution is tied to
  - Quality of discretization
  - Accuracy of solution methods
- Can be memory and FLOP intensive
- Strategically-designed parallelization techniques

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R.N. Slaybaugh, T.M. Evans, G.G. Davidson, and P.P.H. Wilson, “Rayleigh Quotient Iteration with a Multigrid in Energy Preconditioner for Massively Parallel Neutron Transport,” Proceedings of M&C-SNA in Nashville, TN, April 2015.
G.G. Davidson et al., “Massively Parallel, Three-Dimensional Transport Solutions for the k-Eigenvalue Problem,” *Nuc. Sci. and Eng.* **177** (2014) 111-125.

Quick Brief: Monte Carlo

- Physics expressed continuously; sampled with random numbers
- Quality of solution is tied to
  - Number of samples in phase space
  - Adequacy of sampling phase space
- *Variance Reduction* methods can reduce variance faster while maintaining a fair game
- Can be memory and FLOP intensive
- Historically straightforward to parallelize

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Current Projects: WARP and MCATK

- "Weaving All the Random Particles" (Bergmann)
- 3D continuous-energy Monte Carlo neutron transport code developed for efficient implementation of the algorithm on GPUs
- Relative to CPUs, GPUs have higher aggregate memory bandwidth, much higher FLOPS, lower energy consumption per FLOP
- Next up: MC on MICs (Multi Integrated Cores, e.g. Intel XeonPhi—sort of between CPUs and GPUs)
- Particle transport codes need to be rewritten to execute efficiently on GPUs and MICs

Ryan M. Bergmann, Jasima L. Vujic. "WARP – A framework for continuous energy Monte Carlo neutron transport in general 3D geometries on GPUs," *Annals of Nuclear Energy* **77** (2015) 176-193.

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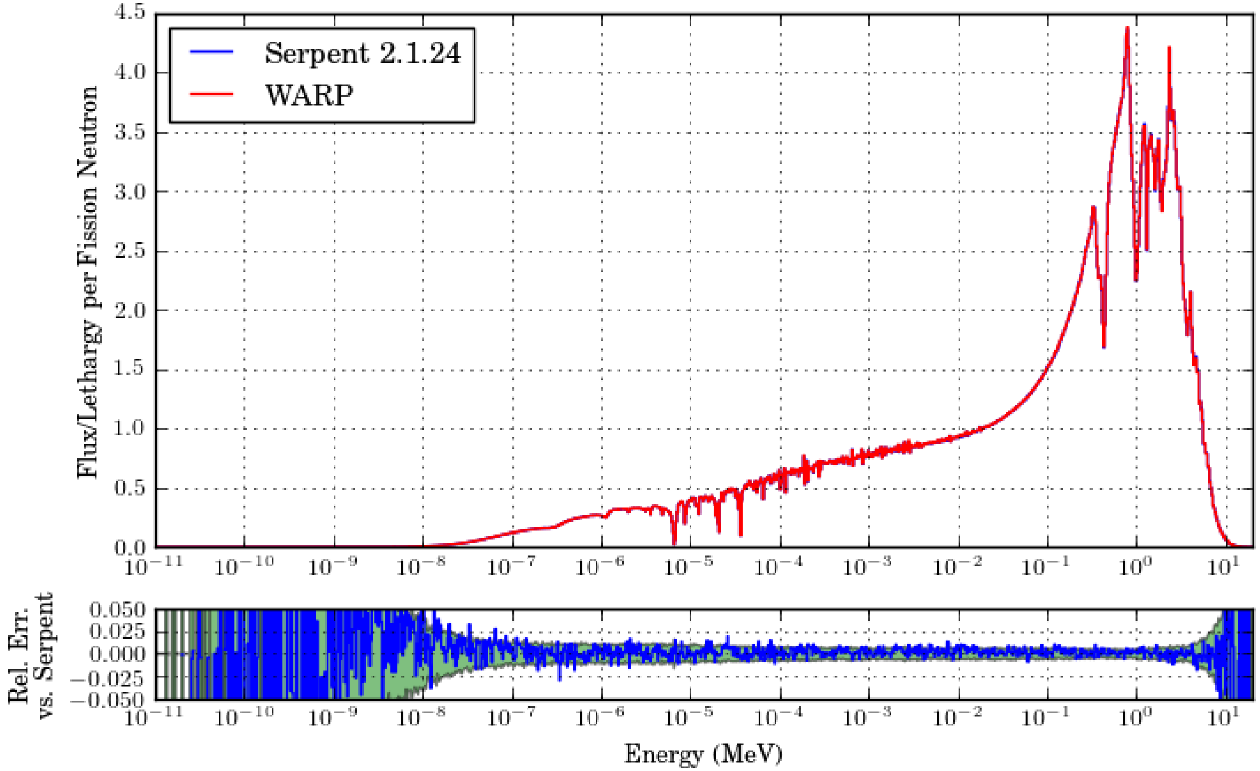
results match standard solvers

WARP took 2.0615 s
(k20; 32 threads)

Serpent took 137 s
(AMD Opteron 6172; 12 cores)



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quick brief: hybrid methods

- Monte Carlo highly accurate; can be slow
- Deterministic methods usually fast; can have accuracy issues
- Hybrid methods use deterministic solutions to create variance reduction parameters for MC
  - Particles are assigned weights that map to impact
  - Set how to update weights
  - Set how to bias the source

Current Projects: Angle-Informed Hybrid Methods

Use adjoint relationship to create VR parameters for MC (which we think of as “importance” of a source to the solution)

$$\int\int q^{+}(r,E)\phi(r,E)\,dr\,dE = \int\int q(r,E)\phi^{+}(r,E)\,dr\,dE$$

$$\boxed{q^{+}(r,E) = f(r,E)}$$

$$R = \int_{E}\int_{V_f} f(r,E)\phi(r,E)\,dr\,dE \quad \longrightarrow \quad R = \int_{E}\int_{V_S} q(r,E)\phi^{+}(r,E)\,dr\,dE$$

Create an importance map augmented by angular information

$$\phi^{\dagger}(\mathbf{r},E) = \frac{\int \psi(\hat{\Omega},\mathbf{r},E)\psi^{\dagger}(\hat{\Omega},\mathbf{r},E)\,d\hat{\Omega}}{\int \psi(\hat{\Omega},\mathbf{r},E)\,d\hat{\Omega}}$$

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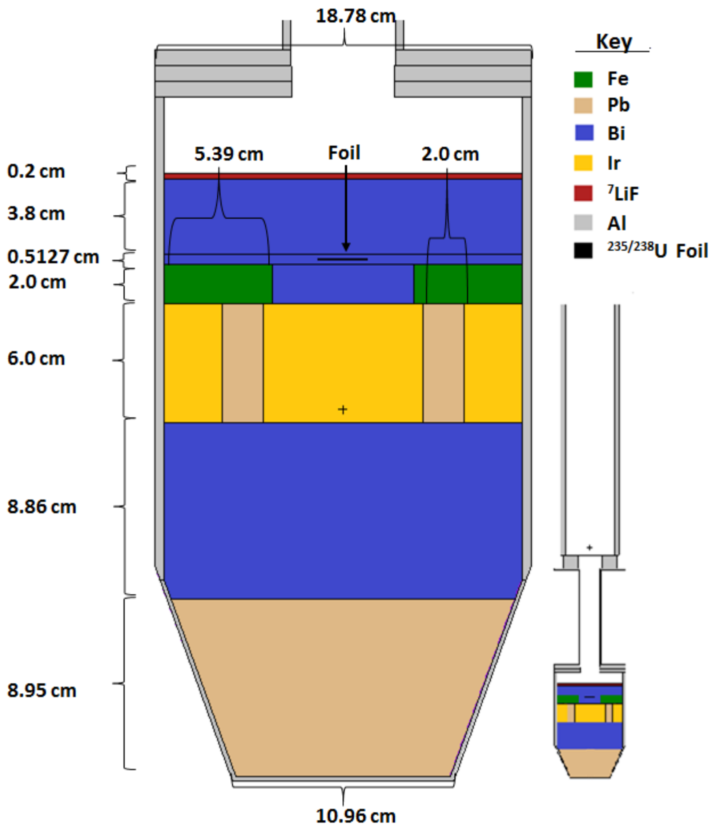
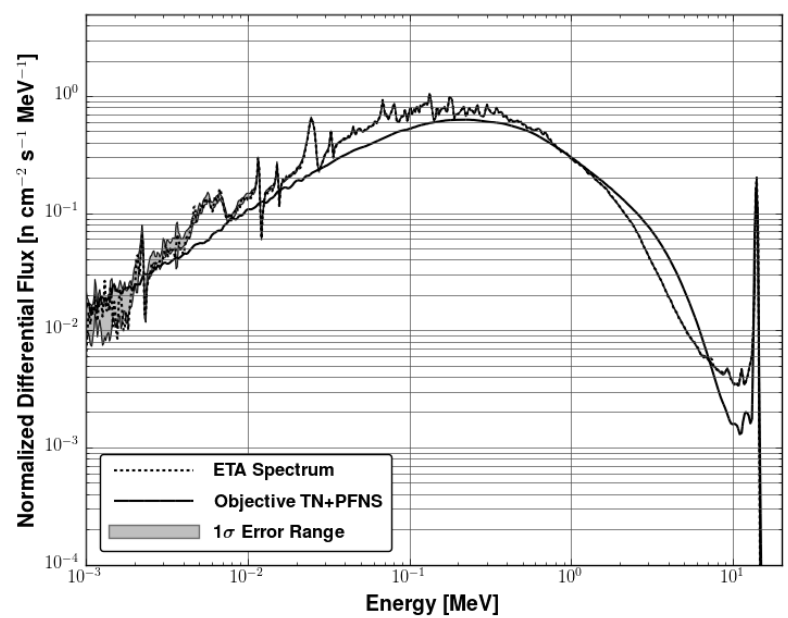
M. Munk, et al., “An Angle-Informed Hybrid Method for CADIS and FW-CADIS.” Proceedings of the PHYSOR 2016 Meeting in Sun Valley, ID, May 2016. (accepted).

Current Projects: Energy Tuning Assembly



ETA Design

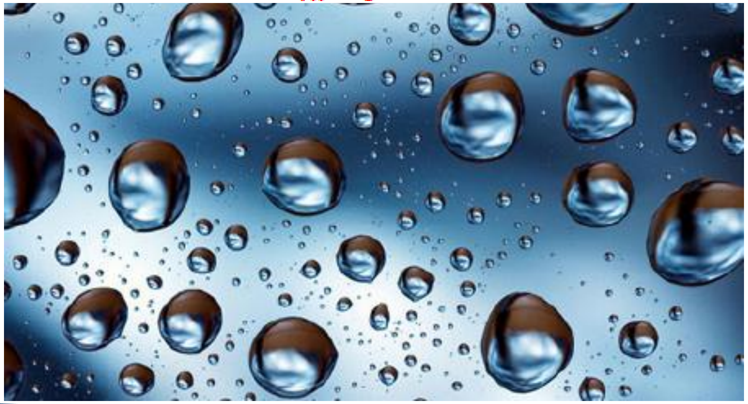
- Use layers of materials to shape neutron energies
- Design by
  - Optimization code
  - Uses predictive computing

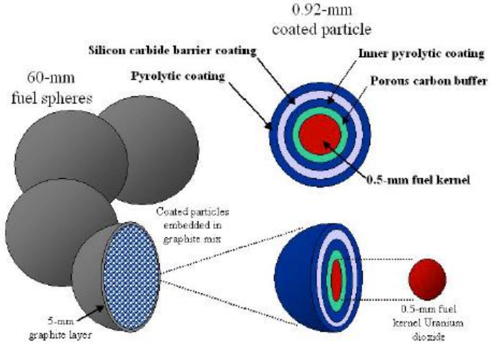


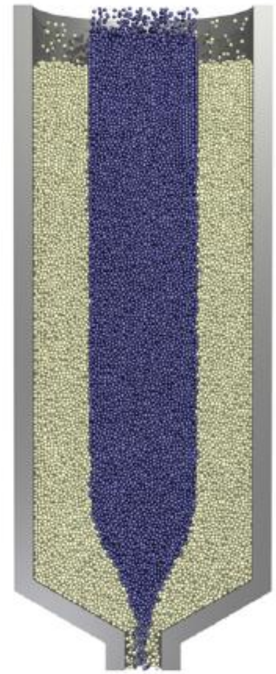
Homogenization: non-classical transport

- Classical Transport inherently assumes that the distances between collisions are exponentially distributed: $p(s)=\Sigma_t e^{\Sigma t}$
- Non-Classical Transport drops this assumption, generalizing the linear Boltzmann equation

$$\frac{\partial \psi}{\partial s}(\mathbf{x},\boldsymbol{\Omega},s) + \boldsymbol{\Omega}\cdot\nabla\psi(\mathbf{x},\boldsymbol{\Omega},s) + \Sigma_t(\boldsymbol{\Omega},s)\psi(\mathbf{x},\boldsymbol{\Omega},s)$$
$$= c\delta(s)\int_{4\pi}\int_0^{\infty} P(\boldsymbol{\Omega}'\cdot\boldsymbol{\Omega})\Sigma_t(\boldsymbol{\Omega}',s')\psi(\mathbf{x},\boldsymbol{\Omega}',s')\,ds'\,d\Omega' + \delta(s)\frac{Q(\mathbf{x})}{4\pi}$$







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UCB TH Group

Led by Per Peterson

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The UC Berkeley TH Group has a Simple Goal

Transform the future of nuclear energy by enabling innovation

- Understand best practices of other technologies: biotech, commercial aviation, commercial space launch
- Leverage “best-estimate” methods to design and license advanced reactors that have passive safety
- Current focus: Accelerate the commercialization of the first reactors to use molten salts

FHRs have unique safety characteristics for accidents resulting in long-term off-site land use restrictions from Cs-137

	FHRs	LWRs
Low Cs-137 inventory	~30 g/MWe	~105 g/MWe
High thermal margin to fuel damage	T_{damage} > 1800°C	T_{damage} ~ 830 – 1250°C
High solubility of cesium in coolant	CsF has high solubility	Cs forms volatile compounds
Intrinsic low pressure	High coolant boiling temperature and chemical stability	High vapor pressure at accident temperatures

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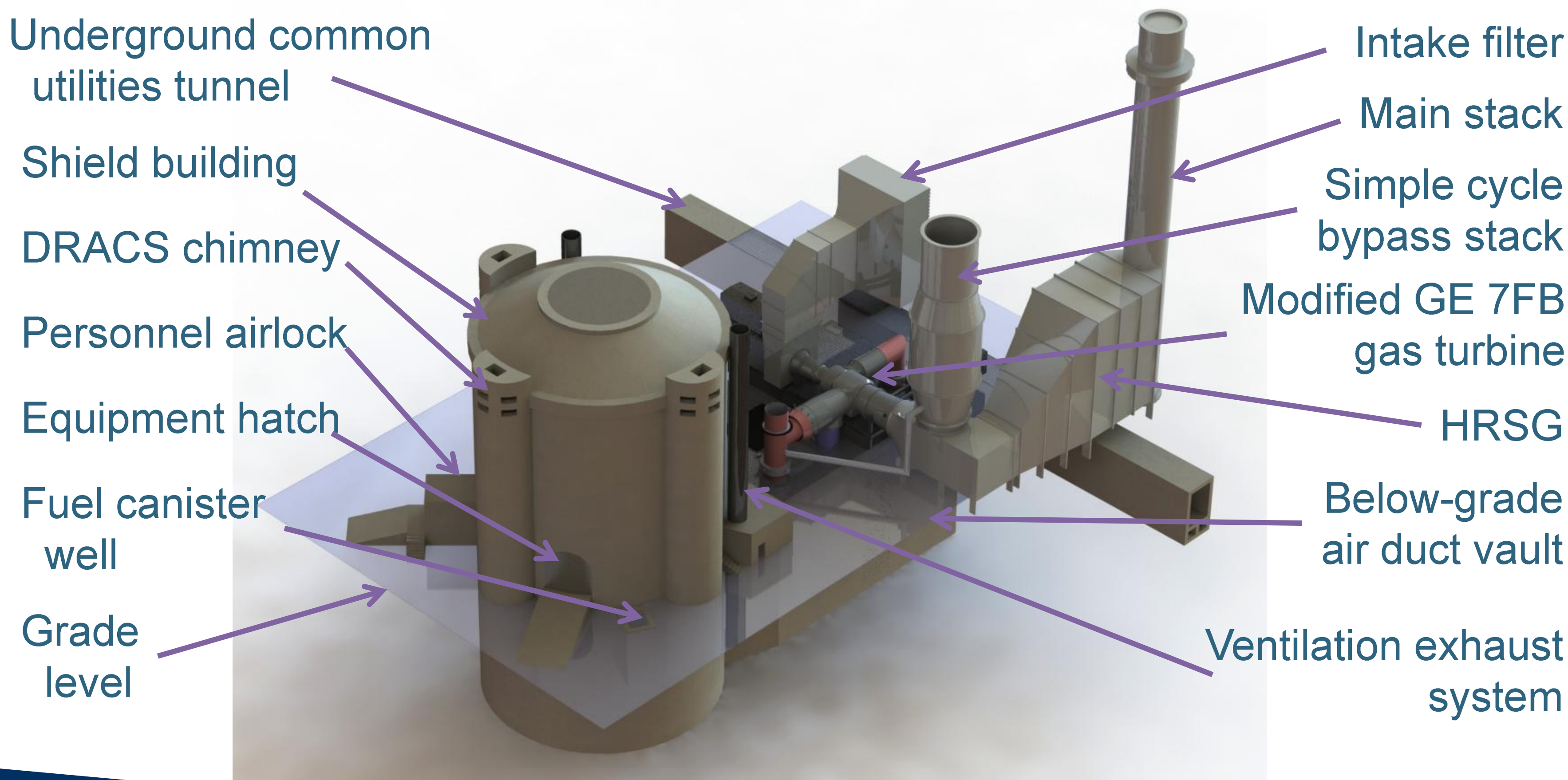
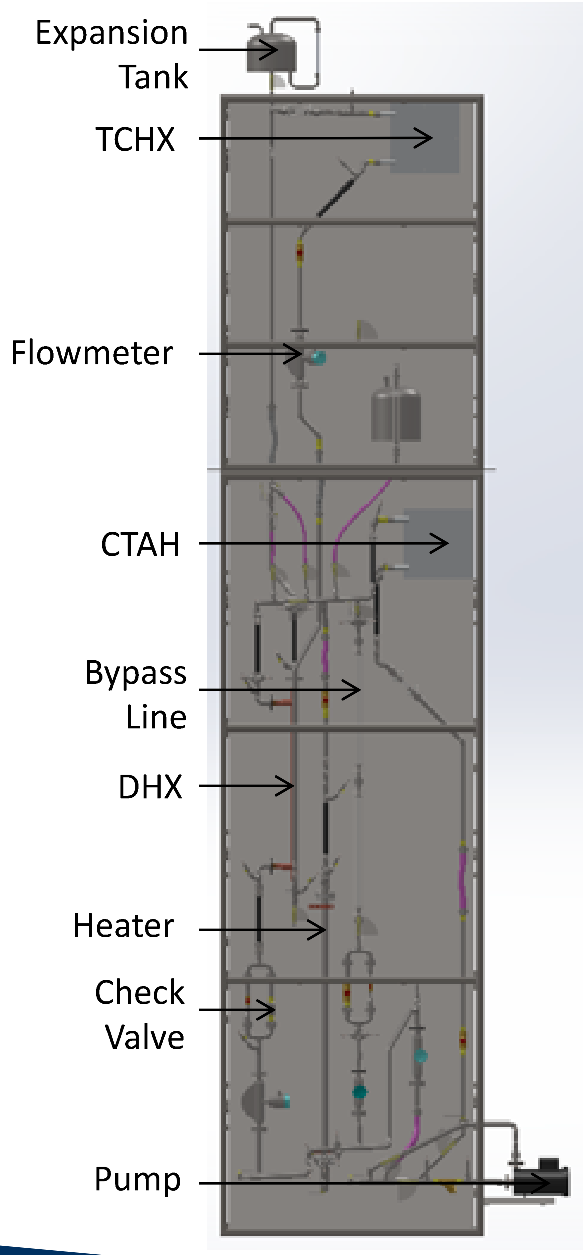
UCB graduate and undergraduate students developed the design for a Mk1 PB-FHR



CIET is the first molten salt Integral Effects Test

Test Plan Progress:

1. Measurement of solid masses and fluid inventory in the loop (focus on major systems for modeling)
2. Isothermal, forced circulation flow around the loop, with pressure data collection to determine friction losses in the system at various flow rates
3. Steady-state **single loop**/coupled natural circulation in the primary loop and the DRACS loop
4. Thermal transients: **startup, shutdown**, loss of forced cooling (LOFC) with scram and loss of heat sink (LOHS) with scram



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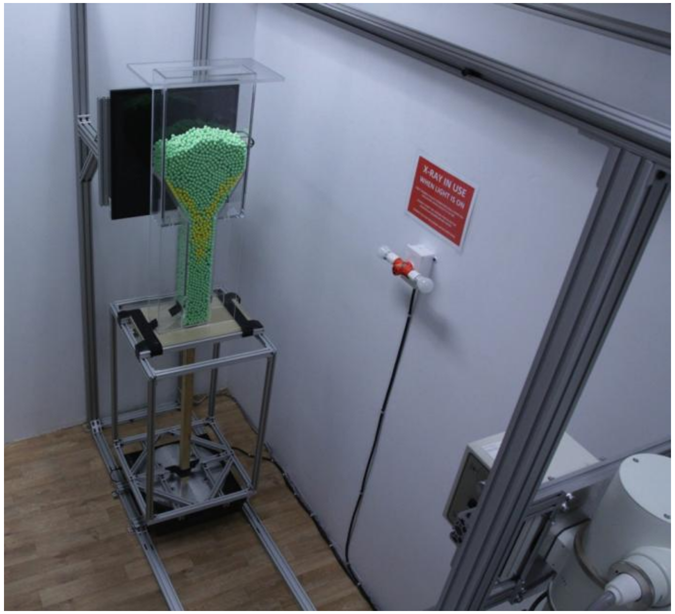
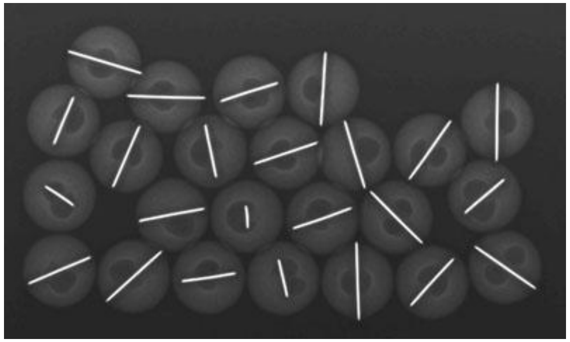
UCB is the first to solve basic science problems in granular flow of packed sphere bed

- X-Ray Pebble Bed Recirculation Experiment (X-PREX) research objective:
  - Generate validation data for discrete element simulations for slow, dense granular flow
- Instrumented polypropylene pebbles with tungsten wire inserts
- Digital x-ray tomography will generate translation and rotation motion data for ALL pebbles
- Facility is fully operational and data collection is underway



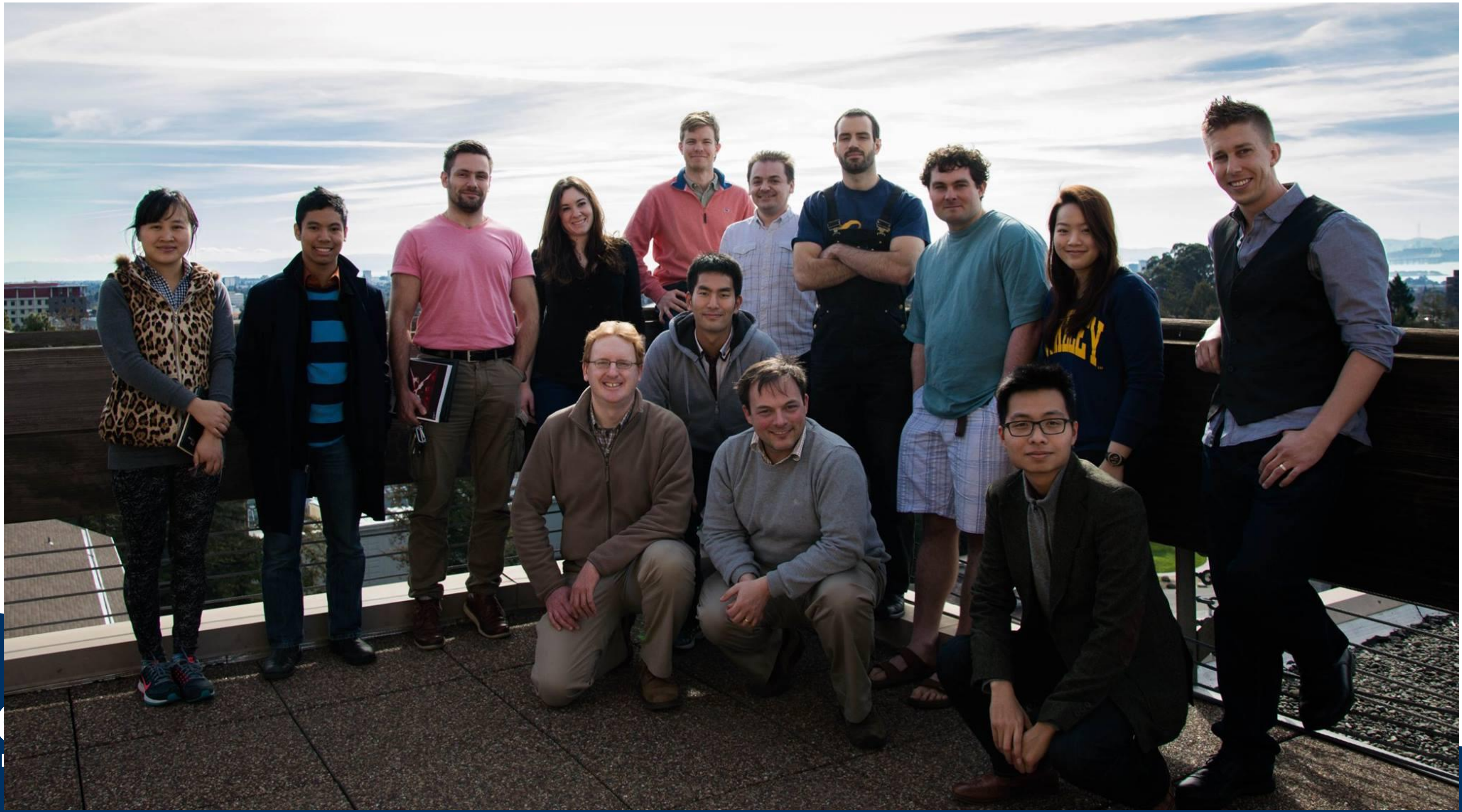
X-PREX Facility



X-Ray Image of Pebbles with Wire Insert

UCB Materials Group

Led by Peter Hosemann



NUCLEAR MATERIALS RESEARCH GROUP STRUCTURE

Peter Hosemann; Lead

Materials in extreme conditions

Environmental degradation	Radiation damage	Alloy development and synthesis, manufacturing
LWR: Investigation of refractory, F/M steels and SiC/SiC composite materials as LWR cladding; IASCC on alloy 304, 600, and 690 (core internals)	Mechanical properties of ion beam and reactor irradiated materials on all length scales. Plasma surface interaction, He, proton, heavy ion irradiations, etc.	Evaluation of new fabrication techniques, additive manufacturing, cold compacting, heat treatments, etc.
Gen IV: Advanced reactor and solar power applications. Investigation of liquid metal corrosion phenomena. Materials in extreme (cold or hot) temperatures	Microstructural characterization of ion beam and reactor irradiated materials APT, TEM , Synchrotron scattering, Neutron scattering	Technique and Instrument development Building of autoclaves Designing and testing new mechanical test devices and techniques

UCB Fuel Cycle Group

Led by Joonhong Ahn

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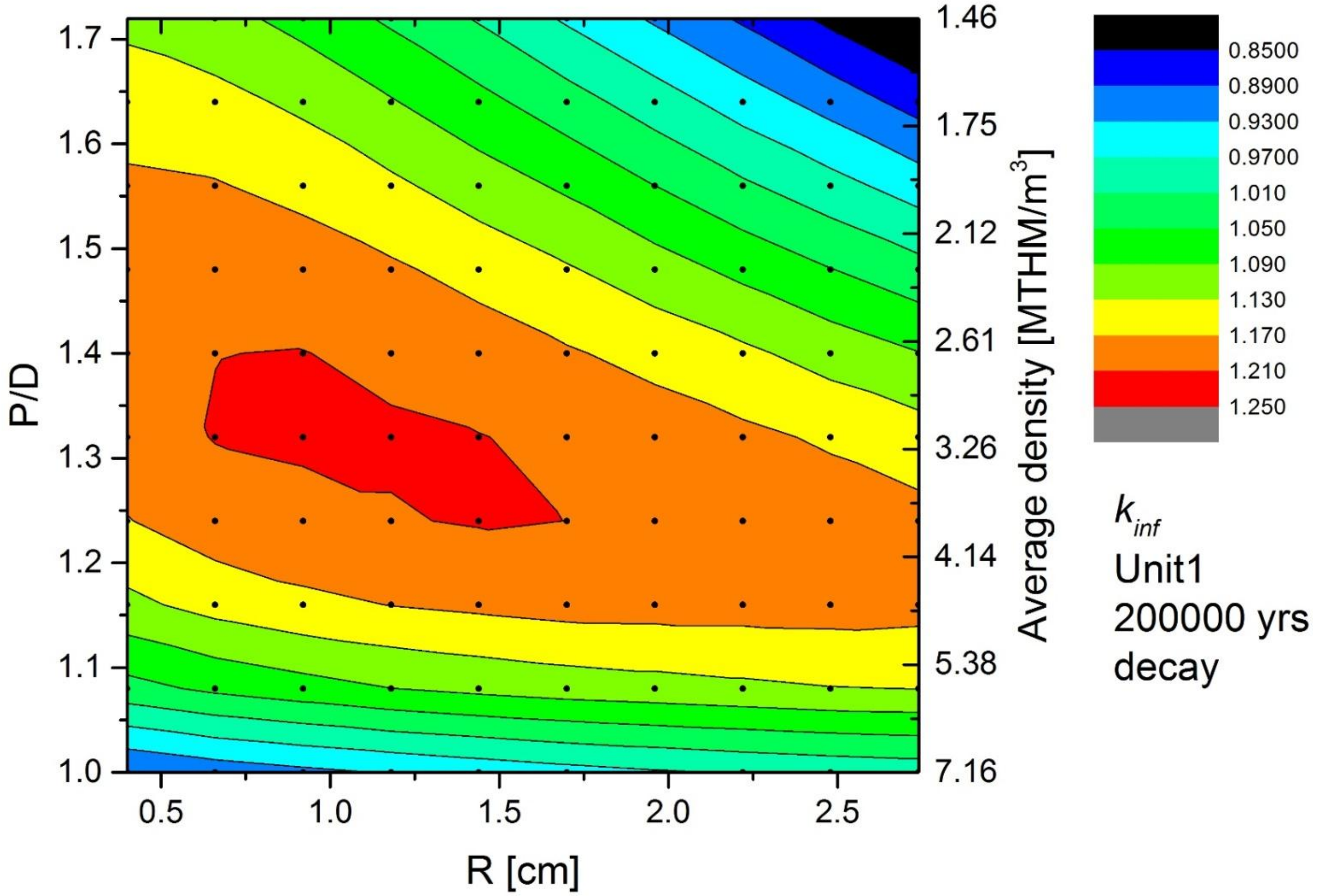
Research Projects (Engineering)

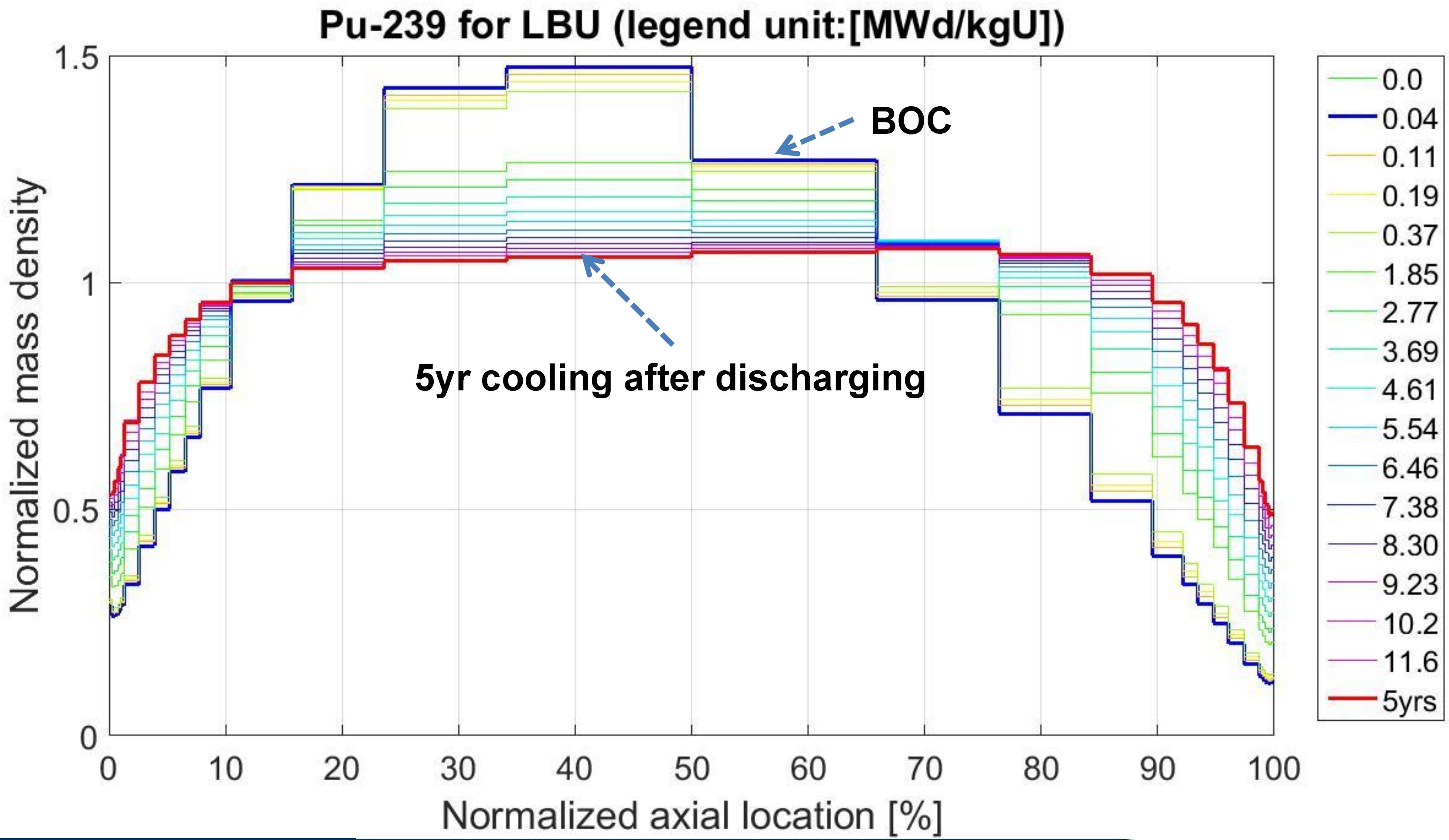
- Criticality Safety assessment for storage and disposal of Fukushima corium and LWR spent nuclear fuel (2011-2017)
  - Funding from JAEA ($100,000/year)
  - Mechanistic modeling for:
    - Release of fissile materials from multiple waste canisters in a repository
    - Transport and accumulation of fissile materials in a geological formation
    - Analysis for criticality with Thermal-Hydrological-Mechanical-Chemical-Neutronic coupling
- Systems analysis for pyro-processing (2008-2011; 2011-2015)
  - Funding from KAERI ($810,000 for 2008-2011 + $400,000 for 2011-2014)
  - Safeguards By Design for Pyroprocessing of spent fuel
    - Analysis of uncertainty in material accountancy due to non-uniformity in spent nuclear fuel
  - Radiological Safety Assessment for HLW from Pyro-Fast Reactor cycle
- Interim Spent Nuclear Fuel Storage (M.Eng. Capstone)
  - Development of a business model and outline of strategies for combining proven technologies in nuclear fuel storage with new ideas of how to site and operate a storage facility

Preliminary Results: k-inf

- Damaged fuels from Fukushima Daiichi Unit 1 after 200,000 years decay
- The k-inf contour largely remains the same, only slightly changes due to decay, indicating the criticality is dominated by the lattice parameters.

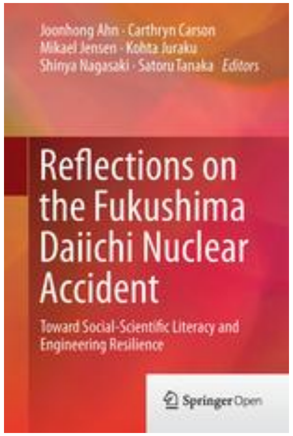


Change of axial Pu-239 distribution as a function of time



Research Projects (Social Responsibility)

- International Workshop on Nuclear Safety: From Accident Mitigation to Resilient Society Facing Extreme Situations (July 2014 – June 2016)
  - Funding from France Berkeley Fund ($10,000), Additional support from Center for Japanese Studies, UC Berkeley ($10,000), University of Tokyo ($10,000), and Mine ParisTech ($20,000)
  - Workshop held on March 22-24, 2015. A book has been published.
- International Symposium: Thoughts from a birthplace of atomic bombs after 70 years (April 2015 – March 2016)
  - Funding from Japan Society for Promotion of Sciences (JSPS)
  - An open symposium held at UC Berkeley in August 6-9, 2015 by inviting experts of various fields to provide various thoughts and observations on atomic bombing and evolution in both countries during the 70 years, not in a confrontational but reflexive/comparative manner



UCB Neutronics Analysis Group

Led by Max Fratoni

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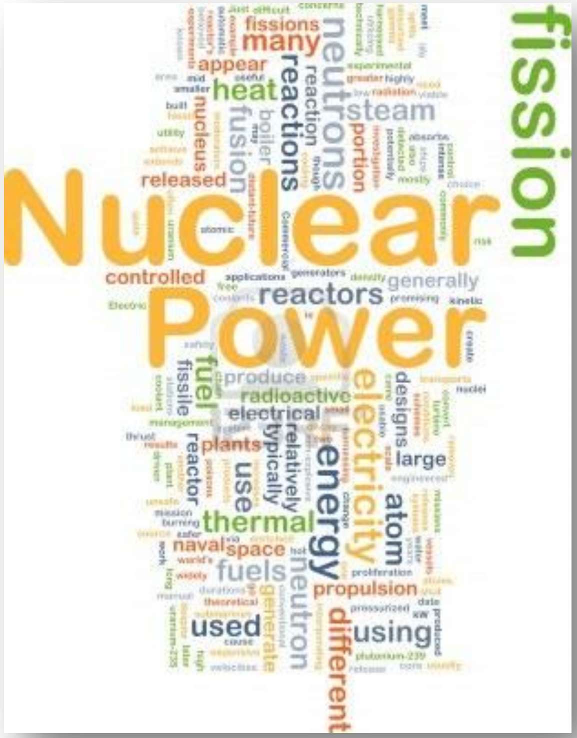
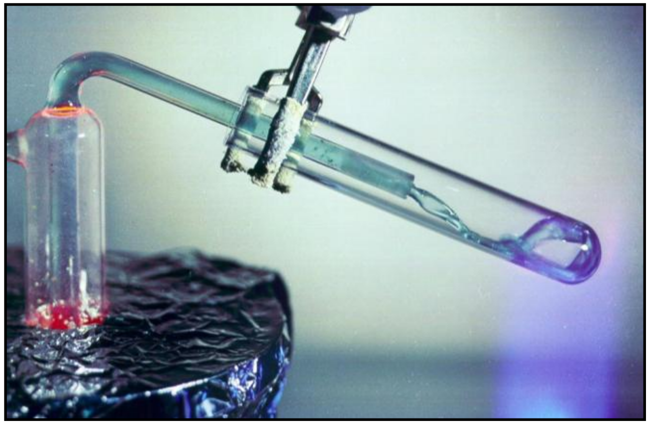
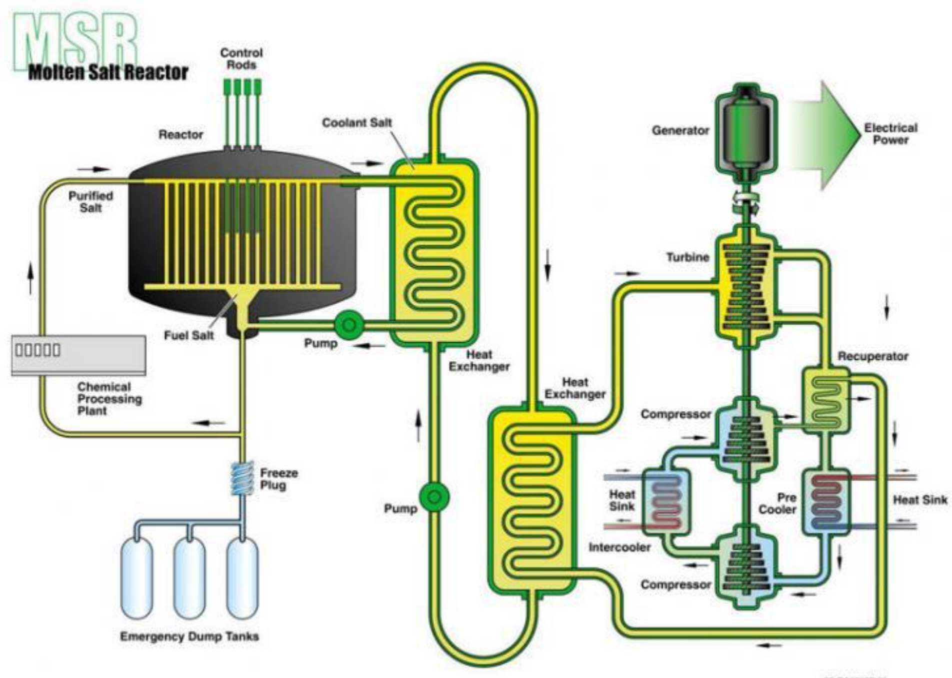
The main thrust of our research is nuclear energy sustainability

- Improving the sustainability of nuclear energy by
  - **increasing the utilization** of the uranium and thorium fuel resources
  - **minimizing** the amount and toxicity of the **nuclear waste**
- Improving proliferation resistance, economics, and safety of nuclear energy
- Support **light water reactor sustainability** through improved safety and performance
- Improving reactor modeling tools capabilities and accuracy



Molten Salt Reactor Technologies





Liquid fluoride salt coolants

Excellent heat transfer

Transparent, clean fluoride salt

Boiling point ~1400ºC

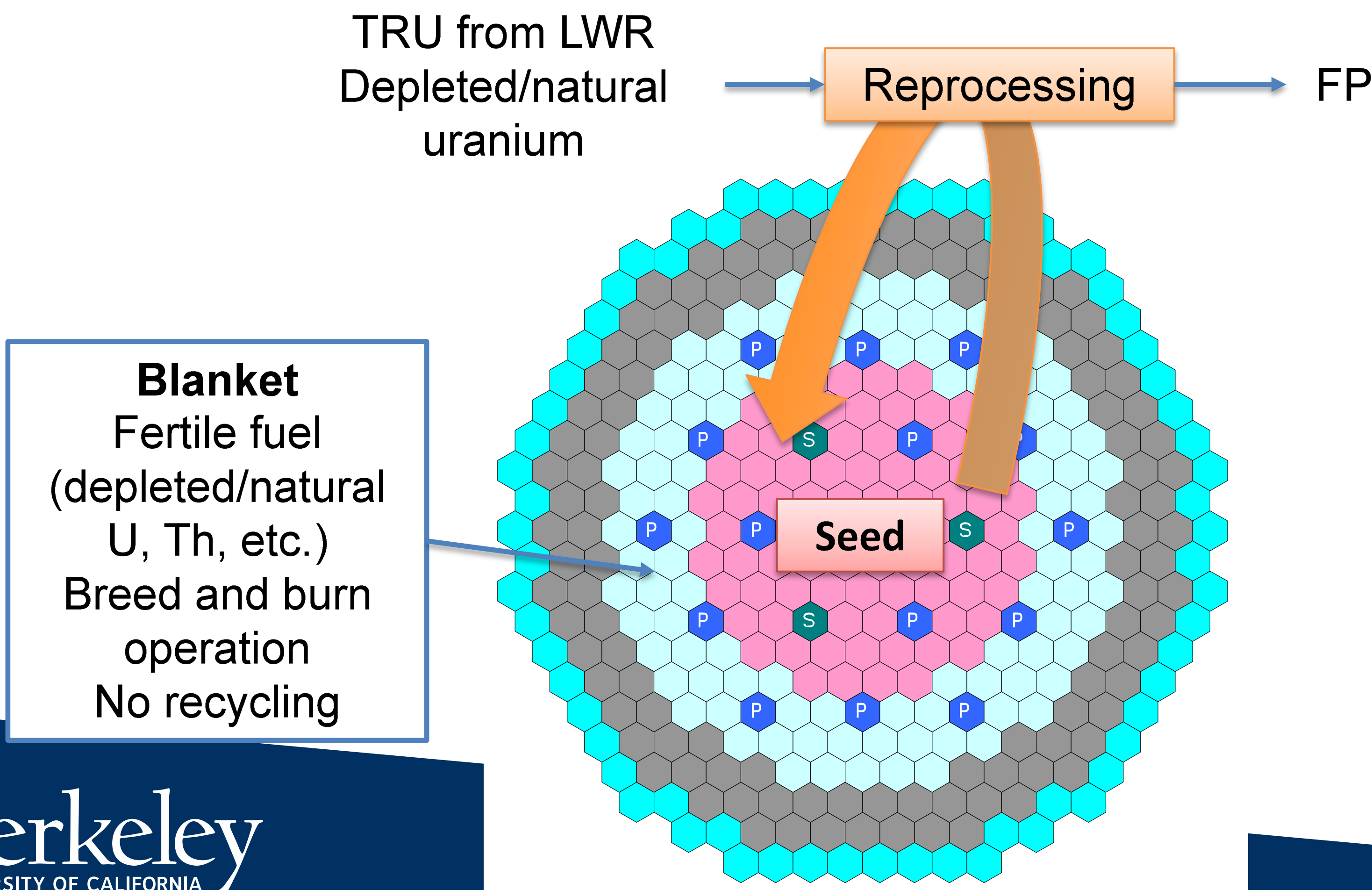
Reacts very slowly in air

No energy source to pressurize containment

<u>But</u> high freezing temperature (459°C)

<u>And</u> industrial safety required for Be

Seed & blanket core will enable breed & burn mode in the near term



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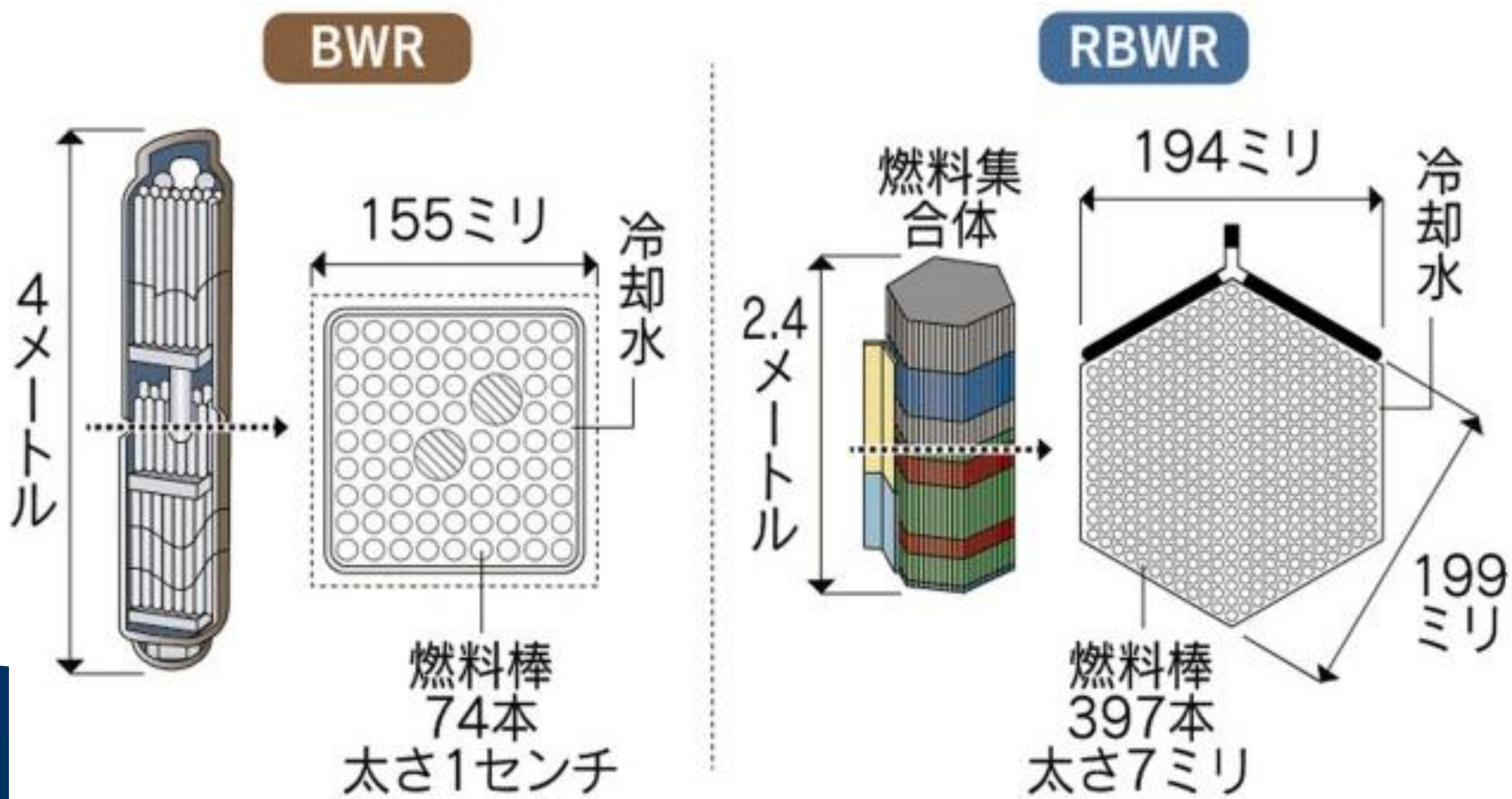
RBWR (resource-renewable BWR) is a light water breeding technology



Current major projects

- Molten salt reactors
  - Fluoride-cooled High Temperature Reactors (solid fuel)
  - Liquid fuel molten salt reactor
- Fast reactors
  - Breed and burn
  - Seed and blanket
  - Multi-tier fuel cycles
- Light water reactors
  - RBWR for transmutation
  - Accident tolerant fuels
- Methods
  - Multi-physics (Serpent/OpenFOAM, COMSOL)
  - Uncertainty quantification

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Nuclear Science Security Consortium

Led by Jasmina Vujic

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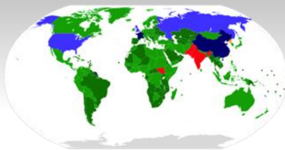
NSSC Overview

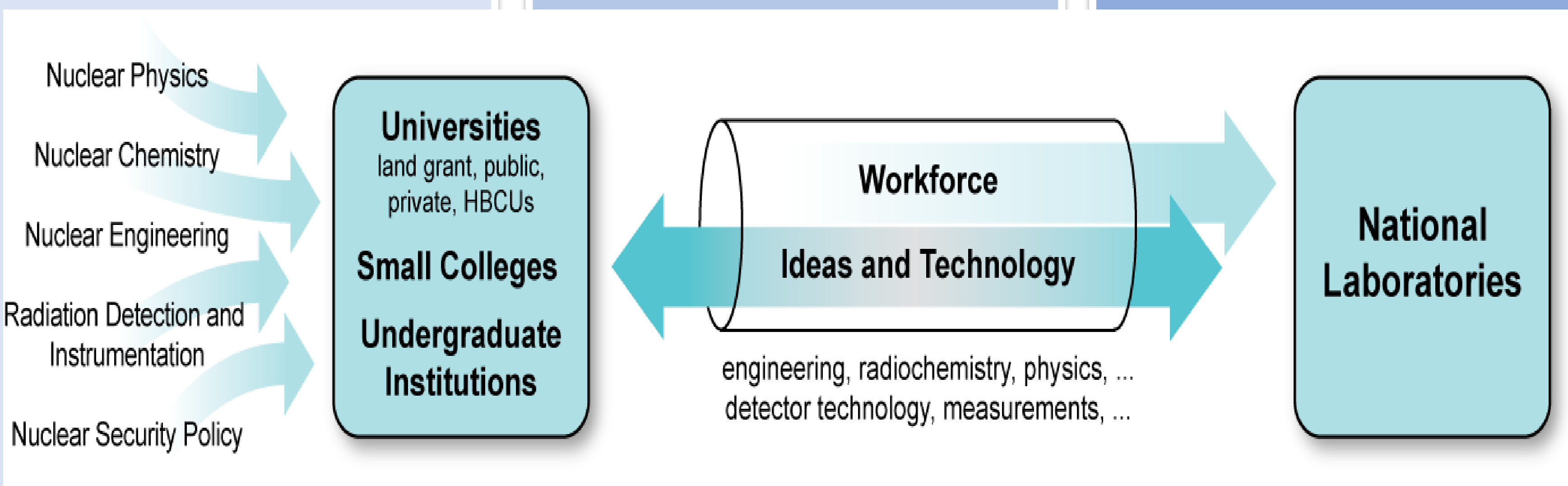
Science

Technology



Policy

PI:	Jasmina Vujic (UCB)
Exec. Dir.:	Karl van Bibber (UCB)
Deputy Exec. Dir.:	Michael Thoennessen (MSU)
Assoc. Dir.:	Bethany Goldblum (UCB)
Dir. For Labs:	Ed Hartouni (LLNL)
NNSA Liaison:	Kai Vetter (UCB-LBNL)



NSSC Status - Summary

- NSSC is running successfully at “full load” for 4.5 years
- More than 370 people engaged in NSSC-supported activities
- 25 NSSC students hired at national laboratories to date
- NSSC undergraduates are transitioning to NSSC graduate students
- Strong relationships between national laboratory scientists and students and post-docs working at national laboratories
  - NSSC PIs and students are collaborating with over 60 national laboratory scientists
- Successful summer schools held for three years in a row
  - 19 total summer schools delivered from 2012 - 2015
  - 6 NSSC supported summer schools planned for Summer 2015
- MSI process executed
  - 18 summer internship and scholarships for MSI students awarded
  - 29 research proposals received and reviewed
  - 5 MSI research proposals awarded

UCB Nuclear Data

Led by Lee Bernstein

Data Evaluation for Applied Nuclear Science (DEANS) Nuclear Physics in HED plasmas

Lee Bernstein; Lead

Nuclear Data Compilation & Evaluation

Students & Contract retirees compile & evaluate data from into the XUNDL and ENSDF databases hosted at the NNDC and the IAEA.
UG: M. Trudel, J. Labrum
Ret: R. Firestone, C. Baglin

Compilation, evaluation and modeling of (n,n') data from the "Baghdad Atlas" & ENSDF code development (w/ Slaybaugh)
J. Labrum (UG), I. Abramovic (Eindhoven)

Nuclear Data Measurements (w/Van Bibber, Goldblum, Bleuel)

Experiments at the HFNG on campus and the 88-Inch cyclotron @ LBNL
Personnel: L. Kirsch (G), A. Voyles (G), N. Nnamani (G), A. Lo (received M.S. spring 2015). LAB

Particle-gamma statistical properties measurements @ Oslo, ANL, LBNL (w/Oslo, iThemba & LBNL)
L. Kirsch (G), R. Firestone (ret.)

NIF/HED science (w/Van Bibber, Goldblum)

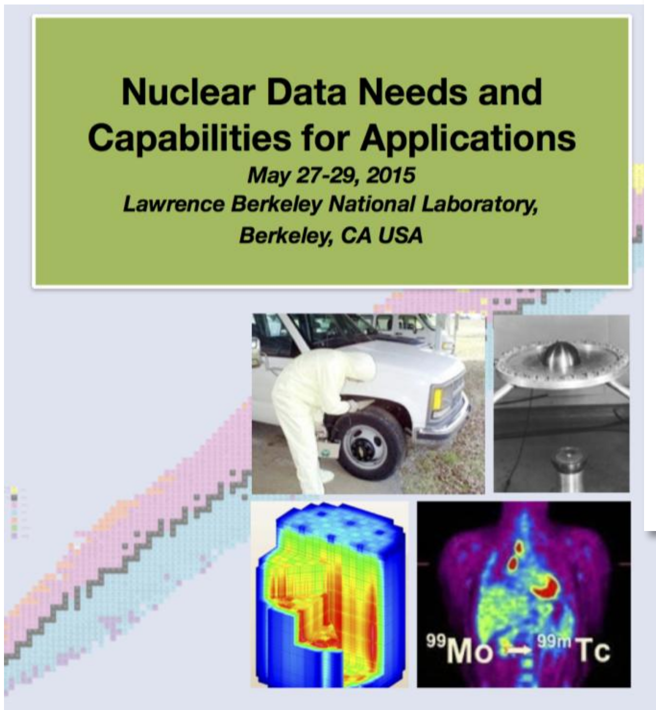
Student recruitment for NIF diagnostics and target engineering design groups & NTOF scintillator development (new LDRD-SI)
Personnel: J. Brown (G)
LAB, KVB, B.L. Goldblum

Nuclear Plasma Interactions

Experiments at the 88-Inch cyclotron, GEKKO-LFEX (Osaka), Omega (Rochester), NIF
A. Voyles (G). B.L. Goldblum

HIGHLIGHTS: Achievements in 2014/2015

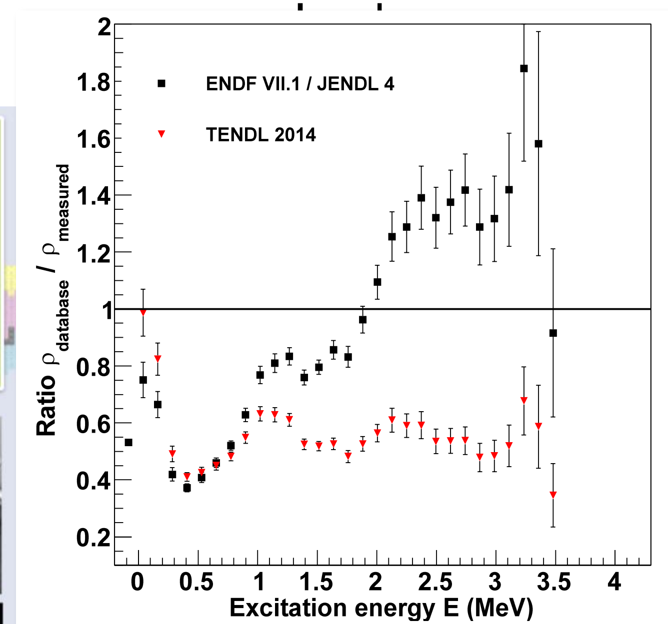
Led the first-ever joint DOE/SC-NNSA workshop on Nuclear Data Needs for Applications (NDNCA)



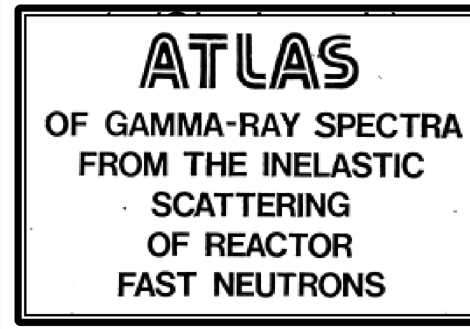
U.S. DEPARTMENT OF ENERGY | Office of Science

97 attendees from
4 program managers

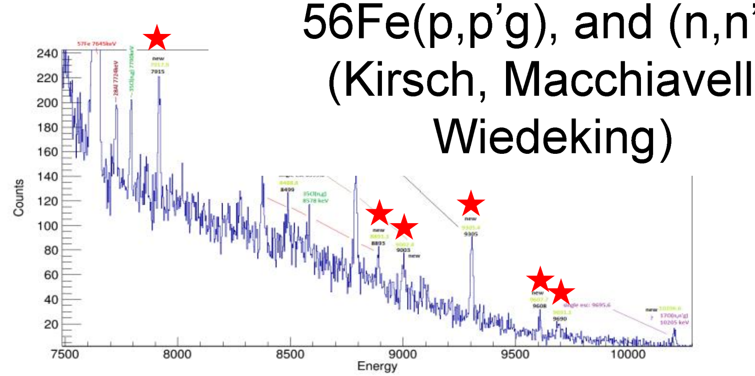
Measured Level Densities in ^{243}Pu (Bleuel, Younes,



Compilation & Modeling of the "Baghdad Atlas" data



56Fe(p,p'g), and (n,n'g) (Kirsch, Macchiavelli, Wiedeking)



Build A Pipeline

TRAIN the current and next generations through Bootcamps

SUPPORT companies through Innovation Centers

LEVERAGE public resources through GAIN

UPDATE Policy and Regulation to support innovation
TRANSFORM Communication

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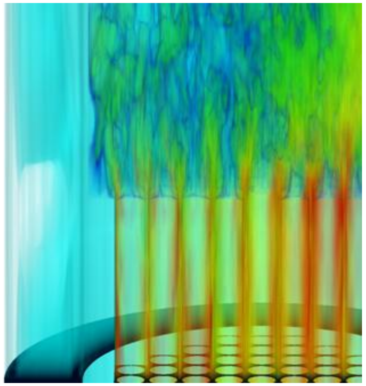
Nuclear Innovation Bootcamp

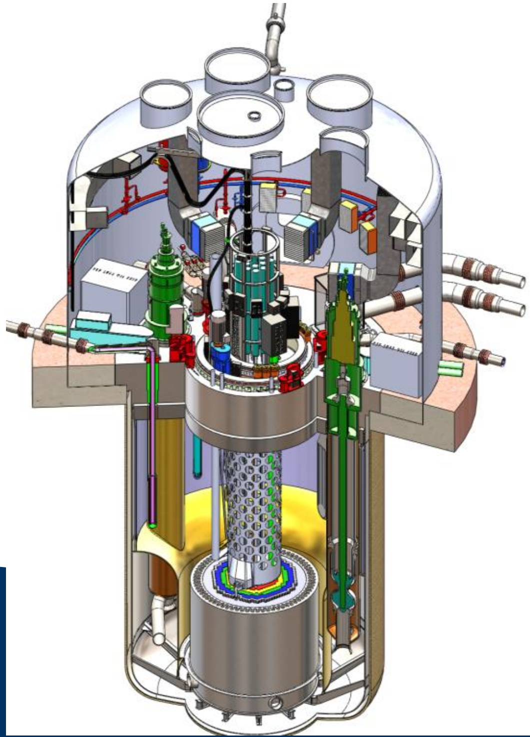
http://www.nuclearinnovationalliance.org/bootcamp

- Teach students *how* to innovate:
  - Entrepreneurship
  - Nuclear aspects
  - Non-traditional material
- Two week pilot program August 1-12
- Team design projects
  - Teams have non-technical member
- Large company involvement
- Experts teach and mentor
- Judged completion

Nuclear Innovation Bootcamp

- Full program Summer 2017
- Deeper content
- Expand to include professionals





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Opportunities for Involvement

- Suggest pre-program reading and project ideas
- Present your approach to innovation at the outset
- Provide or organize training in one of the course areas in the form of a one to several hour session, including Q&A either in person or via videoconference
- Serve as a subject-matter expert or continuous mentor: be (at least virtually) available as a resource throughout the program in a broad area or for a specific team
- Join us for the students' final presentations at the program conclusion, including the opportunity to provide feedback

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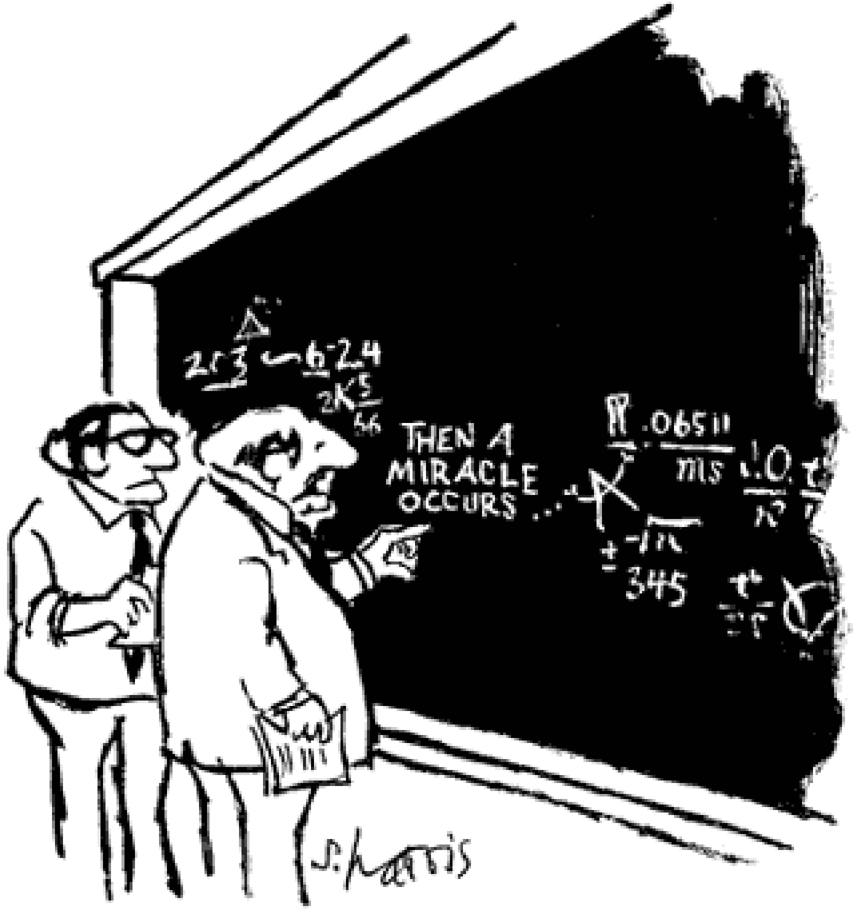
Summary

- UCB has expertise in
  - Computational and analytical neutronics
  - Nuclear materials
  - Thermal hydraulics
  - Nuclear data and physics
  - Detection
  - Fuel cycle design and analysis
  - Fusion
  - Nuclear Security
- And we're organizing the **first nuclear innovation bootcamp**

Questions?



"I think you should be more explicit here in step two."

Berkeley
UNIVERSITY OF CALIFORNIA

P.S. quality software required