U.S. MSR Development Programs & Supportive Efforts

and

Nuclear
Science
Technology and
Education for
Molten Salt Reactors

NEUP Nuclear Energy University Programs
U.S. Department of Energy

Adrien Couet – Assistant Professor
University of Wisconsin – Madison, USA

On behalf of Jean Ragusa, NuSTEM PI, Texas A&M

SAMOFAR Final meeting
Delft, July 5th, 2019

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Berkeley Nuclear Engineering
UNIVERSITY OF CALIFORNIA

NUCLEAR ENGINEERING
TEXAS A&M UNIVERSITY

U.S. MSR* Development Activities

- Include Government Support, Industry, and Regulatory Modernization:
- Department of Energy (DOE)-Office of Nuclear Energy (NE) MSR technical campaign continues into FY'19
  - Core R&D through national laboratories
  - University research (20% of campaign)
  - Small business opportunities
  - Gateway for Accelerated Innovations in Nuclear (GAIN) vouchers to provide private company access to national laboratory resources
  - Multiple industry awards
- Additional government activities are more broadly classified as support for advanced non-LWRs
  - Office of Science and Advanced Research Projects Agency (ARPA-E) projects
- Nuclear Regulatory Commission is developing a technology-neutral, performance-based, risk-informed regulatory framework

***MSR support includes both solid (aka FHRs) and liquid fueled concepts**

DOE-NE Molten Salt Reactor Campaign

Strategy:

Build understanding, establish priorities, and execute R&D activities that will accelerate industry deployment of Molten Salt Reactors.

- Focus areas:
  1. Identifying, characterizing, and qualifying successful **salt and materials** combinations for use in MSRs.
  2. Developing an integrated reactor performance **modeling capability** that captures the appropriate physics needed to evaluate plant performance over all appropriate timescales and license MSR designs.
  3. Establishing a national salt reactor **infrastructure and economy** that includes affordable and practical systems for the production, processing, transportation, and storage of radioactive salt constituents for use throughout the lifetime of molten salt reactor fleets.
  4. Licensing and safeguards framework development to guide research, development and demonstration.

Two Laws Passed Directly Relevant to MSRs

- **Nuclear Energy Innovation Capabilities Act of 2017 - Public Law No: 115-248 (09/28/2018)** https://www.congress.gov/bill/115th-congress/senate-bill/97
- DOE is instructed to (among other items):
  - Enhance its high-performance computation modeling and simulation techniques for advanced reactors.
  - Lead a program for testing of advanced reactor concepts (**including physical testing**), with a focus on removing licensing and technical uncertainty.
  - Submit a budget proposal to Congress to perform the above activities.
  - Develop an "Advanced Nuclear Energy Cost-Share Grant Program" to **assist in paying NRC licensing fees** for new reactor designs, including early stage activities such as development of a licensing plan.

Two Laws Passed Directly Relevant to MSRs

- **Nuclear Energy Innovation and Modernization Act - Public Law No: 115-439 9 (01/14/2019)** https://www.congress.gov/bill/115th-congress/senate-bill/512
- NRC is instructed to (among other items):
  - Develop and implement a staged licensing program (along with conceptual design assessments and licensing project plans).
  - Report on creating a new technology-inclusive regulatory framework for advanced reactor licensing – to be completed by 2027
  - Amending the Atomic Energy Act to allow research/test reactors to sell energy

Two Laws Passed Directly Relevant to MSRs

- NRC Has Begun the Process of Aligning Its Requirements With the Characteristics of MSRs
- Objective is to assure it can efficiently and effectively review advanced reactor license applications
  - Revisiting first principles: radionuclide retention, control of heat generation, control of heat removal
- Licensing Modernization Program
  - DG-1353 *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors*
  - NEI 18-04 *Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development*
- NRC Staff Recommended Policy Changes to the Commissioners
  - SECY-19-0009 – *Advanced Reactor Program Status*
  - *SECY-18-0103 – Proposed Rule: Emergency Preparedness for Small Modular Reactors and Other New Technologies (RIN 3150-AJ68; NRC-2015-0225)*
  - SECY-18-0096 – *Functional Containment Performance Criteria for Non-Light Water Reactor Designs*
  - *SECY-18-0076 – Options and Recommendation for Physical Security for Advanced Reactors*
  - *SECY-18-0060 – Achieving Modern Risk Informed Regulation*

Courtesy of D. Holcomb

Current DOE Thrust Areas

- MSR Modeling and Simulation
- Fuel Cycle Analysis
- Irradiations Campaign Initiated
- ThermoChemical Database
- Reactor Physics Benchmark
- Structural Materials

Current DOE Thrust Areas: Some Highlights

- Peer-reviewed Reactor Physics Benchmark for Molten Salt Technologies is Under Development
- DOE NE awarded an NEUP to UC Berkeley, in collaboration with ORNL and the Grenoble Institute of Technology (France), to create an MSRE benchmark (October 2016)
- The target is to create a benchmark for the International Reactor Physics Benchmark Experiment Evaluation Project (IRPhEP) handbook
  - peer-reviewed set of reactor physics-related integral data
  - used by reactor designers to validate analytical tools for advanced reactors
  - used by safety analysts to establish the safety basis for operation of advanced reactors

Dan Shen, Massimiliano Fratoni, Manuele Aufiero, Adrien Bidaud, Jeffrey Powers and Germina Ilas
ZERO-POWER CRITICALITY BENCHMARK EVALUATION OF THE MOLTEN SALT REACTOR EXPERIMENT
PHYSOR 2018: Reactor Physics paving the way towards more efficient systems
Cancun, Mexico, April 22-26, 2018

CURRENT DOE THRUST AREAS: SOME HIGHLIGHTS

Strategies To Address Structural Materials Issues For MSRs: programs started in ’18

Current metallic alloys permitted for the construction of elevated temperature Class A components contained in Section III Division 5 of the ASME Boiler and Pressure Vessel Code are limited:

First to Market Strategy

- Use ASME Class A material, 316H, and associated 16-8-2 chemistry weld metal

Near-Term Deployment

- Put clad on ASME Class A structural components with corrosion resistant materials

Long-Term Solution

- Develop Next-Gen structural materials with high temperature strength, salt compatibility, irradiation damage resistance (including helium generation from n,α reactions with thermal neutrons), resistance to fission products embrittlement, weldability, long term microstructural stability

To Accelerate Regulatory Acceptance

Regulatory Acceptance

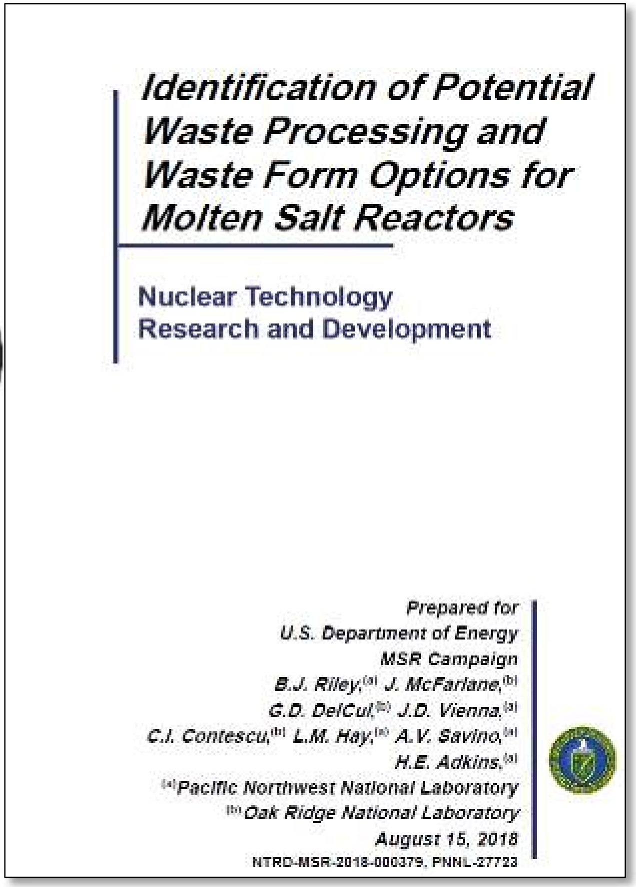
Develop Basis for In-Situ Passive Surrogate Materials Surveillance Program

Current DOE Thrust Areas: Some Highlights

MSR Waste and Effluent Management Evaluated

- Possible waste streams

- Descriptions of streams (estimates)
- Streams have challenges but potential routes for immobilization/disposal
- Storage, transportation, and disposal options
- Recommendations



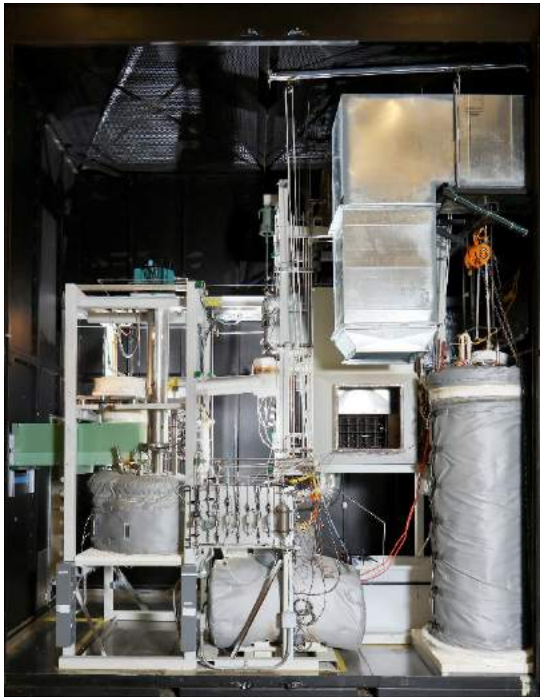
Identification of Potential Waste Processing and Waste Form Options for Molten Salt Reactors

Nuclear Technology Research and Development

Prepared for
U.S. Department of Energy
MSR Campaign
B.J. Riley,[a] J. McFarlane,[b]
G.D. DelCul,[b] J.D. Vienna,[a]
C.I. Contescu,[b] L.M. Hay,[a] A.V. Savino,[a]
H.E. Adkins,[a]
[a] Pacific Northwest National Laboratory
[b] Oak Ridge National Laboratory
August 15, 2018
NTRD-MSR-2018-000379, PNNL-27723

CURRENT DOE THRUST AREAS: SOME HIGHLIGHTS

FLiNaK and FLiBe loop completed and running:



ORNL Liquid Salt Test Loop (FLiNaK) Restarted in 2018

Forced Flow FLiBe Loop Thermal Image, Operating 2GPM, 700°C Hot Side, 650°C Cold Side University of Wisconsin - Madison

DOE-NE Industry Awards

2018:

- Modeling and Optimization of Flow and Heat Transfer in Reactor Components for Molten Chloride Salt Fast Reactor Application
  - Elysium Industries USA - $3,200,000
- Fluorination of Lithium Fluoride-Beryllium Fluoride (FLiBe) Molten Salt Processing
  - Flibe Energy & PNNL - $2,627,482

2015:

- Molten Chloride Fast Reactor (MCFR)
  - TerraPower, ORNL, EPRI, Southern, Vanderbilt - $40,000,000

Gateway for Accelerated Innovation in Nuclear

GAIN
Gateway for Accelerated Innovation in Nuclear

- Chemical Method Development for Quantifying Oxygen in Beryllium Salts
  - Kairos Power with ANL and ORNL
- Assessing Fuel Cycle Options for Elysium Molten Chloride Salt Fast Reactor from Spent Nuclear Fuel, Plutonium, and Depleted Uranium
  - Elysium Industries USA with ANL
- Electroanalytical Sensors for Liquid Fueled Fluoride Molten Salt Reactor
  - ThorCon with ANL
- Quantify Sodium Fluoride/Beryllium Fluoride Salt Properties for Liquid Fueled Fluoride Molten Salt Reactors
  - ThorCon with ANL

NUCLEAR ENERGY UNIVERSITY PROGRAM (18/19)

Structural materials development:

1. Development of Corrosion Resistant Coatings and Liners for Structural Materials for Liquid Fueled Molten Salts Reactors
   - University of Wisconsin - $800,000
2. Advanced Alloy Innovations for Structural Components of Molten Salt Reactors
   - University of Wisconsin - $800,000
3. Corrosion Testing of New Alloys and Accompanying On-Line Redox Measurements in ORNL FLiNaK and FLiBe Molten Salt Flow Loops
   - Georgia Institute of Technology - $800,000
4. Ni-based ODS alloys for Molten Salt Reactors
   - North Carolina State University - $800,000
5. Innovative In-Situ Analysis and Quantification of Corrosion and Erosion of 316 Stainless Steel in Molten Chloride Salt Flow Loops
   - University of Wisconsin - $800,000

Nuclear Energy University Program (18/19)

Thermochemical and thermophysical properties:

1. Understanding Molten Salt Chemistry Relevant to Advanced Molten Salt Reactors through Complementary Synthesis, Spectroscopy, and Modeling
    - University of Tennessee - $800,000
2. in situ Measurement and Validation of Uranium Molten Salt Properties at Operationally Relevant Temperatures
    - University of Connecticut (CFA-18-15065) - $799,979
3. Determination of Molecular Structure and Dynamics of Molten Salts by Advanced Neutron and X-ray Scattering Measurements and Computer Modeling
    - MIT - $800,000
4. Learning-based Computational Study of the Thermodynamic, Structural, and Dynamic Properties of Molten Salts at the Atomic and Electronic Scale and Experimental Validations
    - University of Illinois Urbana Champaign - $800,000
5. Understanding the Speciation and Molecular Structure of Molten Salts Using Laboratory and Synchrotron based In Situ Experimental Techniques and Predictive Modeling
    - University of Nevada Reno - $800,000

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Berkeley Nuclear Engineering

NUCLEAR ENERGY UNIVERSITY PROGRAM (18/19)

Fuel handling and technology development:

1. Development of an MC&A toolbox for liquid- fueled molten salt reactors with online reprocessing
   - University of Tennessee - $799,207
2. Used FHR Pebble Fuel Storage and Handling
   - University of California Berkeley - $800,000
3. Fuel Salt Sampling Technology Development
   - Vanderbilt University - $800,000
4. The Design and Investigation of Novel Mechanical Filters for Molten Salt Reactors
   - Abilene Christian University - $800,000
5. Modeling and Uncertainty Analysis of MSR Nuclear Material Accounting Methods for Nuclear Safeguards
   - The Pennsylvania State University - $800,000
6. A novel high fidelity continuous-energy transport tool for efficient FHR transient calculations
   - Georgia Institute of Technology - $800,000

Courtesy of D. Holcomb

INDUSTRY PROGRAMS

Three Vendors Have Announced Plans for Commercial US MSR Deployment by Early 2030s

TerraPower	Kairos Power	Terrestrial Energy USA
• Separate effects tests (now) • Integrated effects test (2019) • Test reactor – 30-150 MWth – Class 104 License (2023-2028) • Commercial prototype reactor – 600-2500 MWth – Class 103 License (early 2030s)	• Pre-conceptual design – March 2018 • Conceptual – December 2020 • Preliminary – Before 2025 • Detailed – Before 2030 • US demonstration by 2030 • Rapid deployment ramp up in 2030s	• Conceptual design – mid-2016 • Vendor phase 1 design review (Canada) – October 2017 • Vendor phase 2 design review (Canada) – 2020 (starting 4Q2018) • Commercialization before 2030

Nuclear

Science

Technology and

Education for

Molten Salt Reactors

NuSTEM Project Genesis

- FOA DE-FOA-0001515, August 2016

IRP-NE-1: **Grand Challenge Problem for Nuclear Energy**

- *Need for new specialists to become engaged in the nuclear technology field and to bring their creativity to innovate and expand the boundaries of our current knowledge is a key interest for many NEA countries*
- International engagement with OECD/NEA and its proposed *Nuclear Education, Skills and Technology (NEST) Framework*
  - *aimed at addressing important issues in the areas of nuclear skills capability building, knowledge transfer and technical innovation within an international context*
- *This IRP request for proposals is motivated by and supports the NEA effort and is intended to serve as a prototype for a potential larger effort to be undertaken through the NEST Framework.*

WE HAVE CHOSEN MSRS

DOE signs Gen-IV MOU on MSR, Jan. 2017

- Increased interest in MSRs at DOE, in the private sector, and internationally
  - DOE/Sinap CRADA (Cooperative Research and Development Agreement)
  - SAMOFAR (Euratom)

Pursuant to Section 7 of the Generation IV International Forum Memorandum of Understanding for Collaboration on The Molten Salt Reactor System Nuclear Energy System under which cooperation began on 6 October 2010 between the COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES and the EUROPEAN COMMISSION JOINT RESEARCH CENTRE, and to which ROSATOM and the PAUL SCHERRER INSTITUTE subsequently became Participants on 12 November 2013 and 20 November 2015 respectively, the UNITED STATES DEPARTMENT OF ENERGY is a new Participant from the date of signature hereunder:

FOR THE UNITED STATES DEPARTMENT OF ENERGY:

Ray Furstenau

Associate Principal Deputy Assistant Secretary
for the Office of Nuclear Energy

Date: 5 January 2017

Place: Washington, DC

TERRESTRIAL ENERGY
Flibe ENERGY
TerraPower
ThorCon Power
Transatomic Power
moltex energy safer, cheaper, nuclear
COPENHAGEN ATOMICS

NuSTEM: Mission statement

- To **enable and develop technologies needed for the advancement of molten salt reactors**
  - Deliver science and results to stakeholders (reports, publications, workshops)
- To **develop the next generation of nuclear energy/molten salt reactor experts** and inform and attract young people into science, technology engineering and mathematics for MSRs
  - Incorporate results into courses and curriculum development
  - Lack of continuity in R&D/workforce development for MSRs since the 1970s

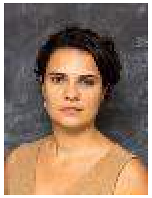
NuSTEM : Areas and Team Overview

Five research tracks:

1. **Material/corrosion science:**

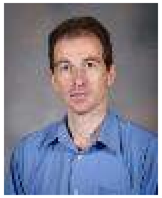


2. **Chemical Technology (Sensors and Waste Forms)**

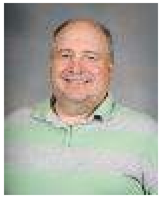


3.a Modeling and Simulation:





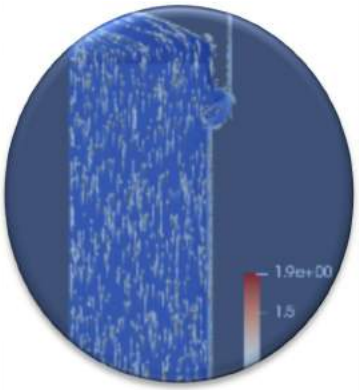

3.c Thermal-hydraulics:

One educational track

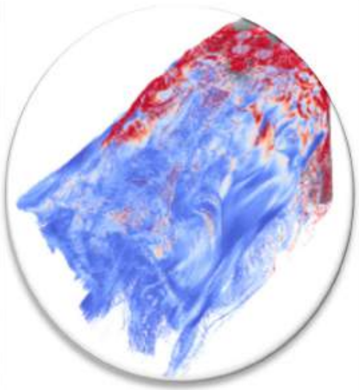
NuSTEM Students	
- Undergraduates	3
- Graduates	14
Add'l contributing students	26

NuSTEM Thrusts



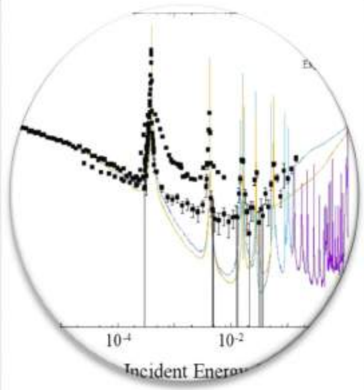
Modeling and simulation

- Develop tools/models for phenomena specific to MSRs
- Develop reduced-order models for rapid design optimization
- System performance and design optimization



Thermal-hydraulics

- V&V of computational CFD models
- Investigation of passive heat removal using heat pipes

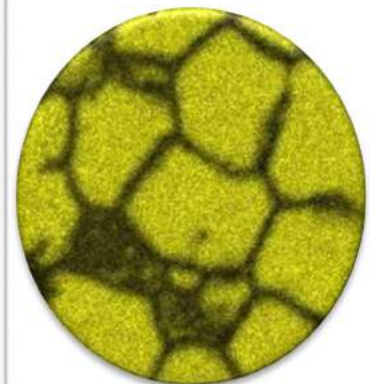


Cross section

- Measurement of Cl-35 (n,p) cross section reaction in the fast spectrum range

Chemical Technologies

- Development and demonstration of chemical and thermal sensors
- Sensor prototype built
- Manufacturing methods and materials for probe
- Waste stream characterization

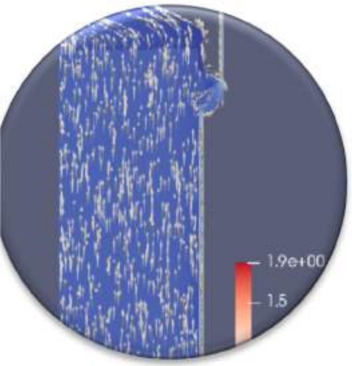


Materials and corrosion

- Corrosion testing with unirradiated and irradiated alloys
- Material characterization and optimization

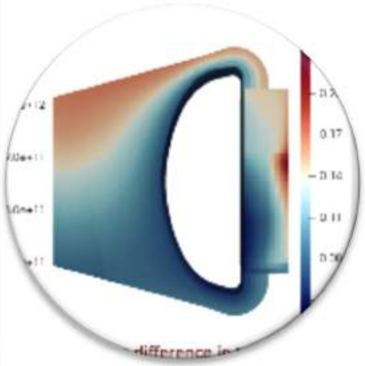
Education and training: development of human capital and expertise

DATA, MODELING & SIMULATION THRUSTS



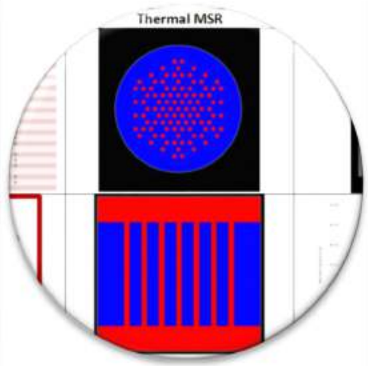
High-fidelity modeling

- Multiphysics model with Monte Carlo + CFD
- Reference solution



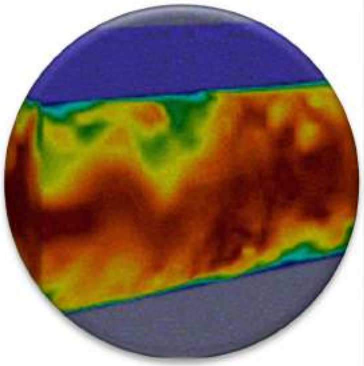
Reduced-order models (ROM)

- Develop ROM for multiphysics simulations of MSRs
- Transient analysis and UQ using ROMs



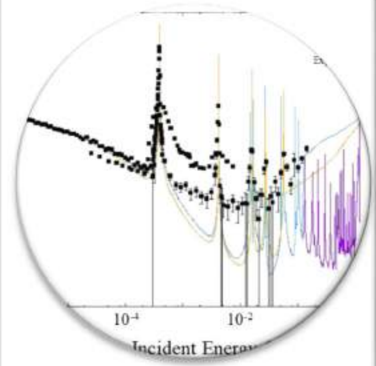
System analysis

- Performance analysis



Thermal-hydraulics

- Investigation of passive heat removal using heat pipes
- V&V of computational CFD models



Cross sections

- Cl-35(n,p) cross section the fast energy range

Enabling technologies for the design, analysis, and optimization of MSRs

HIGH-FIDELITY AND REDUCED-ORDER SIMULATIONS

- Molten salt reactors have unique features related to fuel form and motion that current (e.g., LWRs) code systems cannot model:

  Delayed neutron precursors drift
  Salt (fuel/salt) compressibility
  Radiative heat transfer
  Salt freezing

- **Goal/need**: Understanding such phenomena is necessary for a proper design and safety assessment of MSRs

- **Our approach**:
  - High-fidelity modeling tools based on first principles (due to lack MSR experimental data)
    - Can be very greedy in CPU time + memory

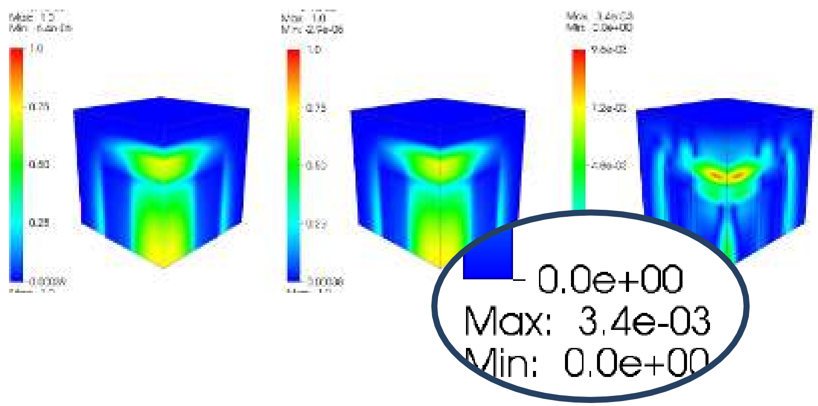
  GeN-Foam

  - Model-order reduction to significantly speed up simulations
    - Requires data produced from high-fidelity simulations to train reduced models
    - Enables faster design & scoping studies and Uncertainty Quantification

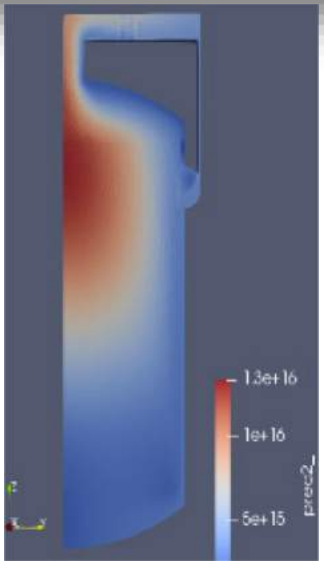
HIGH-FIDELITY AND REDUCED-ORDER SIMULATIONS

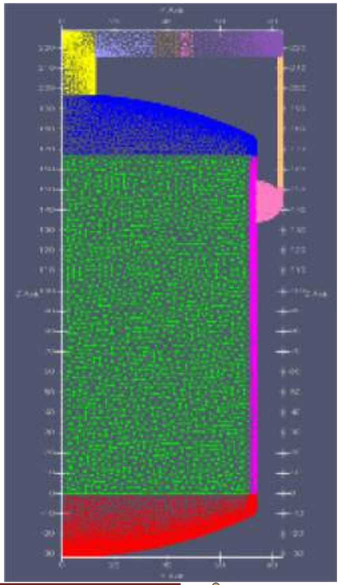
- Multiphysics modeling of delayed neutron precursor drift effect:
- 2000-6000x speed-ups with reduced order models:

FOM ROM Difference



- Joint Collaboration on models:
  - MSRE (UCB)
  - MSFR (TAMU)

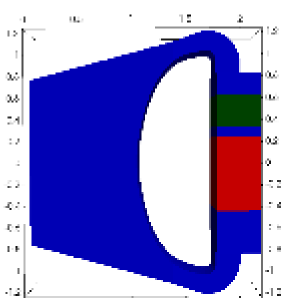




High-fidelity models
Max Fratoni
Jun Shi
Alex Christensen

Reduced-order models
Jean Ragusa
Peter German

Engagements
ORNL



Thermal-Hydraulics

Turbulence Modeling

- Motivation: Robust predictions for full MSR physics indirectly depends on accuracy of turbulence model in capturing those physics. Validation-worthy experimental data is not available.
- Goal: Conduct validation of turbulence models with backdrop of pertinent flow physics in MSRs.
- Approach: Generate DNS data sets for forced convection, internal heat generation, and buoyancy influenced conditions and perform validation of common RANS based models.

Passive Thermal Management Solutions

- Motivation: Increase the performance envelope of MSR systems through the utilization of a passive, robust, high performance heat transfer device.
- Goal: Demonstrate benefits of heat pipe utilization in MSR systems for both normal and off-normal operation.
- Approach: Identify key applications in a typical MSR environment where heat pipes find merit, and establish a toolkit to design and optimize those heat pipes.

THERMAL-HYDRAULICS

Results – Turbulence Modeling

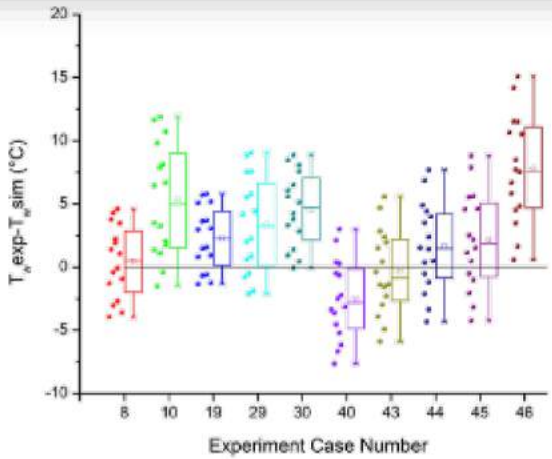
- Variations in RANS simulation results found to be almost exclusively due to uncertainty in material properties of salt (top right).
- Initial buoyancy-aided DNS (isothermal and non-isothermal) completed (far right).

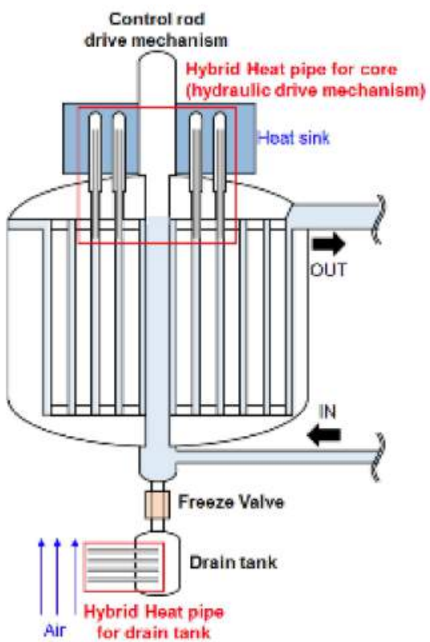
Results – Passive Thermal Management

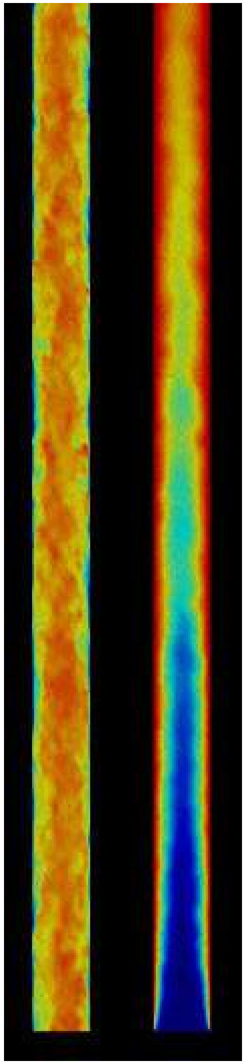
- Feasibility study completed with target applications identified (bottom right).
- Steady state modeling for heat pipes nearing completion with range of valid operation modeled.

Personnel

- Mark Kimber (co-PI, TAMU)
- Cable Kurwitz (co-PI, TAMU)
- Ramiro Freile (TAMU)
- Mohammad Bani Ahmad (TAMU)
- Gerrit Botha (TAMU), now at Advanced Cooling Technologies (ACT)







System Performance and Analysis

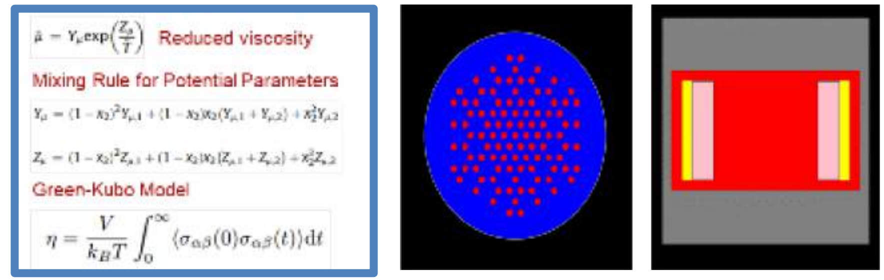
Goal: *Integrated design development and system optimization in support of MSR deployment*

Efforts: *System analysis & optimization framework, UQ Analysis accounting for salt properties, system design evaluations*

Accomplishments:

- Compiled salt property database
- Developed an approach to synthesize salt composition thermo-physical properties
- Assembled a set of reference MSR configurations
- Developed metrics for MSR analytics
- Completed preliminary sensitivity evaluations

Synthesis **Thermal** **Fast**



MSR in-core and primary HX dynamics system modeling

Personnel

- Pavel Tsvetkov (co-PI)
- Graduate students:
  - Dahvien Dean
  - Grace Marcantel
  - Nathan Moffett
  - Jonathan Scherr

Measurement of the ^{35}Cl(n,p) and ^{35}Cl(n,alpha)

- The ^{35}Cl(n,p)^{35}S and ^{35}Cl(n,α)^{32}P reactions were measured using quasi-monoenergetic neutrons from the High Flux Neutron Generator (HFNG).

- The cross-section for ^{35}Cl(n,α) agrees somewhat well with ENDF calculations.
- The ^{35}Cl(n,p)^{35}S cross-section is much lower than the ENDF/B-VII value.

- Structure is observed in the ^{35}Cl(n,p) reaction, consistent with a previously observed level at 11.24 MeV.
- This finding highlights the need for additional energy differential measurements to better understand reactions in this intermediate energy region.

- **Personnel**: Lee Bernstein, Jon Batchelder
- The project involved 5 graduate and 3 undergraduate students.
- The results have been published in Physical Review C, and input into EXFOR is in process.

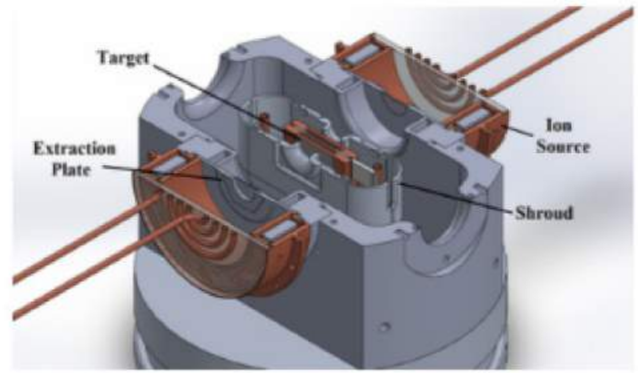
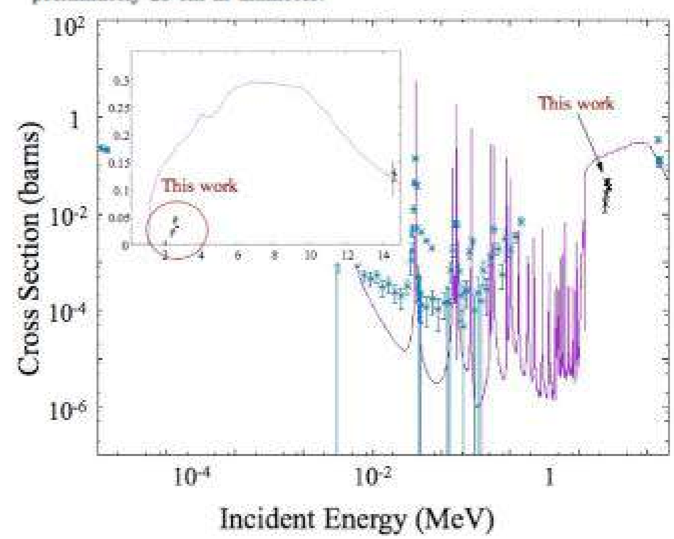
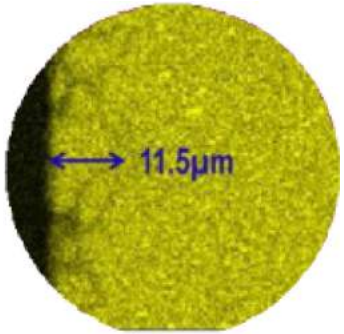


Figure 1. Cut-away schematic of the HFNG. The ion source is approximately 20 cm in diameter.

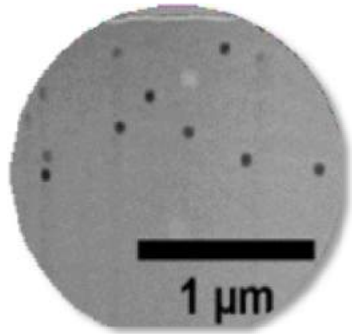


MATERIALS CORROSION AND IRRADIATION: MOTIVATION AND PHILOSOPHY



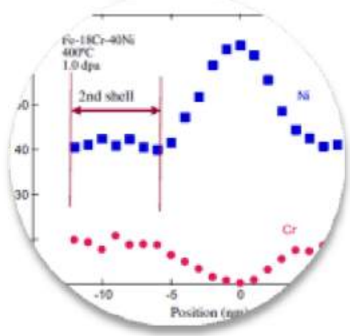
Corrosion Evaluation of Hastelloy-N

- Characterization of corrosion resistance in well controlled conditions
- Corrosion resistance in uranium bearing salts
- Demonstrate in-situ corrosion monitoring



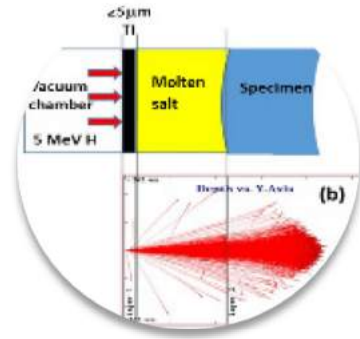
Void swelling study

- Irradiation resistance behavior of Hastelloy-N, A709, and 316SS at very high dpa using ion irradiation
- Simultaneous helium injection and self ion irradiation damage



Synergistic effect of corrosion and irradiation

- Effect of pre- irradiation on corrosion resistance of Hastelloy-N
- Focus on radiation induced segregation
- Cover larger experimental matrix for separate effects



Coupling of corrosion and irradiation

- In-situ irradiation effects on corrosion
- Radiation effect on surface corrosion mechanism
- Steady state behavior representative of MSR

Enhance the **understanding of materials performance** in MSR environments

Materials Corrosion and Irradiation: Broad Objectives

1. Evaluate corrosion performance and mechanisms of Hastelloy-N

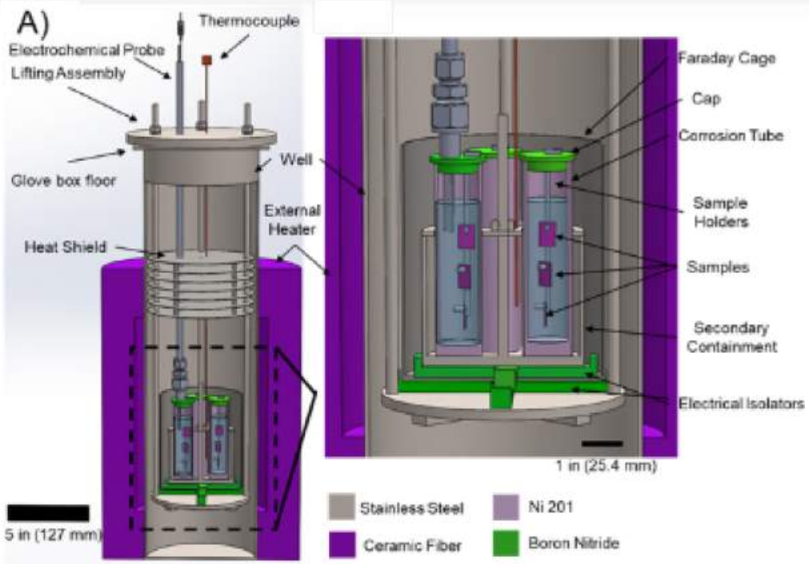
2. *In-situ* electrochemical monitoring of corrosion

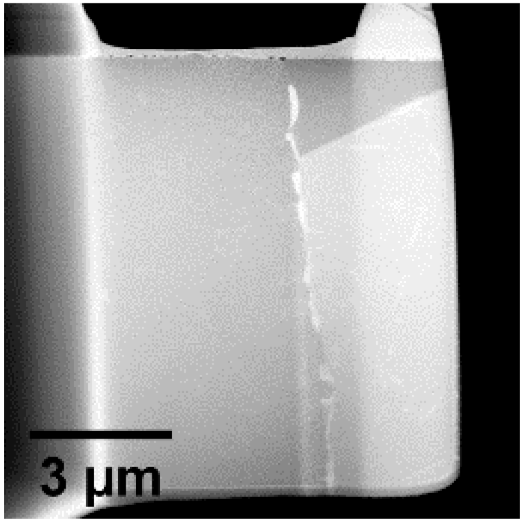
3. Enhanced understanding of dissimilar materials-induced corrosion and mass transport in fluoride salts

4. Effects of proton pre-irradiation on the corrosion of Hastelloy-N

5. Effect of irradiation on swelling and mechanical properties of Hastelloy-N, Alloy 709, 316 stainless steel

MATERIALS CORROSION AND IRRADIATION: HIGHLIGHTS



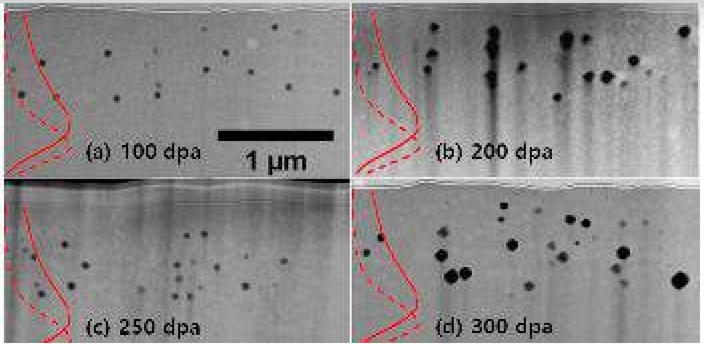


- Post Irradiation FIB sample of Hastelloy-N
- Mo enrichment, Ni depletion along GB (mechanism/analysis discussed in student talks)

- **Principle Investigators:**
- University of Wisconsin, Madison: Adrien Couet and Kumar Sridharan
- Texas A&M: Lin Shao, Frank Garner
- **Students:**
- University of Wisconsin, Madison: Cody Falconer (Principal student); Will Doniger, Evan Buxton (Supporting Students)
- Texas A&M: Aaron French (Principal Student), Hyosim Kim, Adam Gabriel, Andres Morell-Pacheo (Supporting Students)
- **Collaborations** (National Laboratory and universities): Oak Ridge National Laboratory, Idaho National Laboratory, MIT
- **Collaborations** (Industry): Haynes Corporation, Kokomo, IL (for alloys) & Materion Corporation, Cleveland, OH (for salts)

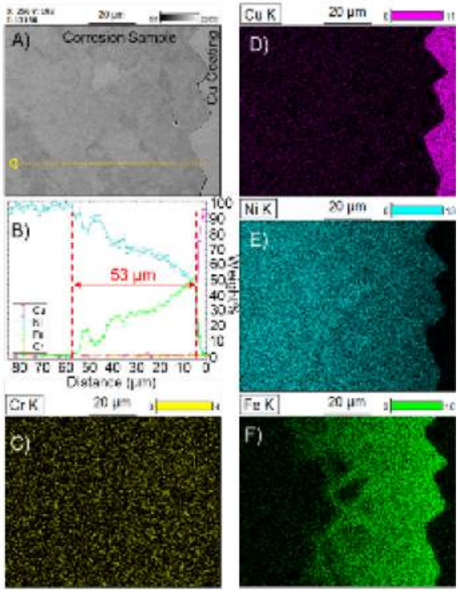
MATERIALS CORROSION AND IRRADIATION: HIGHLIGHTS

- Glovebox for controlling gas environment
- Ultra High purity Ar atmosphere
  - <1 ppm H_2O
  - <10 ppm O_2



- Void Swelling with increasing radiation damage for MSR alloys of interest

- Dissimilar Materials corrosion effects preliminary work



- Corrosion cells are functional

CHEMICAL TECHNOLOGIES

Waste Form Development

Sensors Development

Salt Characterization

Sensors and Chemical Analysis Workshop

Educationand training: development of human capital and expertise

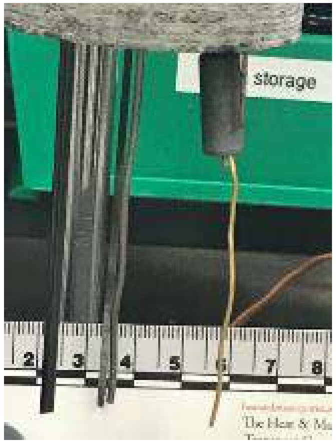
CHEMICAL TECHNOLOGY: CHEMICAL SENSORS

Motivation

- On-line, at-line, and off-line methods for characterization of salt composition and chemical state are limited.
- E.g.: oxide content quantification is a major challenge that impacts operations, and also impacts repeatability of experiments for corrosion and salt physico-chemical properties.
- Once a detection technique is demonstrated, sensor development efforts are an important step of technology transfer to MSR developers

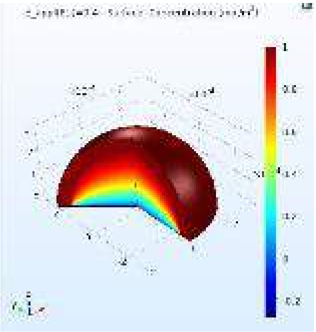
Goals

- Proof-of-principle operation
- Development of data interpretation algorithms
- Development of calibration methods
- Identification of operational environments and design constraints



Approach

- Focus is on oxide content characterization, as a case study problem
- Demonstrate viability of electrochemical method, in FLiBe
- Demonstrate viability of IR optical methods, in FLiBe
- COMSOL is used for chemical + CFD + thermal modeling to inform sensor design
- Generate salt sample library, and initiate round-robins for salt characterization with other groups



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Department of Engineering Physics UNIVERSITY OF WISCONSIN–MAD
Berkeley Nuclear Engineering

CHEMICAL TECHNOLOGY: WASTE FORMS

- ***Motivation:*** The advantages claimed for MSR waste production will only be realized if a credible waste immobilization/disposal pathway is established.
  - These must be MSR-specific.
  - Challenge to define without a well-defined "repository" specification.
- ***Goal:*** NuSTEM focus is on *fueled salt MSRs* where fission products are dissolved in the salt.
  - Presumes fission product (FP) generation during operation with batch removal.
  - Work will be primarily done with surrogate FPs in FLiBe. (FLiNaK may be considered later).
  - Selection of FLiBe principally due to its prominence as a fueled MSR Salt.
    - Financial support for waste form task only enables a single salt for primary experimental work.
- ***Approach:*** Immobilization of the various salt streams to create stable waste forms.
  - Calcining (oxidation), vitrification (glass), ion exchange, mineralization have been explored in the past.
  - Focus on calcination and mineralization methods.

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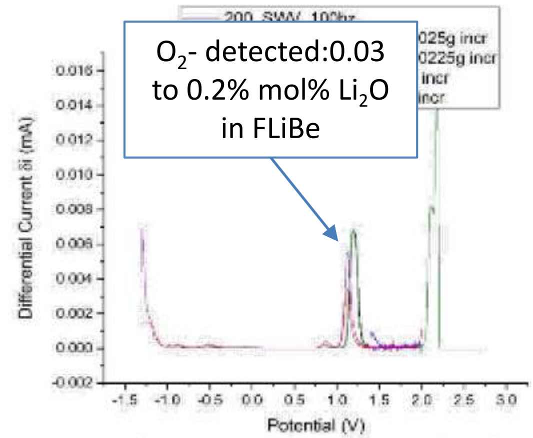
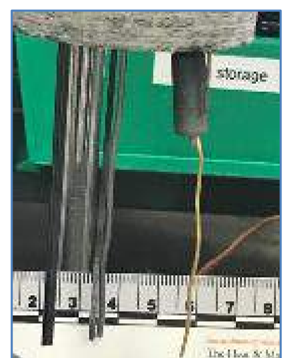
Chemical Technology Highlights

- Molten Salt Chemical Sensors:
  - Electrochemical detection of oxides in FliBe was successful.
  - Sensor design being supported by CFD/Electrochemical modeling.
- Salt characterization continues, as a joint UCB-TAMU effort.
- Waste Forms: Glovebox Workstation Established.
  - Safety protocols and equipment for Be and U handling.
  - Operations now underway to fabricate FLiBe and "loaded" FLiBe salts (not highly purified).

Investigators:
Raluca O. Scarlat, UC Berkeley
Sean M. McDeavitt, Texas A&M
Luis H. Ortega, Texas A&M

Student Participation:	
Primary Graduate:	3
Undergraduate:	8
Supporting Graduate:	4





Chemical Technology Highlights

EDUCATION : NUSTEM-SAMOFAR SUMMER SCHOOL

NEA Nuclear Energy Agency

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Molten Salt Summer Bootcamp

1-3 July 2019, TU Delft, Netherlands

- **Module 1**: Multi-physics modeling, safely, and licensing. Max Fratoni, Jean Ragusa, Pablo Rubiolo
- **Module 2**: Thermochemistry and thermophysical properties, electrochemistry. Ondrej Benes, Anna Smith, Raluca Scarlat.
- **Module 3**: Corrosion & experimental design. Waste conversion. Adrien Couet, Kumar Sridharan, Raluca Scarlat, Luis Ortega, Sean McDeavitt, Anna Smith, Sylvie Delpech.
- **Module 4**: Fuel Cycle & Separations and Mass Transport. Jiri Krepel and Pavel Tsvetkov.
- **Module 5**: Stability Analysis of Natural Convection Loop with Internal Heat Generation. Mark Kimber, Stefano Lorenzi and Antonio Cammi.
- **Poster presentations**: Monday
- **Capstone assignment**: due Wednesday

Education : NuSTEM-SAMOFAR Summer School

Capstone projects:

1. MSR in situ Salt Composition Observation using Raman Spectroscopy (MSR-SCORS)
2. Flow Measurements in MSRs
3. MSFR Fuel Comprehensive Characterization at different burn-up
4. Improving MBE Coatings for Corrosion Protection in Molten Salts
5. Proposed Method for In-Operando Fission Product Removal in Molten Chloride Fast Reactors
6. An investigation of solubility based extraction mechanisms and safety considerations
7. Stress Corrosion Cracking and Irradiation of Alloys in Chlorides
8. Additional Decay Heat Removal System (ADHeR) for MSR in Accident Condition
9. Real-time monitoring of neutron flux and heat generation inside MSR

MSR Workshop in ORNL

2019 Nuclear Innovation Bootcamp in PARIS

Concours Innovatome

+

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NUCLEAR INNOVATION BOOTCAMP

2017 Bootcamp
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=

Train students and early-career professionals in skills essential to accelerate innovation in nuclear energy through self-selected team projects and 6 modules focused on creativity, innovation and entrepreneurship

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