System Integration and Analysis Technical Area Overview

March 8th, 2023

Alexander J. Huning, Oak Ridge National Laboratory

Agenda

10:25 – 10:40 SIA overview	**Alex Huning**
10:40 – 11:10 Emerging markets for microreactors	David Shropshire
11:10 – 11:30 Development of a CRAB/MELCOR framework	Jason Christensen
11:30 – 11:50 Flexible Siting Criteria (NEUP – MIT)	Jacopo Buongiornio
11:50 – 12:10 Well-characterized micro-grid… (NEUP – UIUC)	Caleb Brooks
12:10 – 12:25 Emergency planning for transportation	Steve Maheras
12:25 – 12:30 Wrap up	

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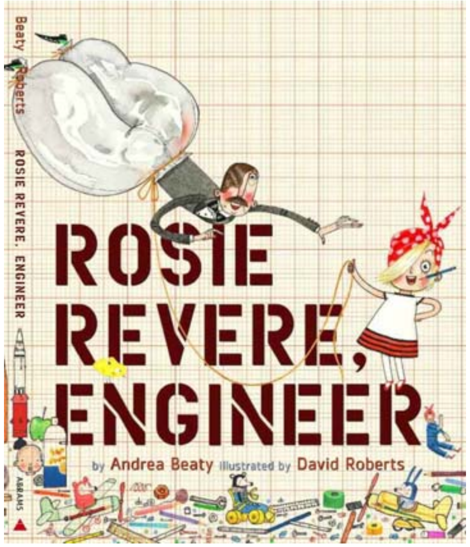
The dictionary is the only place where success comes before work.
– Mark Twain

The most certain way to succeed is always to try just one more time.
– Thomas Edison



The only true way to fail is if you quit.

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National Laboratory Team

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- Steven Arndt ANS
- Randy Belles

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Background

- **DOE Microreactor Program (MRP)** established to support R&D of technologies related to development, demonstration, and deployment of low-power, transportable reactors.
- Fundamental and applied R&D, to de-risk technology performance and manufacturing readiness.
- Key microreactor features:


Factory Fabricated


Transportable


Self-Regulating

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Scope

- **Systems Integration & Analysis (SIA)** – This scope will identify the needs, applications and functional requirements for microreactors through **market analysis** which will be used to drive future focus of the Microreactor Program toward **improving economics and/or viability of microreactors**. It will seek understanding of the microreactor design space by investigating innovative microreactor technology supporting concepts and will **perform regulatory research** to help develop the regulatory basis for microreactor deployments.

- **Key SIA areas of research:**

Efficient Regulations

Economic Viability

Analysis Tools

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Efficient Regulations

- 2019, NEI published a series of microreactor regulatory challenges:
  - Duration and cost of licensing microreactors / NRC review scope and level of effort
  - Operators / remote operations
  - Inspections / resident site inspectors
  - Emergency preparedness
  - Physical security
  - Aircraft impact assessment
- In response, NRC published SECY-20-0093 acknowledging these challenges, with the current state of stakeholder opinions and feedback received
- In 2021, NRC published a draft white paper on microreactor licensing strategies
- Many regulatory challenges remain, some maybe addressed through 10 CFR Part 53 development and associated guidance
  - NRC is open to some new limited rulemaking for microreactors, currently in planning stages
  - Still seeking more stakeholder feedback

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Efficient Regulations, continued

- Focus of SIA has been on “unique” (low-to-mid TRL) microreactor regulatory challenges
  - Manufacturing
  - Transportation
  - Emergency planning
- Several cross-cutting (micro- and large reactors), regulatory challenges appear to have **very little momentum despite significant interest** (lengthy NRC safety and environmental review processes, physical security)
  - No expectation for negotiation on a case-by-case basis either
  - **Licensing modernization** (Part 53 or other?) may offer ***some solutions*** through risk-informing low-hazard (low-power) reactor safety and environmental reviews
    - But what about **quickly deploying** a microreactor to a new location?
    - **Will local and state governments support microreactor deployments** and their unique operational aspects?

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Economic Viability

- Many of the regulatory challenges tie directly to economic viability (transportability, remote operations, review cost and licensing, etc.)
- Geography and regional conditions highly influence microreactor economic viability
  - Alaska, Wyoming are investigating microreactor deployment
  - Remote Canadian communities have significant interest
- District heating may be equally as valued as electricity
- Transportability offers unique advantages for other industries
  - Mining
  - Trona (chemical processing)
- University campuses exploring and planning for microreactor operations (ACU, UIUC)
- Strong DOD and space applications for small power systems

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Analysis Tools

- Many thermal hydraulic, neutronic, fuel performance, and other nuclear engineering analysis tools exist for design purposes… **MRP SIA focus is on tools which support safety and regulatory analysis** (reduces licensing uncertainty and accelerates deployment)
- Critical that all accident phenomena associated with the safety of the plant be modeled with **uncertainties appropriately documented and quality supporting data**
- Gaps and high uncertainty regions may necessitate additional data gathering (experiments)
  - Critical to identify these gaps and uncertainties in the design phase rather than during licensing
- Given the wide range of microreactor developers, technology experience levels, guidance on code usage, integration between codes, and application of the codes to safety analysis **will provide compounding benefits for these companies going into licensing**

FY23 Tasks and Status

Research Area	Task	Description
Analysis Tools	Development of a CRAB/MELCOR framework	(1) perform an assessment of potential microreactor safety analysis scenarios and (2) investigate CRAB tools for the identified scenarios highlighting any potential development needs, coupling challenges between CRAB and MELCOR
Efficient Regulations	Emergency Planning for Transportation	Identify and describe challenges associated with microreactor emergency planning during transportation
Economic Viability	Emerging markets for microreactors (Tasks 1 and 2)	Assess barriers and opportunities for microreactors with an initial focus on Alaska (AK) and Wyoming (WY) energy markets
	Cost Efficient-by-Design Microreactors (Task 3)	Evaluate functional containment aspects for microreactors and how this could result in economic optimizations

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Questions?

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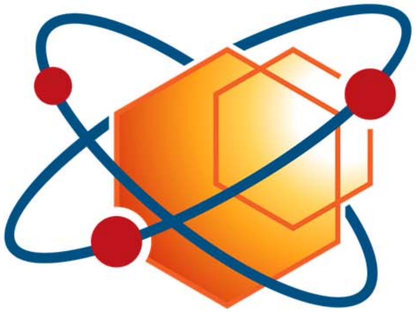

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Systems Analysis and Integration Microreactor Program Review

March 8, 2023

David Shropshire, Idaho National Laboratory

INL Idaho National Laboratory
OAK RIDGE National Laboratory
MRP Microreactor Program
Los Alamos NATIONAL LABORATORY
Argonne NATIONAL LABORATORY

Agenda

- Technical Area Background
- **Technical Area Developments**
  - Licensing and Transportation
  - **Market Analysis and Economic Optimization**
  - Systems Analysis and Source Term Tools
- Path Forward
- Discussion/Questions

FY23 (FY22 c/o) Activity: Market Analysis and Economic Optimization

- Task 1. An assessment of the opportunities and barriers for microreactors in emerging markets will be performed and reported.
- Task 2. A review of current and prospective state policies under consideration for carbon reduction will be evaluated and reported.
- Task 3. A cost reduction investigation will be evaluated on the microreactor system and structure through adoption of a functional containment approach.

Tasks 1 & 2 Updates

- Work is conducted as part of EMA, the Emerging Energy Market Analysis Initiative, led by the INL with collaborators from the U of Alaska, U of Wyoming, U of Michigan, MIT, and the Energy Policy Institute at Boise State University (BSU).
- Draft report (9/30/22) is currently being updated with inputs from the performing organizations.
- Project review conducted Jan. 30-31, 2023 at INL.
- Final report due 3/31/2023

INL/RPT-22-02756

Microreactor Applications in U.S. Markets

September 2022

Evaluation of State-Level Legal, Regulatory, Economic and Technology Implications

DOE Microreactor Program

ema
Emerging Energy Markets
Analysis Initiative

INL Idaho National Laboratory

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Program Highlight

Emerging Energy Market Analysis / Integrated Energy & Market Analysis

Collaboration with Universities to Support Microreactor Program

INL & University Partners meeting Jan. 30-31.

- The Emerging Energy Markets Analysis (EMA) initiative met to review research supporting the Microreactor Program and to strategize ways to help states like Alaska and Wyoming position themselves to attract the low-emissions industry as part of a regional-to-global strategy.
- The EMA team led by INL, is a collaboration with the University of Michigan (UM), University of Wyoming (UW), Massachusetts Institute of Technology (MIT), University of Alaska (UA), and Boise State University (BSU).
- The initiative is dedicated to advancing the understanding of energy market options as the work transitions to new clean energy futures.
- For more information about EMA visit: *https://ema.inl.gov/*

Left-to-right standing: David Shropshire (INL) ,Dr. Todd Allen (UM), Dr. John Parsons (MIT), Selena Gerace and Tara Righetti (UW), Alex Huning (Oak Ridge National Laboratory), Donna Kemp Spangler (INL).
Left-to-right seated: Richelle Johnson (UAA), Paul Kjellander (EMA), Dr. Steven Aumeier (INL), Marcio Paes Barreto (Wyoming Energy Authority) and Eugene Holubynak (UW)
Virtual attendance: Dr. Kathleen Araujo (BSU), Christi Bell (UAA), Cassie Koerner (BSU), and Jessica Lovering and Michael Craig (UM)

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Assessment of Barriers and Opportunities for Microreactors

- Includes an assessment of the opportunities and barriers for microreactors in emerging markets, including applications in energy-intensive industries, e.g., urban fueling nodes, mineral extraction, chemical processing (Trona), etc.
- Initial focus is on Alaska (AK) and Wyoming (WY) energy markets serving location-specific energy needs for electricity and heat.
- Methods include literature review and expert and stakeholder elicitations.
- Research seeks to define key preconditions for microreactor deployment including economic, environmental, workforce, government intervention/regulatory, and tax revenue implications.
- Topics include:
  - Energy System Changes and Energy-Intensive Developments (led by Boise State)
  - Wyoming Market Assessment (led by U Wyoming)
  - Interior-Alaska Market Assessment (led by U Alaska)
  - Economic Assessment of Market (led by MIT)

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Review of Carbon and Nuclear Policies

- Federal and State Policy Focus.
  - Current and prospective state policies (50 states), emphasizing Alaska and Wyoming, with a focus on Renewable Portfolio Standards, Clean Energy Standards, carbon-reduction targets, and nuclear adoption/extension support.
- Carbon Policies/Carbon Targets.
- Nuclear Adoption/Life Extension Support.
- Research on Energy Transition.
  - Uses methods including interviews and focus groups to assess industry awareness of- and sensitivity to- carbon governance including carbon regulations, carbon markets, ESG (Environmental, Social, Governance) disclosures, procurement requirements, supply chain or contract provisions.
  - Research seeks to identify which areas of carbon governance have the most impact on state industries and to what extent industries are motivated to make new investments to decarbonize. Analysis will identify informational requirements, barriers, and opportunities for microreactor applications in established state industries.

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Future Study Areas

- Define MR capabilities (mobility, etc.) to support specific types of industries (e.g., Trona mining in WY) and operate within existing energy systems.
- Identify strategies for low-carbon transition, including interim planning in advance of MRs availability in the market.
- Explore public perceptions on nuclear energy to determine how stakeholders/decision maker's value and prioritize issues important for MR deployment.
- Explore new markets, particularly in the oil and gas industry and mining applications that can tap funding streams in recent passed laws (IRA, IIJA, CHIPS, DPA, etc.).
- Assess key areas in regulatory space related to licensing a facility, access to and interconnection with the grid or ability to sell excess power in deregulated markets.
- Additional study areas forthcoming in March 31 report (TBD).

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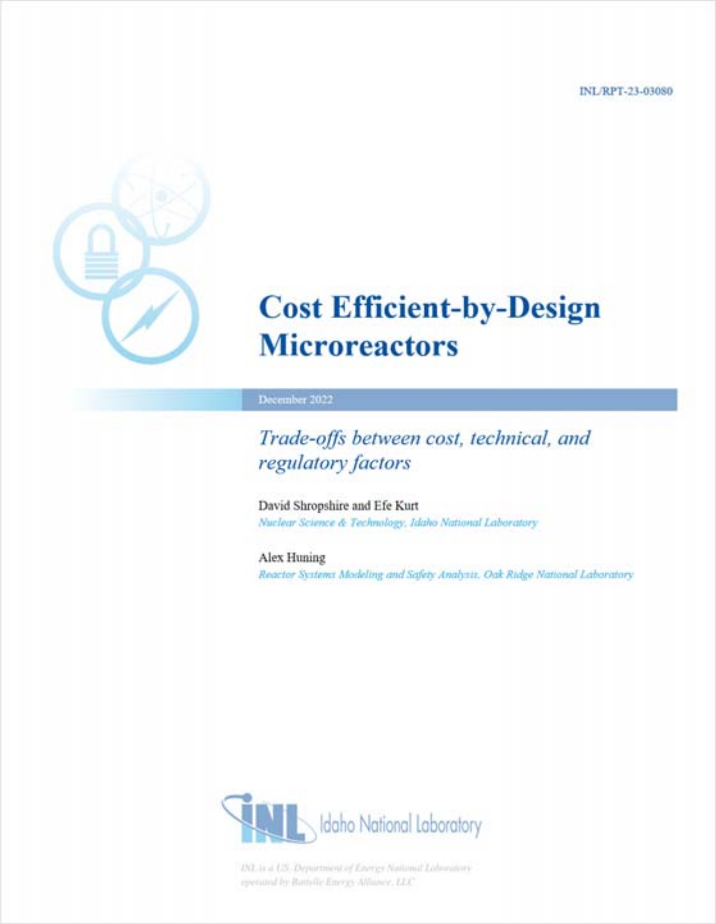
Tasks 3

- Final report submitted 12/30/2022
- Technical reviews conducted and final report was submitted to PICS.



INL/RPT-23-03080

Cost Efficient-by-Design Microreactors

December 2022

Trade-offs between cost, technical, and regulatory factors

David Shropshire and Efe Kurt
Nuclear Science & Technology, Idaho National Laboratory

Alex Huning
Reactor Systems Modeling and Safety Analysis, Oak Ridge National Laboratory

Idaho National Laboratory

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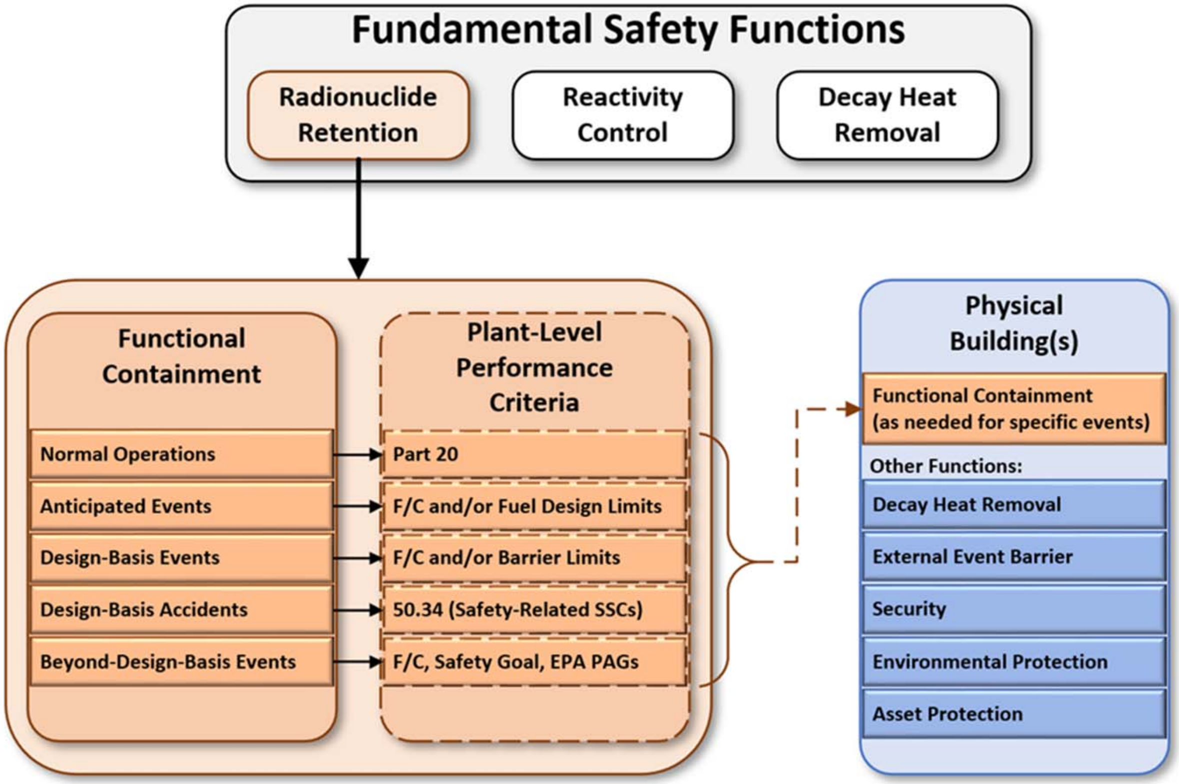
Functional Containment



Fundamental Safety Functions

- Radionuclide Retention
- Reactivity Control
- Decay Heat Removal

Functional Containment

- Normal Operations → Part 20
- Anticipated Events → F/C and/or Fuel Design Limits
- Design-Basis Events → F/C and/or Barrier Limits
- Design-Basis Accidents → 50.34 (Safety-Related SSCs)
- Beyond-Design-Basis Events → F/C, Safety Goal, EPA PAGs

Plant-Level Performance Criteria

Physical Building(s)

Functional Containment (as needed for specific events)

Other Functions:

- Decay Heat Removal
- External Event Barrier
- Security
- Environmental Protection
- Asset Protection

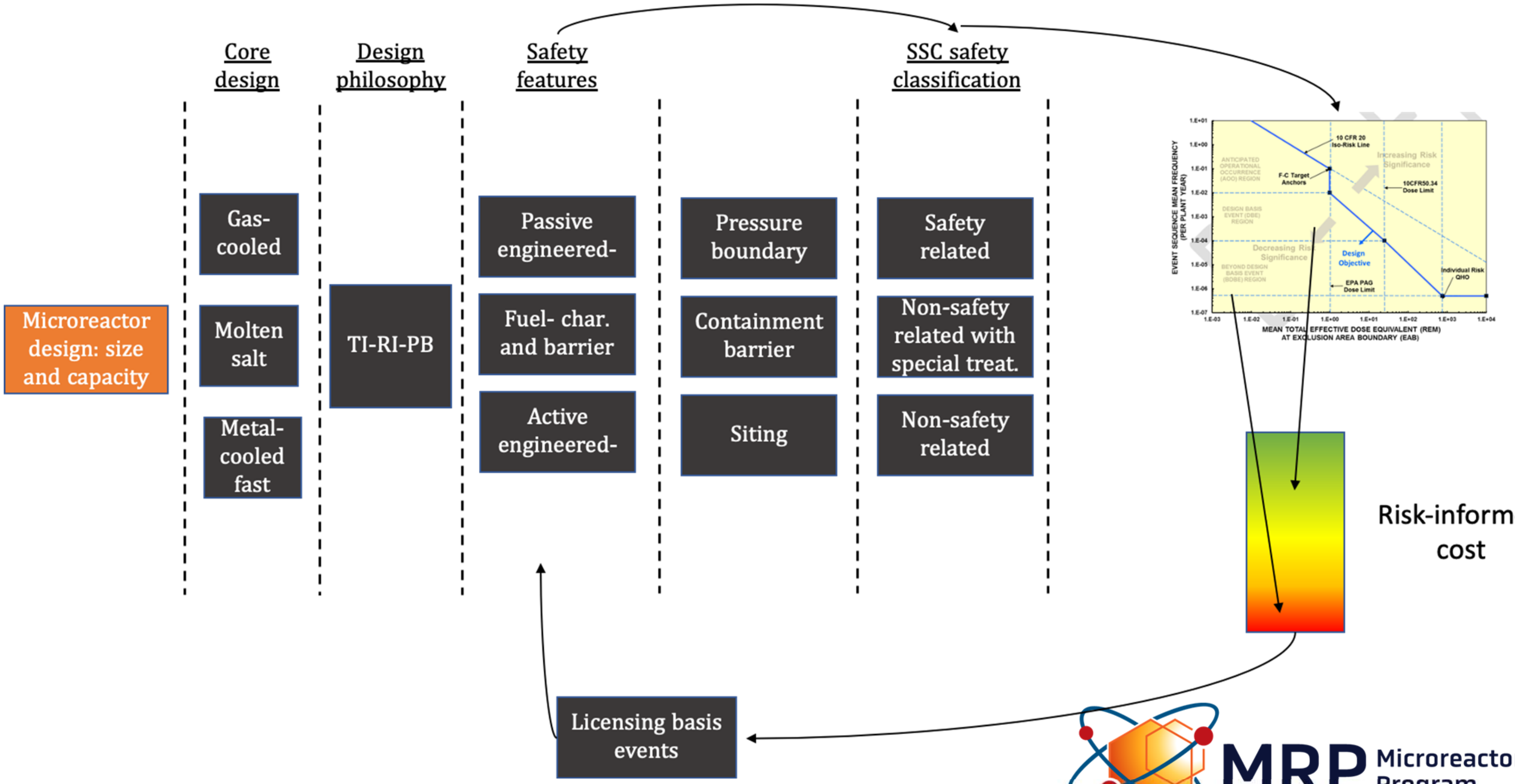
Note: F/C refers to frequency/consequence targets

Functional Containment design is based on a technology-inclusive, risk informed, and performance-based (TI-RIPB) approach:

1. Establishes objective criteria for evaluating performance,
2. Develops measurable or calculable parameters for monitoring system and licensee performance,
3. Provides flexibility to determine how to meet the established performance criteria in a way that will encourage and reward improved outcomes,
4. Focuses on the results as the primary basis for regulatory decision making.

The risk insights from a probabilistic risk analysis (PRA) also form the basis for identifying and setting up decisions regarding anticipated operational occurrences, design-basis events, and beyond-design events.

Possible economic benefits from functional containment



Microreactor design: size and capacity

Core design

Gas-cooled

Molten salt

Metal-cooled fast

Design philosophy

TI-RI-PB

Safety features

Passive engineered-

Fuel- char. and barrier

Active engineered-

Pressure boundary

Containment barrier

Siting

SSC safety classification

Safety related

Non-safety related with special treat.

Non-safety related

Risk-informed cost

Licensing basis events

Functional containment economic evaluation approach

- Different microreactor technologies were analyzed and assessed based on their safety systems, release fractions, and radionuclide release rates. Generic dose and radionuclide dispersion calculations were performed for:
  - GCRs,
  - MSR (liquid fuel),
  - Heat Pipe Reactors.
- For all technologies at very small capacities, e.g., 1 MWt, the microreactors would be unlikely to challenge any limits on radiological release during an accident.
- GCRs using TRISO fuel have the lowest “worst case” or bounding release from the fuel.
- MSRs and HP microreactors can particularly benefit from using a functional containment approach to improve safety performance.
- A systematic approach is recommended for further evaluation of microreactor specific conditions to determine potential benefits from various design options (e.g., stack and exhaust fans, embedment).

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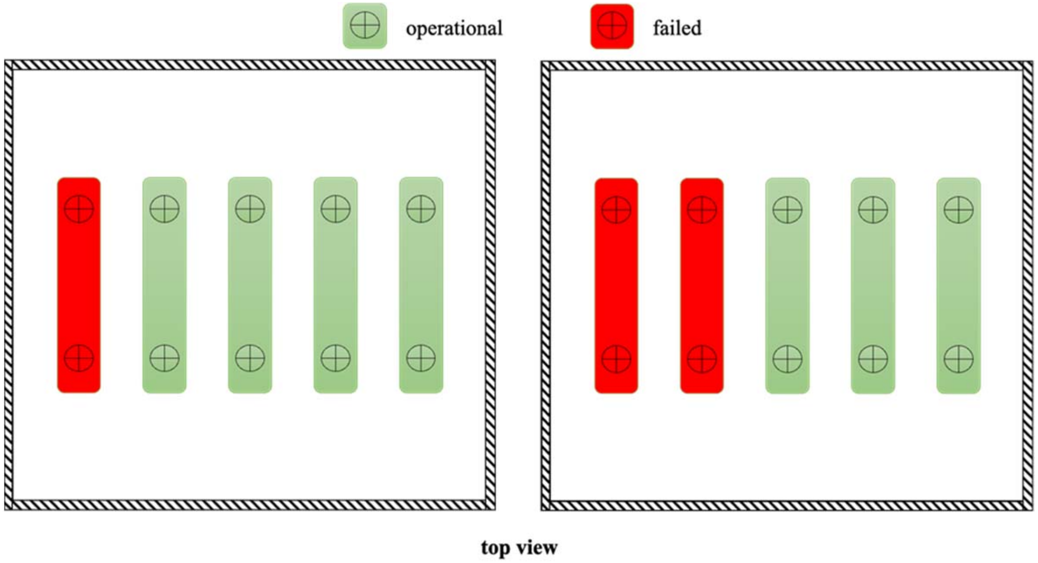
Cost Trade-offs and Relationships (Example)

Hypothetical case studies using F/C curves showed that:

1. For 10 MWt reactors, an additional barrier may not be needed.
2. As individual reactor capacities were increased from 10-50 MWt, high-performance structures were increasingly necessary to stay within safety limits.
3. Normalized delta costs ($/MWt) for the structures decreased as microreactor capacity increased.



Schematic representation of operational (green) and failed (red) MRs sharing a common barrier/structural enclosure.

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Future Study Areas

- New methodologies of TI-RIPB from an economics perspective as topical reports to NRC based on the existing literature, codes, and standards.
- Investigation of composite materials for retention barriers that are both resilient to internal and external hazards and have good retention capabilities.
- Testing and evaluating the performance of new microreactor containment designs under multi-hazard conditions (earthquake, flood, tornado, impact and similar).
- Assess the cost/risk/proliferation tradeoffs from using a high confinement barrier system for microreactor transport, operation, refueling, and decommissioning as an alternative to approaches using CONEX boxes and on-site reactor facilities/infrastructure.

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Development of a CRAB/MELCOR Framework for Microreactor Safety Analysis

March 8th, 2023

Jason Christensen, Idaho National Laboratory

INL Idaho National Laboratory

Oak Ridge National Laboratory

MRP Microreactor Program

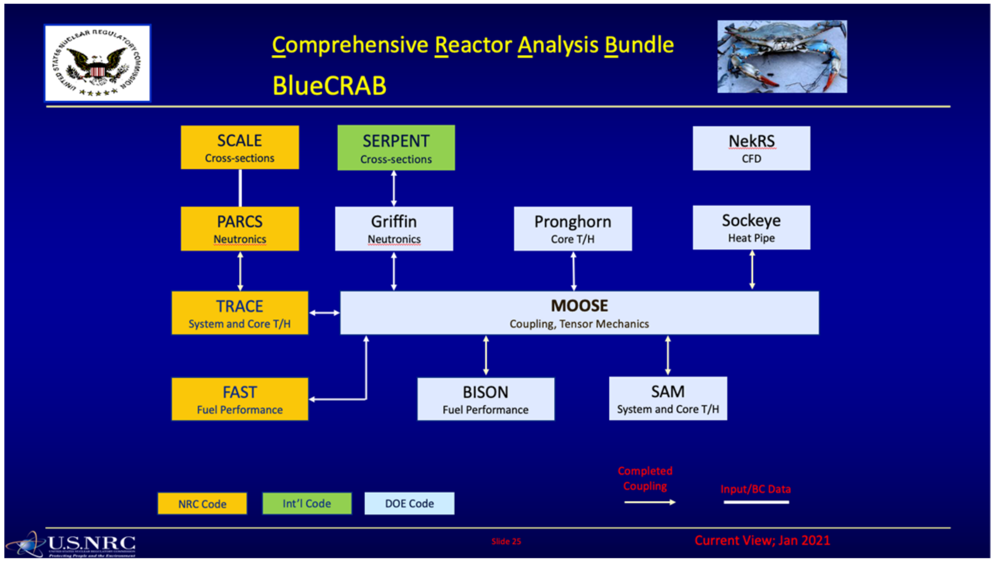
Los Alamos National Laboratory

Argonne National Laboratory

What is BlueCRAB?

Background:

- In recent years, the NRC has been working on a vison for addressing non-LWR needs
  - Inventory of existing codes and assessment of adaptability to advanced reactors
  - “Multi-physics” environment needs
  - Several advanced reactor designs each with different characteristics
  - Analysis done on adapting existing codes or switching to new codes
- In 2017, INL began a collaboration with the NRC on a new shared repository
  - MOOSE as a coupling framework with several promising NEAMS-built tools
  - “MOOSE-Wrapping” TRACE activity
  - LOFT (Loss of Fluid Transient) with BISON/TRACE
  - Parallel effort to leverage clusters of INL-NEAMS tools for Multiphysics core modeling efforts



Comprehensive Reactor Analysis Bundle

BlueCRAB

Current View; Jan 2021

- This culminated into the ‘BlueCRAB’ package that brings together various NEAMS tools as well as some NRC ones
- 'CRAB' = Comprehensive Reactor Analysis Bundle
- So-called 'MOOSE super-app' that enables simulatenously using a wide range of MOOSE-based codes as well as NRC legacy codes (e.g., TRACE)

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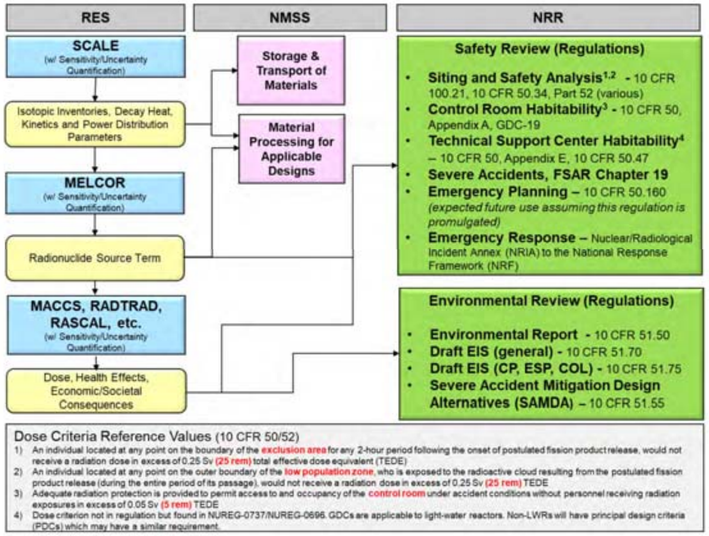
What is MELCOR?

- MELCOR is an integrated thermal hydraulics, accident progression, and source term code for reactor safety analysis
  - Principal tool for NRC confirmatory analysis of accident consequence analysis for licensing and other regulatory activities
  - Developed at Sandia since the early 1980s
  - Undergone a range of enhancements to provide analytical capabilities for modeling the spectrum of advanced non-LWRs
- Workshops on SCALE/MELCOR non-LWR source term demonstration projects held in 2021 and 2022
  - Reference MELCOR heat pipe model was created using the “INL Design A reactor”
- **Significant interest by applicants/vendors in using MELCOR to inform and understand potential regulatory analyses**
  - **Applicants/vendors may pursue BlueCRAB codes in addition to SCALE**

Ref.:

WAGNER, K., C. FAUCETT, R. SCHMIDT, and D. LUXAT, “*MELCOR Accident Progression and Source Term Demonstration Calculations for a Heat Pipe Reactor,*” Sandia National Laboratories, SAND2022-2745, (2022).

Role of NRC severe accident codes



Dose Criteria Reference Values (10 CFR 50/52)

1) An individual located at any point on the boundary of the **exclusion area** for any 2-hour period following the onset of postulated fission product release, would not receive a radiation dose in excess of 0.25 Sv **(25 rem)** total effective dose equivalent (TEDE)
2) An individual located at any point on the outer boundary of the **low population zone**, who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage), would not receive a radiation dose in excess of 0.25 Sv **(25 rem)** TEDE
3) Adequate radiation protection is provided to permit access to and occupancy of the **control room** under accident conditions without personnel receiving radiation exposures in excess of 0.05 Sv **(5 rem)** TEDE
4) Dose criterion not in regulation but found in NUREG-0737/NUREG-0696. GDCs are applicable to light-water reactors. Non-LWRs will have principal design criteria (PDCs) which may have a similar requirement.

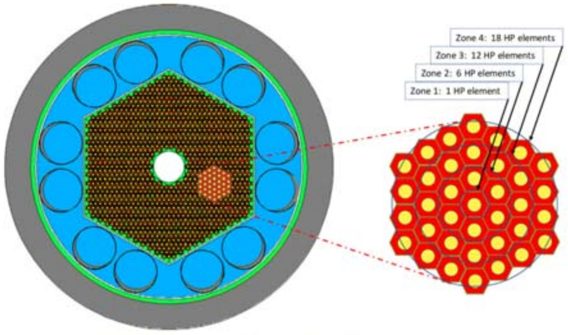
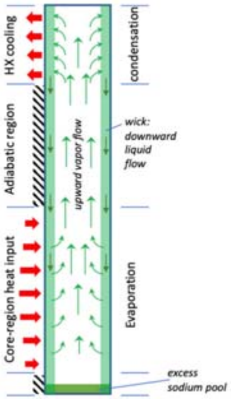


Figure 2-4 Example of cascading HP nodalization.

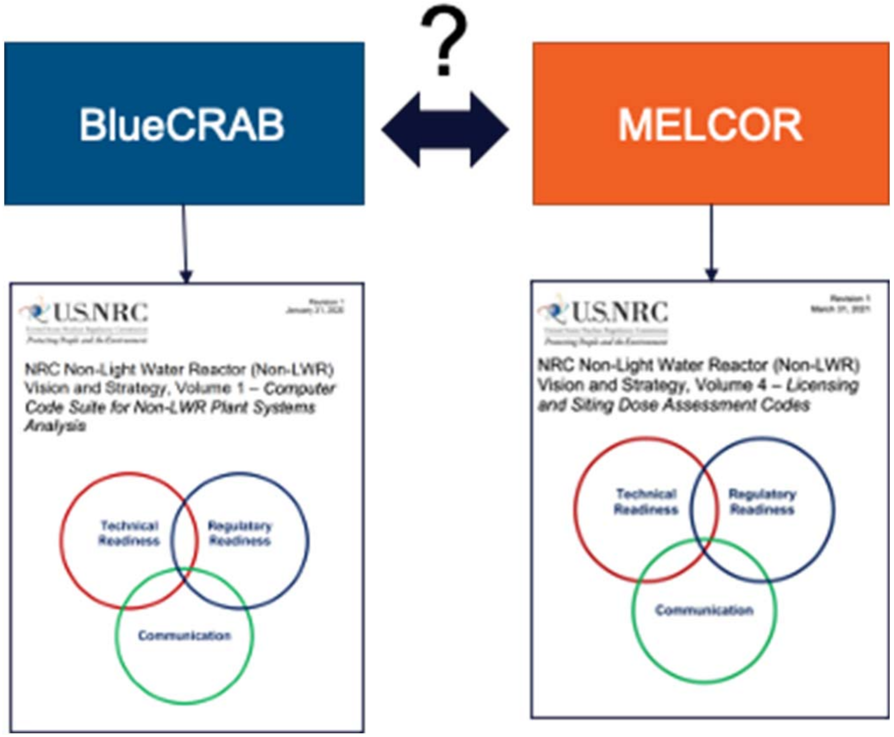


BlueCRAB and MELCOR to be used by NRC and developers

- BlueCRAB: evaluate detailed reactor kinetics and behaviors
- MELCOR: evaluate severe accidents
- Microreactors have:
  - **smaller source terms,**
  - **smaller site boundaries**
  - **smaller emergency planning zones**

Public health *risk* is not *inherently* smaller than traditional reactors

Strong potential need for microreactors (and NRC) to leverage modsim and mechanistic source term tools to demonstrate adequate safety

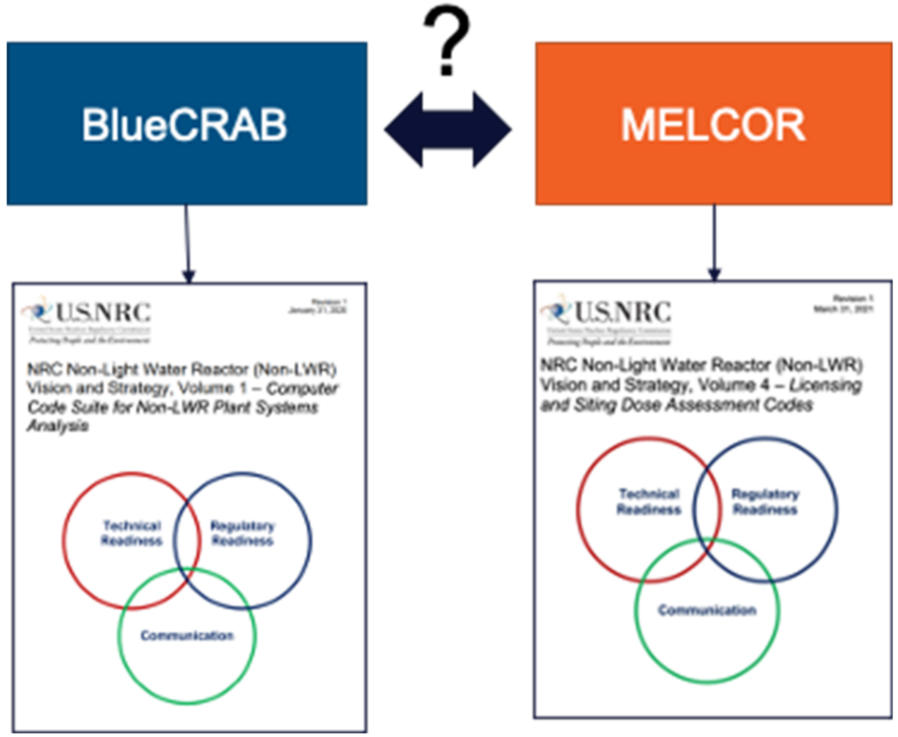


NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 1 – *Computer Code Suite for Non-LWR Plant Systems Analysis*

NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 4 – *Licensing and Siting Dose Assessment Codes*

Assess microreactor safety analysis challenges and provide recommendations for modsim utilization

- Since the safety basis may depend on these tools, it is important to **identify the types of accidents and licensing basis events** that are associated with some commercial microreactor concepts (initial task focus)
- Phenomena critical to the consequences (or the uncertainty) of these events is then to be identified and connected to the CRAB tools
- Gaps and areas of development may be identified and discussed
- Any recent or ongoing microreactor simulations may be leveraged to gain an understanding of phenomena



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Motivation from relevant microreactor reviews by the NRC

- Westinghouse eVinci (ML22084A223):
  - NRC advised eVinci to address non-reactor core radiological sources as well as events with multiple reactor modules
    - **Implies an expanded use of mechanistic source term (MST) analysis**
  - Additional feedback on MST was provided in another white paper, but was restricted from public disclosure

- Oklo, Aurora COL Application (ML21357A034)
  - Following a maximum credible accident (MCA) approach, but did not specify enough details around the identification of the MCA, how bounding the MCA was, and other phenomenological details surrounding the MCA sequence of events
    - **Emphasizes the importance of having a broad range of accidents evaluated with MST and having all relevant phenomena modeled correctly**

Expected outcomes

- Develop guide/recommendations on code interfaces
  - Microreactor developers may not have the same expertise and safety analysis and PRA department size as larger vendors
  - Novel applications bring new challenges to safety analysis modeling

- Identify gaps between what is needed to model in terms of safety analysis and what the current capabilities are
  - Accident sequence progression challenges
  - Better to identify and learn now than during an application review

  - (If possible) Demonstrate an example case

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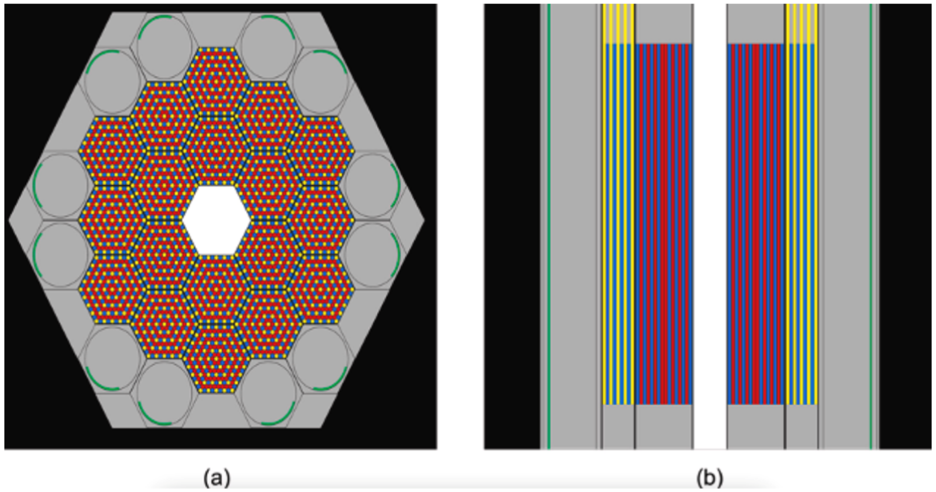
Demonstration using Empire-like Reactor Reference Model

- Modified Empire problem, called the Simplified Microreactor Benchmark Assessment (SiMBA) problem, was chosen as a reference to leverage cross-cutting work between DOE programs
  - Minimize re-modeling efforts
- Published in open-literature
  - Non-proprietary
- Small design changes to obtain a negative temperature reactivity coefficient
- Uses heat pipes which many microreactor design rely on
  - Similarities between designs sufficient for useful demonstration



Stefano Terlizzi, Vincent Labouré, "*Asymptotic hydrogen redistribution analysis in yttrium-hydride-moderated heat-pipe-cooled microreactors using DireWolf*", Annals of Nuclear Energy, Volume 186, 2023.

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Requirements for accident sequence modeling

- Following an MCA (or similar worst-case) approach
  - Alternative is a risk-informed selection of LBEs
    - Requires a PRA, more reactor design detail than available for Empire
    - More comprehensive (but not necessarily needed to demonstrate adequate safety)
- The MCA must include a failure of containment boundaries
  - Could be due to a beyond design basis earthquake, fire, etc.
  - Introduces a pathway for radionuclide release to the public
  - May also involve a security event (for security planning and evaluation), sabotage or theft/diversion
- Should follow standard requirements for MST analysis (see ASME/ANS RA-S-1.4-2021)

Potential accident sequences for microreactors

Event	LBE Type	Reactor Type
Negative reactivity insertion (scram)	AOO	All
Positive reactivity insertion	AOO—DBE	All
Loss of offsite power	AOO—DBE	All
Heat pipe failure (single)	DBE	Heat pipe
Loss of flow	DBE	All
Loss of heat sink	DBE	All
Overcooling	DBE	All
Seismic and other external hazards	DBE	All
Station blackout	DBE	All
Transportation accidents (preoperation)	DBE	All
Transportation accidents (postoperation)	DBE	All
D-LOFC	DBE—BDBE	HTGR
Heat pipe failure (multiple)	DBE—BDBE	Heat pipe
Salt spill	DBE—BDBE	MSR
Salt spill	DBE—BDBE	MSR

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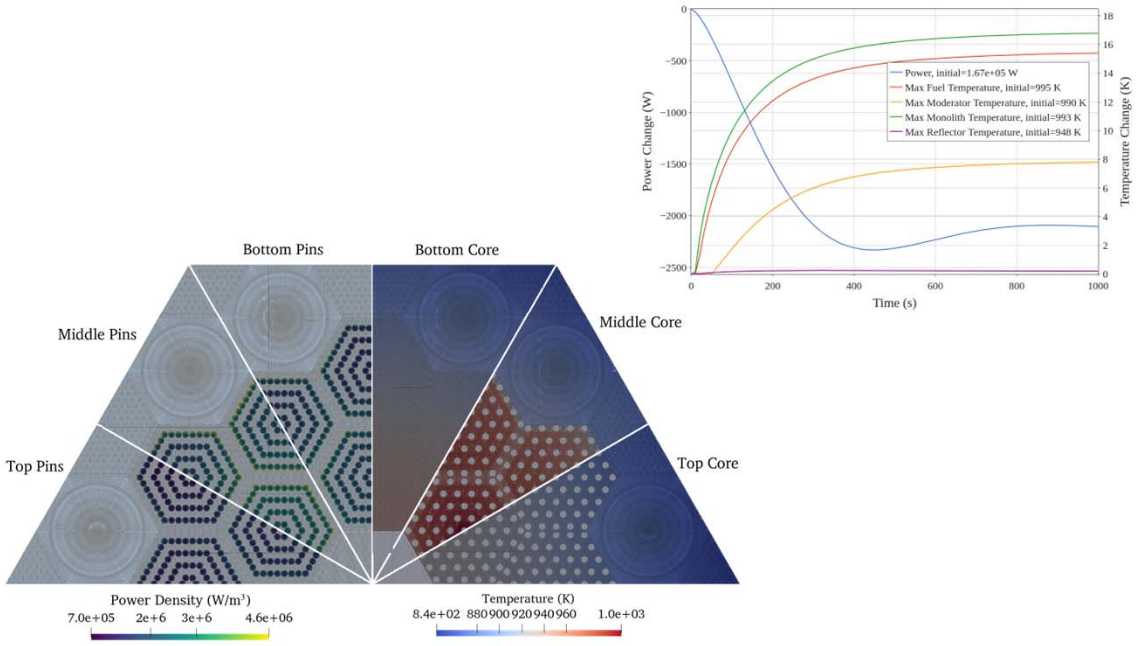
Reference accident sequence of interest to Empire - Heat pipe failure (multiple)

- Transient overpower scenario leading to fuel cladding and multiple heat pipe cladding failures
- HP depressurization on failure drive release from the vessel
- Some radionuclides may enter the failed heat pipe and are then transported to a release from the secondary system (creep failure in the condenser section)
- Building leakage is drive by the temperature gradient
  - Leakage is linear with area



Zach Prince et al., "*Neutron Transport Methods for Multiphysics Heterogeneous Reactor Core Simulation in Griffin*", to be submitted to Annals of Nuclear Energy, 2023.

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Report Outline and Expected Content

- Intro, background, our approach, observations and recommendations, conclusions
- Microscopic cross-section generation
- Perform full-core multi-region micro-depletion multiphysics calculation to determine initial source term
- Preliminary HP failure transient
- Identify gaps in tools to perform HP failure transient and communicate with MELCOR (isotopics, temperature evolution, power evolution, etc.)

Next Steps

- ORNL has been granted access to MELCOR, explore heat pipe and microreactor models
- MELCOR workshop along with demonstration examples
  - 18th International Probabilistic Safety Assessment and Analysis Conference
  - July 15 – 20, 2023, Knoxville TN
- Mutliphysics BlueCRAB model of the Empire/SIMBA problem already exists:
  - Need more refined transient model to simulate temperature evolution
  - Need depletion calculation to intialize source term for severe accident simulation in MELCOR
- In future work, a model including radionuclide diffusion (BISON) should be targeted.

Wrap-up discussion and questions?

Questions/comments?

MRP Microreactor Program

Flexible Siting Criteria and Staff Minimization for Micro-Reactors

NEUP Project #: 20-19042
Schedule: Oct 2020 → Sep 2022 (completed)
Budget: $434k

MITei
MIT Energy Initiative

NSE
Nuclear Science
and Engineering
science : systems : society

THE PROJECT TEAM

Isabel Naranjo
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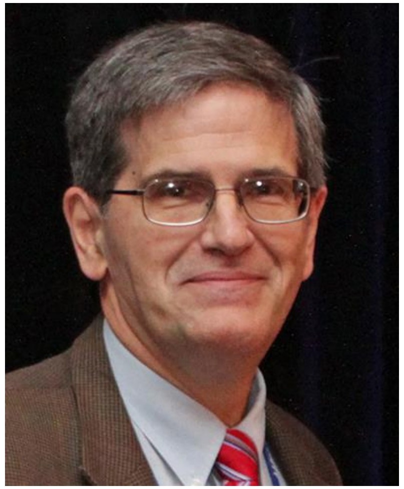
THE ADVISORY COMMITTEE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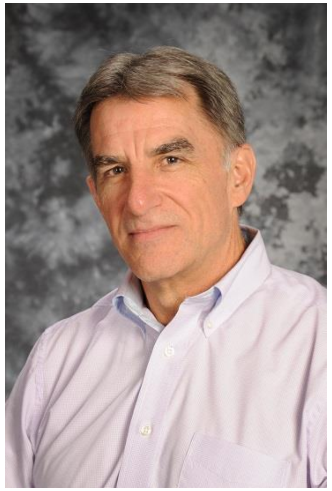
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EXTERNAL COLLABORATORS


Enrico Zio
(POLIMI)


Piyush Sabharwall
(INL)

ECONOMIC IMPERATIVES FOR MICROREACTORS

- To access large markets, microreactors must be licensable for deployment near and within population centers ⇐

- LCOE and LCOH analysis suggests that microreactors can meet the heat and electricity cost targets for large markets, if:
  - ➢ Power output is maximized, within microreactor constraints (e.g., truck transportability, passive decay heat removal)
  - ➢ Staff is in the 0.5-1.5 FTE/MW range ⇐
  - ➢ Enrichment <10% and burnup >20 $\mathrm{MWd/kg_U}$
  - ➢ Microreactor fabrication cost (excluding fuel) <5000 $/kW
  - ➢ Discount rate <10 %/yr

⇐ focus of this project

PROJECT OBJECTIVES

- Develop siting criteria that are tailored to micro-reactors deployable in densely-populated areas, e.g., urban environments.
- Identify optimal licensing path for micro-reactors in Part 50 and Part 52 framework
- Conceptualize a model of operations and security for micro-reactors that would minimize the staffing requirements, and thus reduce the cost of electricity and heat generated by these systems.
- Develop a new Type B transport cask design for fueled micro-reactors *(ADDED IN YEAR 2)*
- Develop a risk-informed framework for threats and vulnerabilities assessment of micro-reactors *(ADDED IN YEAR 2)*

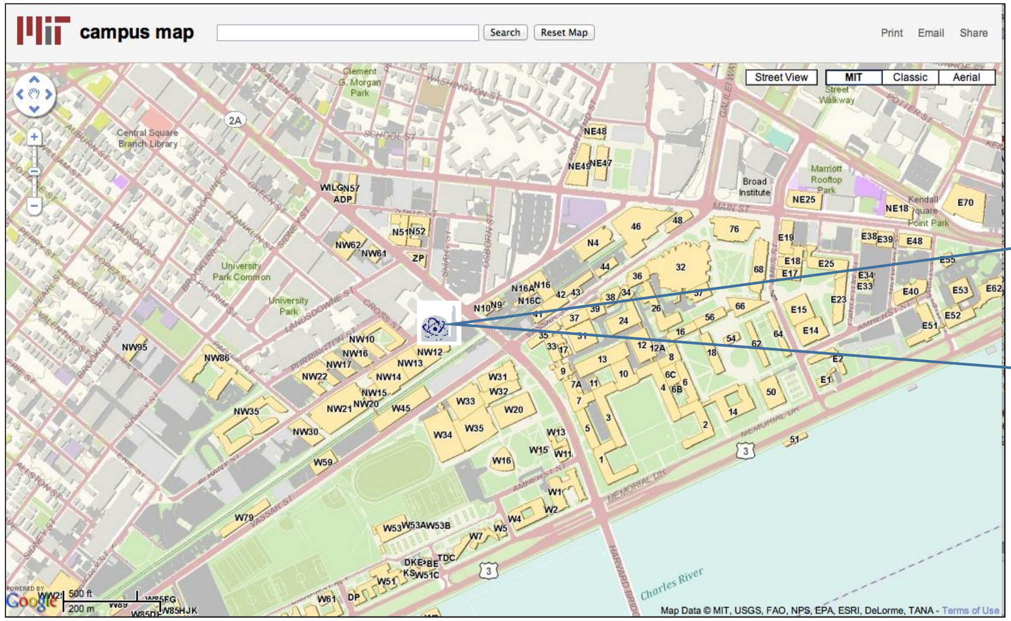
APPROACH

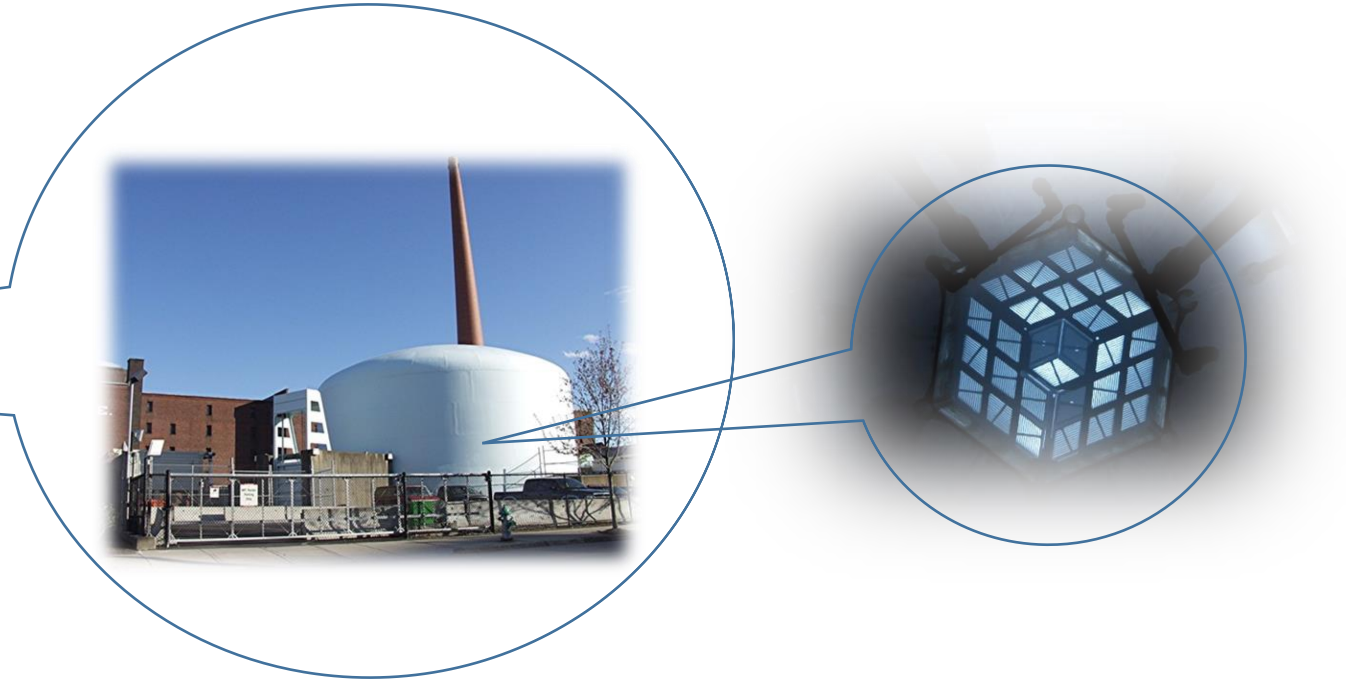
- Compare MIT nuclear reactor (MITR) with leading micro-reactor concepts, and evaluate whether and how the MITR design basis (e.g., inherent safety features, engineered safety systems, source term, emergency planning and emergency operating procedures) and associated regulations may be applicable to micro-reactors.

- Review the MITR experience and requirements, as well as survey the innovations in autonomous control technologies (e.g., machine learning) and monitoring (e.g., advanced sensors, drones, robotics) that may permit a dramatic reduction in staffing at micro-reactor installations.

THE MITR

MITR is an urban micro-reactor:
- low power (6 MWt)
- 24/7 ops
- ultra-safe

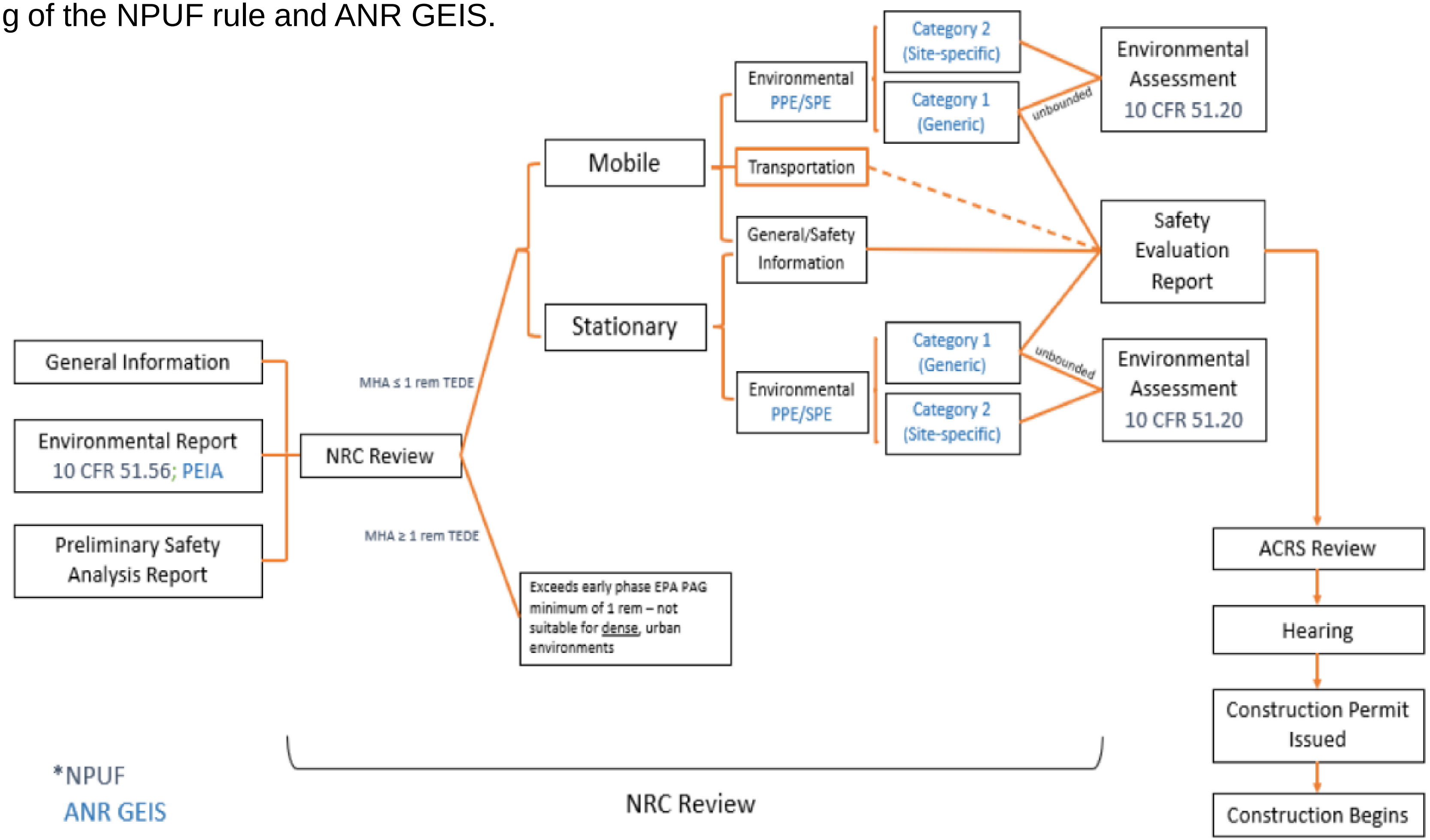




But there are major differences:
- the mission is research (vs. commercial)
- unsuitable for heat utilization and electricity generation (<60°C core outlet temperature)
- frequent refueling (every 10 weeks)
- non-transportable
- large staff (operations + research + admin = 60 FTEs)

MAIN FINDINGS

- Developed scaled micro-reactor siting criteria and requirements to reflect those of research reactors specifically for deployment in densely populated urban environments. In doing so, we found that the main difference between a commercial micro-reactor and a research reactor is simply the end destination of their products, which should not warrant a substantially different regulatory treatment of the two classes of reactors. Thus, adoption of the so-called Non-Power User Facility (NPUF) rule and Advanced Reactor Generic Environmental Impact Statement (ANR GEIS) is recommended.
- Developed an optimal licensing path for micro-reactors under the existing 10 CFR Part 50 and 10 CFR Part 52 frameworks with integration and leveraging of the NPUF rule and ANR GEIS.



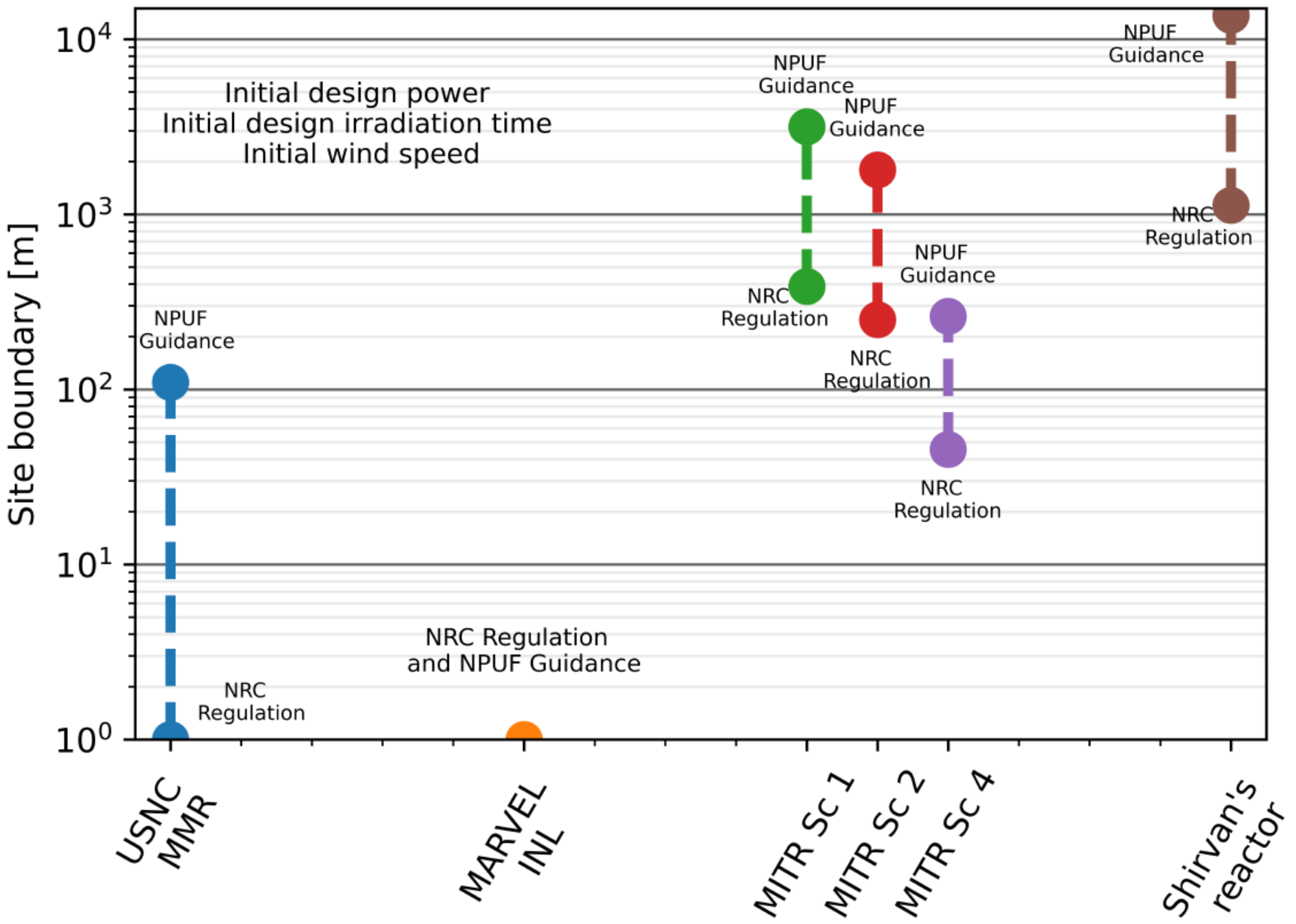
MAIN FINDINGS (cont.)

- Quantified the staffing needs for operations and maintenance for four classes of micro-reactors and compared them with various non-nuclear power facilities (i.e., small aero-derivative gas turbines, and transportable supercritical CO2 power units). The analysis shows that with proper use of automation and remote monitoring, the staffing required onsite can be kept at a fairly low level, e.g., order of 1 FTE, but significant offsite staffing is still required for monitoring and servicing the micro-reactors.

Category	Description	MIT research reactor	Gas V16 2.4 MWe	Gas aero-derivative 1.5 MWe	sCO2 power unit	eVinci	Holos	Aurora	MMR
Maintenance – total	Total h of maintenance per year [h]	738	195	92	277	367	388	552	613
Maintenance – onsite, nuclear specific	Total h of onsite nuclear maintenance per year * FTEs [h]	557	0	0	0	118	143	118	143
Maintenance – onsite, non-specific	Total h of onsite non-specific maintenance per year * FTEs [h]	559	354	100	277	506	501	689	729
Maintenance – offsite, nuclear specific	Total h of offsite nuclear maintenance per year * FTEs [h]	0	0	0	0	44	46	44	46
Maintenance – offsite, non-specific	Total h of onsite non-specific maintenance per year * FTEs [h]	0	18	44	0	44	44	0	0
Maintenance – total	Average FTEs for maintenance during 1 year	0.35	0.23	0.09	0.17	0.44	0.46	0.53	0.57
Operation	Average FTEs for operations during 1 year	16	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Total	TOTAL	16.35	0.86	0.71	0.80	1.07	1.08	1.16	1.20
Total	Per MWe	-	0.36	0.48		0.21	0.08	0.77	0.24

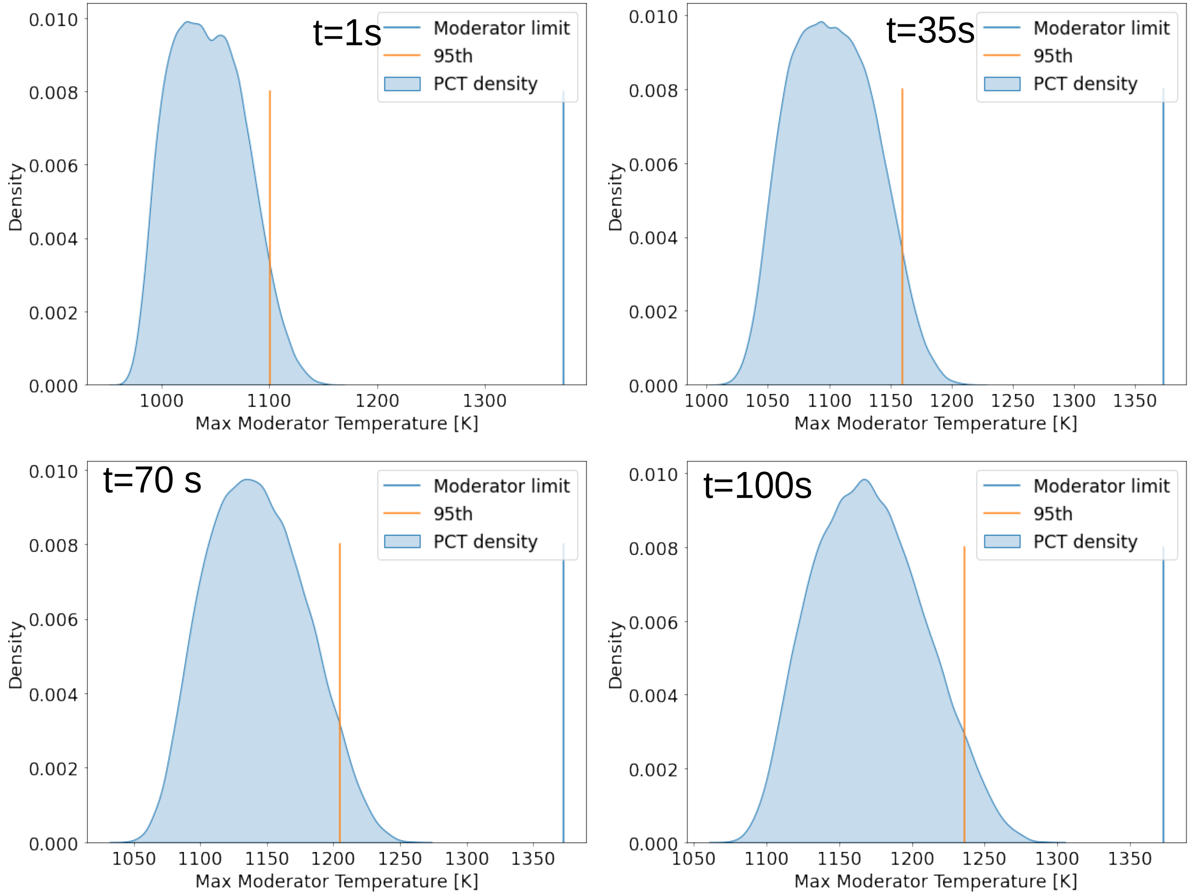
MAIN FINDINGS (cont.)

- Identified the worst-case radiological consequences of a situation in which a hostile force gains control of a micro-reactor facility and deliberately damages it. This consequence-based security analysis allowed to quantify the size of the site boundary that is required to meet the radiation dose limits for various micro-reactors.



MAIN FINDINGS (cont.)

- Developed a risk-informed methodology that embeds (i) System-Theoretic Accident Model and Processes (STAMP) principles to guide a qualitative exploration of the system threats and hazards, (ii) Modeling and Simulation (M&S) to investigate the system dynamic behavior during accidental scenarios, and (iii) the Goal-Tree Success-Tree Master Logic Diagram framework to assess risk quantitatively. The integration of these three elements allows for a systematic identification of the risks and a dynamic (time-dependent) assessment of the risk profile.
- Demonstrated this methodology for a micro-reactor design with heat pipes, showing the ability to quantify the time-dependent probability density function for key safety variables (e.g., peak cladding temperature, moderator temperature) and their margin to postulated limits.



FINDING DISSEMINATION

Papers:

- F. Antonello, J. Buongiorno, E. Zio, “Insights in the Safety Analysis of an Early Microreactor Design”, *Nuc Eng Des*, Vol. 4, 112203, Apr 2023.
- F. Antonello, J. Buongiorno, E. Zio, “A Methodology to Perform Dynamic Risk Assessment Using System Theory and Modeling and Simulation”, *Reliability Engineering & System Safety*, 228, 108769, 2022.
- E. Garcia, L. Nester, J. Buongiorno, “Scaling Siting Criteria and Alternative Licensing Pathways for Micro-Reactors”, *Proc. of ANS Meeting*, June 12-16, Anaheim CA, 2022.
- I. Naranjo de Candido, J. Buongiorno, “Staffing minimization for micro-reactors”, *Proc. of ANS Meeting*, June 12-16, Anaheim CA, 2022.
- E. Gateau, N. Todreas, J. Buongiorno, “Consequence-based security for microreactors”, *Proc. ICAPP 2023*, Gyeongju, South Korea, April 23-27, 2023.
- I. Naranjo De Candido, J. Buongiorno, S. Cetiner, “Onsite staffing for micro-reactors: models, needs and business case”, in preparation, *journal TBD*, 2023.
- 1 journal paper in preparation based on E. Garcia’s work.

FINDING DISSEMINATION (cont.)

Thesis dissertations:

- E. Garcia, “Scaling siting criteria and identifying alternative licensing pathways for micro-reactors within the existing regulatory framework”, M.S. Thesis, October 2022
- I. Naranjo de Candido, “Staff minimization strategy for micro-reactors”, M.S. Thesis, November 2022
- E. Gateau, “Consequence-based Security for Micro-Reactors”, M.S. Thesis, August 2022
- L. Galanek, “Physical Security Requirements for Micro-Reactors”, B.S. Thesis, May 2021

Briefings to:

- Micro-reactor program leadership at INL, August 2022
- Micro-reactor principals at the NRC, August 2022
- Micro-reactor group at NEI, August 2022
- eVinci group at Westinghouse Electric Company, August 2022

Evaluation of microreactor requirements and performance in an existing well-characterized microgrid

Project 20-19693

Alvin Lee, Dimitri Kalinichenko, Lucas Wodrich, Caleb S. Brooks, Tomasz Kozlowski
University of Illinois

March 8th , 2023

Project Purpose:

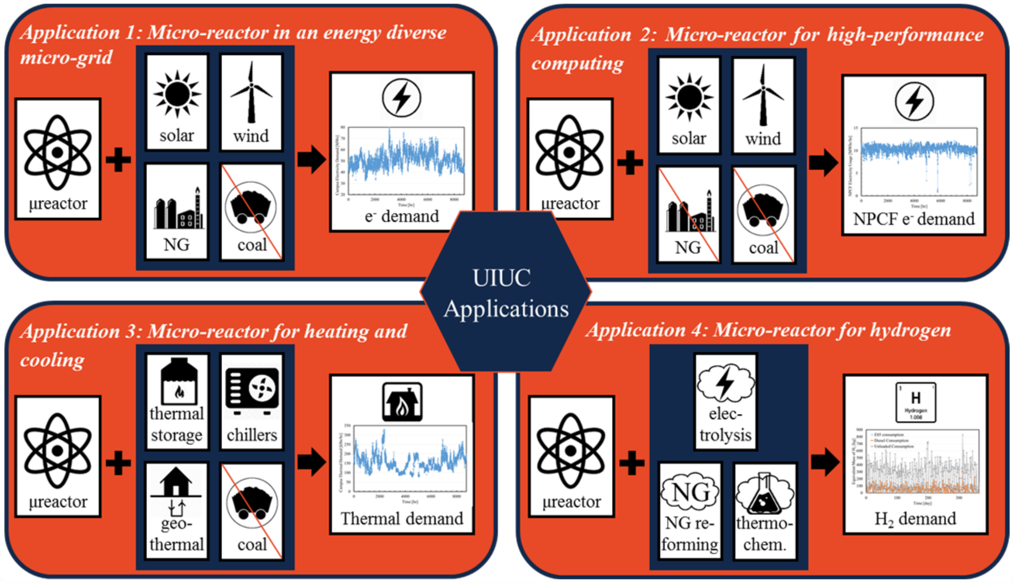
To quantify the opportunities and challenges of operating micro-reactors in populated, decentralized power generation environments and the potential for deployment in established micro-grids with diverse power generation sources.

Project Objectives:

1) Develop integrated system modeling of micro-reactor applications.
2) Incorporate available data to validate modeling.
3) Simulate normal and bounding events.
4) Determine economic performance requirements across applications.
5) Identify operational requirements and opportunities across applications.
6) Determine the scalability of microreactor deployment at campuses and other existing microgrids.

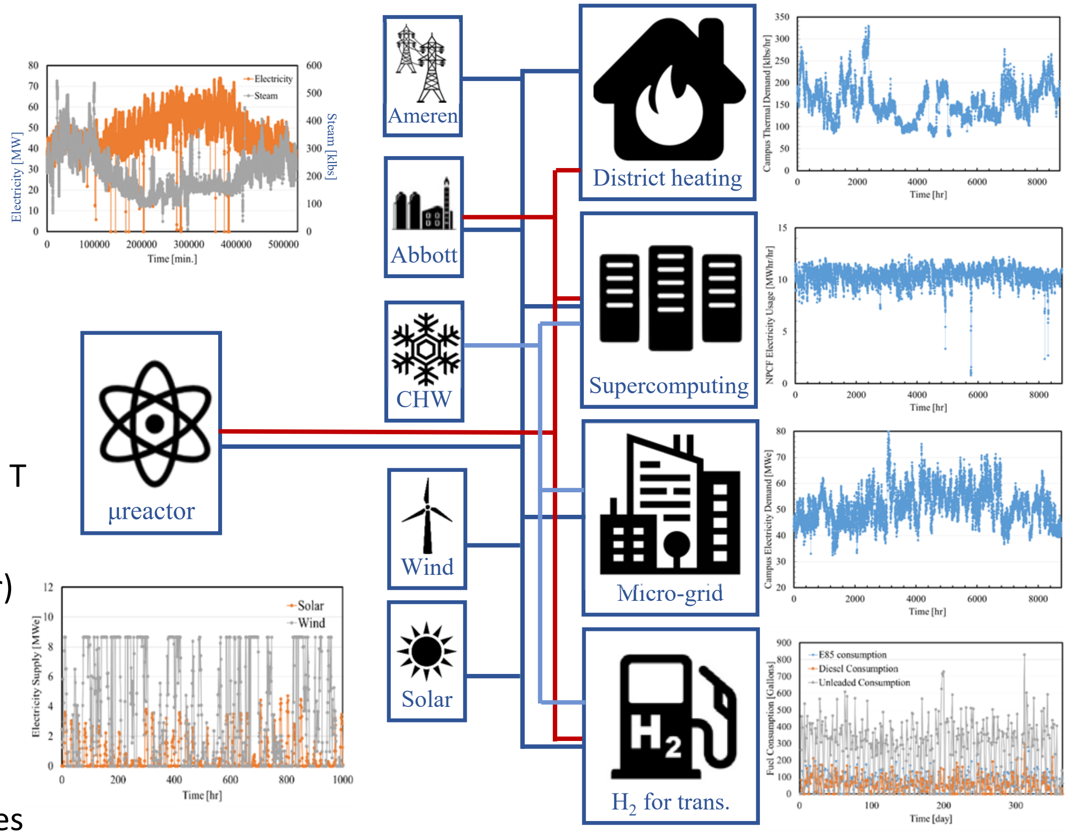
Project Outcomes:

1. Detailed analysis of the market potential for micro-reactors in existing microgrids
2. Expansion of the Modelica-based hybrid energy system modeling to include the existing well-characterized environment of a functioning microgrid with diverse energy generation and dispatch portfolio,
3. Economic target for microreactors deployed as electricity producers, thermal energy producers, and hydrogen producers,
4. Identification of specific economic and technical opportunities to guide technology development efforts,
5. Foundational training of the next generation of nuclear engineers in the critical path for the wide adoption of clean, safe, reliable nuclear power.



Overview of UIUC Microgrid

- Electrical
  - 55 MW_e average demand (Peak 80 MW_e)
  - Blue Waters Supercomputer up to 15 MW_e
  - Wind: ~25,000 MWhr/yr
  - Solar: ~7,200 MWhr/yr (20,000 MWhr/yr new installation)
  - Chillers: ~20 MW_e peak
- Thermal
  - 50 MW_{th} average demand
  - High P steam constant, Low P steam varies with T
  - 6 Chilled water plants (2 steam, 21 electric)
  - Energy storage (6.5 million gallons chilled water)
- Transportation
  - Campus fleet ~ 800 gallons/day
  - Campus bus system: up to 3,400 gallons/day
  - Bus system already investing in 10 new H_2 busses



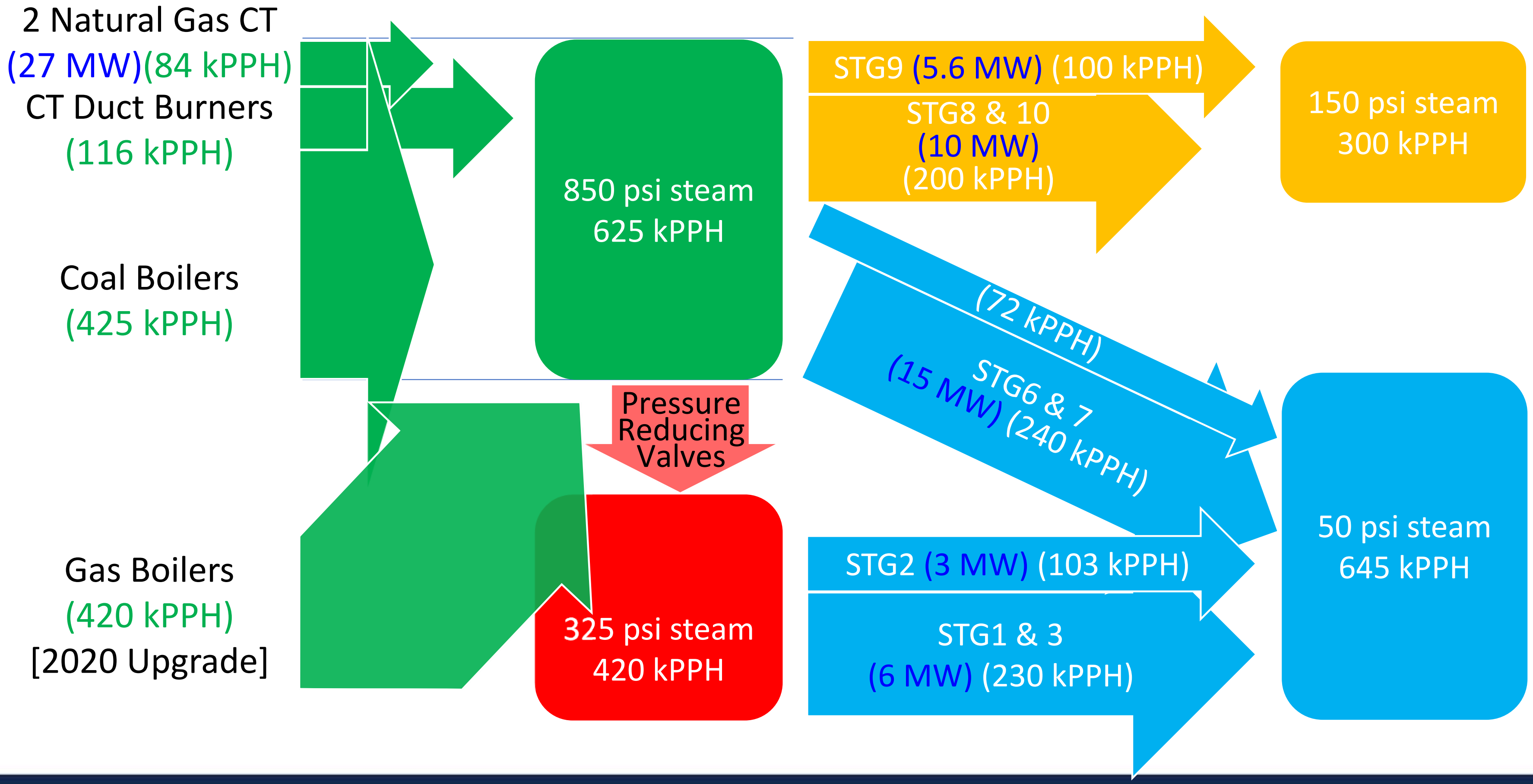
Overview of UIUC Microgrid

- 2019 UIUC emission sources:

Scope	Scope Definition	Emissions (MTCO2e; %)	Campus Energy Source %	Campus Electricity %
1	Emissions produced on campus within UIUC control	195,459; 45.1%	80%*	43.10%
2	Emissions from purchased electricity	183,595; 42.3%	20%	56.90%
3	Emissions from off campus university activities	54,743; 12.6%	N/A	N/A

*Calculated from fuel consumption

Overview of UIUC Abbott Power Plant



2 Natural Gas CT
(27 MW)(84 kPPH)

CT Duct Burners
(116 kPPH)

Coal Boilers
(425 kPPH)

Gas Boilers
(420 kPPH)
[2020 Upgrade]

850 psi steam
625 kPPH

Pressure Reducing Valves

325 psi steam
420 kPPH

STG9 (5.6 MW) (100 kPPH)

STG8 & 10
(10 MW)
(200 kPPH)

150 psi steam
300 kPPH

(72 kPPH)

STG6 & 7
(15 MW) (240 kPPH)

STG2 (3 MW) (103 kPPH)

STG1 & 3
(6 MW) (230 kPPH)

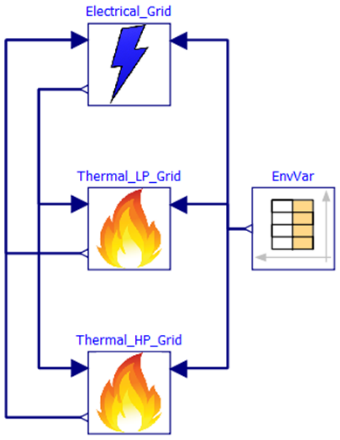
50 psi steam
645 kPPH

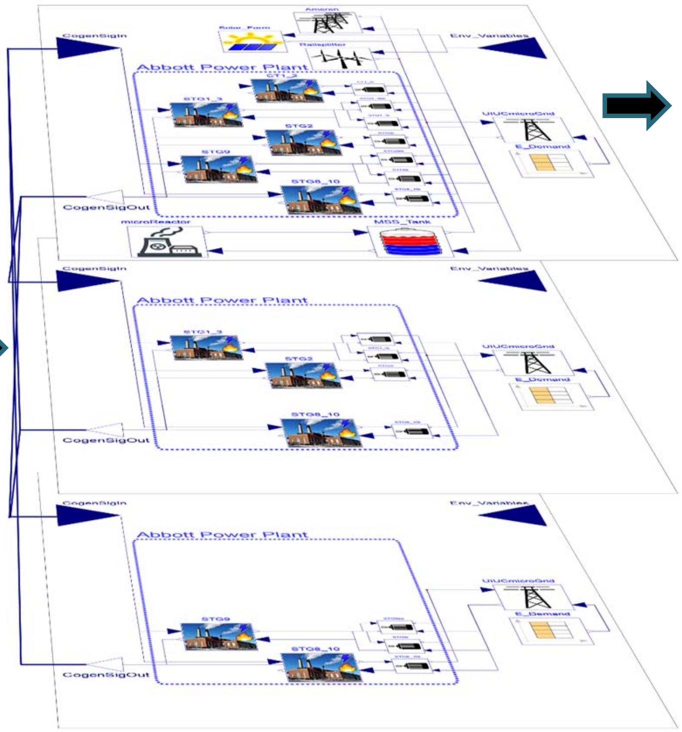
Approach – Microgrid Modeling

- Main idea: Create a simplified model of the microgrid to provide information <u>on the minutes scale</u> and perturb component parameters and configurations to obtain optimal solution

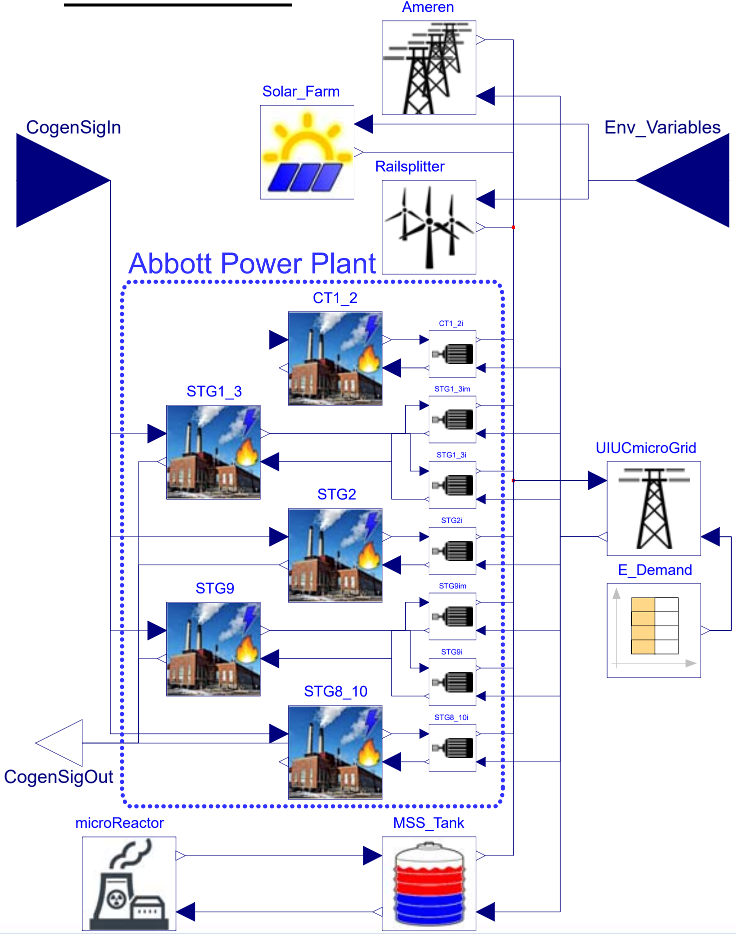
- Simplified in terms of variables used
    - E.g. For electrical grid: MW and MWhr for power and energy exchange instead of the more fundamental variables (Volt, Ampere, Hertz)

Microgrid Model



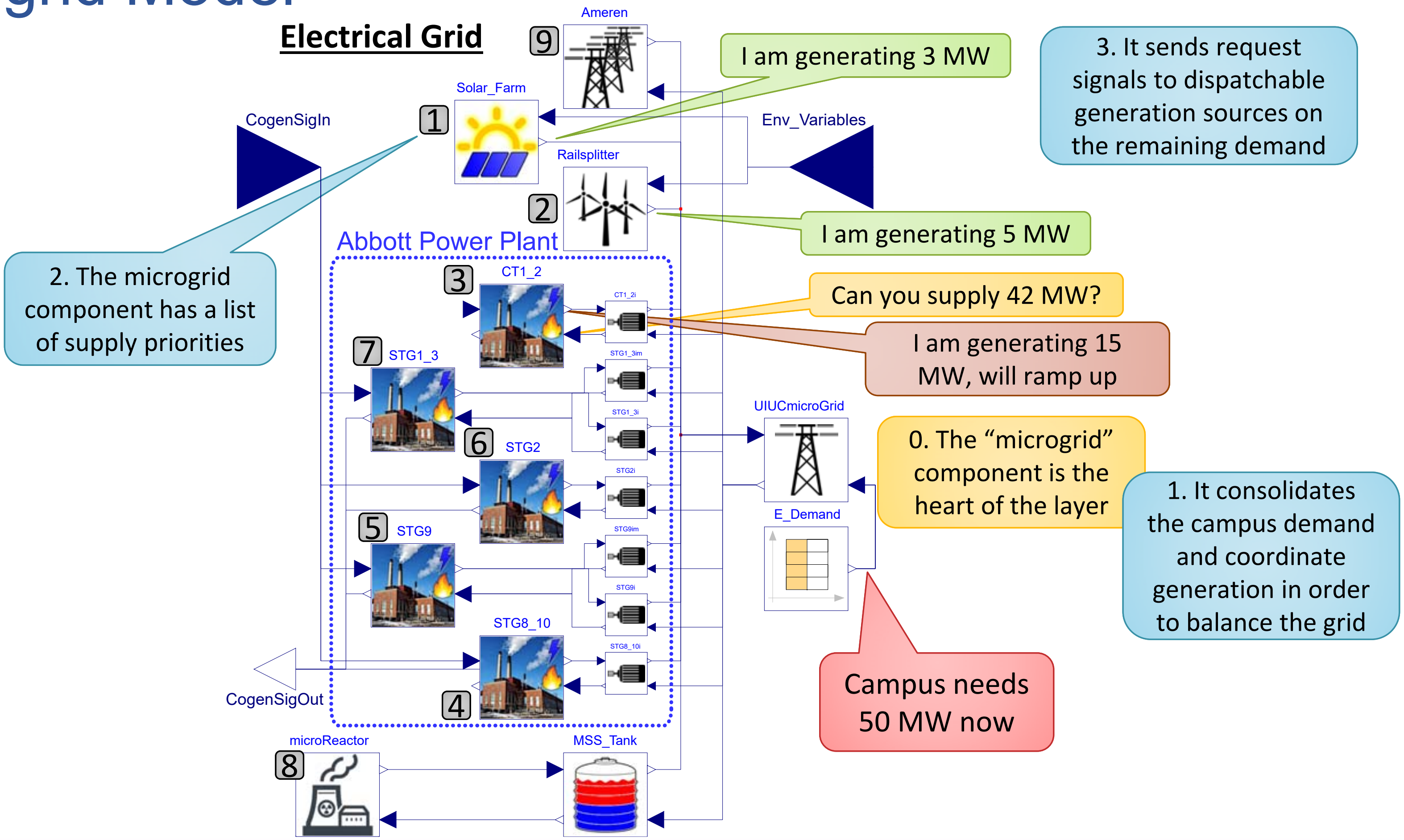


Electrical Grid



Microgrid Model

Electrical Grid



I am generating 3 MW

3. It sends request signals to dispatchable generation sources on the remaining demand

2. The microgrid component has a list of supply priorities

I am generating 5 MW

Can you supply 42 MW?

I am generating 15 MW, will ramp up

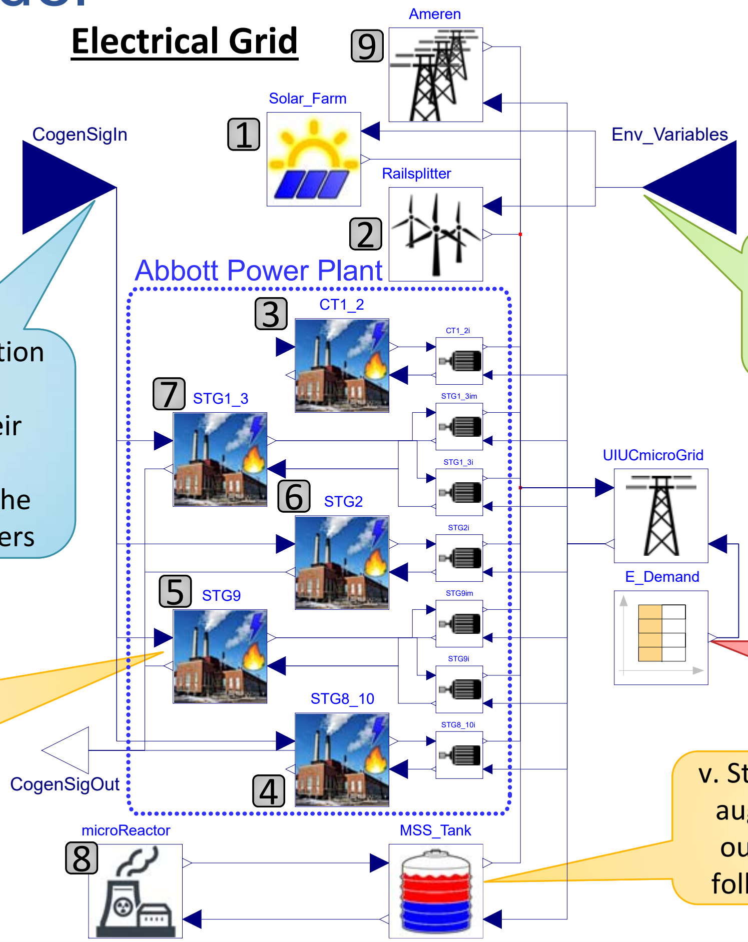
0. The “microgrid” component is the heart of the layer

1. It consolidates the campus demand and coordinate generation in order to balance the grid

Campus needs 50 MW now

Microgrid Model

Electrical Grid



ii. The cogeneration components coordinate their outputs via signaling with the other utility layers

iii. The generation behavior of the renewables is influenced by the Environmental Variables

iv. The campus demand can also be modeled to depend on Environmental Variables

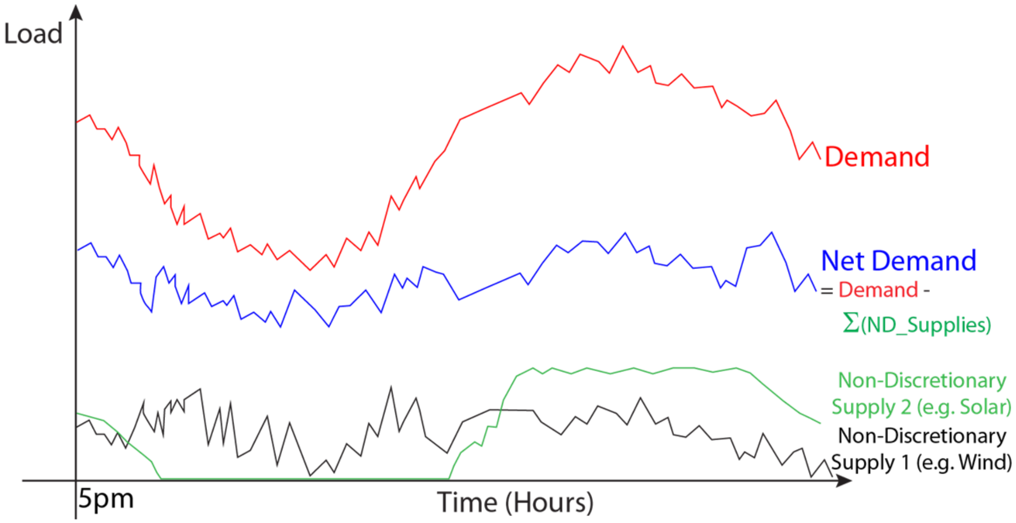
i. The generation characteristics of dispatchable components are primarily based on capacity and ramp rate

v. Storage components can augment the generation output to assist in load-following or conditioning

Microgrid Model

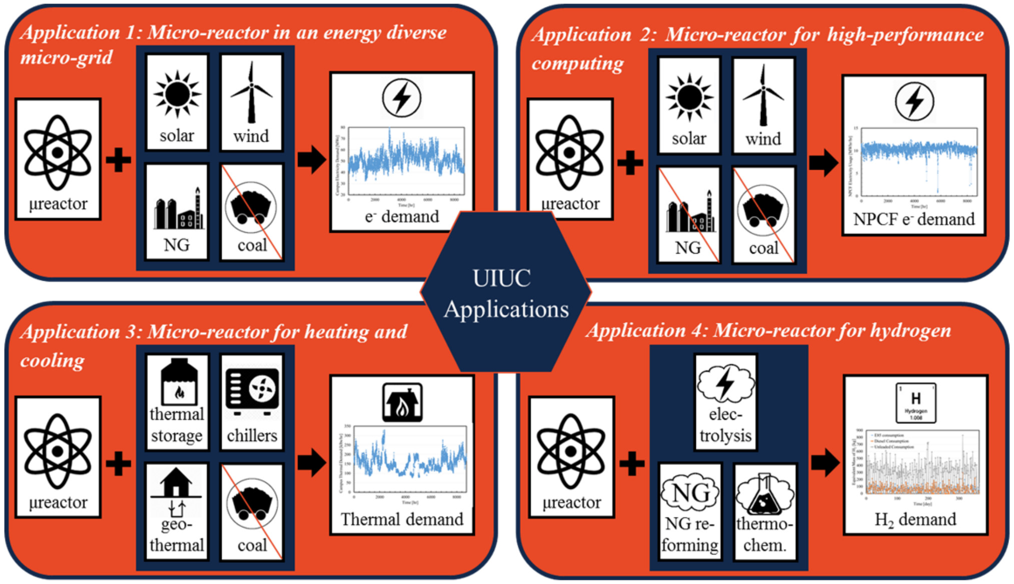
With a sufficiently accurate model, we can determine:

i. Demand, based on environmental variables such as temperature, time of year, etc.
ii. Supply behavior, in response to demand and other internal system complexities such as cogeneration.
iii. Tally total demand & supply, fuel usage, costs, greenhouse gas emissions, etc.



Overview of Subtasks 2.1 and 2.3 Results

- Task 2.1: Use of microreactor solely for electricity generation in an energy-diverse UIUC microgrid.
- Task 2.3: Use of microreactor for steam (and electricity) generation with a focus on heating and cooling.



Select Key Scenarios From Subtasks 2.1 and 2.3

Task	Configuration	Cost Savings[1] [$M/y]	Emissions Reduction [MTCO2/y]	Key Findings
2.1: Electricity Generation ($5\ MW_e$)	Baseload CT with load-following μR	1.98	UIUC: 0 Grid: 28.4 Total: 28.4	• CTs baseload while μR+MSS provides load-following • μR+MSS helps to condition power by reducing fluctuations and provide some electricity arbitrage
	Baseload μR with load-following CT	1.10	UIUC: 11.3 Grid: 9.0 Total: 20.3	• μR baseloads with load-following CT to minimize fossil fuel usage • Some emissions reduction but less cost savings due to lower export of excess electricity • Resistant against increase in natural gas prices, esp. above $3.86/MMBTU
2.3: Steam & Electricity for UIUC ($15\ MW_{th}$)	Boiler Retrofit	1.45	UIUC: 25.1 Grid: 1.2 Total: 26.3	• μR retrofitted onto existing coal boiler in APP to produce boiler steam • Relegates production to APP using existing APP infrastructure • 1.9 MW_e + 36.8 kPPH steam, or throttle up to 3.7 MW_e + 0 kPPH steam (condensing mode)
	Cogeneration 50 psi with MSS	1.60	UIUC: 24.1 Grid: 4.3 Total: 28.4	• STG exhaust as 50 psi steam for campus heating • MSS enables load-following • 2.3 MW_e + 35.3 kPPH steam

[1] Cost savings refer to the reduction in electricity and fuel expenses as compared to the current UIUC microgrid without a microreactor.

Some Key Takeaways From Subtasks 2.1 and 2.3 Results

- Ideal microreactor deployment approach depends on the specific goal and scenarios

  E.g., If reduction of local emissions is a priority, then cogeneration is better than sole electricity generation which only offset grid emissions.
  E.g., If existing infrastructure is available, then retrofit may be better than cogeneration due to cost and complexity reduction.

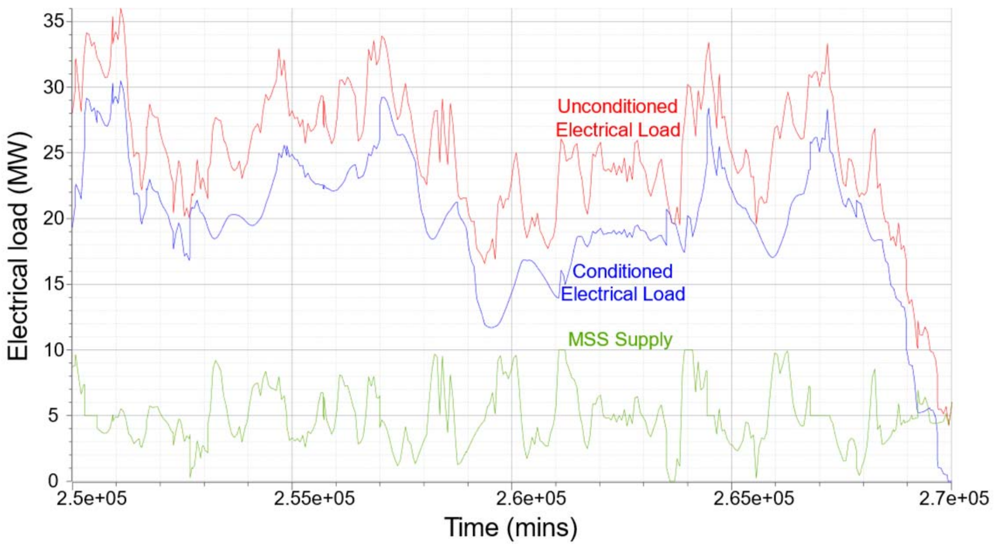
- Potential cost reduction from a microreactor is highly dependent on price of electricity and the fuel it replaces (i.e. natural gas). In the simulated period, the average electricity price was about $25/MWh and $2.87/MMBTU for gas.
  The prices have increased significantly over the years and would result in much greater cost reduction for present microreactor deployments.

- As the electricity grid shifts towards clean energy sources, the focus would be on reducing local emissions generation.

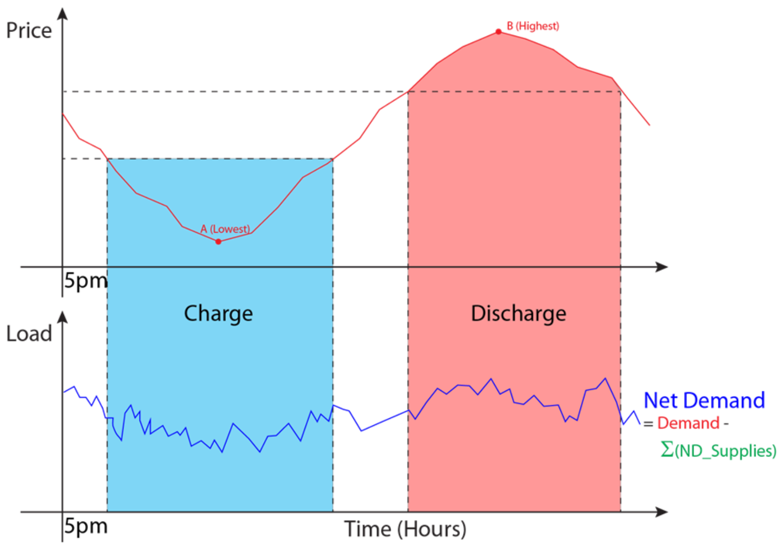
Load-Conditioning and Electricity Arbitrage by MSS

- Load-conditioning by the Molten Salt Storage (MSS) system attempts to smooth the electrical load which is important for achieving a self-reliant microgrid.
- Electricity arbitrage by the MSS allows additional cost reduction by charging the MSS during periods of low electricity prices and discharging during periods with high prices.

<u>Load-conditioning</u>



<u>Electricity Arbitrage</u>



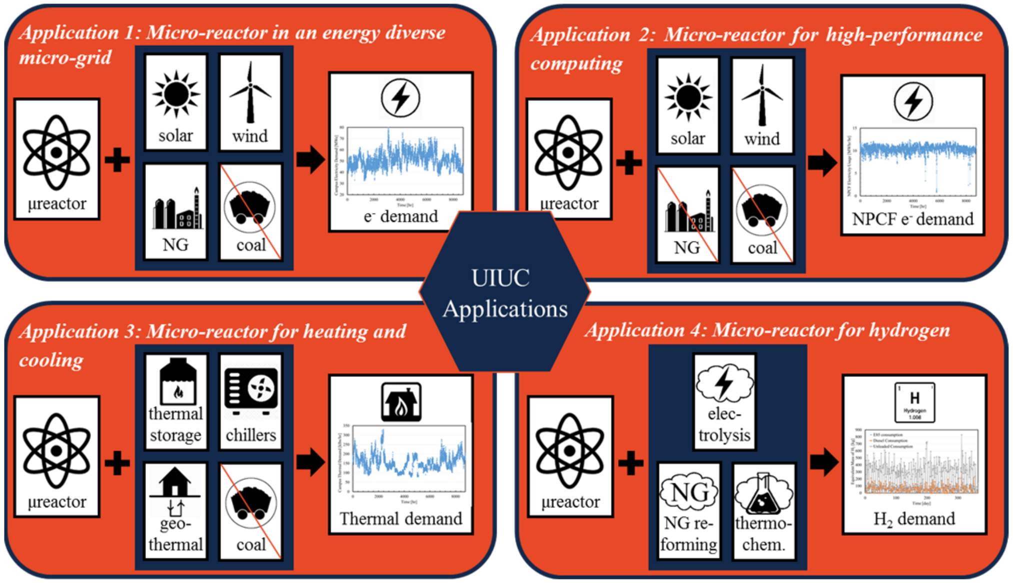
Load-Conditioning and Electricity Arbitrage by MSS

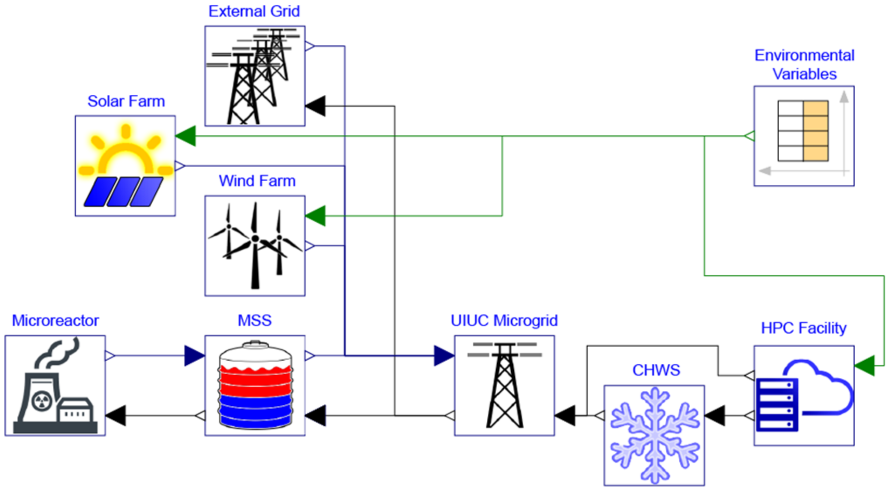
- Load-conditioning and electricity arbitrage provide small amounts of energy cost savings ($60k/y and $90k/y, respectively) as compared to the energy cost savings by the microreactor itself ($1.9M/y).

- However, besides market based optimization, an MSS can provide value through other aspects as well:
  1. An MSS system can decouple the demand load variation from the microreactor neutronics by providing buffer to the load variation. This reduces the number and frequency of control rods maneuvers
  2. An MSS system can enhance the short term load-following capability of a microreactor-MSS system.
  3. An MSS system can serve as a heat reservoir in removing decay heat during SCRAM.

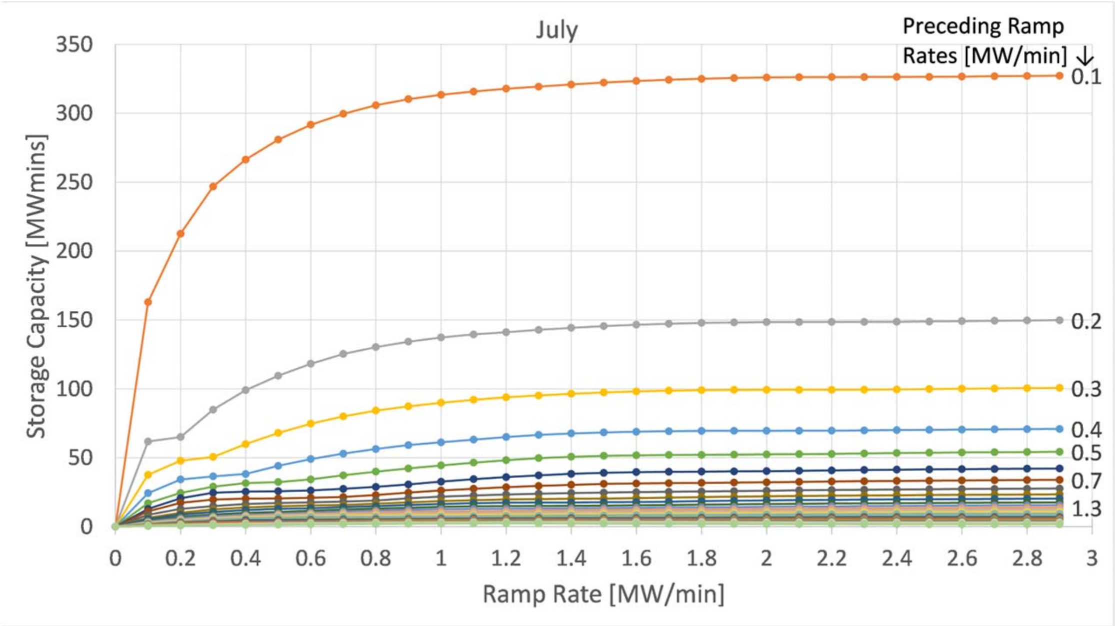
Overview of Subtask 2.2

- Task 2.2: Use of microreactor for High-Performance Computing (HPC).
- HPC is an energy intensive but high-value application.





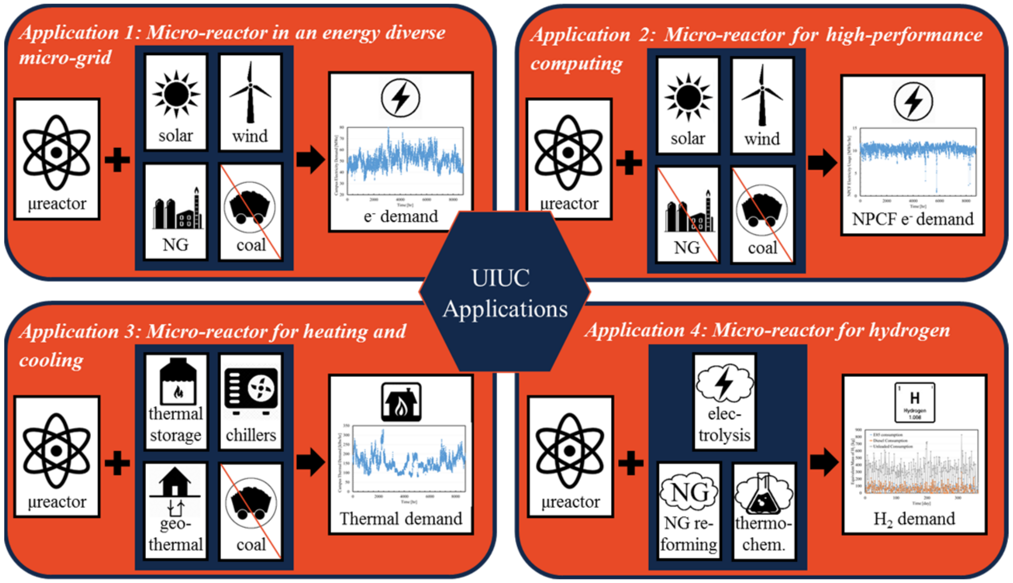
Key Results from Subtask 2.2

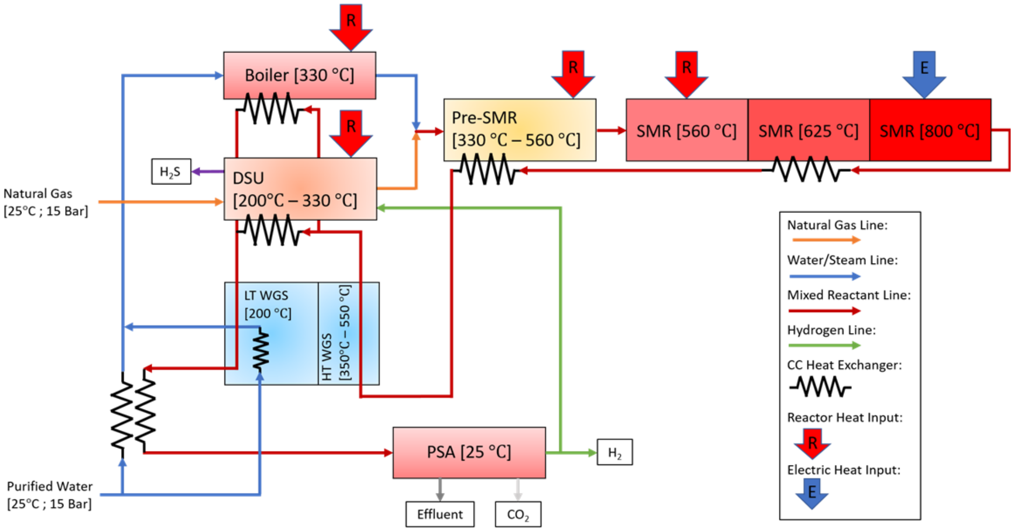


- HPC has very high load variation, requiring up to around 4 MW_e/min of ramping.
- Energy storage devices (MSS, batteries, flywheels) needed for load-following.
- Storage capacity reduced by 2 orders of magnitude if μR can ramp at just 0.3 MWe/min.
- Microreactor designs can greatly enhance versatility and expand use cases by including some load-following capability.

Overview of Subtask 2.4

- Task 2.4: Use of microreactor for hydrogen production.
- Task explored the pairing of a microreactor with low-temperature electrolysis (LTE), high-temperature electrolysis (HTE), and Steam-Methane Reforming (SMR)



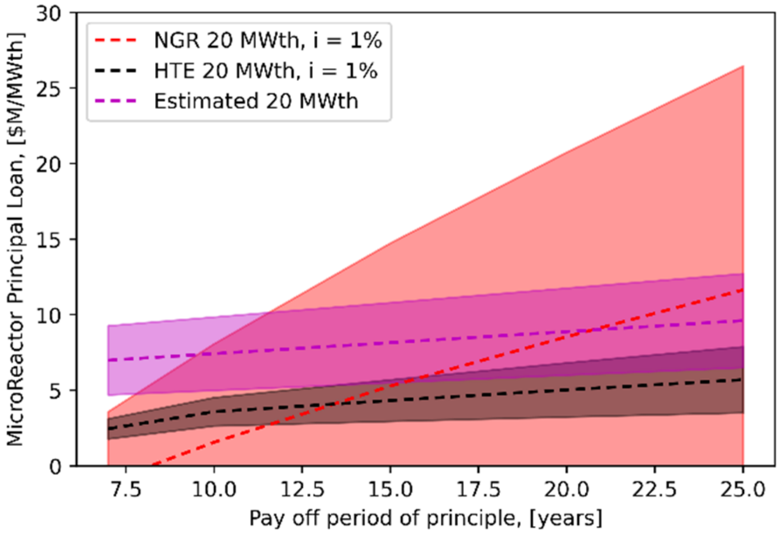


Key Results from Subtask 2.4

Production Method	Yearly H_2 Production [10^3 Tonnes/y]	Emissions Reduction [$MTCO_2/y$]	Emission Reduction Coefficient [$MTCO_2/MWh_e$-equivalent]
LTE	0.93	16.63	0.379
HTE	1.08	19.15	0.437
NGR	4.63	55.21	1.261

- LTE and HTE provide less emissions reduction than if the electricity input was used to offset grid electricity usage (emission coefficient 0.65 $MTCO_2/MWh_e$)
- NGR has process emissions, but the significantly larger production makes for the biggest reduction in emissions
- Hydrogen is a more valuable commodity compared to electricity, provided a demand is available
- All systems are able to fulfill the fueling needs and produce additional hydrogen for sale or export electricity to the grid
- Significant losses in hydrogen yield for transportation occur due to the compression to 700 bar

Stand-alone Hydrogen Systems



- Hydrogen provides a high-value commodity that can help pay off the principal loans required for first-of-a-kind microreactors
- NGR systems are more economically competitive than HTE, with the ability to meet available cost estimates with a 20 year pay-off period
- Tax credits in the Inflation Reduction Act of 2022 provide limited support for the economic viability of hydrogen generating systems

Summary and Conclusion

- A modular modeling framework was developed to simulate the impact of a microreactor deployment within the UIUC microgrid.
  The modeling approach can be extended to other similar microgrids.

- The project explored four main applications for microreactor deployment:
  1. µGrid Electricity Generation 2. Steam & Electricity for Heating/Cooling
  3. Generation for High-Value HPC 4. Production of Hydrogen

- The optimal microreactor configuration depends on the specific application

- In all cases, a microreactor:
  1. Reduces emissions 2. Enhance resiliency from external factors
  3. Could provide process heat, thereby expanding range of possible products

Key Products/Publications

Journal Papers:

- L. Wodrich, A. J. H. Lee, C. S. Brooks, T. Kozlowski, Modeling of an Energy Diverse Embedded Grid for Microreactor Integration, Nuclear Technology, (in-press)
- A. J. H. Lee, L. Wodrich, D. Kalinichenko, C. S. Brooks, T. Kozlowski, Modeling Microreactor Application for High-Performance Computing, Applied Energy, (Under Review)
- D. Kalinichenko, L. Wodrich, A. J. H. Lee, C. S. Brooks, T. Kozlowski, Microreactor Efficacy With Hydrogen Production Methods, (Under Review)

Conference Papers:

- A. J. H. Lee, L. Wodrich, C. Brooks, T. Kozlowski, Modeling and evaluation of micro-reactor deployment within existing microgrids, American Nuclear Society Winter Meeting, Washington D.C., November 30–December 3, 2021
- L. Wodrich, A. J. H. Lee, C.S. Brooks, T. Kozlowski, Determining Economic Efficacy of a Microreactor Within a University Campus, American Nuclear Society Winter Meeting, Washington D.C., November 13–November 17, 2022

Milestone Reports:

- L. Wodrich, D. Kalinichenko, A. J. H. Lee, C. S. Brooks, T. Kozlowski, Evaluation of microreactor requirements and performance in an existing well characterized grid; Task 2.4: Modeling Hydrogen Production Fulfilled by a Microreactor; Milestone ID: M3NU-20-IL-UIUC-030205-026, December 2022.
- A. J. H. Lee, L. Wodrich, D. Kalinichenko, C. S. Brooks, T. Kozlowski, Evaluation of microreactor requirements and performance in an existing well characterized grid; Task 2.2: Modeling Microreactors for High-Performance Computing; Milestone ID: M3NU-20-IL-UIUC-030205-024, September 2022.
- A. J. H. Lee, L. Wodrich, C. S. Brooks, T. Kozlowski, Evaluation of microreactor requirements and performance in an existing well-characterized microgrid; Task 2.1: Modeling Microreactors in an Energy Diverse Micro-Grid, UIUC Technical Report, Milestone ID: M3NU-20-IL-UIUC-030205-023, June 2022.
- L. Wodrich, A. J. H. Lee C. S. Brooks, T. Kozlowski, Evaluation of micro-reactor requirements and performance in an existing well-characterized micro-grid; Task 2.3: Modeling Microreactors for Building Climate Control, UIUC Technical Report, Milestone ID: M3NU-20-IL-UIUC-030205-025, November 2021.
- L. Wodrich, A. J. H. Lee, S. G. Dotson, R. E. Fairhurst Agosta, O. R. Yardas, C. S. Brooks, T. Kozlowski, K. D. Huff, Evaluation of micro-reactor requirements and performance in an existing well-characterized micro-grid; Task 1: Overview of campus energy portfolio and available data, UIUC Technical Report, Milestone ID: M3NU-20-IL-UIUC-030205-022, May 2021.

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Microreactor Transportation Emergency Planning Challenges

Steven J. Maheras

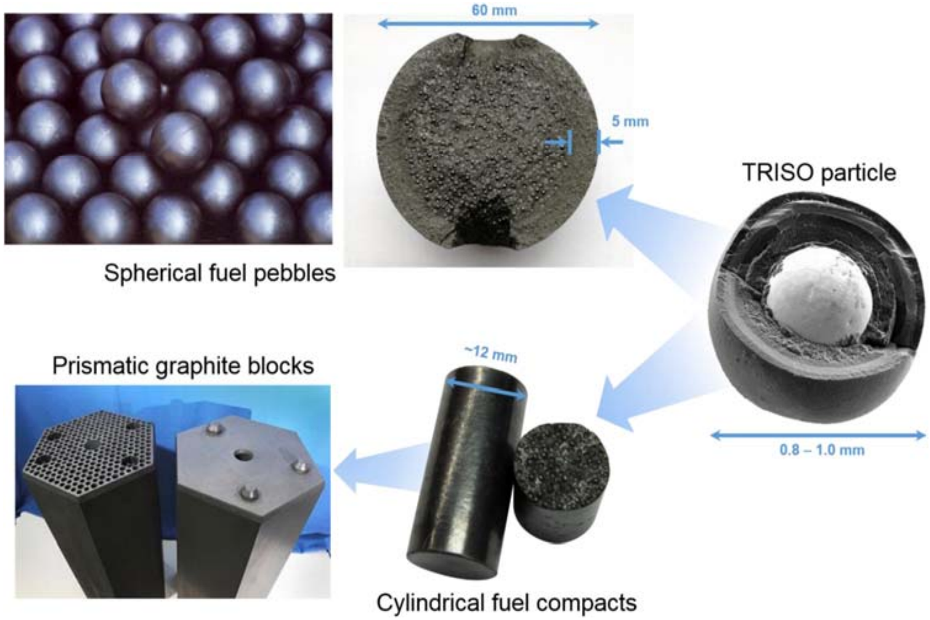
DOE-NE Microreactor Program
Winter Review Meeting
March 8-9, 2023

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

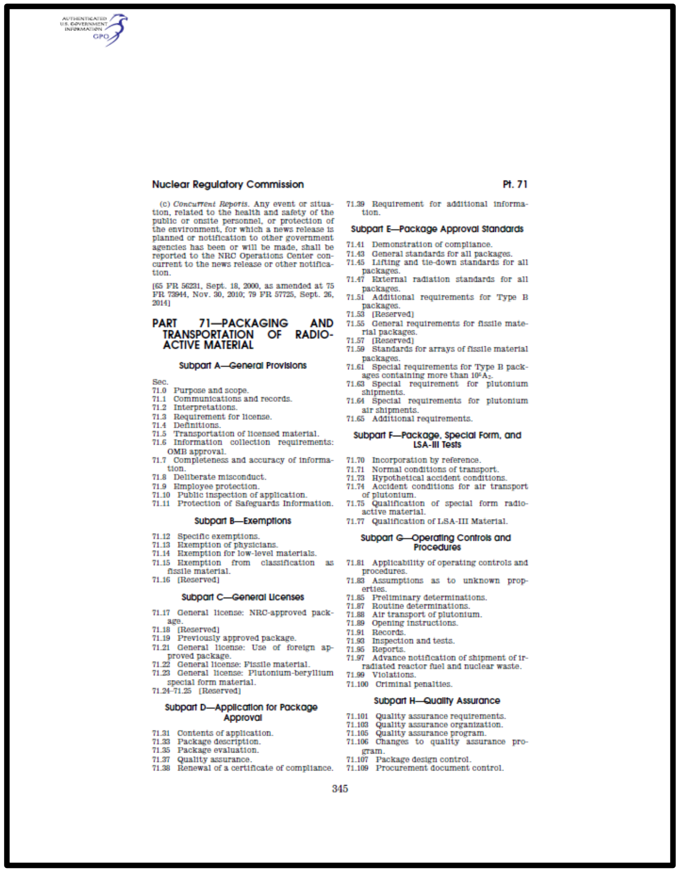
Microreactor Properties

- ≤ 20 MW electrical power
- Factory built and fueled
- Modular
- Highly transportable
- Tristructural isotropic (TRISO) fuel
- Goal is to develop a microreactor that can be shipped containing its unirradiated or irradiated contents
- These microreactors are known as transportable nuclear power plants (TNPPs)



TNPP Transportation Package Approval Options

- U.S. transportation package approval regulatory requirements are contained in 10 CFR Part 71
- A TNPP with its unirradiated or irradiated contents is unlikely to meet the entire suite of regulatory requirements in 10 CFR Part 71
- If all Fissile Material or Type B package regulatory requirements cannot be met, several options are possible
    - Alternate environmental and test conditions [10 CFR 71.41(c)]
    - Special package authorization [10 CFR 71.41(d)]
    - Exemption [10 CFR 71.12]
        - ✓ Requires Environmental Assessment and DOT Special Permit



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Nuclear Regulatory Commission **Pt. 71**

(c) *Concurrent Reports.* Any event or situation, related to the health and safety of the public or onsite personnel, or protection of the environment, for which a news release is planned or notification to other government agencies has been or will be made, shall be reported to the NRC Operations Center concurrent to the news release or other notification.

[65 FR 56231, Sept. 18, 2000, as amended at 75 FR 73944, Nov. 30, 2010; 79 FR 57725, Sept. 26, 2014]

PART 71—PACKAGING AND TRANSPORTATION OF RADIOACTIVE MATERIAL

Subpart A—General Provisions

Sec.
71.0 Purpose and scope.
71.1 Communications and records.
71.2 Interpretations.
71.3 Requirement for license.
71.4 Definitions.
71.5 Transportation of licensed material.
71.6 Information collection requirements: OMB approval.
71.7 Completeness and accuracy of information.
71.8 Deliberate misconduct.
71.9 Employee protection.
71.10 Public inspection of application.
71.11 Protection of Safeguards Information.

Subpart B—Exemptions

71.12 Specific exemptions.
71.13 Exemption of physicians.
71.14 Exemption for low-level materials.
71.15 Exemption from classification as fissile material.
71.16 [Reserved]

Subpart C—General Licenses

71.17 General license: NRC-approved package.
71.18 [Reserved]
71.19 Previously approved package.
71.21 General license: Use of foreign approved package.
71.22 General license: Fissile material.
71.23 General license: Plutonium-beryllium special form material.
71.24–71.25 [Reserved]

Subpart D—Application for Package Approval

71.31 Contents of application.
71.33 Package description.
71.35 Package evaluation.
71.37 Quality assurance.
71.38 Renewal of a certificate of compliance.
71.39 Requirement for additional information.

Subpart E—Package Approval Standards

71.41 Demonstration of compliance.
71.43 General standards for all packages.
71.45 Lifting and tie-down standards for all packages.
71.47 External radiation standards for all packages.
71.51 Additional requirements for Type B packages.
71.53 [Reserved]
71.55 General requirements for fissile material packages.
71.57 [Reserved]
71.59 Standards for arrays of fissile material packages.
71.61 Special requirements for Type B packages containing more than 10^6A_2.
71.63 Special requirement for plutonium shipments.
71.64 Special requirements for plutonium air shipments.
71.65 Additional requirements.

Subpart F—Package, Special Form, and LSA-III Tests

71.70 Incorporation by reference.
71.71 Normal conditions of transport.
71.73 Hypothetical accident conditions.
71.74 Accident conditions for air transport of plutonium.
71.75 Qualification of special form radioactive material.
71.77 Qualification of LSA-III Material.

Subpart G—Operating Controls and Procedures

71.81 Applicability of operating controls and procedures.
71.83 Assumptions as to unknown properties.
71.85 Preliminary determinations.
71.87 Routine determinations.
71.88 Air transport of plutonium.
71.89 Opening instructions.
71.91 Records.
71.93 Inspection and tests.
71.95 Reports.
71.97 Advance notification of shipment of irradiated reactor fuel and nuclear waste.
71.99 Violations.
71.100 Criminal penalties.

Subpart H—Quality Assurance

71.101 Quality assurance requirements.
71.103 Quality assurance organization.
71.105 Quality assurance program.
71.106 Changes to quality assurance program.
71.107 Package design control.
71.109 Procurement document control.

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Preferred Regulatory Pathway

- 10 CFR 71.41(c) process used for the 10-160B and 8-120B transportation casks
- 10 CFR 71.41(d) process used for the West Valley Melter Package
- 10 CFR 71.12 process used for the Trojan Reactor Vessel
- Preferred regulatory pathway identified by PNNL is the 10 CFR 71.12 exemption process for initial or first-of-a-kind TNPP transport
  - Use compensatory measures to provide the basis for the exemption
  - Demonstrate that the risk to the public is low
- For fleet of TNPPs, an NRC transportation Certificate of Compliance (CoC) will likely be pursued

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PNNL-31867

Proposed Risk-Informed Regulatory Framework for Approval of Microreactor Transportation Packages

August 2021

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U.S. DEPARTMENT OF ENERGY

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Purpose

- In general, the transportation emergency response community is not familiar with microreactors or the concept of transporting a microreactor containing its irradiated fuel
- The purpose of this work is to describe the emergency planning challenges associated with the transportation of a microreactor containing its irradiated fuel
- The challenges are not likely to be the same as for shipments of spent nuclear fuel in transportation casks (the current paradigm)
- Some challenges are likely to be mode-specific (i.e., different for shipment by truck, rail, air, and vessel)
- Some challenges will be design-specific, e.g., presence of other hazardous materials

Assumptions

- The microreactor shipment would be a commercial shipment and would receive transportation package approval from the NRC
- Truck and rail transport modes are being evaluated. Transport by air and vessel are not being evaluated at this time.
- The microreactor containing its irradiated fuel will contain a highway route controlled quantity of radioactive material (i.e., 3000 A_2)
  - For truck shipments this means that a CVSA Level VI inspection and safety permit would be required (see 49 CFR 385 and 49 CFR 397)
  - For rail shipments this means that the transportation planning requirements in 49 CFR 172.820 would apply
- The analysis will assume that the microreactor is fueled by LEU or HALEU. To the extent that information is available, the report will identify the potential for unique challenges associated with different fuel forms.
- For rail shipments, transport will be via Association of American Railroads (AAR) Standard S-2043 railcars

Areas To Be Examined In Identifying TNPP Transportation Emergency Planning Challenges

• Assignment of Responsibility	• Accident Assessment
• Emergency Response Organization	• Protective Response
• Emergency Response Support and Resources	• Radiological Exposure Control
• Emergency Classification System	• Medical and Public Health Support
• Notification Methods and Procedures	• Recovery, Reentry, and Post-Accident Operations
• Emergency Communications	• Exercises and Drills
• Public Education and Information	• Radiological Emergency Response Training
• Emergency Facilities and Equipment	• Responsibility for the Planning Effort: Development, Periodic Review, and Distribution of Emergency Plans

Potential Compensatory Measures (I)

- This section will discuss potential compensatory measures that may be required to obtain NRC transportation package approval, and for a DOT special permit, if required.
- TNPPs containing irradiated fuel shipped by highway will be highway route-controlled quantities (HRCQ) (> 3000 A_2) and will need to meet the routing requirements in 49 CFR Part 397
  - Interstates, beltways around cities, state identified preferred routes
- TNPPs will likely be overweight/overdimension and will require state permitting when transported by highway
  - Specific heavy haul truck or superload permit requirements could be considered as compensatory measures

Potential Compensatory Measures (II)

- Other potential compensatory measures that may be credited in the transportation PRA or identified as a defense-in-depth measure such as:
  - Increased exclusion zone around TNPP because of radiation dose rate
  - Real time health/fitness onboard monitoring/diagnostics of reactor package
  - Escorting of the reactor forward and aft for the entire route
  - Travel at reduced speeds
  - Choosing a route that avoids bodies of water (balanced by quality of road)
  - Controls for bridges over bodies of water (bridge inspection, speed reduction, close bridge to other traffic)
  - Judicious use of time-of-day and day-of-week restrictions
  - Avoid shipping during severe weather
  - Conduct training for emergency responders along the route

Cross-Cutting Issues Also Being Identified

- For transportation, there is no process equivalent to the 10 CFR 50.59 or 10 CFR 72.48 processes for reactors or storage systems
- Implication– change to microreactor design could mean resubmittal of microreactor transportation safety analysis

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Thank you