Friday, April 16, 2021

Maria Avramova
Associate Professor, North Carolina State University

Fission Battery Initiative Workshop Series
Safety & Licensing Workshop

INL & NUC POC:

Jason Christensen
Idaho National Laboratory

Maria Avramova
North Carolina State University

Dean Wang
The Ohio State University

Local Organizers:

Scott Palmtag
North Carolina State University

Mihai A. Diaconeasa
North Carolina State University

Jason Hou
North Carolina State University

Idaho National Laboratory

Workshop Objectives & Outcomes

- The objectives of this workshop are to understand the challenges and gaps that exist in developing:
  - computational and validation tools needed for fission battery safety analysis and confirmatory regulatory evaluations;
  - approaches for preparing fission battery safety analysis reports and initial license applications;
  - implementation of design control practice defined in ASME-NQA-1 to fission battery safety analysis and report.

- The expected outcomes should include:
  - identifying the research and development required to perform fission battery safety analyses and evaluations;
  - proposing graded preparation approach and content of the fission battery safety analysis report;
  - establishing the technical bases for licensing and operation of fission batteries, processes to control the design and design changes of items that are subject to the quality assurance requirements.

Webinar Agenda

Opening Session 10:00 – 10:20 a.m. EDT	Opening Statement and Introduction………………………………………………...*Vivek Agarwal, (INL)*
Modeling & Simulation of FB Safety *Moderator: S. Palmtag, NCSU* 10:20 – 11:35 a.m. EDT	Evaluation Model Content for New Reactor Licensing………………..........…*Robert Martin (BWXT)* Industry Approaches for Microreactor Modeling and Simulation……….*Bradley T. Rearden (X-energy)* Transient Modeling and Safety Issues of Fission Battery Reactors……………....*T.K. Kim (ANL)* Highlights on MOOSE Capabilities for Safety Analyses of FB……………………..*Nicolas Martin (INL)*
11:35 – 11:45 a.m. ***Break***	
Safety Design Basis and Strategy for FB. Content of FB Safety Analysis *M. A. Diaconeasa, NCSU* 11:45 – 1:15 p.m. EDT	NRC Perspectives on the Safety and Licensing of Fission Batteries ……………………………………………………………………….*Jan Mazza & Martin Stutzke (U.S. NRC)* Licensing Issues for Fission Batteries: Working INSIDE the Box ……………....*Ronald Ballinger (MIT)* Perspectives on the Role of PRA in Fission Battery Development …………………………………………………………. *Karl Fleming (KNF Consulting Services LLC)*
1:15 – 1:45 p.m. EDT ***Lunch Break***	
Licensing & Regulatory Research for FB J. Christensen, INL 1:45 – 2:35 p.m. EDT	Developments in Digital Twins: Applications to the Future of FB…………….*Christopher Chwasz (INL)* Proposed Licensing Basis for FB Reactors - Three Critical Issues…………… *Richard Denning (OSU)*
2:35 – 2:45 p.m. EDT ***Break***	
Design Control of the Design-Basis Envelope for FB. Support for DOE's Authorization Process J. Hou, NCSU 2:45 – 3:50 p.m. EDT	Overview of U.S. DOE Authorization Pathways……………………….*Thomas Sowinski (U.S. DOE NE)* Preparation of Safety Basis Documents for DOE Authorization of FB …………….*Jason Andrus (INL)* DOE Safety Authorization Process for New Reactors ……………….*Charles Maggart (U.S. DOE NE)*
Concluding Session 3:50 – 4:00 p.m. EDT	Outcomes and Closing remarks ……………………………………………….*Jason Christensen (INL)*

April 16, 2021

Vivek Agarwal, Ph.D.
Technical Lead, Fission Battery Initiative

Fission Battery Initiative

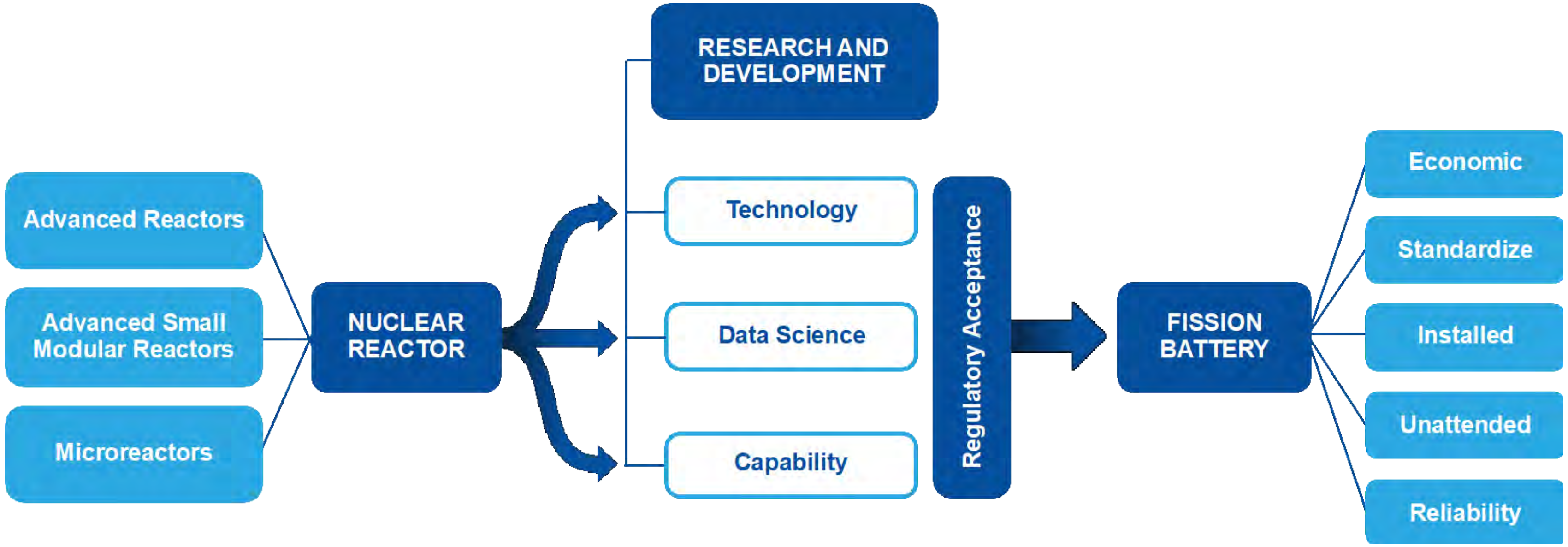
Nuclear Science and Technology

Idaho National Laboratory

Fission Battery Initiative

Vision: Developing technologies that enable nuclear reactor systems to function as batteries.

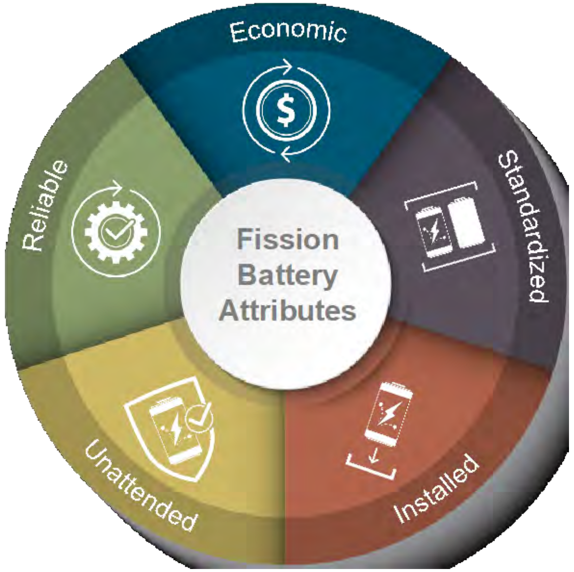
Outcome: Deliver on research and development needed to provide technologies that achieve key fission battery attributes and expand applications of nuclear reactors systems beyond concepts that are currently under development.



Research and development to enable nuclear reactor technologies to achieve fission battery attributes

Fission Battery Attributes

- **Economic** – Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as distributed energy resources.
- **Standardized** – Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment.
- **Installed** – Readily and easily installed for application-specific use and removal after use. After use, fission batteries can be recycled by recharging with fresh fuel or responsibly dispositioned.
- **Unattended** – Operated securely and safely in an unattended manner to provide demand-driven power.
- **Reliable** – Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation.



Fission Battery Workshop Series

- **Jointly INL and National University Consortium are organizing workshops across five areas:**
  - Market and Economic Requirements for Fission Batteries – January 13 & 27, 2021
  - Technology Innovation for Fission Batteries – January 20, February 10 & 24, 2021
  - Transportation and Siting for Fission Batteries – March 15, 2021
  - Domestic & International Safeguards & Security for Fission Batteries – April 02, 2021
  - **Safety and Licensing of Fission Batteries – April 16, 2021**

- **Expected outcomes:**
  - Each workshop outcomes are expected to outline the goals of each fission battery attribute

INL

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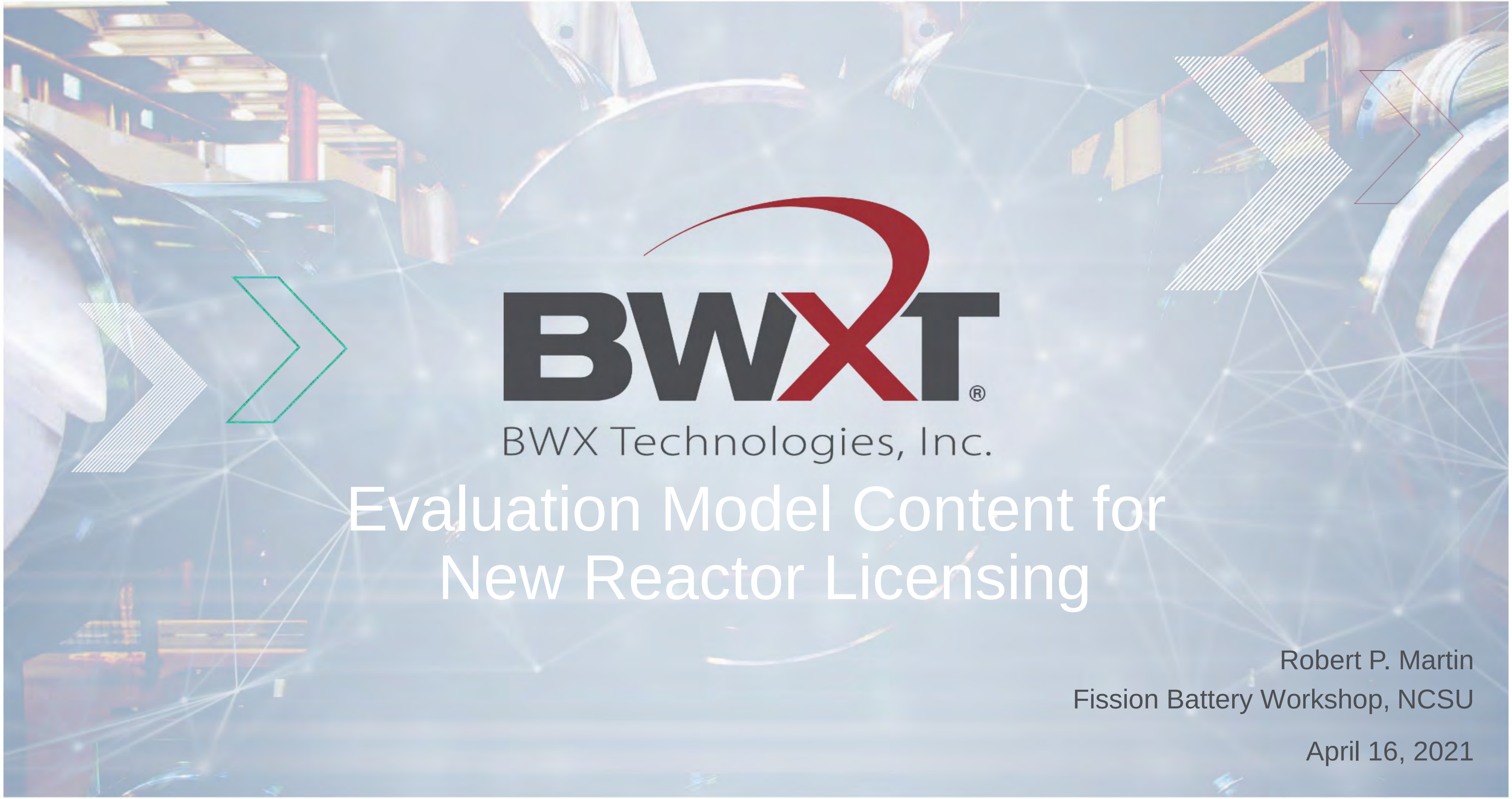


BWX Technologies, Inc.

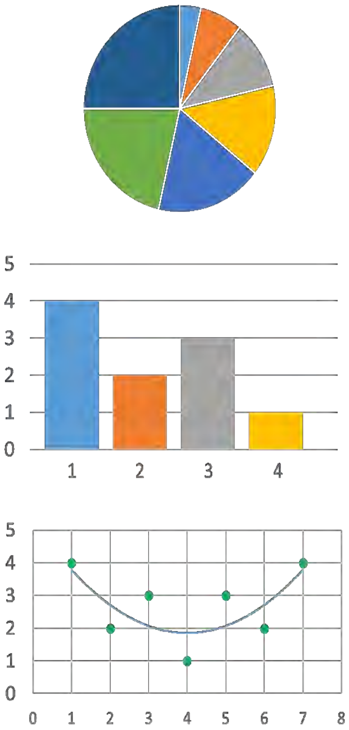
Evaluation Model Content for New Reactor Licensing

Robert P. Martin
Fission Battery Workshop, NCSU

April 16, 2021

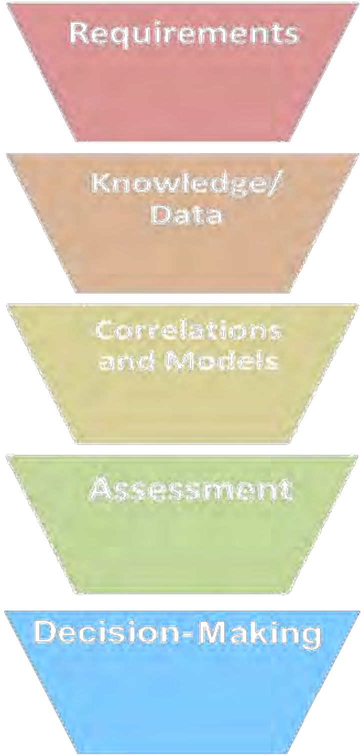
Possible Safety Case Gaps for New Reactor Licensing

- Design status questions
  - Unidentified safety metrics?
  - Unresolved safety issues?
  - Incomplete test programs?
- Little/no operation and maintenance experience
  - Design-specific risk measures (e.g., frequency of equipment malfunction and failure)
  - Occupation dose estimates (ALARA)
  - Reliability and resilience of safety controls
  - Human factors statistics



Contemporary practice benefits from years of data collecting, naturally lacking for new reactors

New Nuclear Safety Case, Evaluation Model Development and Application Process (EMDAP)



Safety case element definitions

- Imagine (v) – to form a mental image of
- Design (v) – to devise for a specific function or end
- Engineer (v) – to guide the course of
- Prove (v) – to establish the validity of (by evidence or logic)
- Permit (v) – to consent to formally

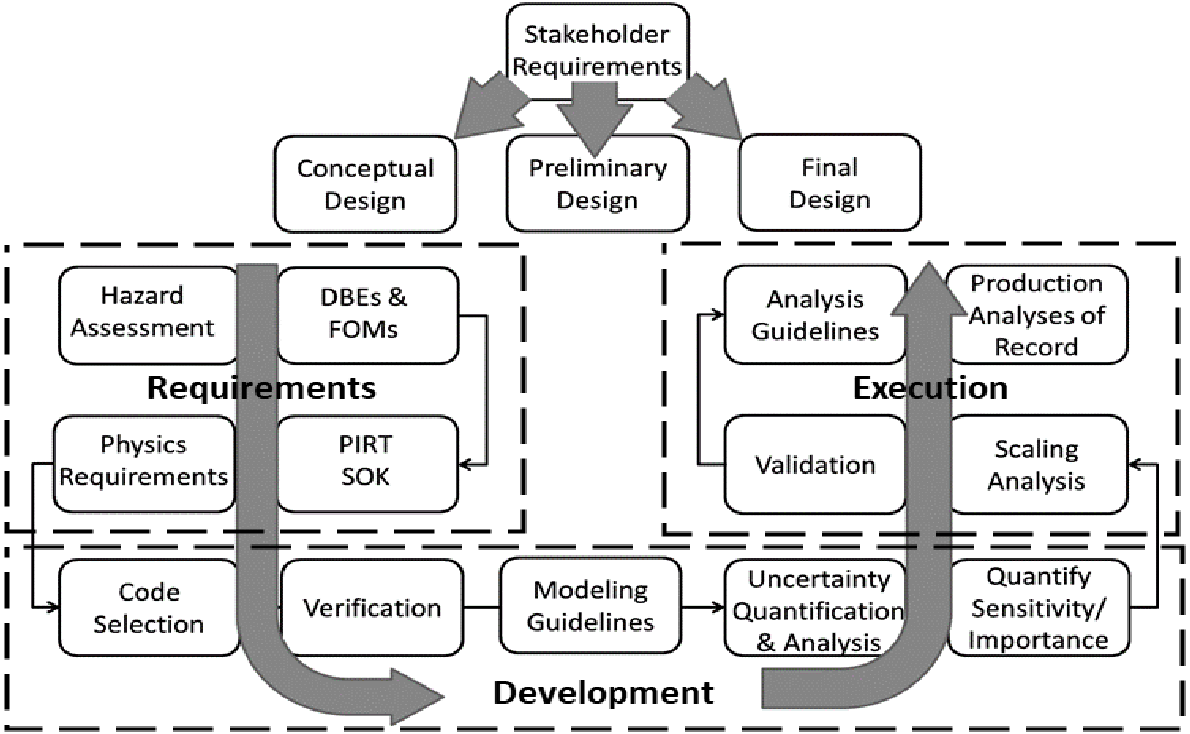
Breath of safety case, and supporting analysis relies on the application of existing and new knowledge

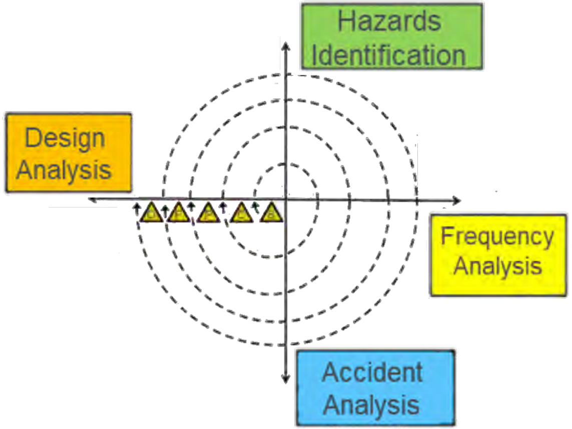
Enter Modeling and Simulation (M&S)

- 10 CFR 50.43(e)(1) that:
    - The performance of each safety feature of the design has been demonstrated through analysis, test programs, experience, or a combination thereof.
    - Interdependent effects among the safety features of the design have been found acceptable by analysis, appropriate test programs, experience, or a combination thereof.
    - Sufficient data exist on the safety features of the design to assess the analytical tools used for safety analysis over a range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.
- 10 CFR 50.2
    - Safety-related SSC - The capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the applicable guideline exposures
        - » Avoid direct comparisons to LWRs (or others designs), new reactor safety case must stand alone
        - » Radiological measures are (still) the primary safety metric; fission product containment (e.g., fuel) testing can allow for surrogate safety metrics

Regulations recognizes value of knowledge captured in M&S, emphasis on radiological consequences

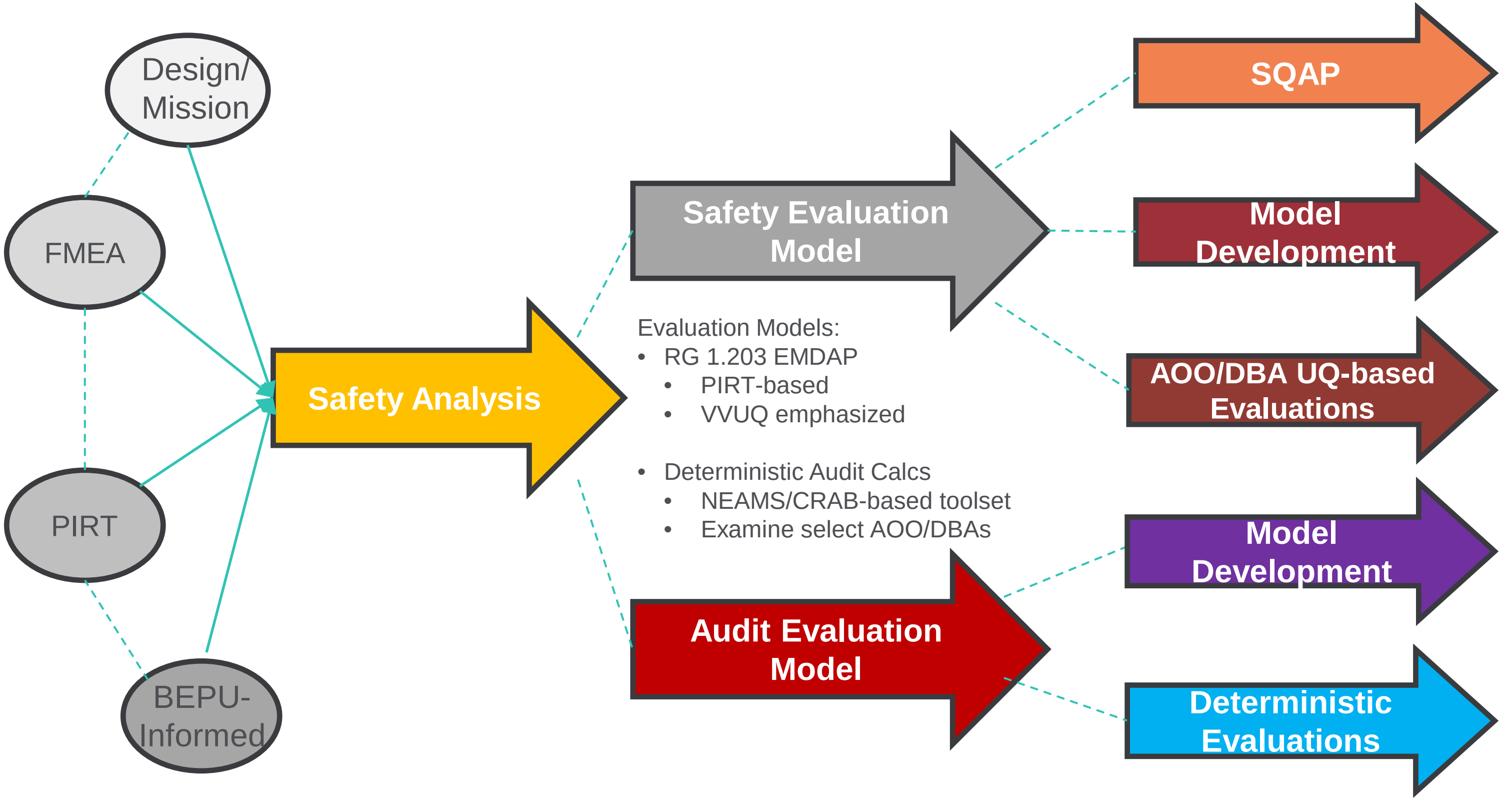
M&S Activities Supporting Safety-in-Design





Design controlled evaluation models rely on verification, validation and uncertainty quantification

Safety Analysis Roadmap – Strength in Numbers



Evaluation Models:

- RG 1.203 EMDAP
  - PIRT-based
  - VVUQ emphasized
- Deterministic Audit Calcs
  - NEAMS/CRAB-based toolset
  - Examine select AOO/DBAs

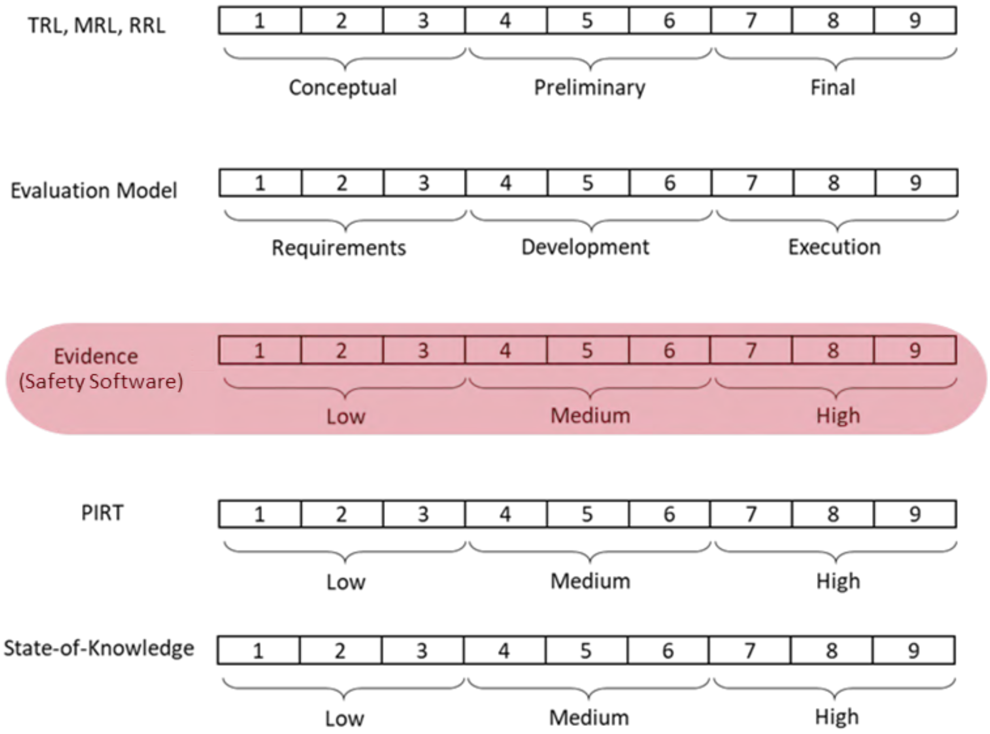
Scope of safety analysis requires verification via independent solutions; lacking data, this is more important

Decision-making metrics – Technology Readiness Levels

TRL Ranking	Evaluation Criteria
9	Actual system proven through successful operations
8	Actual system completed and qualified through test and demo
7	System prototype demonstration in operational environment
6	System/subsystem prototype demonstration in relevant environment
5	Component level tests in simulated environment
4	Component level tests in lab environment to validate technology
3	Active R&D initiated
2	Practical applications, start invention
1	Basic principles observed

Decision-making involves the tractability of technology readiness metrics

Decision-Making and Modeling & Simulation Adequacy



Safety Software Evidence Ranking for RELAP5-3D for HTGRs

Phenomena	Code Status	Data Status	Code Status Rationale	TRL
Core				
Nuclear (power)	ADQ	ADQ	Use of validated monte carlo or nodal kinetics models can inform heat deposition in the HTGR cores. Accurate cross sections are necessary.	8-9
Nuclear (reactivity coefficients)	ADQ	VAL	The primary feedback mechanism is Doppler resonance broadening. Use of validation monte carlo or nodal kinetics models can inform the reactor kinetics model. Accurate cross sections are necessary.	7
Air ingress, graphite oxidation	VAL	VAL	RELAP5-3D has some capability to address air ingress related phenomena, but integral effects data is lacking.	6
Dust release	DEV/ ALT	VAL	An analysis code with the appropriate models has not been identified for this evaluation; although, dust is not expected to be significant in prismatic HTGRs (in contrast to pebble-bed designs).	5

DEV/ALT: Further development or an alternative is required.

VAL: Additional validation is required to cover the range of expected conditions (i.e., pressure, temperature, etc.).

ADQ: Phenomena are modeled in the analysis code, the range of applicability is adequate and the model has been validated.

Tiers of technology readiness measures recognized in EMDAP, do we need another?

Conclusions

- Relative newness of everything presents several M&S challenges
  - Safety case preparation
  - Knowledge of design-specific processes
  - Analysis fidelity
  - Data for VVUQ, risk measures, ALARA methods
  - Consensus-building for technology readiness metrics
- To fill safety case evidence gaps, there is a need for low-power prototype(s)
  - Data to support M&S applications and evaluation model validation
  - Some separate-effects testing may still be necessary
  - Low-power, defined based on a deterministic radiological consequence analysis?

Many (technology-dependent) paths to the same destination, but we must all get there safely

Industry Approaches for Microreactor Modeling and Simulation

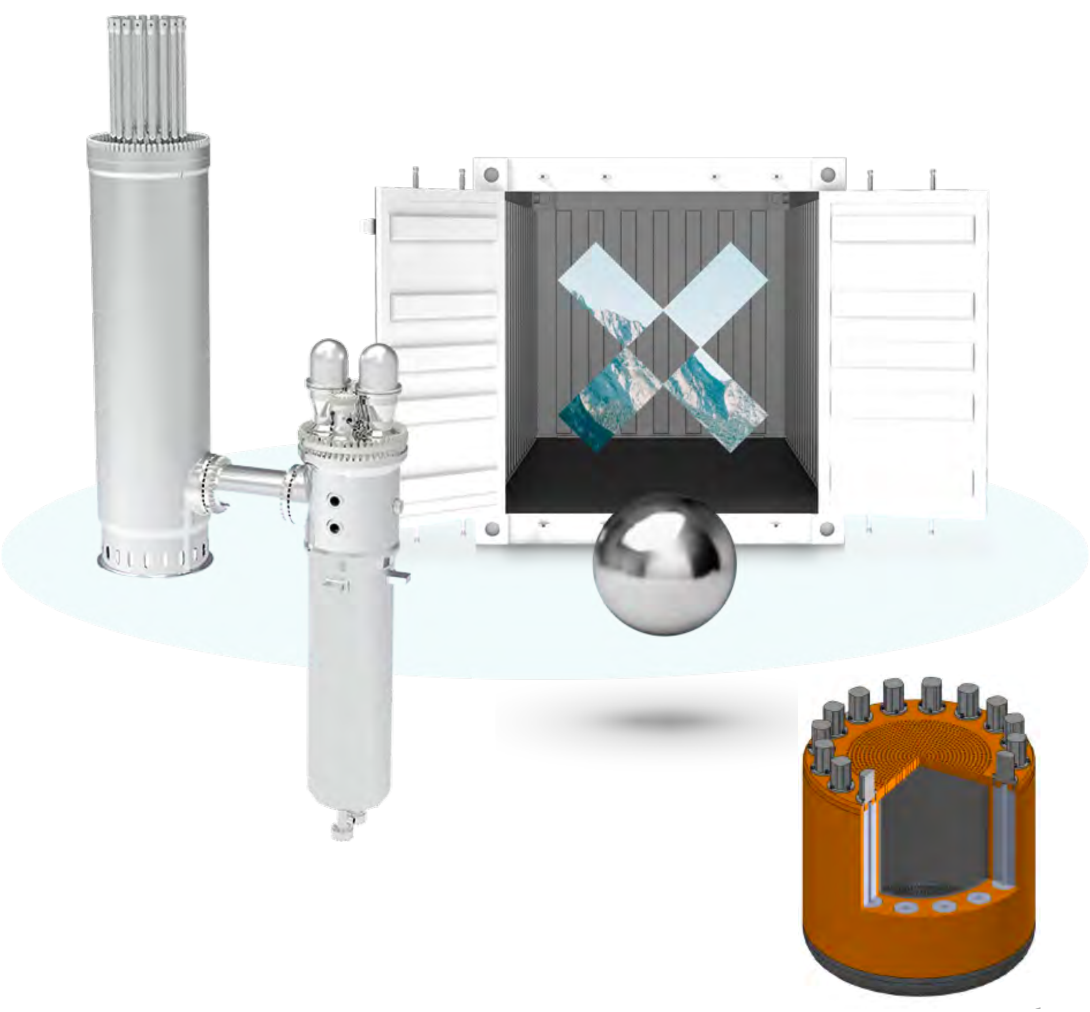
Presented to:
Workshop on Safety and Licensing of Fission Batteries
Fission Battery Initiative

Dr. Bradley T. Rearden

Director of Engineering, Xe-Mobile

April 16, 2021

We design & build reactors and the fuel that powers them



Reactor: Xe-100

We are focused on Gen-IV High-Temperature Gas-cooled Reactors (HTGR) as the technology of choice, with advantages in sustainability, economics, reliability and safety. We have completed conceptual design and entering the Basic Design Phase of design development.

Reactor: Xe-Mobile

To address the need for ground, sea and air transportable small power production. We've completed the preliminary design of this nuclear fission-based power generation system, with potential applications to DOD, civilian government, remote community, and critical infrastructure applications.

Fuel: TRISO-X

Our reactors use tri-structural isotropic (TRISO), ceramic-coated particle fuel, developed and improved over 60 years of R&D and commercial production. We manufacture our own proprietary version (TRISO-X) to ensure commercial supply quantities and quality control.

Space Applications

NASA, DOE, and DOD are exploring our reactor and fuel technologies for nuclear thermal propulsion, nuclear electric propulsion, and fission power for lunar and Mars surface continuous electricity delivery.

X-energy: Success Building On Success

Office of Nuclear Energy

U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program

OCTOBER 13, 2020

Home » U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program

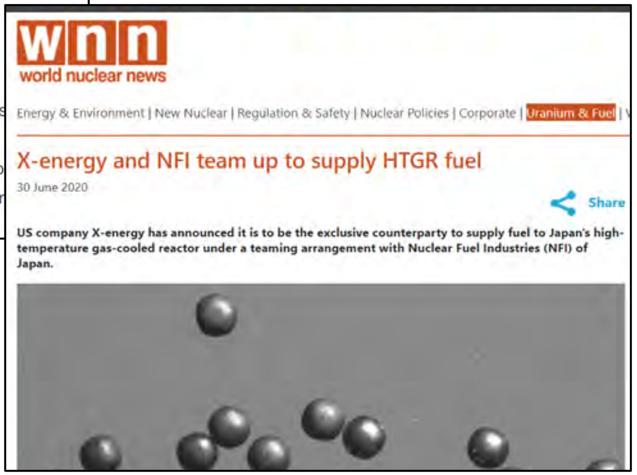
WASHINGTON, D.C. – The U.S. Department of Energy (DOE) today announced it has selected two U.S.-based teams to receive $160 million in initial funding under the new Advanced Reactor Demonstration Program (ARDP). ARDP, announced in May, is designed to help domestic private industry demonstrate advanced nuclear reactors in the United States.

DOE is awarding TerraPower LLC (Bellevue, WA) and X-energy (Rockville, MD) $80 million each in initial funding to build two advanced nuclear reactors that can be operational within seven years The awards are cost-shared partnerships with industry that will deliver two first-of-a-kind advanced reactors to be licensed for commercial operations. The Department will invest a total o $3.2 billion over seven years, subject to the availability of future appropriations, with our industr partners providing matching funds.

X-energy to work with Ontario Power Generation to advance clean energy technology in Canada

NEWS PROVIDED BY
X-energy →
Oct 06, 2020, 15:38 ET

TORONTO, Oct. 6, 2020 /PRNewswire/ -- X-energy is plea
advance the engineering and design work of the Xe-10



X-energy and NFI team up to supply HTGR fuel

30 June 2020

US company X-energy has announced it is to be the exclusive counterparty to supply fuel to Japan's high-temperature gas-cooled reactor under a teaming arrangement with Nuclear Fuel Industries (NFI) of Japan.

IMMEDIATE RELEASE

Strategic Capabilities Office Selects Two Mobile Microreactor Concepts to Proceed to Final Design

MARCH 22, 2021

The Department of Defense (DOD) exercised contract options for two teams— led by BWXT Advanced Technologies, LLC, Lynchburg, Virginia; and X-energy, LLC, Greenbelt, Maryland—to proceed with development of a final design for a transportable advanced nuclear microreactor prototype. The two teams were selected from a preliminary design competition, and will each continue development independently under a Strategic Capabilities Office (SCO) initiative called Project Pele.

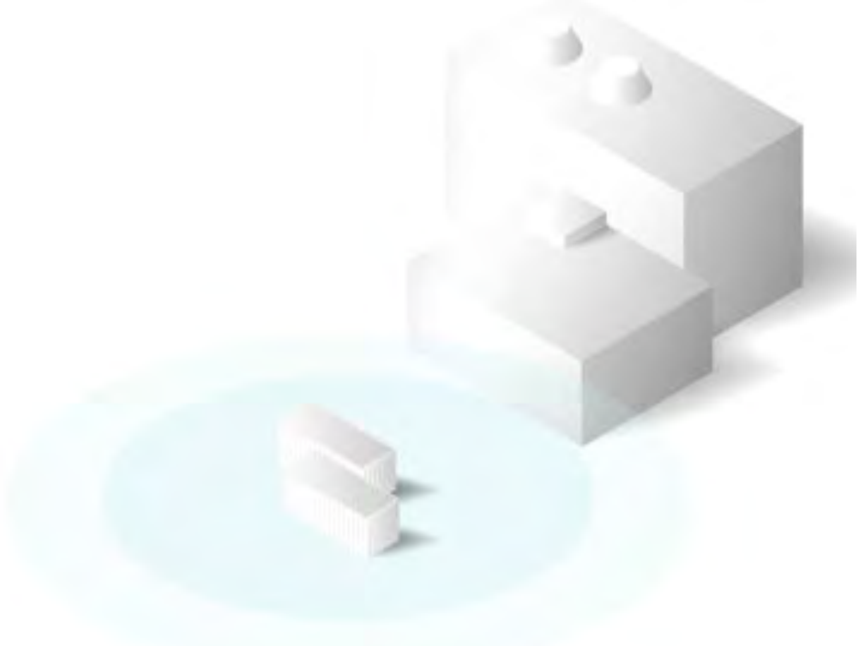
After a final design review in early 2022 and completion of environmental analysis under the National Environmental Policy Act, one of the two companies may be selected to build and demonstrate a prototype. This selection follows an April 2019 request for solutions through which three companies were awarded competitively other transaction agreements for prototyping to develop preliminary designs.

X-energy's Novel Applications of Microreactors

Defense & forward bases

As the US Military prepares for "near-peer" adversaries of the future, highly portable power with a high energy density will be a game-changing technology.

Highly Portable Power



Disaster Relief

The ability to transport flexible electricity solutions that do not require fueling for months or years provides critical infrastructure to get railroads, water purification facilities, and hospitals powered again – within one week.

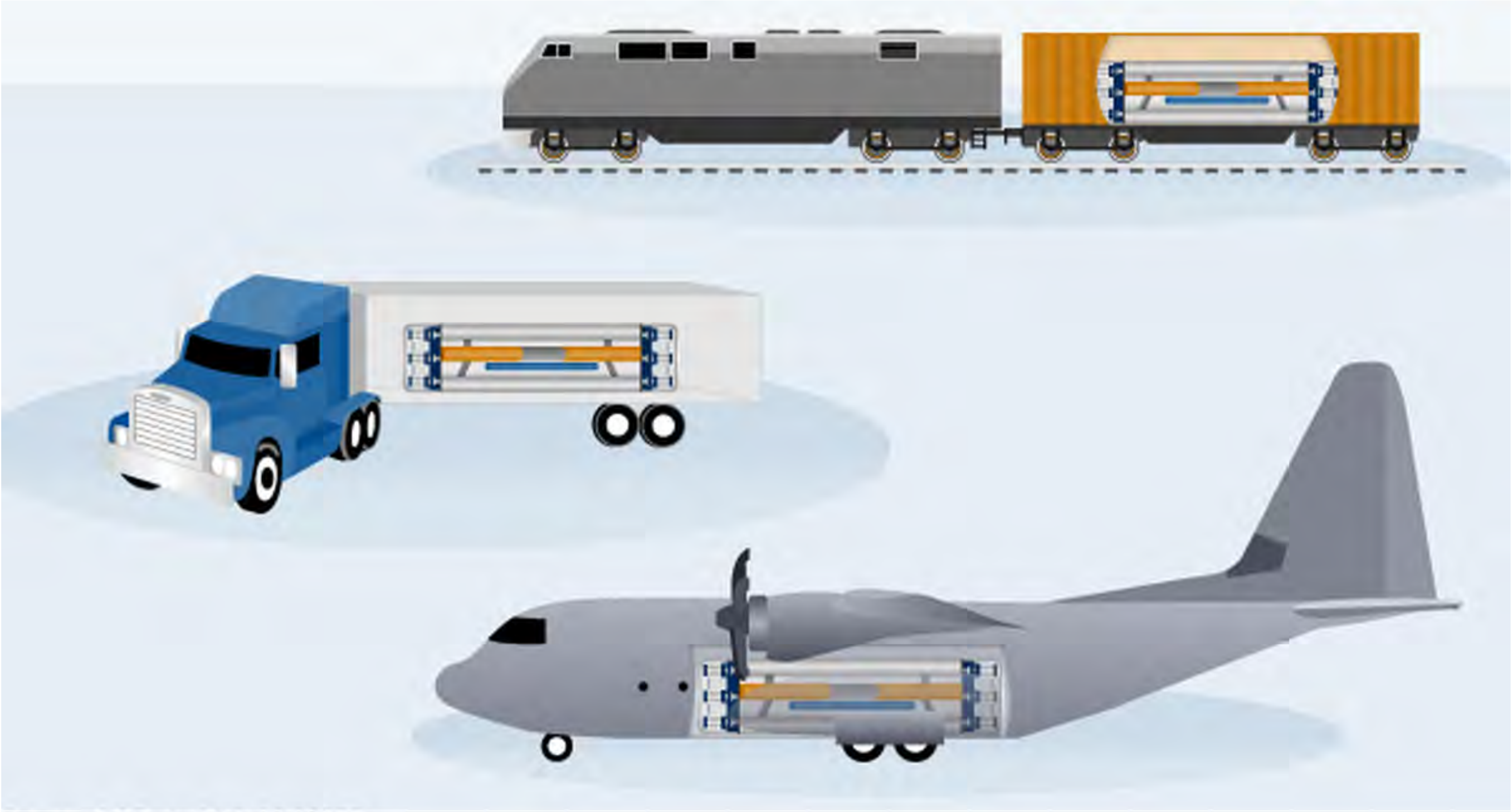
Be powered again – within one week

Remote Communities

Arid, Island and Alaskan/Canadian communities often use government-subsidized petroleum fuel deliveries to maintain their power. If their deliveries are disrupted, the impact can be significant.

Maintain Power

Portable Microreactors will be in close contact with people before, during, and after operation

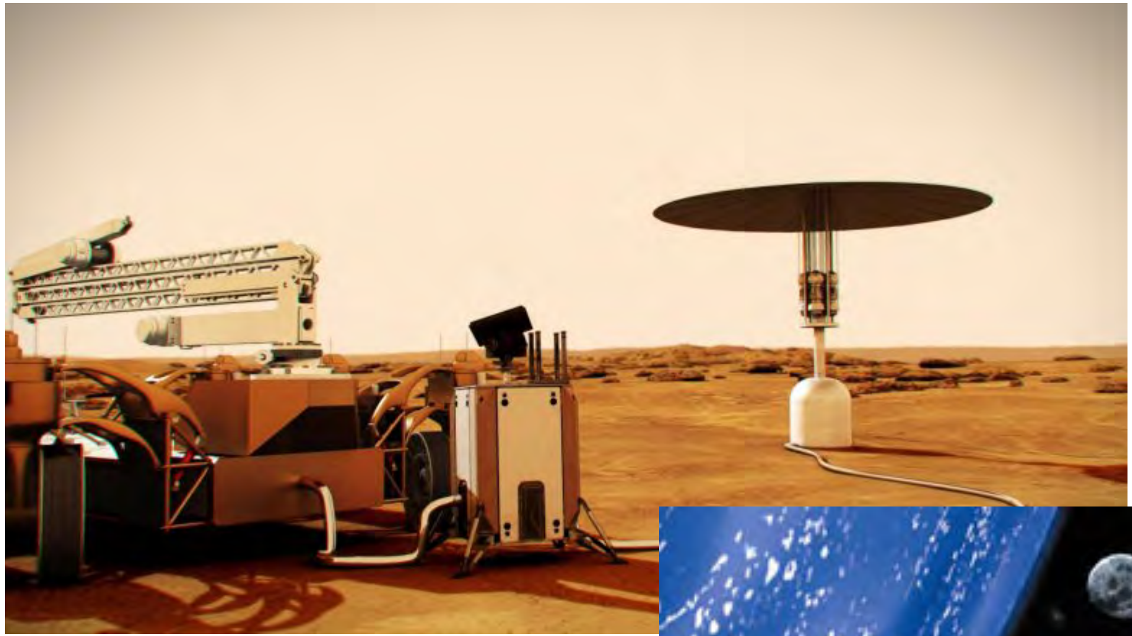


Source: GAO. | GAO-20-380SP

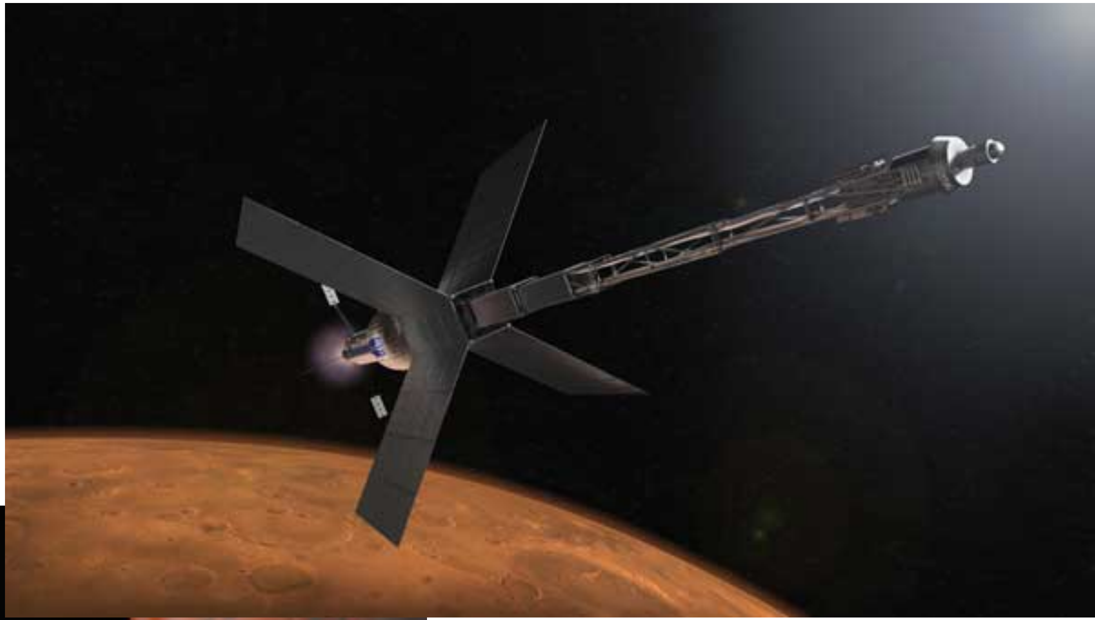
These concepts from the Government Accountability Office show potential ideas for transport and deployment. (U.S. Government Accountability Office)

Emerging Opportunities in Space Nuclear Applications

Fission Surface Power System



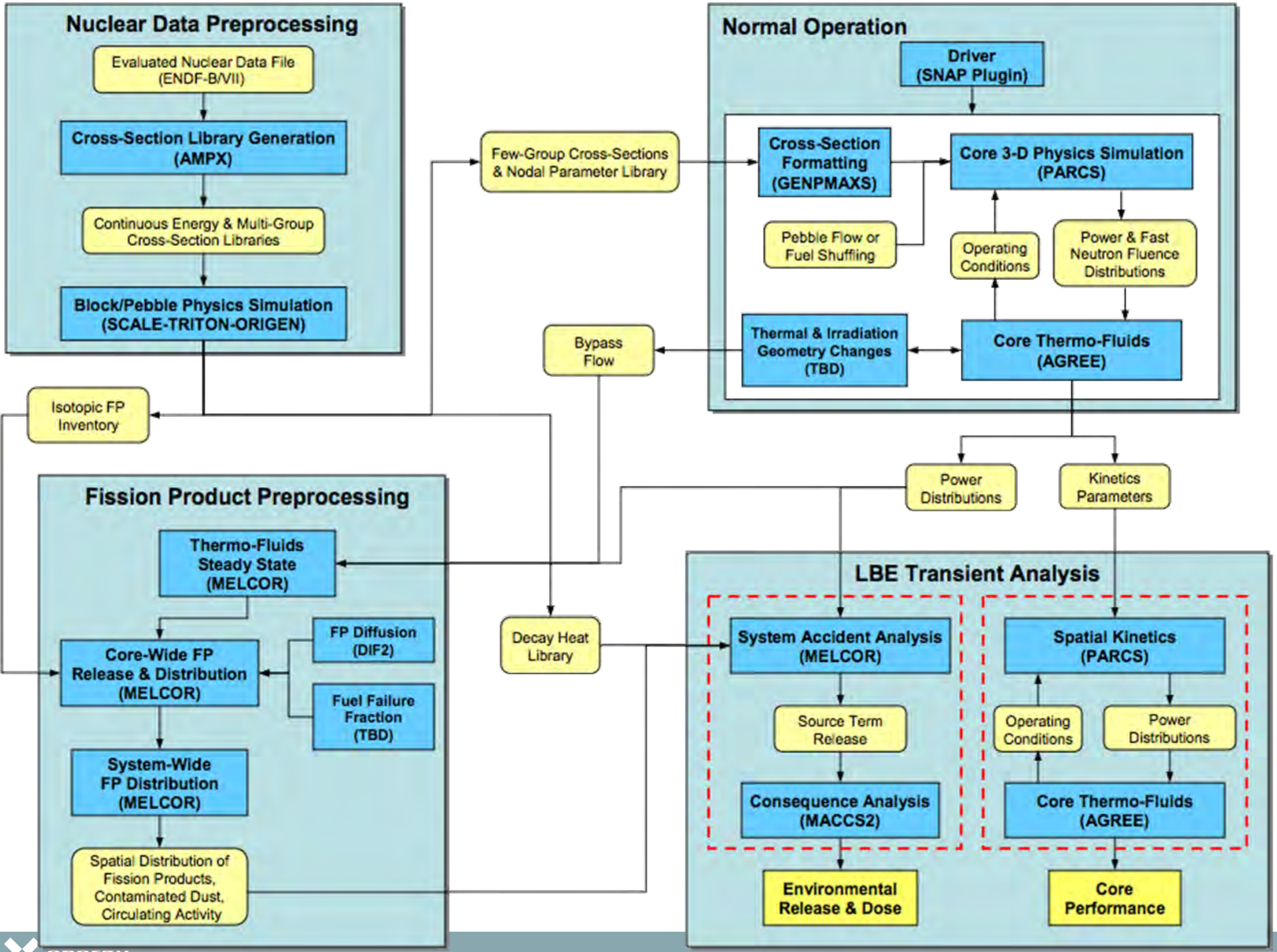
Nuclear Electric Propulsion

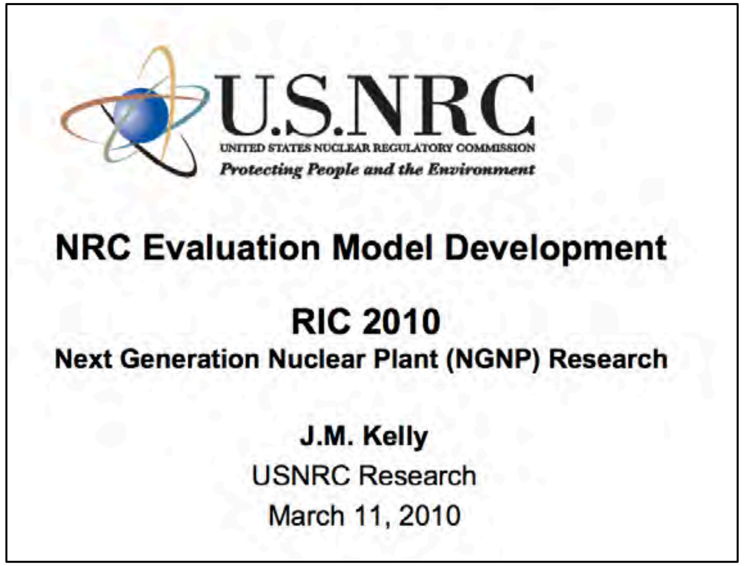


Nuclear Thermal Propulsion

Images: NASA

Example of robust, integrated toolkit: NRC NGNP Evaluation Model (2008)

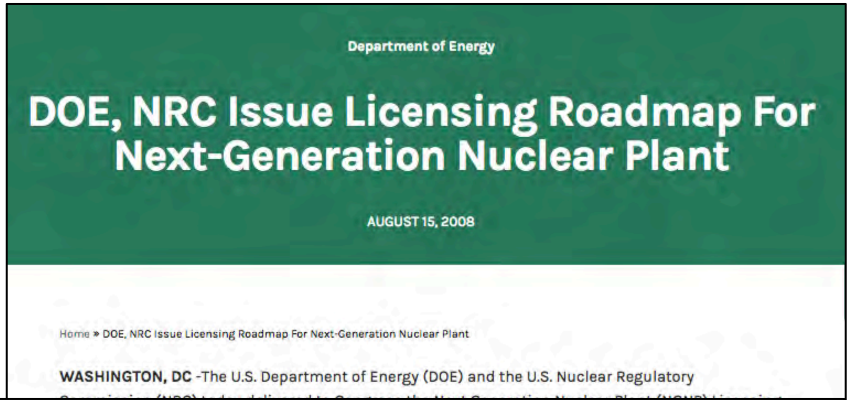



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

NRC Evaluation Model Development

RIC 2010
Next Generation Nuclear Plant (NGNP) Research

J.M. Kelly
USNRC Research
March 11, 2010


Department of Energy

DOE, NRC Issue Licensing Roadmap For Next-Generation Nuclear Plant

AUGUST 15, 2008

Home » DOE, NRC Issue Licensing Roadmap For Next-Generation Nuclear Plant

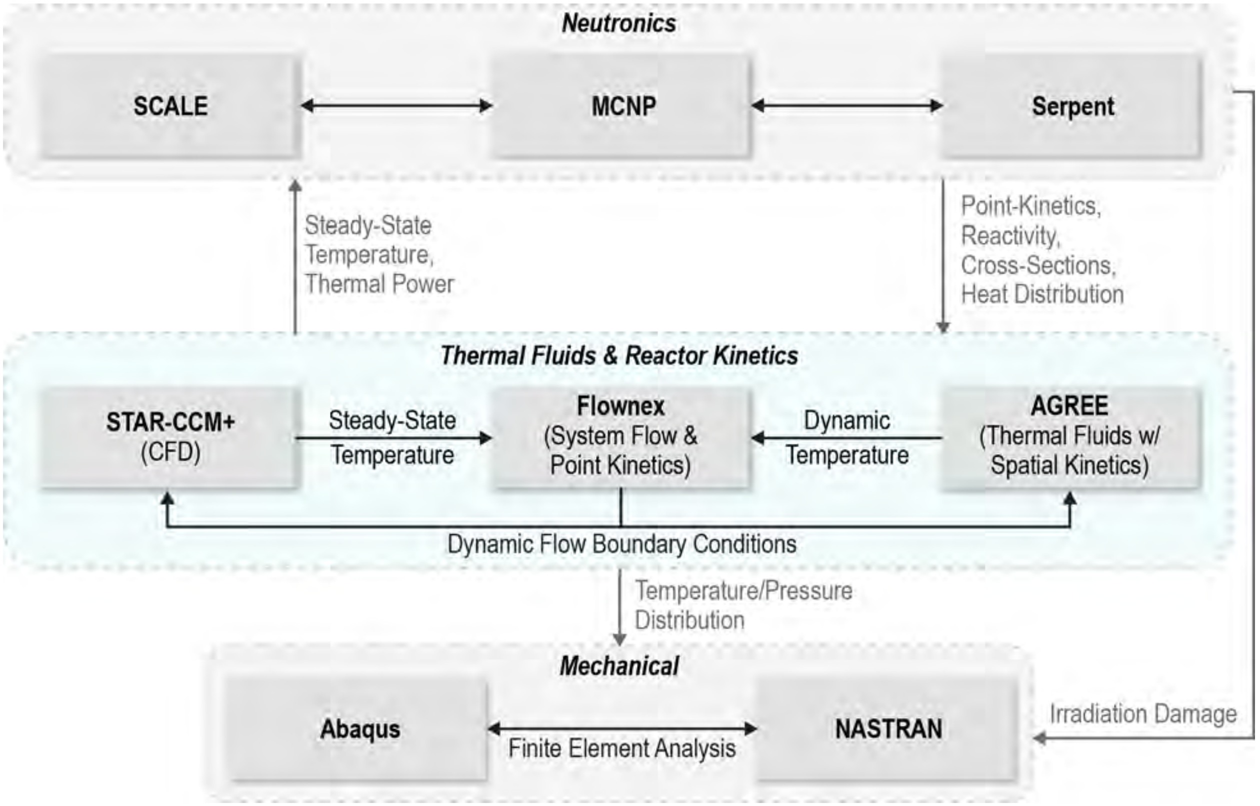
WASHINGTON, DC -The U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory

"The NRC's new reactor licensing process is currently focused on light-water reactors, and the staff is confident this basic framework can also support an NGNP review," said NRC Chairman Dale Klein. "We will work with DOE to supplement that framework with NGNP-specific items."

Types of tools needed for design, licensing, deployment, and operation of advanced nuclear energy systems

	Conceptual Design	Production	Reference	R&D
Purpose	Rapid prototyping of new concepts low fidelity, surrogate models	Design, licensing, operation informed by reference tools	Verification of production tools, validation of data	Specialized studies of new approaches for future use as conceptual design, production, or reference tools
Targeted Users	Industry, lab, university	Industry, regulator, utility, lab, university	Industry, regulator, lab, university	Lab, university
Validation Basis	Moderate – Needs to provide reasonable results	High – Needs to provide reliable results with quantified biases	High- Method biases must be low so data biases and needs can be assessed	Low – Activities are focused on method/solver/coupling
Ease of use	Very easy – Models quickly generated, data easily updated, fast runtimes, models generated in hours	Easy – Established input models, user interfaces, models generated in hours/days	Moderate - Established input for detailed models, user interfaces, models generated in days	Difficult – Developers with specialized set of auxiliary tools and associated compute resources, models generated in weeks/months, many additional libraries/resources required to build/use
Deployment/ Support	Open source, tutorials available	Versioned releases, training routinely available, large user community, technical support team	Versioned releases, training routinely available, large user community, technical support team	Repository access, specialized tutorials
QA Requirements	Low to Moderate – Used only for scoping, not licensing	High – Need robust program with ability to quickly address extent of condition for any issues that arise	High – Need robust program with ability to quickly address extent of condition for any issues that arise	Low – Mostly need configuration control and test infrastructure until transitioned to reference or production tool
TRL Level	3-7 for framework 1-6 for models	7-9 for various components	7-9 for various components	1-6 for various components
Recommended Investment	15%	40%	30%	15%

Ready-now tools for microreactor design and deployment



Analysis	Tool/Model	Analysis Type	Outcome
Core neutronics	SCALE/ KENO/ORIGEN	Steady-state Monte Carlo neutron transport and transmutation	Power Profiles, Core life, Burnable poison design, Temperature and control element reactivity, Fission product inventories, Component activation
Cross section generation	Serpent	Steady-state Monte Carlo neutron transport	Few-group cross sections for AGREE-Xe, verified with reactivity results from SCALE and MCNP
Photon/Neutron Transport	MCNP	Steady-state Monte Carlo neutron and photon transport	Ex-core heating rates
Reactor Thermo-fluid Analysis	Star-CCM+	High fidelity heat conduction and thermo-fluid dynamic behavior	Spatially resolved temperatures and coolant flow rates
Coupled neutronic-thermal fluid analysis	AGREE-Xe	Steady-state and time-dependent neutron diffusion/heat conduction/ subchannel fluid behavior	Peak and average temperatures of structures during transient scenarios
Plant Dynamics	Flownex	Steady-state and time-dependent analysis of plant-wide behavior	Plant/Reactor response to perturbations and fault conditions. Startup, shutdown, and critical power maneuvers
Shielding	SCALE/ MAVRIC/ ORIGEN	Steady-state neutron and gamma transport, activation, decay	Ex-vessel dose and activation rates
Structural Dynamics	NASTRAN	Dynamic Finite Element Analysis	Static-equivalent accelerations to be used for stress analysis, Load Isolation System evaluation
Mechanical and thermal stress	Abaqus	Steady-state Finite Element Analysis	FEA-calculated stresses, to be compared against material allowables to determine if the parts meet design requirements

Codes are math solvers, data provide physics and tie to reality

- **Nuclear Data**
  - **Accurate reaction rates for every nuclide, not just integrated k_{eff}**
    - Power distribution
    - Reactivity control and shutdown margin
    - Doppler feedback
  - **Fission product inventories, with accurate data for individual and cumulative yields**
    - Power and lifetime
    - Reactor kinetics
    - Xenon transients
    - Decay heat source terms for inherent safety confirmation
    - Radionuclide source terms for AOO, DBE, and BDBE analysis
    - Volatile radionuclide source terms for lift-off and plate analysis
  - **Secondary radiation generation and deposition**
    - Prompt neutrons and gammas from fission
    - Gamma emissions from fission product decay
    - Neutron capture and gamma emission data
    - Material activation and decay
    - Neutron and gamma attenuation
    - Energy deposition in all materials
  - **Thermal scattering law data**
    - Advanced moderators/reflectors are needed for small HA-LEU cores
- **Irradiation damage assessment is needed for wide range of materials**
  - Damage factors are not available in ENDF libraries
- **Fission product retention can be bounded by experimental observations**
- **Other physical data are generally available, CTE, heat capacity, specific heat, stress/strain limits**

Requirements for engineering software

Purpose: get answers to engineering questions at lowest cost and schedule

- Usability
  - Easy installation “one-click executable”
  - Runs on common platforms
  - Easy to learn –intuitive interfaces
  - Flexible/tolerant w.r.t. input format
  - Easy to model complex systems
  - Clarity on methods and data used
  - Comprehensive documentation
  - Consistency between documentation and software
  - Reviewable with wide base of expert users in many organizations, including regulators

- Robustness
  - Runs stable -never freezes
  - Built-in measures/limits against diverging –math modeling and solution approaches
  - Returning information (warnings & errors) to the user more important than higher order accuracy, i.e. rather use stable 1st order methods than unstable 2nd order methods
  - Does not require numerous time-consuming studies to obtain convergence of solution

- Efficiency
  - Quick runtime
  - Low resource requirement
    - Computer
    - Analyst training
  - Speed and Clarity of results – detail is only warranted when it provides insight

- Support from developer/vendor
  - Systematic training on how to obtain timely analysis of our systems (not scripted stunt calculations)
  - On-call support
  - System bug reporting, tracking and correction

- Quality Assurance
  - Comprehensive program from a proactive and responsive team

- The final word: Validation
  - Calculation of actual cases
  - Sufficient cases to cover the field of application
  - Comparison of same cases with alternative calculations
  - Invaluable feedback into code and model setup

FISSION BATTERY INITIATIVE WORKSHOP

TRANSIENT MODELING AND SAFETY ISSUES OF FISSION BATTERY REACTORS

TAEK K. KIM

Senior Nuclear Engineer
Manager, Nuclear Systems Analysis Department
Nuclear Science and Engineering Division,
Argonne National Laboratory

April 16, 2021

Acknowledgments

Thanks for comments and information from Dr. C. Filippone, the President and CEO of HolosGen LLC, for design information and safety issues regarding Holos microreactor, and Drs. L. Zou, N. Stauff, and B. Feng of Argonne National Laboratory for their experience on micro reactor assessment.

Content

- **Modeling and simulation capabilities for FB/MR (tools)**

- **Transient analyses (samples)**

- **Topics for Safety Analyses and FB/MR Licensing (selective)**

Fission Battery (Micro) Reactors

- Common design features based on factory-fabricated, transportable, and self-adjusting design
  - Target markets include isolated grid, emergency energy supply to areas hit by natural disaster, harsh locations, military bases, space (Mars), and electricity supply to electric-vehicles
  - Mainly gas-cooled (TRISO fuel) or heat-pipe (metal, oxide, or TRISO fuels) reactors

Reactor type	Reactor Name, Vendor [a)]	Status of Licensing Application [b)]
Gas-cooled reactor	MsBN, MicroNuclear	Information is not publicly available
	NuGen, NuGen	Information is not publicly available
	MMR, USNC	CNSC Vendor Design Review (VDR) phase I completed
	U-Battery, URENCO	Applied to CNSC for VDR phase I in 2017
	GA microreactor, General Atomics	Information is not publicly available.
	Holos, HolosGen LLC	Pre-application interactions with US-NRC planned
	X-Energy microreactor, X-Energy	Under final design phase under DOD microreactor project
	BWXT microreactor, BWXT	Under final design phase under DOD microreactor project
Heat-pipe-cooled reactor	eVinci, Westinghouse	Applied to CNSC for VDR phase II in 2018
	Aurora, Oklo	Safety Analysis Report submitted in 2020
	NuScale microreactor, NuScale	Information is not publicly available
Lead-cooled reactor	LFR-TL-X, Hydromine	Information is not publicly available

a) Reactor concepts introduced in GAIN/NEI Workshop in 2019 or announced through DOD microreactor project

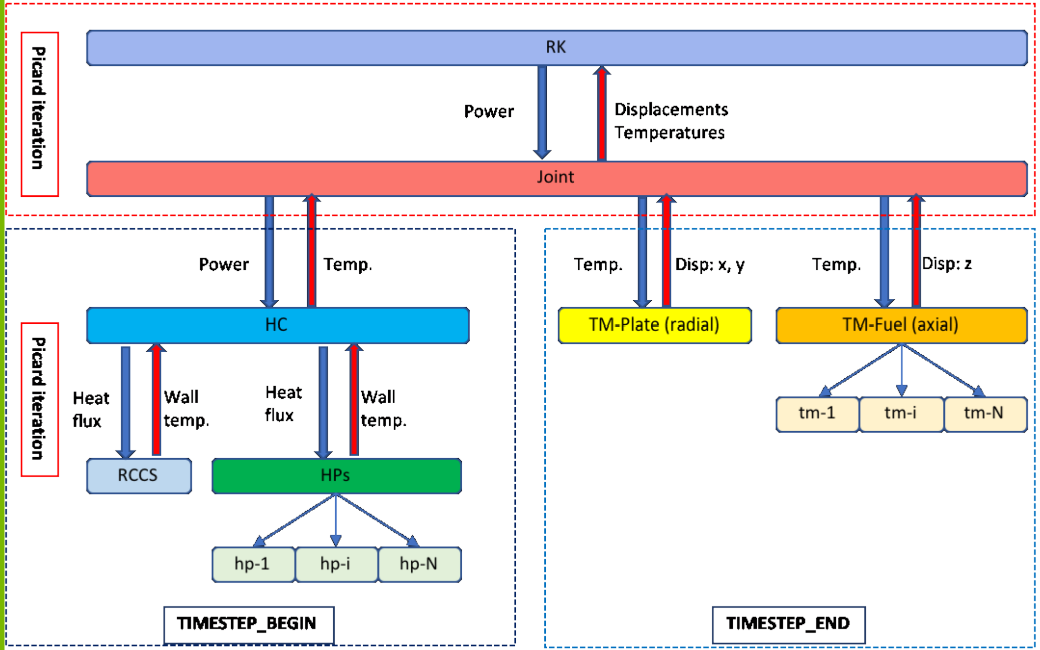
b) Based on publicly available information on licensing application status as of early 2020

Modeling and Simulation Capabilities

- **M&S capabilities on multi-physics and full core/reactor analysis required**

Function	Features	DOE tools	Others
Neutronics/reactor physics	High fidelity transport analysis (complex geometry, streaming, large leakage, etc.)	GRIFFIN (Rattlesnake/ MAMMOTH,ROTEUS) w/ right cross section tools	Stochastic codes (Serpent, etc.) Industry own tools
Thermal-hydraulics	Heat-pipe performance, coolant flow in compact and integral design	SOCKEYE, Pronghorn, Nek5000	ANLHTP, STAR-CCM+, ANSYS (Fluent)
Fuel and mechanical analysis	Various fuel forms (metal, oxide, TRISO), graphite or metallic monolith block, thermal and irradiation deformations	BISON, GRIZZLY	
System analysis	Integral reactor concept, Multiphysics simulation	SAM, RELAP-7, MOOSE Apps	

HP Reactor Transient Analysis (I) a)

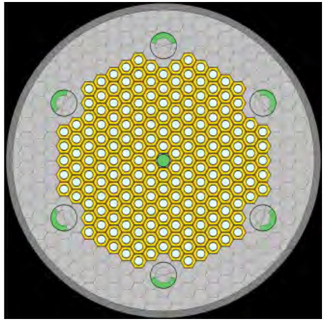


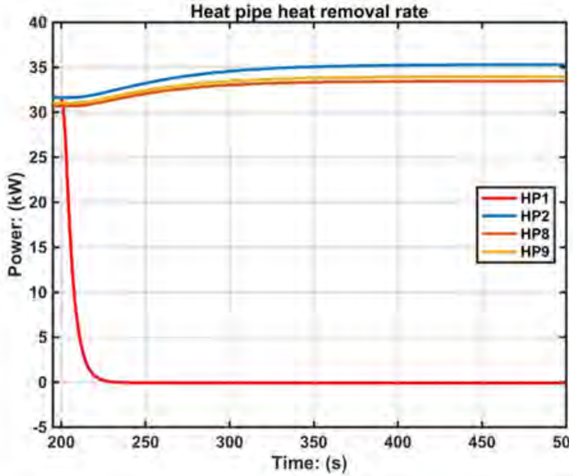
a) Hu, et al., "Multi-physics Simulations of Heat Pipe Micro Reactor," ANL-NSE-19/25

Function	Tools
RK/Neutronics/reactor physics	GRIFFIN (Mammoth)
HC/Heat conduction/convection	SAM
RCCS: Reactor cavity cooling system	SAM
TM-fuel/fuel expansion	MOOSE - Tensor Mechanics (BISON)
TM-plate/core expansion	MOOSE- Tensor Mechanics (BISON)
HP/Heat pipe model (heat flow from fuel to HP wall)	SAM (Sockeye)
Joint/coupling (data flows)	MOOSE

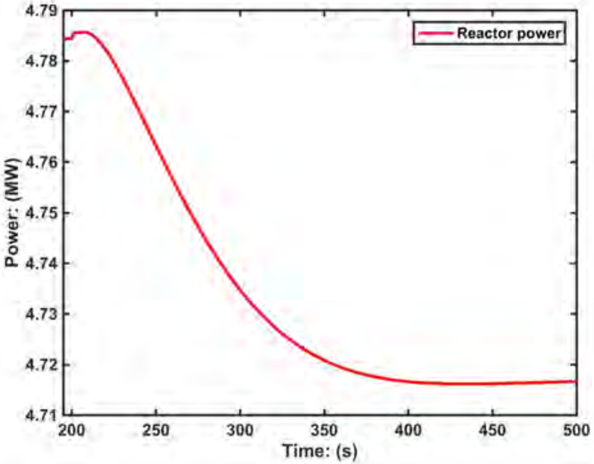
HP Reactor Transient Analysis (II)

- **Transients of single heat-pipe failure and unprotected loss of heat sink (ULOHS) events** $^{a)}$
  - 5 MW HP reactor with 192 heat pipes (26kW/heat pipe)
  - Passive safety feature from negative feedbacks from Doppler and thermal expansions

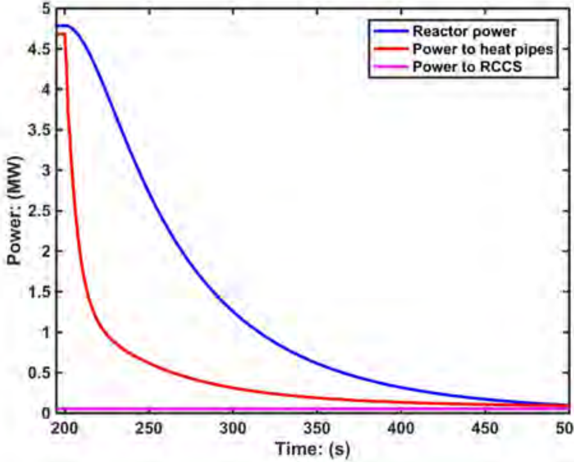




Heat removal rate near failed HP



Reactor power for single HP failure

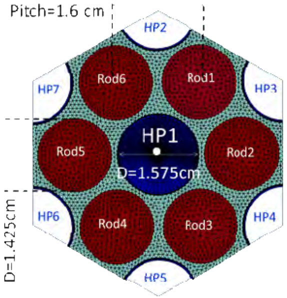


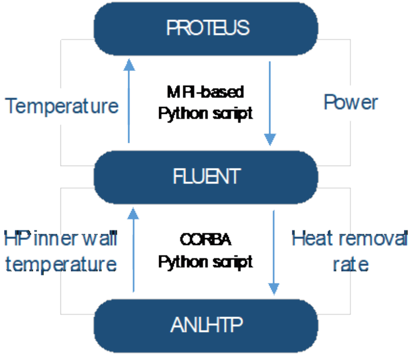
Reactor power for ULOHS

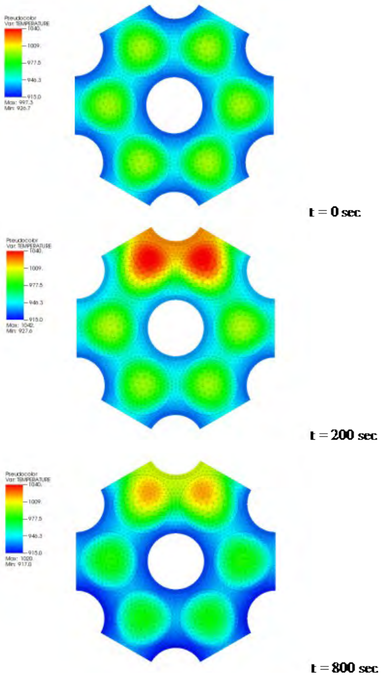
a) Hu, et al., "Multi-physics Simulations of Heat Pipe Micro Reactor," ANL-NSE-19/25

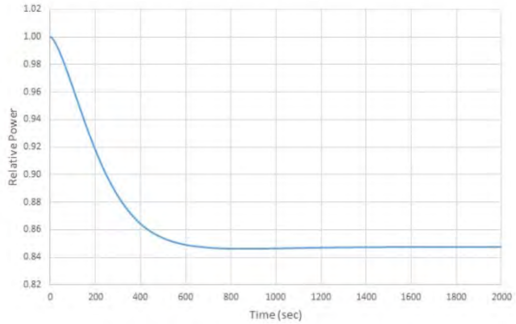
Coupling DOE and Industry Tools for HP Reactor

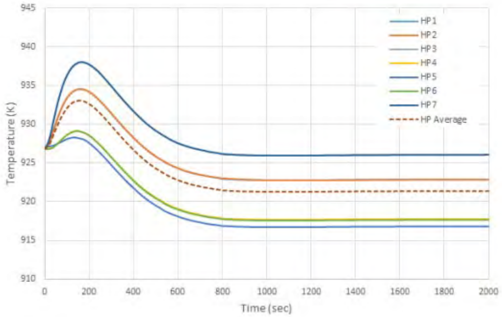
- **Steady and transient (single HP failure) analyses for HP reactor lattice (7 HPs with 6 fuels pins) performed by Griffin (PROTEUS)/FLUENT/ANLHTP a)**







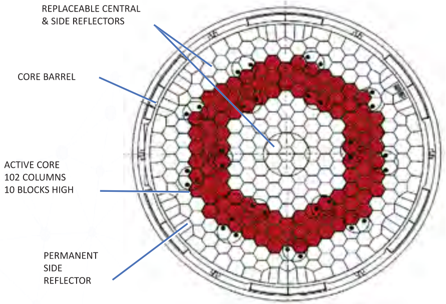


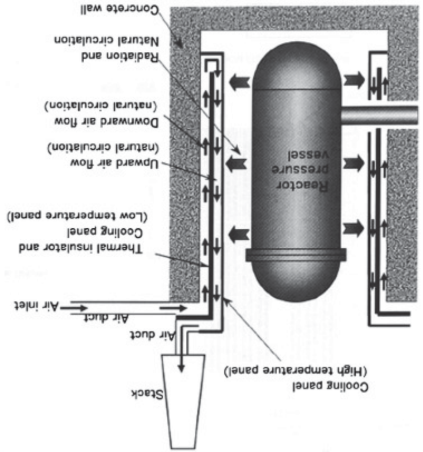


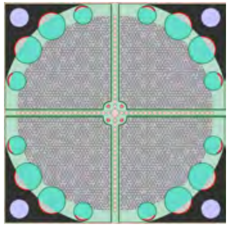
a) C. Lee, et al., "Micro Reactor Simulation Using the PROTEYS Suite in FY19," ANL-NSE-19/33

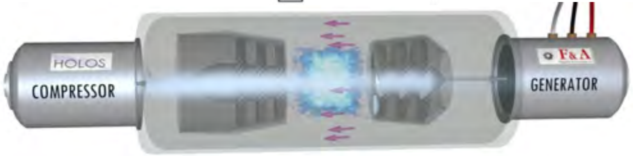
Transient Analysis of Gas-cooled FB/MR

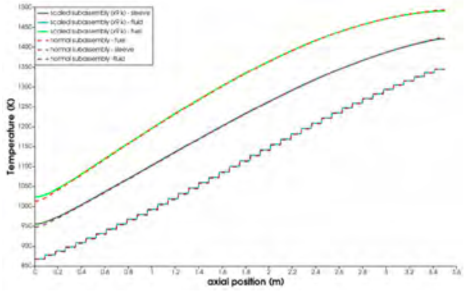
- **M&S capabilities developed through HTGR/AGR/NEAMS programs and industry efforts**
- **Different design features of FB/MR request specific transient analyses**
  - Reactivity feedbacks and fuel performance are comparable to HTGR
  - Similar inherent safety performance expected in AOO/DBE transient events, but potential differences from <u>compact and integral/modular</u> design features and <u>reactivity control systems</u> should be confirmed
  - See ongoing effort on evaluation of decay heat removal and thermal stress of reactor components

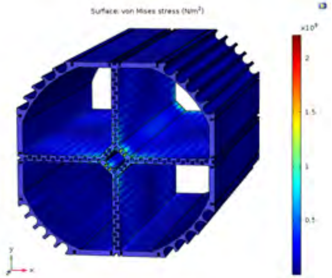












Summary of Transient Analysis M&S Capabilities

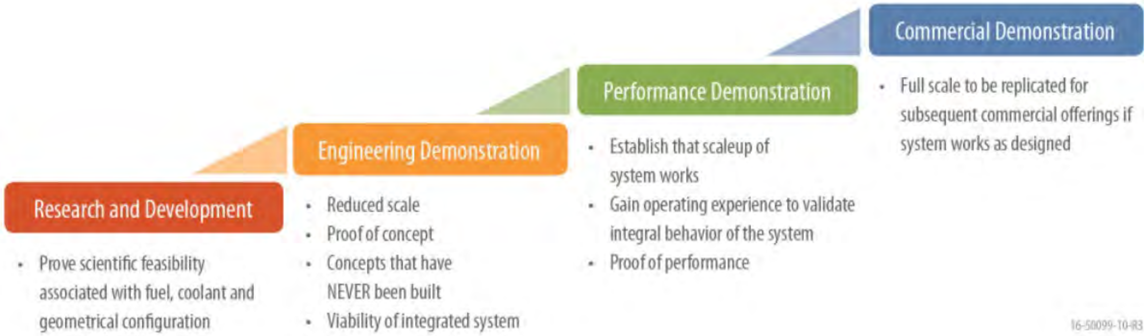
- **Heat-pipe FB/MR**
  - Expect favorable inherent safety features from negative reactivity feedbacks, thermal inertia from structure, passive heat removal from heat-pipe, and low power density
  - M&S capabilities are under development by DOE-NE and industry programs, but need whole core M&S effectively and validations through full-size experiments
  - Lack of HP reactor operation experience
    - Demonstrate HP reactor concept through KRUSTY experiment, but insufficient in terms of reactor size, number of heat pipes, materials, etc.
    - Need Licensing Basis Events (LBE) selection/evaluation and probabilistic risk assessment (PRA) for informing risk and prioritization of challenges (E.g., bounding conditions for avoiding propagation of heat pipe failures)
- **Gas-cooled FB/MR**
  - Expect favorable inherent safety features from negative reactivity feedbacks, thermal inertia from solid moderator (graphite), and low power density
  - Need efforts for assessment of transient behaviors from FB/MR unique design features
    - Compact and integral/modular design with self-adjusting control mechanism
    - Combined multiple accident conditions (reactivity control failure by stuck of control drum, graphite fire with air ingress or battery fire and reduction of thermal transfer surface) would be most challenging accident scenario

Additional Considerations for FB/MR Licensing

- **Smaller EAB and EPZ**
  - Most FB/MR vendors claim smaller (or zero) EAB/EPZ based on sealed fuel (TRISO) and small source term inventory and lower FP release rate, etc., but need to ensure consequences would not exceed criteria at EAB and Protective Action Guides (PAGs) outside EPZ
- **Radiation protection based on Defense-in-Depth**
  - Expected shorter/smaller Exclusion Area Boundary (EAB) with reduced barriers and functional containment concept
- **Transportation and security issues**
  - Transportation (in particular, operated reactor from site to central location) would be challenging
    - Cooling time and shielding issues
  - Safeguard and security issues by terrorism, sabotage, and attack (see next slide)
- **Reactor development and deployment steps (see next slide)**

Reactor Development and Deployment Steps

- **Q. Able to skip demonstration steps for FB/MR deployment?**
- **Previous operated HTGR demos/reactors could be used as demos**
  - Need technology development to demonstrate unique FB/MR features
- **Heat-pipe FB/MR may need performance demonstration**
  - KRUSTY could be an engineering demonstration
  - Need performance demonstration with scaled up system to gain operation experience to validate integral behavior



Research and Development

- Prove scientific feasibility associated with fuel, coolant and geometrical configuration

Engineering Demonstration

- Reduced scale
- Proof of concept
- Concepts that have NEVER been built
- Viability of integrated system

Performance Demonstration

- Establish that scaleup of system works
- Gain operating experience to validate integral behavior of the system
- Proof of performance

Commercial Demonstration

- Full scale to be replicated for subsequent commercial offerings if system works as designed

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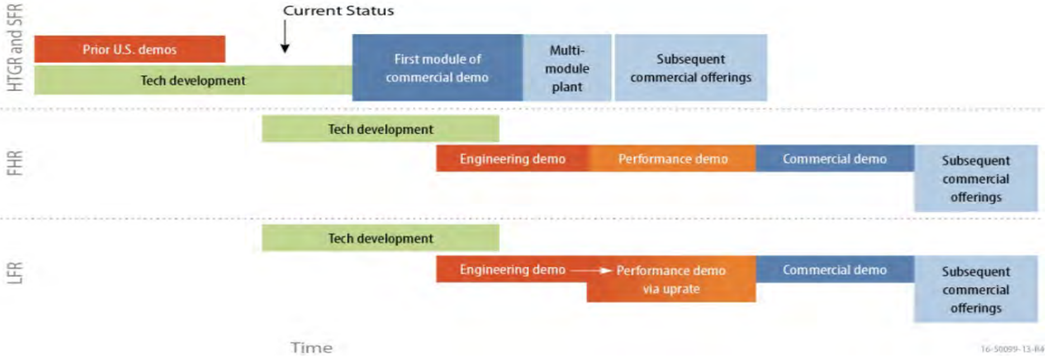


a) D. Petti, et al., "Advanced Demonstration and Test Reactor Options Study," AINL/EXT-15-37867 (2017)

THANKS

April 16th, 2021

Nicolas Martin
Reactor Physics Methods and Analysis Department
Idaho National Laboratory

Highlights on MOOSE Capabilities for Safety Analyses of Microreactors & Fission Batteries

Agenda

- Overview of MOOSE-based modeling capabilities for Fission Batteries (FB) / Microreactors (MR)
  - Standalone physics capabilities
  - Multiphysics capabilities
- Thoughts on VVUQ in the context of MOOSE-based models for safety analyses of FB/MRs

MOOSE for Microreactors / Fission Batteries

- First publicly documented analyses released in 2019
  - *Task 1: Evaluation of M&S tools for micro-reactor concepts*, LA-UR-19-22263 (2019)
  - *Application of Integrated Modeling and Simulation Capabilities for Full Scale Multiphysics Simulation of Microreactor Concept*, INL/EXT-19-55159 (2019)
  - *Multi-Physics Simulations of Heat Pipe Micro Reactor*, ANL/NSE-19/25 (2019)
- Initial focus was on demonstrating capabilities to capture multi-physics aspects, e.g., the integration of different physics models into one single computational scheme.
- Significant growth in the number of use cases over the last couple years
  - Multi-physics steady-state, transient (AOO/DBE), startup simulations performed so far for various MR/FB designs.

MOOSE for Microreactors / Fission Batteries (cont.)

- MOOSE export-controlled applications currently used in micro-reactor M&S
  - **Griffin**: radiative transport / neutronics
  - **BISON**: thermo-mechanical fuel behavior
  - **RELAP-7**: 1D compressible flow model, and system components for primary/secondary (compressor, turbine, etc.)
  - **SAM**: 1D incompressible flow model and system components
  - **Sockeye**: heat pipe model
  - **Pronghorn**: multi-dimensional porous media model
- Open-source MOOSE modules relevant for micro-reactors:
  - Heat conduction
  - Gap heat transfer model
  - Tensor mechanics

MOOSE for Microreactors / Fission Batteries (cont.)

- Three pre-packaged software stacks are currently used.
  - All include Griffin and BISON

1. Heat-pipe cooled micro-reactors: **DireWolf**
   - Sockeye

2. Gas-cooled micro-reactors: **Sabertooth**
   - RELAP-7: thermal-hydraulic

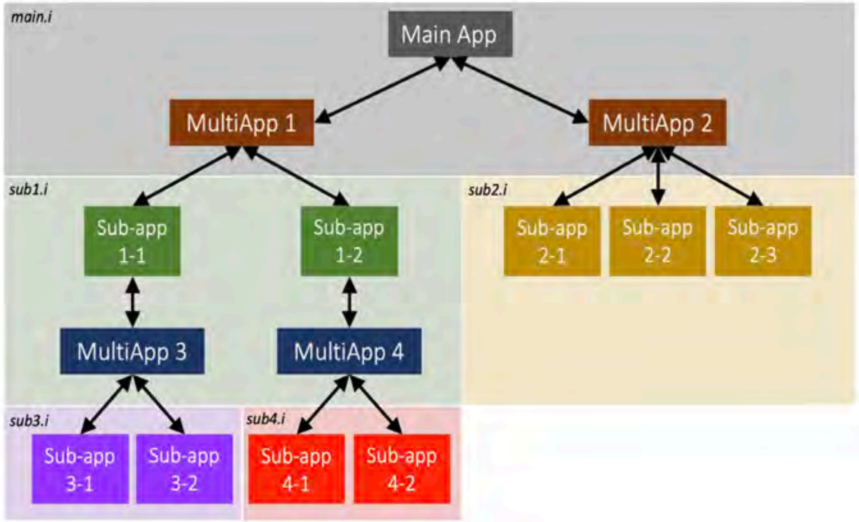
3. generic: **CRAB**
   - Contains both SAM and Pronghorn

- Streamline compilation dependencies and provide a single executable, convenient for MultiApp setup
- Might be revisited in the future (dynamic linking, etc.)

MOOSE Computational Scheme

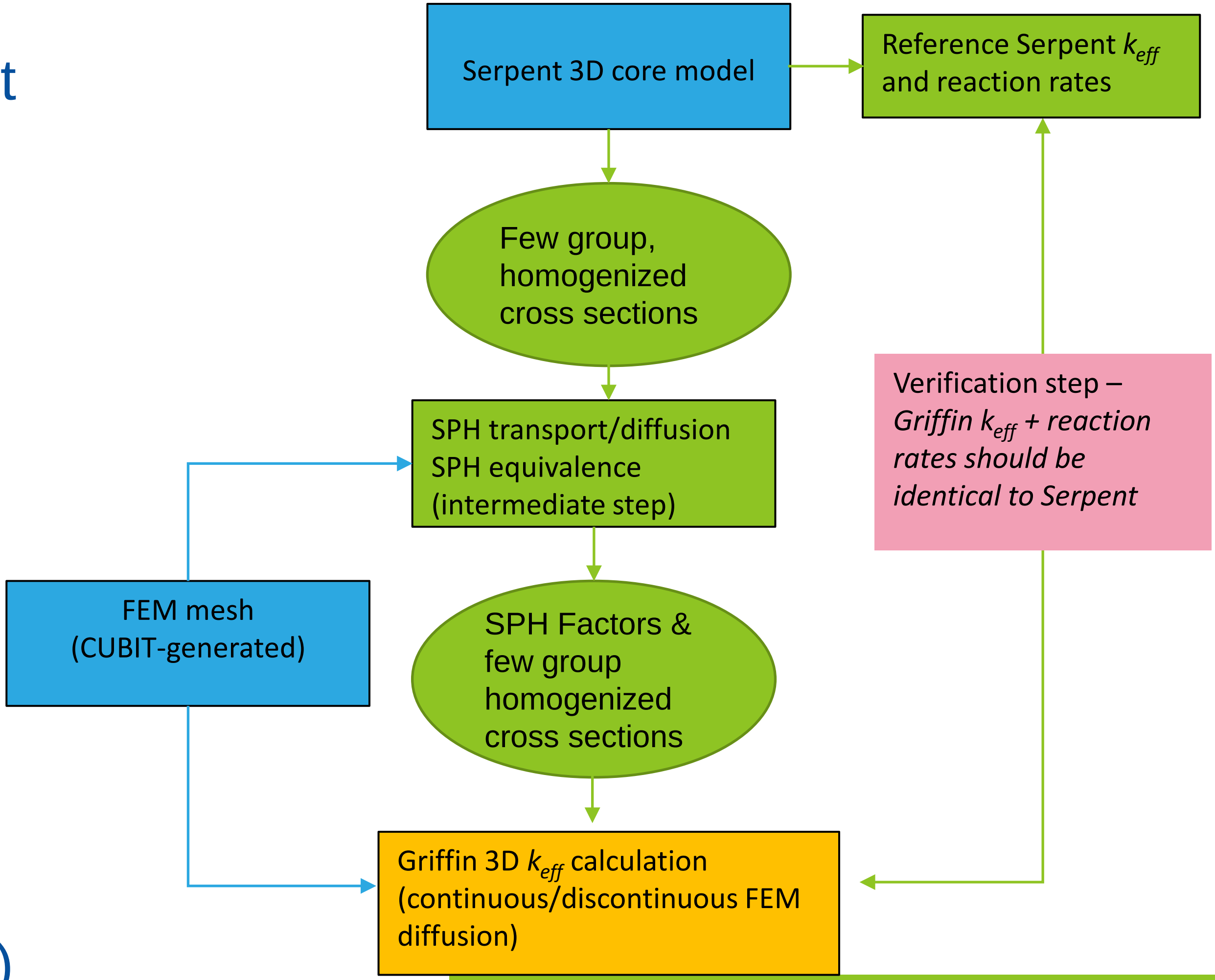
- Given a proposed MR/FB design, the steps required to build a MOOSE model are generic.

1. Identify the physics required, and build a standalone physics input for each
   - Neutronics
   - Thermal-hydraulic
   - Fuel model
   - Mechanical expansion (tensor mechanics), etc.
2. Organize the multiphysics system via MultiApps/Transfers
   - Be cognizant of the dependencies between the physics, identify input and output for each, and properly transfer (communicate) the data



MOOSE Neutronics Model for microreactors

- Two-step approach relying on the Serpent Monte Carlo code for group constant generation (cross sections, kinetics parameters, etc.)
- Griffin incorporates different spatial and angular discretization schemes for the transport equation
  - Diffusion, 1st and 2nd order SN or PN formulations
- Diffusion with Continuous finite element method has been successfully applied to both thermal and fast spectrum reactors
  - In conjunction with an Equivalence methods (SPH and/or hybrid DF/SPH)



Serpent 3D core model

Reference Serpent k_{eff} and reaction rates

Few group, homogenized cross sections

SPH transport/diffusion SPH equivalence (intermediate step)

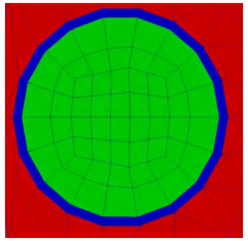
Verification step – *Griffin k_{eff} + reaction rates should be identical to Serpent*

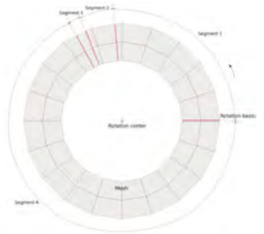
FEM mesh (CUBIT-generated)

SPH Factors & few group homogenized cross sections

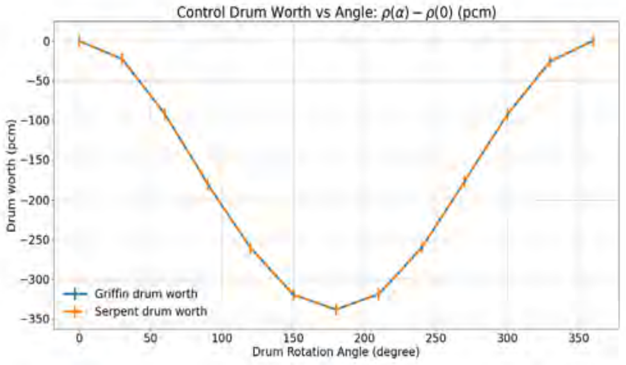
Griffin 3D k_{eff} calculation (continuous/discontinuous FEM diffusion)

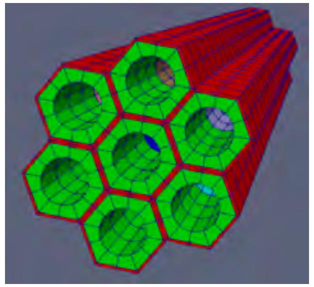
MOOSE models for microreactors (cont.)





- Some of the relevant functionalities for microreactors/fission batteries include:
  - **Explicit reflector modeling**, thanks to unstructured mesh capability (no need to simplify geometry)
  - **Preserving control drum worth**, thanks to unstructured mesh, generalized rod/drum cusping treatment, and SPH
  - **Gap heat transfer model**, useful for microreactors with fuel cells with hexagonal cladding
  - **Reactivity changes due to mesh displacement** (i.e., due to thermal expansion) automatically accounted for by the cross section model
- Verified on several MR designs against Monte Carlo reference calculations or explicit mesh deformed calculations (for gap heat transfer model)

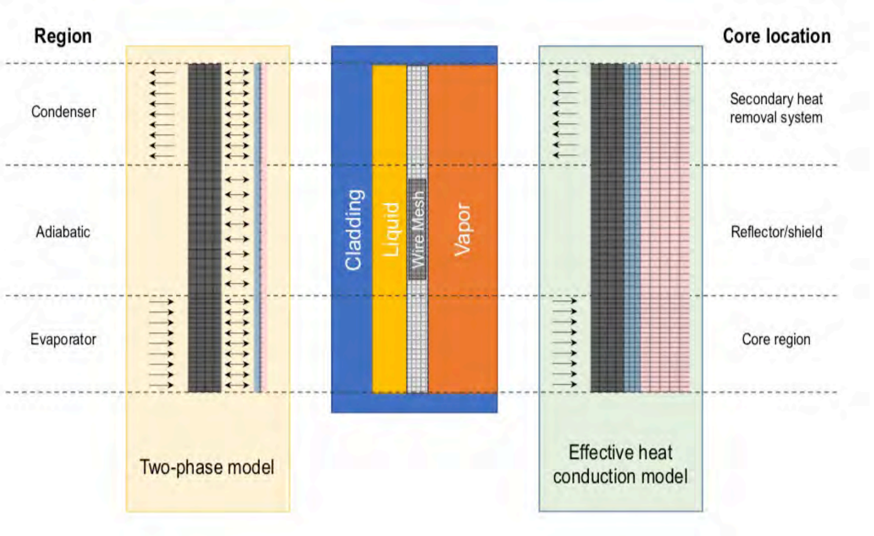




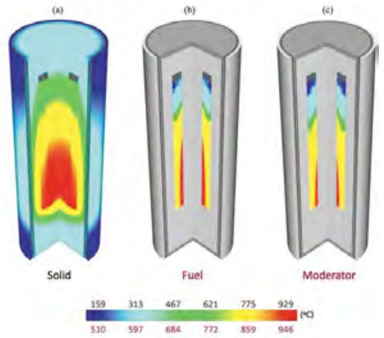
$$\Sigma_{r,g}(\mathbf{r},t) = \frac{\rho^{displaced}(\mathbf{r},t)}{\rho^{nominal}(\mathbf{r},t)}\Sigma_{r,g}(\mathbf{r},t)$$

Core thermal-hydraulic models for Microreactors

- Heat-pipe cooled microreactors: Sockeye
  - 1D two-phase compressible flow model coupled with a 2D-RZ heat conduction model
  - Simplified effective heat conduction model
- Gas cooled microreactors:
  - 1D compressible flow model (THM/RELAP-7)
  - 1D incompressible flow model (SAM)
  - Multi-dimensional porous media model for pebble bed reactors (Pronghorn)



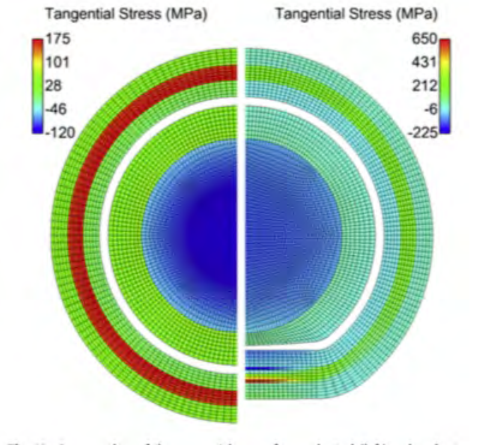
Taken *from C. Matthews et al. “Coupled Multiphysics Simulations of Heat Pipe Microreactors using DireWolf’, in press, Nuclear Technology (2021)*



Taken *from A. Novak et al. “Pronghorn: A Multidimensional Coarse-Mesh Application for Advanced Reactor Thermal Hydraulics’, Nuclear Technology (2021)*

Fuel thermo-mechanical modeling

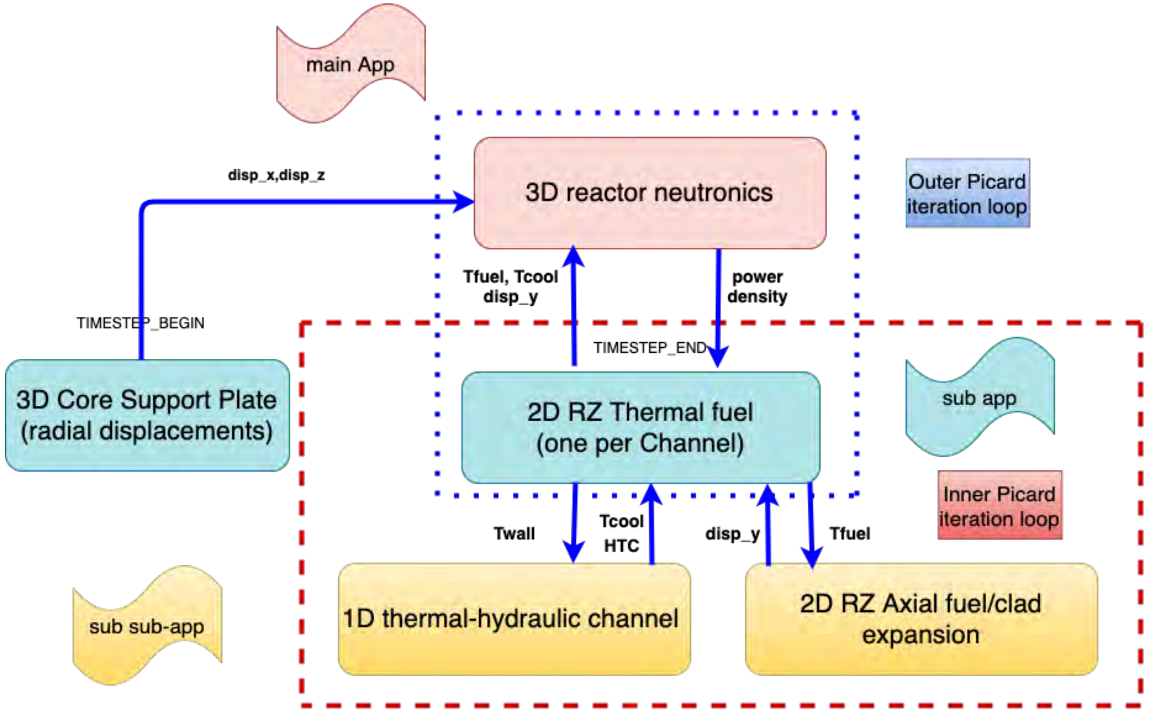
- BISON can model virtually all the fuel types considered for microreactors
  - 1D spherical (TRISO), 2D-RZ, 3D fuel model
- Implements material properties for fuel and cladding
  - thermal properties: heat conduction
  - mechanical properties: tensor mechanics
  - Gap heat transfer (thermal contact)
- In standalone model, requires simplified coolant channel / power history / LHGR
- In coupled model, provides the fuel temperature and/or mesh displacement given the power density and relevant boundary conditions (from T/H)



J. Hales et al "Multidimensional Multiphysics simulation of TRISO particle fuel", Journal of Nuclear Materials, 2013

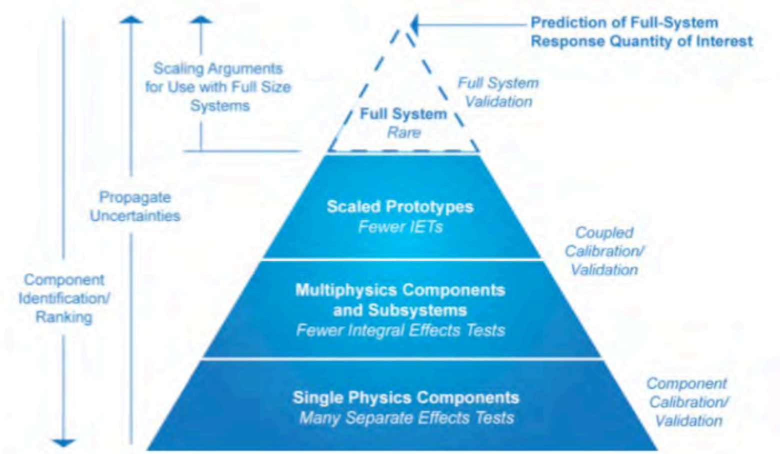
Example of Multiphysics computational scheme

- Example for a fast spectrum reactor model with tight coupling between:
  1. Neutronics : main App
  2. Mechanics (core plate expansion): level 0 sub-app
  3. Thermal fuel: level 0 sub-app (1 per fuel assembly)
  4. Channel Thermal-hydraulics: level 1 sub-app
  5. Fuel axial expansion: level 1 sub-app
- Customizable variable transfer (when and where), iteration between physics, etc.
  - Can virtually suits any type of reactor and scenario



VVUQ in the context of MOOSE

- A MOOSE microreactor model will consist of the union of:
    1. Standalone physics models (one per physics)
    2. Multiphysics scheme (one per scenario)
- The hierarchical nature of the MOOSE models fit well within VVUQ frameworks (EMDAP, PCMM, etc.)
    - Code verification for standalone codes
    - Separate effects validation for single physics
    - Integral effects for coupled model
    - Uncertainty quantification supported through stochastic tool module
    - MOOSE framework consistent with NQA-1 requirements, useful for Commercial Grade Dedication



Taken from CASL VVUQ framework , SAND2010-234P

Application-driven (reactor, and scenario specific)

Conclusion

- MOOSE safety analyses of microreactors/fission batteries can be customized to whatever licensing strategy being pursued (conservative or BEPU), depending on margin requirements
  - Can help justify single physics analyses with biased input
  - Ready for audit/confirmatory analyses and soon in safety/licensing analyses
- As for any other code/system, deploying a MOOSE-based microreactor model will require dedicated VVUQ for each technology and scenario considered
- Potential improvements could be on “best-practice” guidelines with respect to data transfer between physics, and improving the robustness/speedup of tightly coupled algorithms (Picard-iteration dependent convergence criteria, etc.)

NRC Perspectives on the Safety and Licensing of Fission Batteries

Jan Mazza and Marty Stutzke

Division of Advanced Reactors and
Non-Power Production and Utilization Facilities
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission

April 16, 2021

Recent NRC Publications Relevant to the Safety and Licensing of Fission Batteries

Title	ADAMS	Date
SECY-20-0093, Policy and Licensing Considerations Related to Micro-Reactors	ML20254A363	10/6/2020
Draft NRC Staff White Paper: Demonstrating the Acceptability of Probabilistic Risk Assessment Results Used to Support Advanced Non-Light Water Reactor Plant Licensing	ML21015A434	1/13/2021
Design Review Guide (DRG): Instrumentation and Controls for Non-Light-Water Reactor (Non-LWR) Reviews • Does not specifically address autonomous control using machine learning (Ml) and artificial intelligence (AI)	ML21011A140	2/26/2021
Draft NRC Staff White Paper: Risk-Informed and Performance-Based Human-System Considerations for Advanced Reactors	ML21069A003	March 2021

NRC Rulemakings Relevant to the Safety and Licensing of Fission Batteries

Title	Docket	RIN	Schedule
Emergency Preparedness for Small Modular Reactors and Other New Technologies	NRC-2015-0225	3150-AJ68	Final rule by April 2021
Alternative Physical Security Requirements for Advanced Reactors	NRC-2017-0227	3150-AK19	NPRM by April 2021
Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors (10 CFR Part 53) • Subpart D – Siting (will include population-related considerations) • Subpart F – Requirements for Operations (will address staffing, emergency preparedness, physical security, and cybersecurity)	NRC-2019-0062	3150-AK31	Final rule by October 2024

Observations and Questions (1 of 6)

1. Of the five fission battery attributes provided in the INL white paper, NRC has regulatory authority over the unattended operation, part of the reliability (robust and fail safe) and, part of the installed (no siting or security issues) aspects. The “Fission Battery Initiative” is currently a research activity and there are no current applications for the fission battery as defined in the report in front of the NRC. What is the role of the NRC for this initiative?
2. Depending on the business model, which could be that an entity leases equipment from an owner, clarification for the roles and responsibilities will be important.
   a. Which entity is financially responsible for Price Anderson, fees, decommissioning/waste issues?
   b. Who does the regulator interact with on issues concerning safety, security, etc.?

Observations and Questions (2 of 6)

3. The “installed” attribute specifies “prompt within a few hours installation and operation upon delivery, with no or minimal onsite construction, security, siting, and infrastructure requirements.”
    a. Are fission batteries hazard proof?
    b. Is an environmental GEIS similar to the GEIS for advanced reactors needed for fission batteries?
4. How to consider the societal impacts resulting from accident in one reactor that could take a whole fleet out of service (enterprise risk)?

Observations and Questions (3 of 6)

5. How would a Reactor Oversight Program work for fission batteries?
    a. For microreactors, the NRC staff is developing an appropriate oversight program in which monitoring and inspection will focus on those plant activities having the greatest impact on safety and overall risk. The oversight program would also address construction inspection.
    b. Considerations for the micro-reactor construction inspection program include:
        i. Leveraging lessons learned from the development of construction inspection procedures to support the 10 CFR Part 50 construction permit granted to Shine Medical Technologies Inc. for a medical radioisotope production facility.
        ii. The need to address the use of factory fabrication for much of the facility and the shorter construction timelines expected for these facilities.
    c. For the operational phase, the staff is considering whether to conduct periodic inspections of micro-reactors in a similar fashion to nonpower reactors, as appropriate. The scope and focus of inspection efforts developed to include structures, systems, and components and associated operational programs commensurate with their risk and safety significance.

Observations and Questions (4 of 6)

6. Oklo calls its Aurora design a “fission battery” but does not have all of the stated fission battery attributes. Does a specific definition need to be developed and socialized?
7. What are some examples of technologies that can fully achieve battery-like functionality for nuclear energy system? Project Pele designs BWXT and X-Energy?

Observations and Questions (5 of 6)

8. The concept of remote monitoring of fission batteries is supported by “intelligent automation, machine learning, and decision-making capabilities with minimal human intervention.” This technology needs to be demonstrated that it has a high degree of reliability etc. Successfully licensing a facility with remote operation will require the NRC staff to reassess its current practices related to HFE. Historically, the NRC and licensees have relied upon the ability of operators co-located with the reactor facility that they are controlling to receive sensory feedback in addition to the information provided to them through the plant’s instrumentation and control interfaces.
   a. How can remote monitoring and control be demonstrated to be 100% reliable?
   b. How do we go from concept to deployment?
9. Stakeholders have expressed potential interest in manufacturing licenses; however, no entities have described definitive plans to develop applications using the related provisions under 10 CFR Part 52. Ongoing efforts by the U.S. Department of Energy (DOE) and the DOD to develop and test transportable so-called “mobile” micro-reactor designs could result in such concepts being proposed for NRC-licensed commercial uses in the future. Would this licensing pathway work for FBs?

Observations and Questions (6 of 6)

10. For physical security the NRC staff is proposing that an applicant for a microreactor either protect against the design-basis threat in order to prevent radiological sabotage and offsite consequences or demonstrate through a consequence-based analysis that a range of credible malicious acts could not cause offsite consequences. Could this be done for FBs?
11. In the absence of rulemaking to establish a new category of reactors that would not require licensed operators, exemptions from existing regulations would be necessary. Provided that accident consequences can be shown to be low and significant releases are unlikely to occur during the life of the facility, exemption requests could be considered on a case-by-case basis. Could this be done for FBs?

Fission Battery Initiative, Safety and Licensing of Fission Batteries, April 16, 2021

Licensing Issues for Fission Batteries: Working INSIDE the Box

R. G. Ballinger*, C. W. Forsberg**

***Professor Emeritus, Department of Nuclear Engineering**
Massachusetts Institute of Technology
****Department of Nuclear Engineering**
Massachusetts Institute of Technology

Note: The opinions of RGB are his own and not intended to represent the ACRS

MIT Nuclear Science and Engineering

10 CFR Part 53
"Licensing and Regulation of Advanced Nuclear Reactors" (As of 4/16/21)

Nuclear Energy Innovation and Modernization Act (NEIMA; Public Law 115-439) signed into law in January 2019 requires the NRC to complete a rulemaking to establish a technology-inclusive, regulatory framework for optional use for commercial advanced nuclear reactors no later than December 2027

ADVANCED NUCLEAR REACTOR—The term "advanced nuclear reactor" means a nuclear fission or fusion reactor, including a prototype plant… with significant improvements compared to commercial nuclear reactors under construction as of the date of enactment of this Act, …

*Adapted from Staff Presentation to Advisory Committee on Reactor Safeguards, January 2020

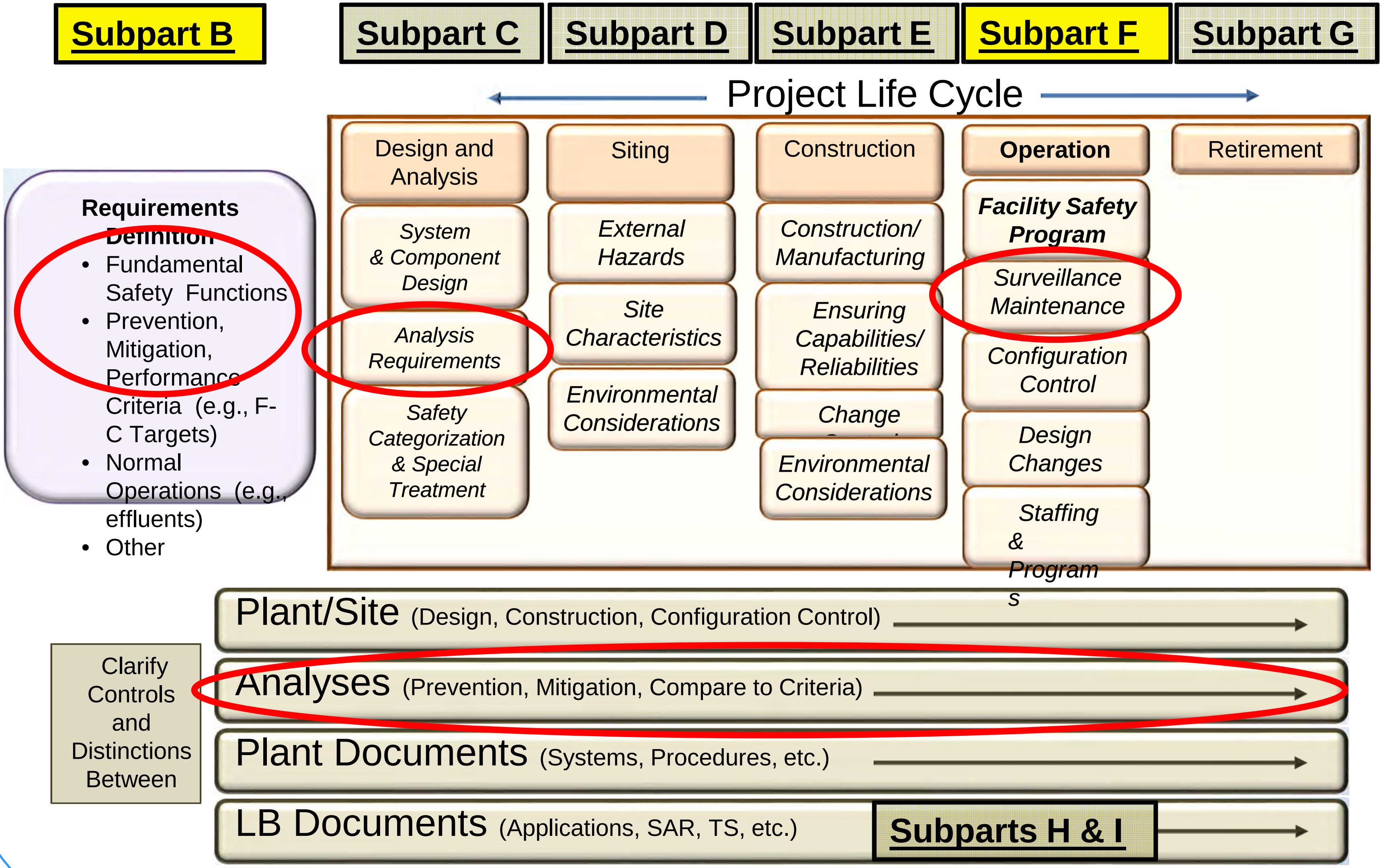
Current Milestone Schedule*

Major Rulemaking Activities/Milestones	Schedule
Submit Draft Proposed Rule Package to Commission	May 2022
Publish Proposed Rule and Draft Key Guidance	October 2022
Public Comment Period – 60 days	November and December 2022
Public Outreach and Generation of Final Rule Package	January 2023 to February 2024 (14 months)
Submit Draft Final Rule Package to Commission	March 2024
Office of Management and Budget and Office of the Federal Register Processing	July 2024 to September 2024
Publish Final Rule and Key Guidance	October 2024

The Bottom Line: Fission Batteries will Likely be Licensed Under 10CFR 53

*Adapted from Staff Presentation to Advisory Committee on Reactor Safeguards, January 2020

NRC Plan to Develop Part 53



Subpart B

Subpart C

Subpart D

Subpart E

Subpart F

Subpart G

Project Life Cycle

Requirements Definition

- Fundamental Safety Functions
- Prevention, Mitigation, Performance Criteria (e.g., F-C Targets)
- Normal Operations (e.g., effluents)
- Other

Design and Analysis
- *System & Component Design*
- *Analysis Requirements*
- *Safety Categorization & Special Treatment*

Siting
- *External Hazards*
- *Site Characteristics*
- *Environmental Considerations*

Construction
- *Construction/ Manufacturing*
- *Ensuring Capabilities/ Reliabilities*
- *Change Control*
- *Environmental Considerations*

Operation
- ***Facility Safety Program***
- *Surveillance Maintenance*
- *Configuration Control*
- *Design Changes*
- *Staffing & Programs*

Retirement

Clarify Controls and Distinctions Between

Plant/Site (Design, Construction, Configuration Control)

Analyses (Prevention, Mitigation, Compare to Criteria)

Plant Documents (Systems, Procedures, etc.)

LB Documents (Applications, SAR, TS, etc.) **Subparts H & I**

*Adapted from Staff Presentation to Advisory Committee on Reactor Safeguards, January 2020

Top Tier Safety Criteria

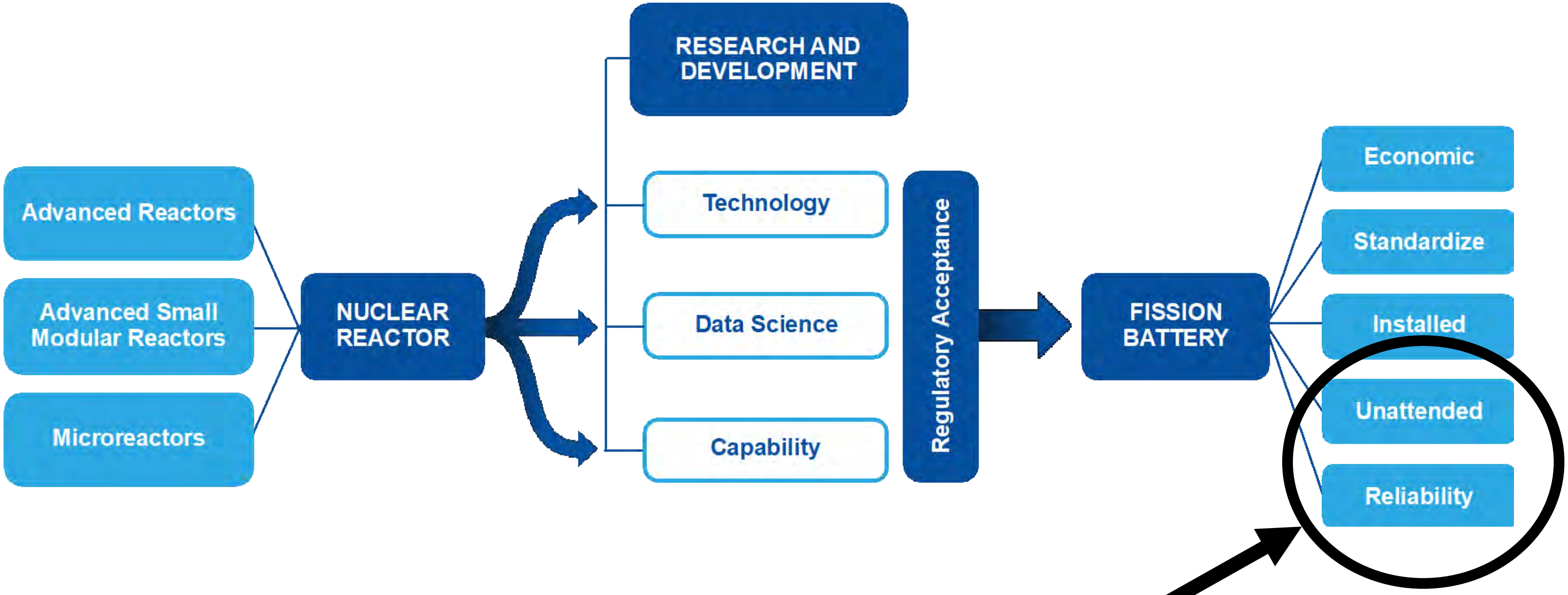
- Normal operations

o Contribution to total effective dose equivalent (TEDE) to individual members of the public from normal plant operation does not exceed
0.1 rem (1 mSv) in a year
o Contribution to dose in any unrestricted area does not exceed 0.002 rem (0.02 millisievert) in any one hour

- Licensing basis events
  - o Upper bound frequency > once per 10,000 years
  - o An individual located at exclusion area boundary for any 2-hour period following the onset of release would not receive a radiation dose in excess of 25 rem (250 mSv) TEDE
  - o An individual located at outer boundary of the low population zone 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 25 rem (250 mSv) TEDE
- Additional requirements established by the NRC for reasonable assurance of adequate protection

*Adapted from Staff Presentation to Advisory Committee on Reactor Safeguards, January 2020

Research and development to enable nuclear reactor technologies to achieve fission battery attributes



Advanced Reactors

Advanced Small Modular Reactors

Microreactors

NUCLEAR REACTOR

RESEARCH AND DEVELOPMENT

Technology

Data Science

Capability

Regulatory Acceptance

FISSION BATTERY

Economic

Standardize

Installed

Unattended

Reliability

Autonomous Operation
Resilience

Important NOTE: Data is Non-Existent

What Does This Mean for Fission Battery Development?

- Unattended (Autonomous) Operation

Extreme Reliability

Resilience

- Self Monitoring
- Self Correcting

One-Way Communication
(Cyber Security)

- Emergency Planning Zone at Site Boundary

Source Term
(Accident Tolerance)

- Bounding
- PRA Driven

Prototype vs. Analysis?

Do we need a full up prototype or can the design be done (and licensed) using separate effects tests combined with analysis?

“Risk Informed” is allowed, “Risk Based” is Not (or has not)

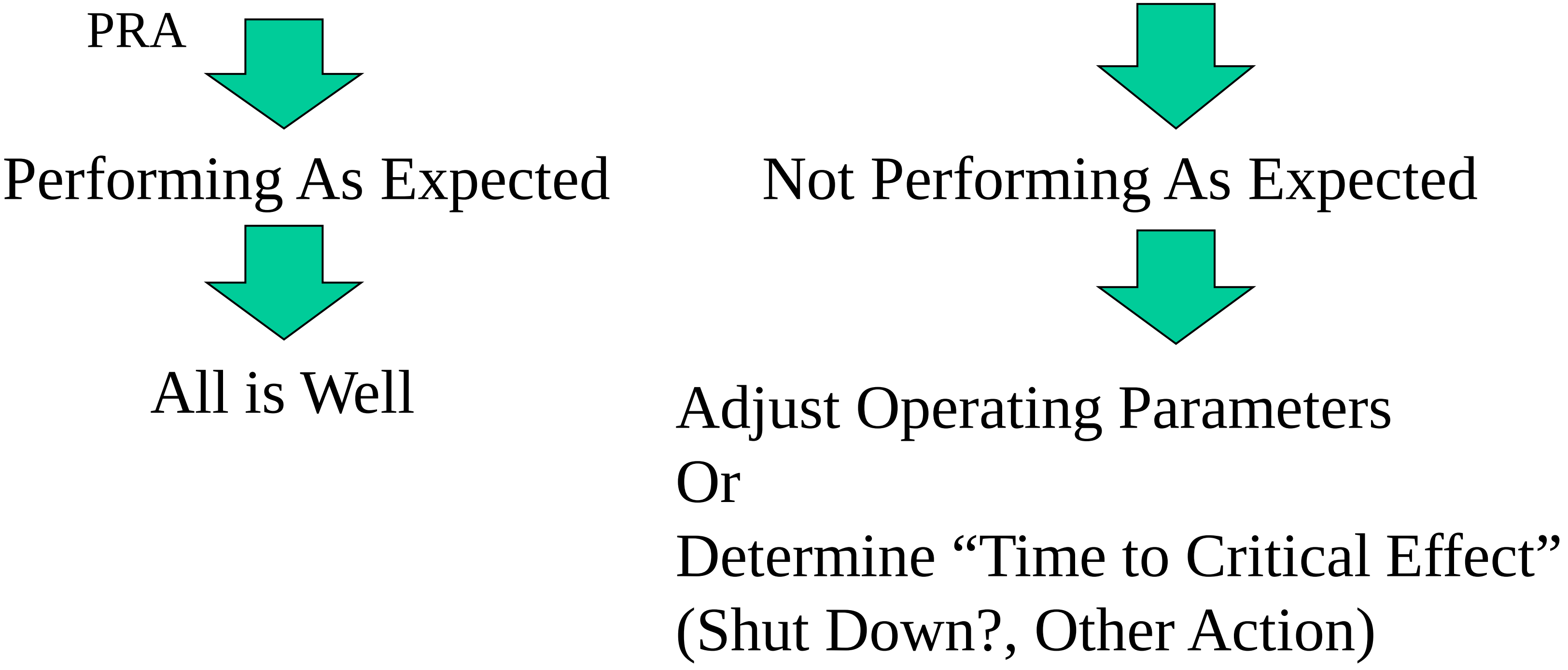
↓

Unless the Design Uses Bounding Analysis, an “Accurate” PRA will be Critical to Success

Source Term!

Enabling Resilience Using PRA?

- Incorporating PRA into System Model
  - Monitoring System Compares Actual Performance with "Expected" Performance
  - Monitoring System Compares Actual Performance (sequences) with PRA



Performing As Expected

All is Well

Not Performing As Expected

Adjust Operating Parameters
Or
Determine "Time to Critical Effect"
(Shut Down?, Other Action)

Conclusion (Partial)

- Probabilistic Risk Assessment (PRA) will be key to success.
  - Enables Lowest Cost Design
  - Ensures Adequate Protection
    - Helps Define EPZ
    - See 1st Bullet
  - Enables Transportation

"I get to test my software and am often present when it's put into production. The creators of the *Ingenuity* have undoubtedly tested to the best that NASA's ample budget and their project time constraints allowed. But I will be very surprised if any of the developers sleep soundly the night before the machine flies — and I'm sure that, when it does, its programmers will experience the longest 15 minutes of their lives."

" Ingenuity Delayed", Henry Racette, April 11, 2021

The great tragedy of engineering-the slaying of a beautiful design by an ugly fact, Adapted from Thomas Huxley

Thank You

PERSPECTIVES ON THE ROLE OF PRA IN FISSION BATTERY DEVELOPMENT

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DISCUSSION TOPICS

- Why bother to do a PRA?
- Is there a reactor size that justifies skipping the PRA?
- What is the role of the Licensing Modernization Project?
- What is the role of PRA standards?
- What are the key challenges?

WHY BOTHER TO DO A PRA?

- PRA provides a systematic and reproducible method for:
  - ✓ identifying initiating events;
  - ✓ exhaustively enumerating event sequences;
  - ✓ Identifying the failure modes and causes of safety system failure
  - ✓ Avoiding need for ad hoc judgments about what is credible
- ✓ Introduction of PRA helps to minimize over-reliance on subjective ad hoc judgements in establishing the safety and licensing bases
- ✓ Early introduction of the PRA can support optimization of designs and reduce the needs for costly backfits
- ✓ The PRA standard for advanced non-LWRs, ASME/ANS RA-S-1.4-2021 is now available to support PRAs for any technology and reactor size
- ✓ A safety and licensing infrastructure is available from the NEI Licensing Modernization Project, Regulatory Guide 1.233, and 10 CFR 53 is being developed. This infrastructure relies on a technically acceptable PRA

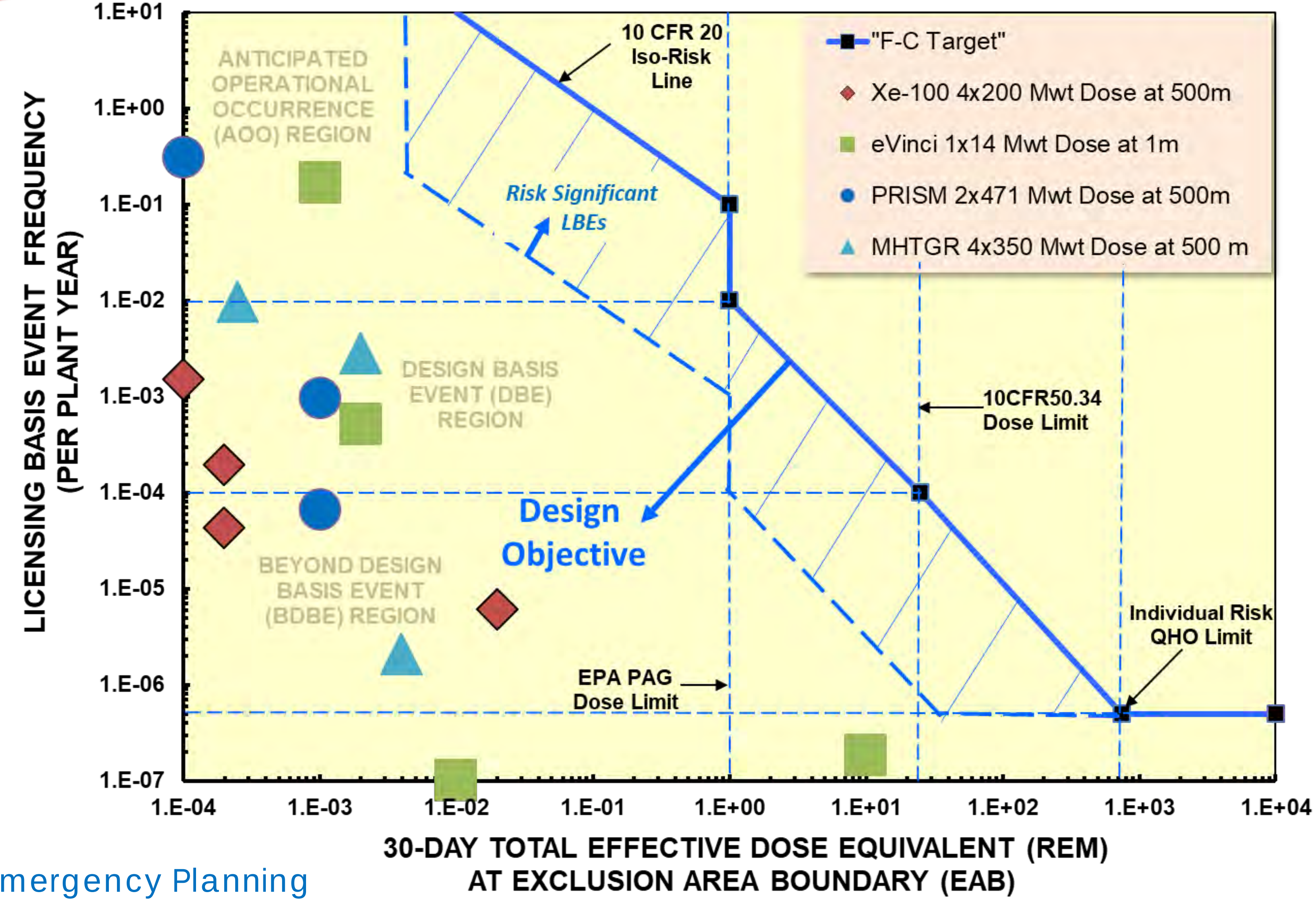
IS THERE A REACTOR SIZE THAT JUSTIFIES SKIPPING THE PRA?

- Historically small research and test reactors have used so-called bounding source terms to support the safety and licensing bases.
- Such bounding source terms based on a “maximum credible accident”.
- The modifier “credible” is key as it brings in a qualitative notion of probability or frequency.
- The term “maximum” suggests a “worst case scenario”, but is it really?
- It is extremely doubtful that these concepts have been applied consistently across the different cases as this is highly subjective and not really reproducible.
- There are no industry standards on how to come up with these MCAs and source terms
- It was found following the TMI-2 accident that the design basis source term for Iodine and Cesium isotopes into the containment for licensing LWRs were exceeded.
- One can only “bound” the accidents that one has considered and to make this robust one needs a comprehensive enumeration of the possibilities.

PRINCIPAL FOCUS OF LMP METHODOLOGY

- Systematic, reproducible, robust ,and integrated processes for:
  - Identification of safety significant LBEs appropriate for each non-LWR design based on a design specific PRA;
  - Safety classification of SSCs and selection of SSC performance requirements;
  - Establishing the risk and safety significance of LBEs and SSCs;
  - Demonstrating enhanced safety margins consistent with Advanced Reactor Policy;
  - Identification of key sources of uncertainty;
  - Evaluation of the adequacy of plant capabilities and programs for defense-in-depth including special treatment requirements for safety significant SSCs
- Appropriate balance of deterministic and probabilistic inputs to risk-informed decisions involved in design, operations, programs and licensing.
- Performance-based approach to setting plant and SSC performance requirements and monitoring performance against requirements.
- SSC performance requirements linked to balancing prevention and mitigation functions identified in LBEs.

LICENSING BASIS EVENTS FROM LMP PILOTS



SCOPE OF NON-LWR PRA STANDARD

- Multiple plant operating and shutdown states
- Event sequences developed to include end states with mechanistic source terms and offsite radiological consequences (similar to LWR Level 3 PRA)
- Technology inclusive end states and risk metrics
  - Frequencies of event sequences, event sequence families, and release categories
  - Mechanistic source terms and radiological doses and health effects
  - Options with requirements for user defined end states (e.g sodium boiling)
- Event sequences involving two or more reactors or radionuclide sources
- Requirements for PRAs done at preoperational design stages
- Requirements to address uncertainties in establishing passive system reliability
- Both absolute and relative risk significance criteria may be used
- Risk significance based on quantified estimates of frequency and consequence

NRC PLAN TO ENDORSE NON-LWR PRA STANDARD

- Meeting standard requirements including performance of peer reviews key element to assure technical adequacy of PRA for both LMP and alternative safety case approaches
- NRC participated on the Working Group responsible for the standard and is represented on the JCNRM
- NRC staff provided extensive comments on the first and second ballots leading to unanimous approval by the JCNRM
- Final standard was published on February 8, 2021
- NRC plans to issue a RG similar to RG 1.200 to endorse the next edition of the non-LWR standard to be balloted in 2020
- A white paper indicating staff plans for endorsement has been issued and is the topic of recent public meetings

KEY CHALLENGES FOR FISSION BATTERIES

- LMP and NLWR PRA standard are independent of reactor power level but are only fleshed out for stationary reactors
- Research and testing required to validate analytical tools for plant transient and mechanistic source term development
- Limitations of tools such as MAACS to evaluate radiological doses close to reactor
- Gaps in suitable codes and standards to support design and special treatment requirements non-LWRs
- Unique challenges for storage of radioactive waste
- Lack of experience in carrying the safety and licensing case to completion

SUMMARY

- LMP, RG 1.233, and 10 CFR 53 provide an appropriate licensing infrastructure to advance fission battery development
- The LMP pilot studies that have been performed and the ongoing TICAP pilots are helping to validate this infrastructure
- The size and complexity of the necessary PRA models will be highly correlated to the size and complexity of the reactor systems
- PRA supplemented by established defense-in-depth principles provide the best available tools to work out the reactor design and technology specific licensing basis events and design criteria for the fission batteries

April 16, 2021

Christopher Chwasz

Regulatory Development and Licensing
Nuclear Science and Technology (NS&T)

Developments in Digital Twins

Applications to the future of fission batteries

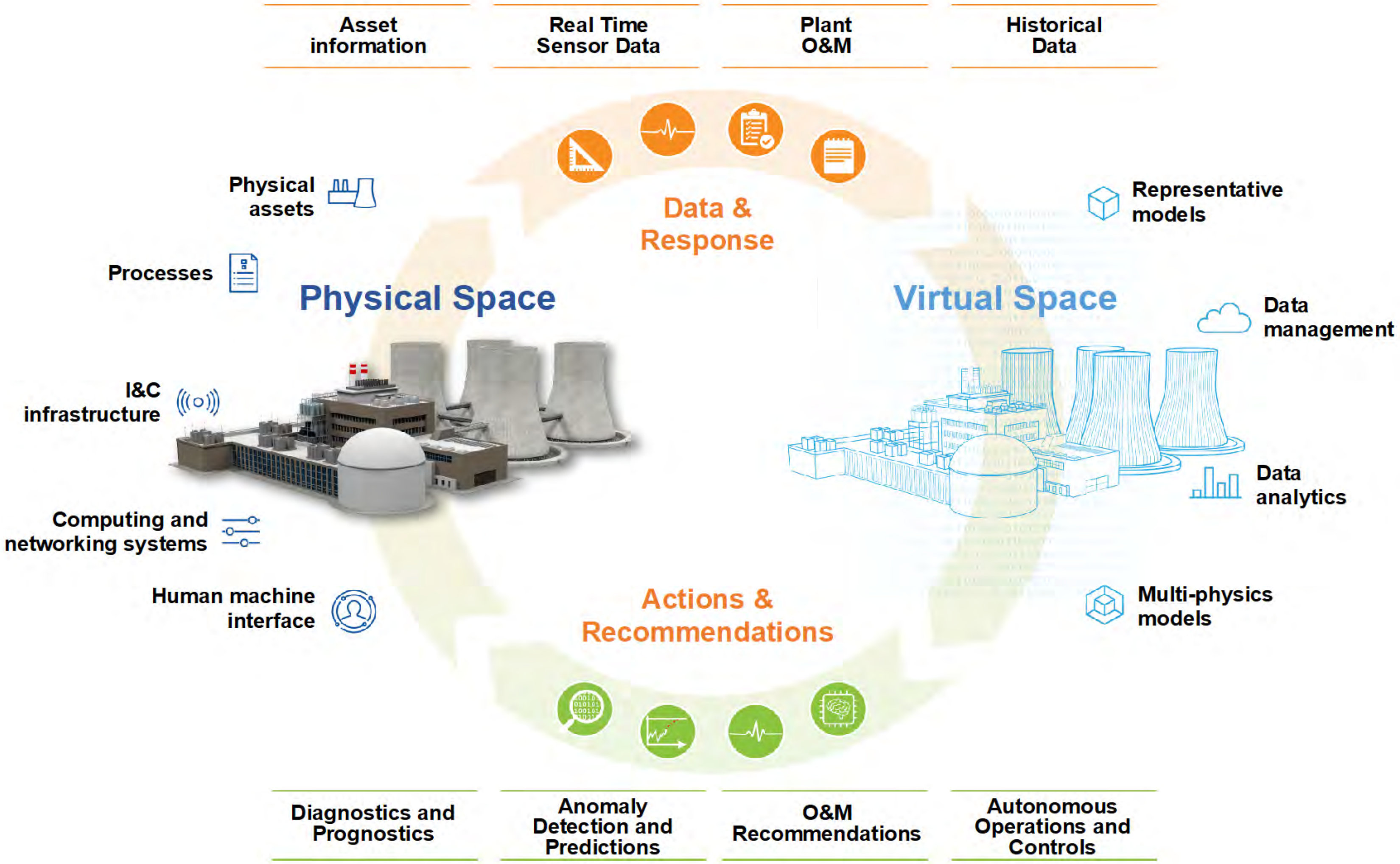
Idaho National Laboratory

Digital Twins: A Background

- A digital twin is comprised of:
  - A physical item, system, or process
  - A virtual representation of that item, system, or process
  - The exchange of data between the physical and virtual “twins”

- The purpose of a digital twin is to leverage data acquisition, management, and analytics to create a digital model to inform the physical.

Digital Twins: A Background



Asset information

Real Time Sensor Data

Plant O&M

Historical Data

Physical assets

Processes

I&C infrastructure

Computing and networking systems

Human machine interface

Data & Response

Physical Space

Virtual Space

Actions & Recommendations

Representative models

Data management

Data analytics

Multi-physics models

Diagnostics and Prognostics

Anomaly Detection and Predictions

O&M Recommendations

Autonomous Operations and Controls

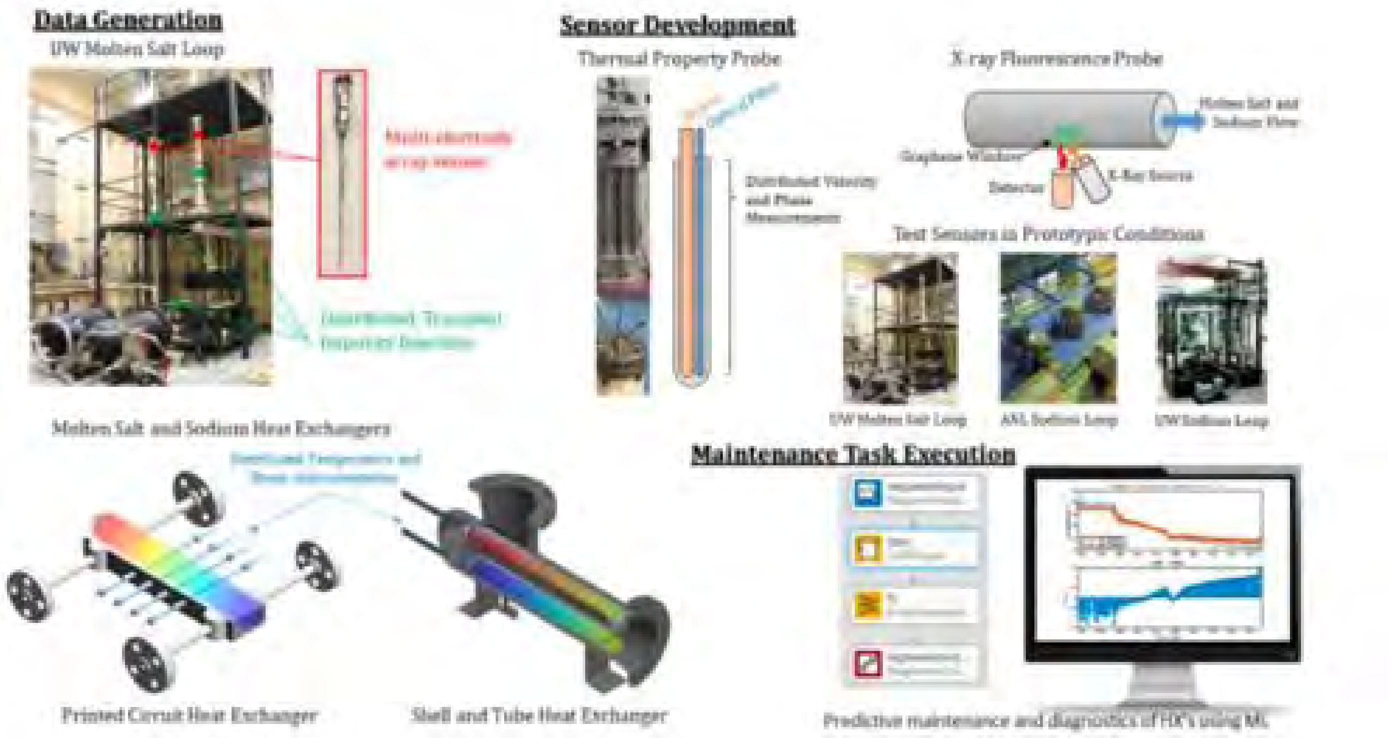
ARPA-E

- Advanced Research Project Agency–Energy: DOE program that “advances high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E awardees are unique because they are developing entirely new ways to generate, store, and use energy.”

- Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA)
  - Seeks to develop digital twin technology and apply it Operations and Maintenance (O&M) for advanced nuclear reactors.
- Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER)
  - Seeks to identify and develop technologies that lead to more cost effective and safer advanced nuclear reactors

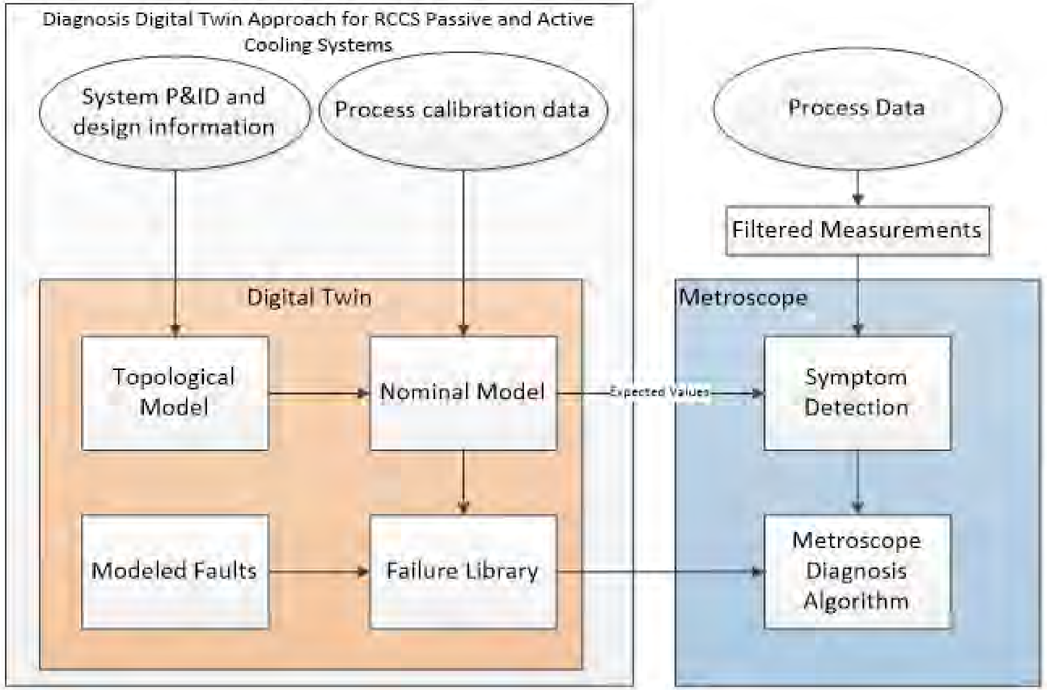
ARPA-E: GEMINA

- Argonne National Laboratory (ANL) – Maintenance of Advanced Reactor Sensors and Components (MARS)
  - Developing advanced sensors and data techniques to reduce O&M costs for the Kairos molten salt reactor.



ARPA-E: GEMINA

- Electric Power Research Institute (EPRI) Build-to-Replace: A New Paradigm for Reducing Advanced Reactor O&M Costs
  - Study to analyze components designed for greater reliability over shorter lifetimes for planned replacement to reduce O&M costs.
- Framatome – Digital Twin-Based Asset Performance and Reliability Diagnosis for the HTGR Reactor Cavity-Cooling System Using Metroscope
  - Project looks to pair a digital model of the HTGR reactor Cavity-Cooling system with fault libraries and simulate a passive cooling system to determine sensor sensitivity and reliability.



Diagnosis Digital Twin Approach for RCCS Passive and Active Cooling Systems

System P&ID and design information

Process calibration data

Process Data

Filtered Measurements

Digital Twin

Topological Model

Nominal Model

Modeled Faults

Failure Library

Metroscope

Symptom Detection

Metroscope Diagnosis Algorithm

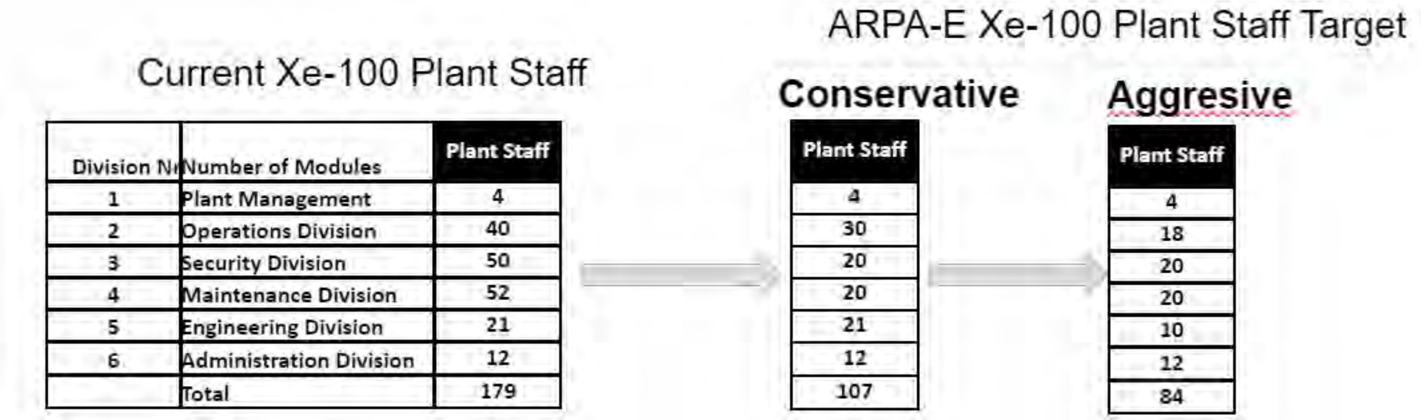
ARPA-E: GEMINA

- General Electric (GE) Global Research – AI-Enabled Predictive Maintenance Digital Twins for Advanced Nuclear Reactors
  - Research will explore creating digital twins for the BWRX-300 to enable predictive maintenance.
- Massachusetts Institute of Technology (MIT) – High-Fidelity Digital Twins for BWRX-300 Critical Systems
  - Work will seek to create a digital twin of an SMR and model mechanical and thermal fatigue.
- Massachusetts Institute of Technology (MIT) – Generation of Critical Irradiation Data to Enable Digital Twinning of Molten-Salt Reactors
  - Data will be collected from irradiated molten salts for the creation of a MSR digital twin to model fuel salt behavior.

BWRX300

ARPA-E: GEMINA

- Moltex Energy – SSR APPLIED - Automated Power Plants: Intelligent, Efficient, and Digitized
  - Development of a multiphysics digital twin of the SSR-W reactor with a non-nuclear effects test loop to validate flow uncertainties and supporting O&M tests
- X-Energy - Advanced Operation & Maintenance Techniques Implemented in the Xe-100 Plant Digital Twin to Reduce Fixed O&M Cost
  - Study will create a digital twin of a salt flow test loop to model flow conditions and provide opportunities to simulate strategies to reduce O&M costs.



Current Xe-100 Plant Staff

Division N	Number of Modules	Plant Staff
1	Plant Management	4
2	Operations Division	40
3	Security Division	50
4	Maintenance Division	52
5	Engineering Division	21
6	Administration Division	12
	Total	179

ARPA-E Xe-100 Plant Staff Target

Conservative

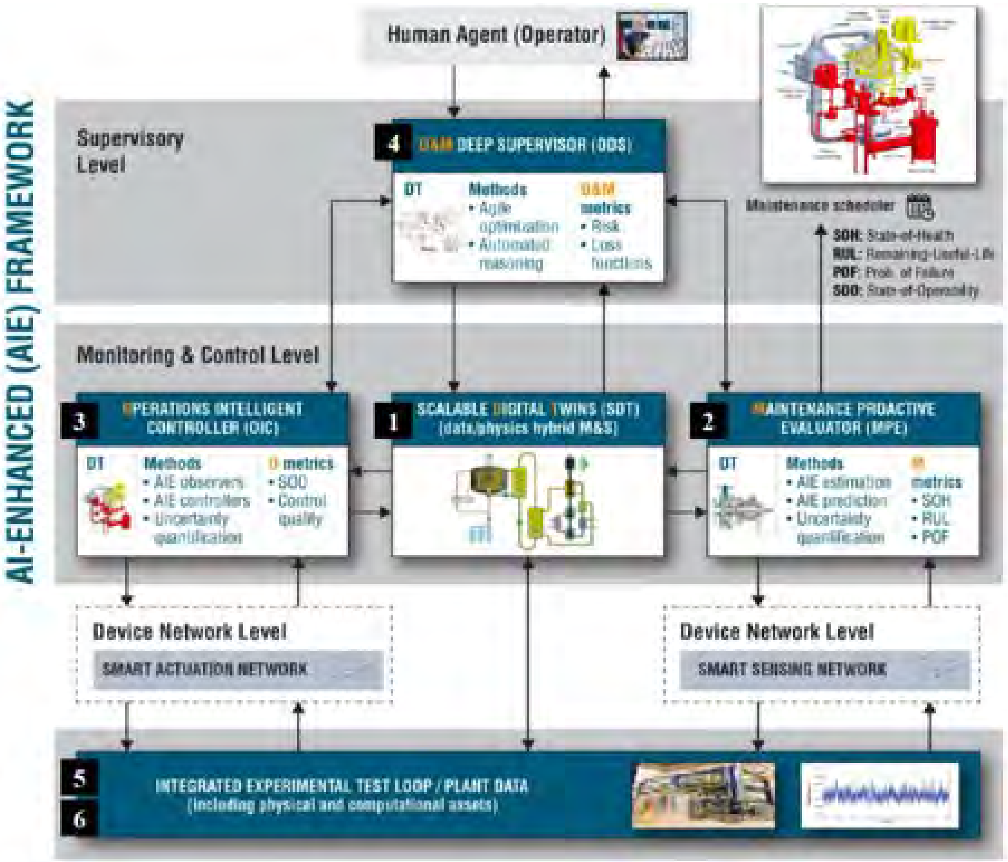
Plant Staff
4
30
20
20
21
12
107

Aggresive

Plant Staff
4
18
20
20
10
12
84

ARPA-E: GEMINA

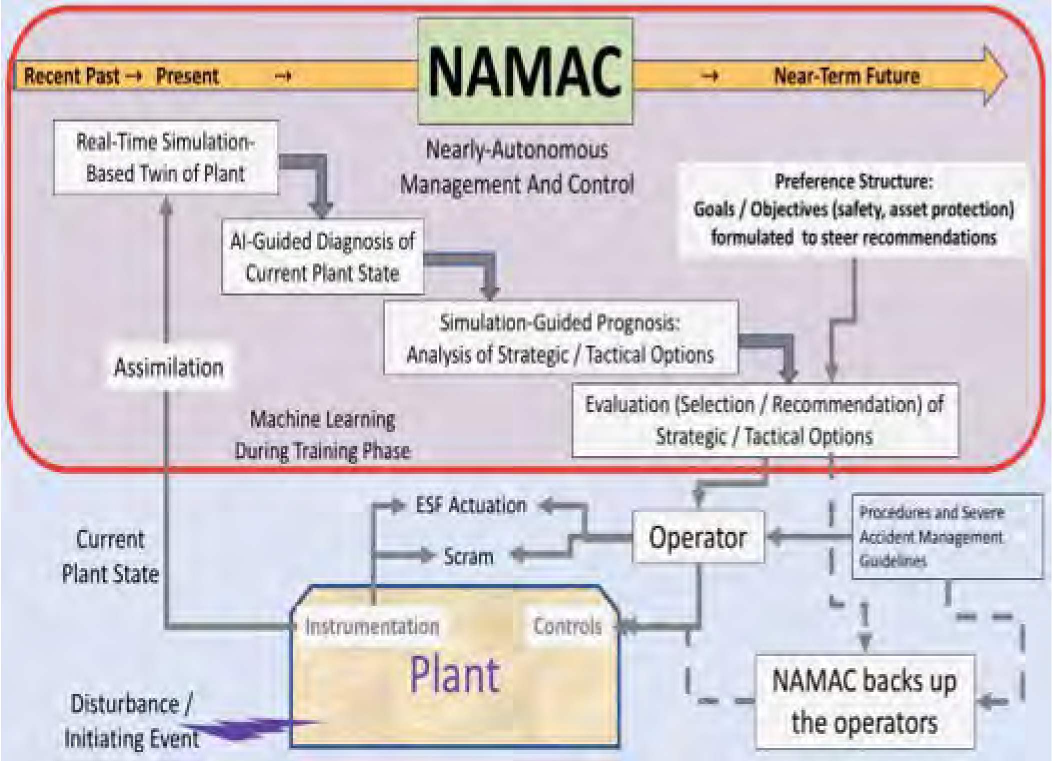
- University of Michigan – PROJECT "SAFARI” – Secure Automation For Advanced Reactor Innovation



- Project seeks to:
  - Develop scalable digital twin of an MSR
  - Develop maintenance evaluator to monitor plant health and assess maintenance needs
  - Develop an operations controller for autonomous operation during normal and accident conditions
  - Develop an O&M deep supervisor
  - Demonstrate the digital twin and modules on a non-nuclear molten salt loop
  - Apply the digital twin to the Kairos FHR advanced reactor design

ARPA-E: MEITNER

- HolosGen – Transportable Modular Reactor
  - Digital twin development of the gas-cooled modular reactor coupled with subscale simulators will generate data to inform the reactor design
- North Carolina State University – Management and Control System for advanced reactors
  - Nearly Autonomous Management and Control system (NAMAC)
    - A digital twin control system to provide recommendations to operators



Recent Past → Present →

NAMAC

→ Near-Term Future

Real-Time Simulation-Based Twin of Plant

Nearly-Autonomous Management And Control

Preference Structure: Goals / Objectives (safety, asset protection) formulated to steer recommendations

AI-Guided Diagnosis of Current Plant State

Simulation-Guided Prognosis: Analysis of Strategic / Tactical Options

Assimilation

Evaluation (Selection / Recommendation) of Strategic / Tactical Options

Machine Learning During Training Phase

ESF Actuation

Scram

Operator

Procedures and Severe Accident Management Guidelines

Current Plant State

Instrumentation

Controls

Plant

Disturbance / Initiating Event

NAMAC backs up the operators

INL: DICE

- INL has developed DICE – Digital Center of Excellence
  - Developed as a virtual center to coordinate digital engineering, digital twinning, and digital transformation for advanced power systems
  - In support of VTR, a data warehouse-linking technology, Deep Lynx, was created to support the design and operation of large projects. Deep Lynx integrates digital models, requirements, risk, schedule, and analysis to maintain continuity through the design process and reduce errors.
  - Deep Lynx supports:
    - National Reactor Innovation Center
    - Versatile Test Reactor
    - Transformation Challenge Reactor
    - National Nuclear Security Administration

INL

VTR SOLVING ENERGY CHALLENGES THROUGH SCIENCE™

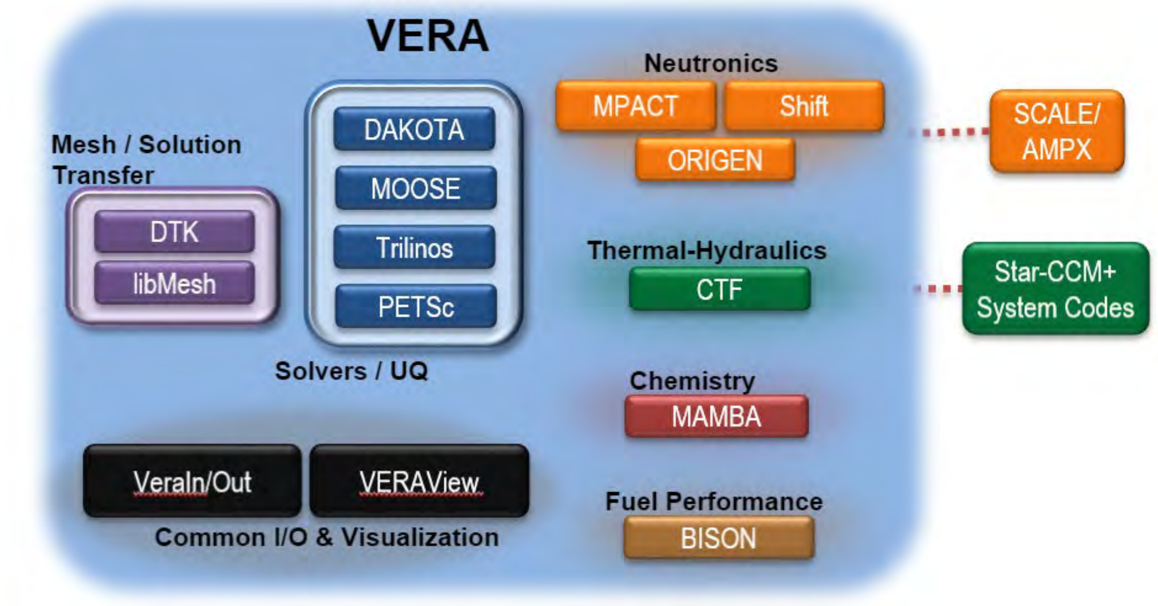
- Versatile Test Reactor (VTR)
  - VTR is being designed with the use of Deep Lynx, and a virtual design construction and building information management tool for 2D and 3D models
- Microreactor AGile Non-nuclear Experimental Testbed (MAGNET)
  - Digital twin of MAGNET will display live sensor data, update physics model, and provide predictive analysis using artificial intelligence. Will use Deep Lynx and Multiphysics Object-Oriented Simulation Environment (MOOSE)
- Microreactor Applications Research Validation & EvaLuation (MARVEL) –
  - Will test, demonstrate, and address issues associated with unattended operation
- National Nuclear Security Administration (NNSA)
  - Digital twin development for diversion detection from advanced reactors

ORNL

- Transformation Challenge Reactor (TCR)
  - Will be designed, built, and operated using digital twins for additive manufacturing (Digital Platform), integrated sensor deployment, and autonomous operation
- Virtual Environment for Reactor Application (VERA)
  - A hybrid digital twin model that couples neutronics, thermal hydraulics, chemistry, and isotopic decay for existing LWRs
- Digital Platform
  - A rapid prototyping and quality evaluation tool that couples data analytics and design/manufacturing data to optimize and validate the additive manufacturing process
- Prognostic Health Management (PHM)
  - ML method for diagnostic and system health models

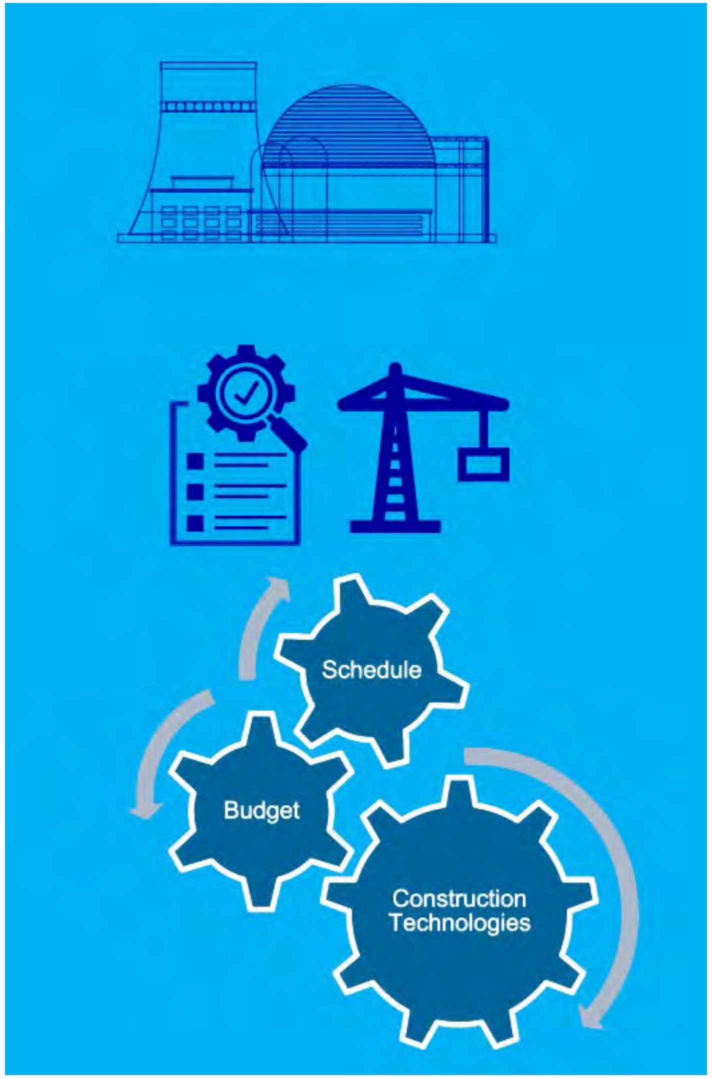
Electric Power Research Institute

- Water Chemistry
  - Coupled water chemistry tools, simulation, real-time data importing to model the plant steam heat balance
  - Virtual Environment for Reactor Application (VERA)
    - Collaboration with ORNL in the application of VERA to existing LWR plants



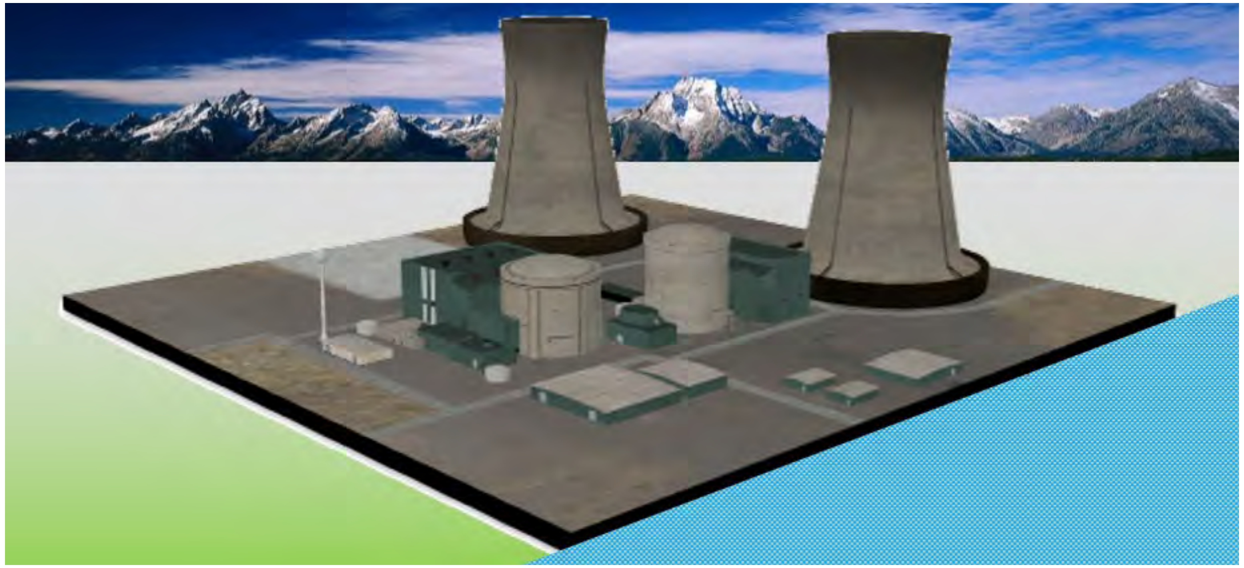
Digital Twin Applications for Fission Batteries

- Safety Analysis
  - Integrated multiphysics modeling for the coupling of safety codes
  - Will require
    - Assurance
- Design, Construction, and Manufacturing
  - Integration of 2D/3D models, scheduling, sensors, budget
    - Planning, tracking, training, inspections / tests
  - Will require
    - Advanced sensors



Digital Twin Applications for Fission Batteries

- Operation
  - Autonomous operation and response to:
    - Load following
    - Normal transient response
    - Accident scenarios
  - Will require
    - Advanced sensors
    - Data processing
    - Assurance



Digital Twin Applications for Fission Batteries

- Maintenance
  - Predictive maintenance - Refurbishment - Replacement
    - Determination of component reliability, efficacy, and lifetime
  - Will require
    - Advanced sensors
    - Data processing
    - Material/component data
    - Assurance

Diagnostic/Predictive Model Selection

Contact and Information Slide (Not for Presentation)

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708-220-4352

April 16, 2021

Rich Denning
Prof of Nuclear Engineering
The Ohio State University
(retired)

Proposed Licensing Basis for Fission Battery Reactors- Three Critical Issues

Compliance with a Risk-informed Licensing Basis under Development as 10CFR53

Idaho National Laboratory

Contact and Information Slide

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Licensing Modernization Project

- In April 2012, the NRC issued NUREG-2150, “A Proposed Risk Management Regulatory Framework”
  - Product of Risk Management Task Force led by George Apostolakis
  - Proposed comprehensive risk-informed approach to regulation.
- In December 2016, the NRC issued “NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness,” which supported a risk-informed, performance-based approach to non-LWR regulation.
- Licensing Modernization Project (LMP) approach was developed involving NEI, Southern Company, and DOE (INL)
  - NEI-18-04 describes approach to advanced (non-LWR) reactor licensing
  - Regulatory Guide 1.233 essentially adopts NEI-18-04 approach
  - 10CFR53 under development with adoption planned for 2022.
  - Would include micro-reactors and fission batteries under general approach.

Risk-Limit Curve

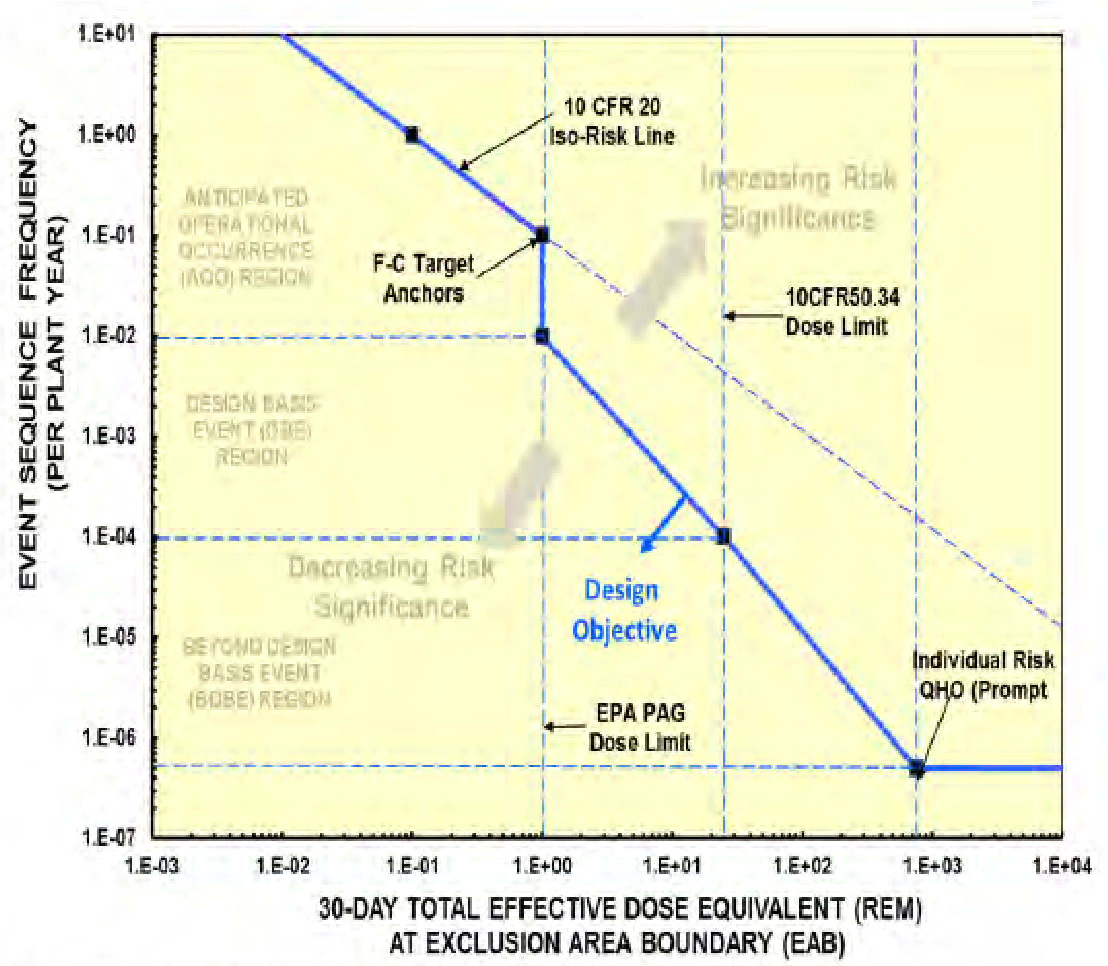


Figure 3-1. Frequency-Consequence Target

<u>Risk Limit Curve (RLC) based on existing regulations</u>
Pinning points: 25 rem at 1E-4 per yr
1000 rem at 5E-7 per yr (lethal offsite dose)
Compliance with quantitative health objectives

<u>Categorization of events:</u>
Anticipated Operational Occurrences
>1E-2 per yr
Design Basis Events
1E-4 per yr to 1E-2 per yr
Beyond Design Basis Events
<1E-4 per yr
Ranges are consistent with historic treatment.

<u>Risk Significant LBEs</u>
Within 1% of dose or consequence

Advantages of LMP Approach

- Consistent with NRC’s advanced reactor policy statement
- Accounts for uncertainties (5th and 95th percentile values)
- Risk-informed, performance-based
- Common approach for the licensing of advanced reactor designs
- Supports the selection of licensing basis events
- Provides for the assurance of adequate levels of defense-in-depth
- Supports the classification of SSCs
- Can be harmonized with international standards

Safety Classification of Equipment

- Safety related:
  - Selected by designer to satisfy the RLC that only rely on SR SSCs to satisfy 25 rem dose limit <u>using conservative assumptions</u>
  - Prevent BDBE with consequences greater than 25 rem increase in frequency into DBE regime
- Nonsafety-related with special treatment (New concept)
  - If make significant contribution to integral risk metrics
  - Or support defense-in-depth
- Nonsafety related with no special treatment

Issue 1. Interpretation of Farmer Curve (Risk Limit Curve)

- In 1967, R. Reginald Farmer proposed the use of a risk limit curve in which a curve displaying frequency as a function of consequence would be used to establish regulatory limits for accident sequences.
  - The consequence measure proposed was curies of I^{131}.
- However, the mathematical meaning of the curve was not described and has been a subject of intense debate since.
  - It is clear what the curve is not: Given a sequence of consequence C, the curve does not provide a limit on the frequency F.
    - Example: C=4.2 Ci (by which we mean 4.20000…) the frequency F is 0.

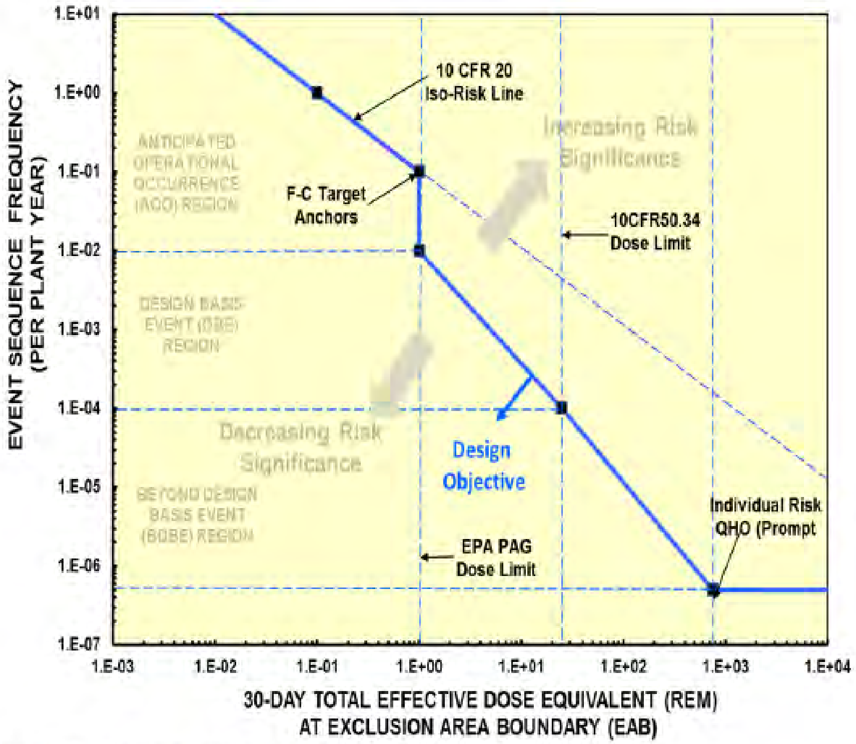


Figure 3-1. Frequency-Consequence Target

Farmer Curve (Risk Limit Curve)

- Must integrate over an interval to have non-zero frequency
  - The curve could be divided into consequence intervals of size ΔC (the histogram approach) but then the allowed F_i would depend on the size of ΔC but the curve is based on regulatory pinning points.
- For a specified consequence, we would like to assure that the frequency of events of that consequence or greater is limited, **which is the complementary cumulative distribution function, CCDF**
  - Compliance with CCDF establishes a limit on risk – Integral of CCDF along the frequency axis (area between the curve and the y-axis) is identically equal to the mean risk over that interval.
  - It makes mathematical sense (which should be an essential characteristic of the basis for a complete change in licensing approach)
  - In fact, that risk is approximately equal to 100 mrem/yr, which is the regulatory limit for annual exposures

R.G. 1.233 Implementation

- Rather than individual scenarios, R.G. 1.233 treats families of accident sequences with similar behavior and safety related systems
- This is an important improvement versus original NEI-18-04 approach
- There is analyst judgment in defining what constitutes a sequence
  - E.g. for pipe breaks: hot-leg, cold-leg, large break, intermediate break, small break LOCAs can be separately considered for good reason including different emergency core cooling system components.
  - The analyst could game the system by dividing a sequence that doesn’t satisfy the RLC criteria into two sequences that do.
- By treating families of sequences, that have similar characteristics and rely on the same safety related equipment, this element of arbitrariness is reduced.
- Includes uncertainty bars for frequency and consequence as margin to limit curve.
- Accidents within 1 percent of limit curve are focus of regulatory review.

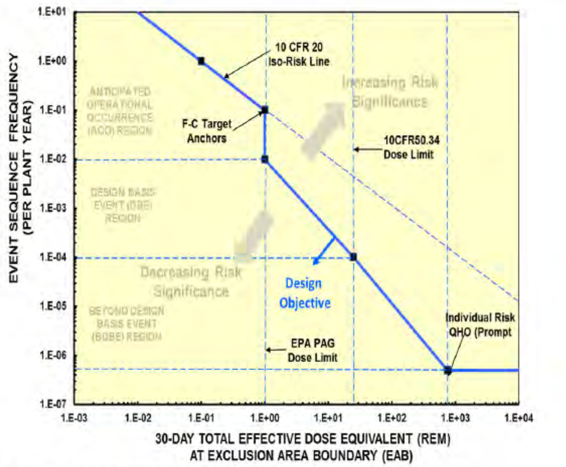


Figure 3-1. Frequency-Consequence Target

Quick History Lesson on MCA and Design Basis Accidents

- The first mention of Maximum Credible Accident (MCA) is in 1956 by AEC Advisory Committee (predecessor to ACRS) associated with fast reactor licensing.
- In 1960, MCA is defined for LWRs as rupture of largest diameter primary system pipe (Loss of coolant accident, LOCA) leading to melting of fuel with release
  - 100 percent noble gases, 50 percent of halogens, 1% solids from fuel (TID-14844 source term)
  - Release rate from containment less than 0.1 %/day
  - Associated maximum dose at exclusion area boundary 25 rem whole body dose, 300 rem thyroid dose

LWR Design Basis Events

- The MCA provided the design bases for a number of LWR systems, structures and components (SSCs) including
  - Containment pressure capability – based on steam release in large LOCA (failed to consider zirconium-steam generation of hydrogen)
  - Containment leak rate – whole body dose of 25 rem and thyroid dose of 300 rem at site boundary
  - Control room habitability
  - Hydrogen control system – based on radiolysis of released radionuclides in sump water
  - Post-accident operability of safety-related equipment subject to radiation exposure

ECC Design Basis

- 1969 Ergen Report – LWRs need more robust emergency core cooling systems to respond to LOCAs
- Design basis for ECCS
  - Instantaneous double-ended guillotine break of largest diameter pipe
  - Leads to substantial model development and experimental effort (much at INL)
  - Discover that small breaks also have special requirements
  - Within the context of demonstrating adequacy of ECCS there is evolution of regulatory oversight in
    - Treatment of uncertainties (aleatory and epistemic),
    - Validation, verification and uncertainty quantification

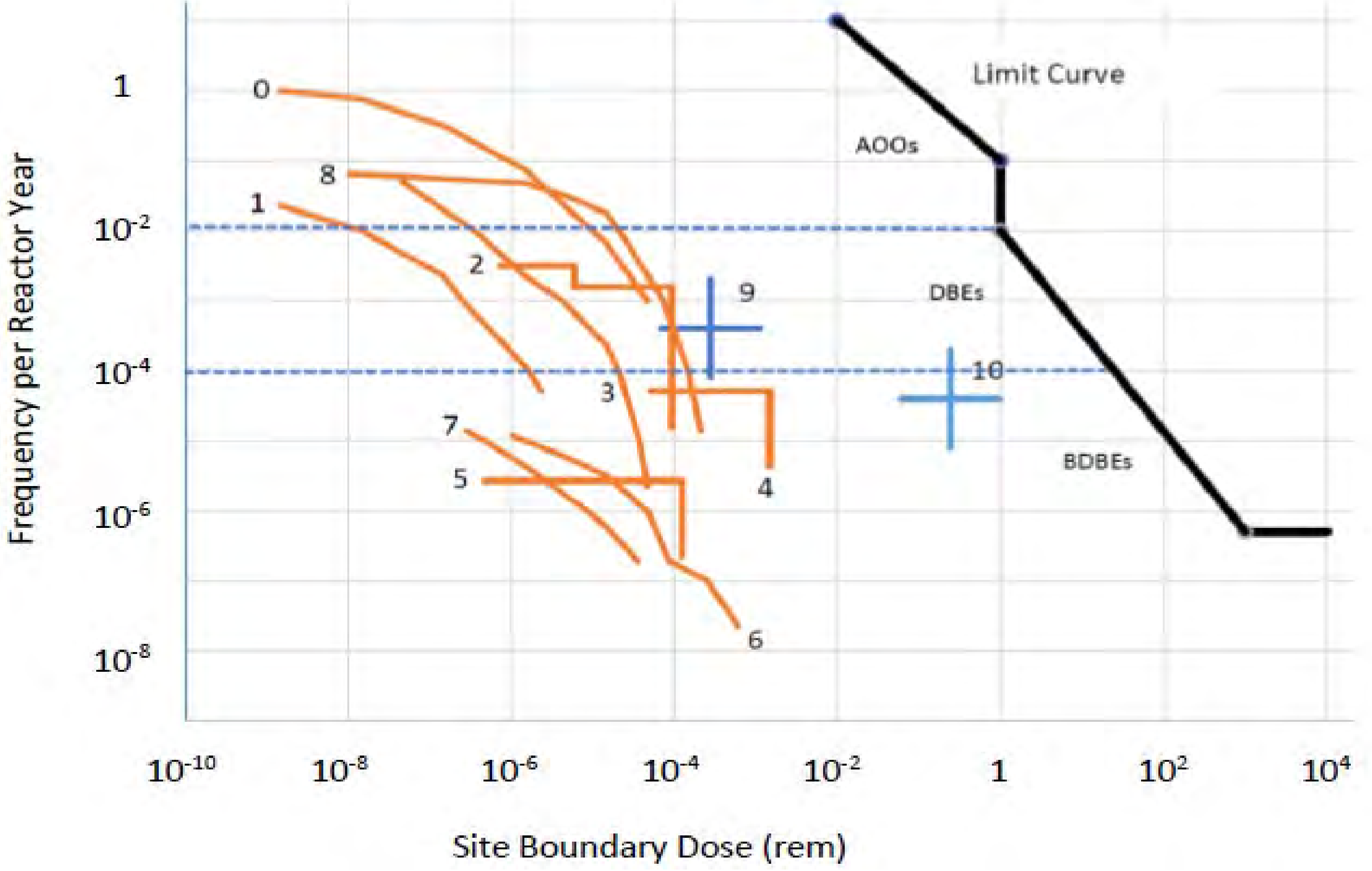
WASH-1400/TMI-2/NUREG-1150

- 1975 WASH-1400 risk assessment
  - Frequency of severe accidents is greater than thought but risk is small relative to other risks
  - Hydrogen generated during meltdown provides threat to containment integrity
    - Confirmed by TMI-2 accident (one atmosphere hydrogen deflagration)
    - Leads to Hydrogen Rule Making and higher capacity hydrogen control systems
  - BNL study undertaken to determine relative risk of design basis events versus severe accidents – risk dominated by severe accidents
- 1979 NUREG-1150 risk assessment
  - Nuclear power plants satisfy probabilistic safety goals with wide margin
  - TID-14844 not representative of severe accident radioactive material release
  - NUREG-1465 more mechanistic treatment of severe accident source terms based on analysis of severe accidents in variety of LWR designs

Trial Application of Limit Curve

- A pinning point of the RLC is 25 rem at 1x10^{-4} per year
  - For LWRs, the 25 rem site boundary dose is calculated for a severe accident source term, not for a best-estimate plus uncertainty source term
  - BNL study provides an assessment of the risks for AOOs and DBEs in terms of curies of I^{131} inhaled at site boundary
  - I have converted from I^{131} to whole body dose in rem at site boundary to support a trial application of the LMP approach

Comparison of LWR Non-Severe Accident Events with RLC



No.	Sequence
0	Licensee Event Reports
1	Loss of Offsite Power
2	Fuel Assembly Drop in Containment
3	Fuel Assembly Drop in Spent Fuel Pool
4	Steam Line Break
5	Core Barrel Drop
6	Steam Generator Tube Rupture
7	Loss of Offsite Power for Cooling of Spent Fuel Storage Pool
8	Decay Tank Rupture
9	WASH-1400 Large LOCA
10	WASH-1400 Large LOCA with Failure of Containment Isolation

Issue 2. Degree of conservatism of analysis of LBEs

- The regulations don’t currently address the degree of conservatism of the consequence analysis of LBEs
- The intent is to use conservative but realistic analysis of LBEs but that is inconsistent with current practice (which involves conservative severe accident source terms)
- Should the limit curve be more restrictive or should conservative source terms be used?

Issue 3. How to apply 10CFR53 to Fission Battery?

- 10CFR53 is intended to be applicable to all advanced reactor designs including microreactors and fission batteries
- The likely approach is to apply the risk limit curve at the boundary of the device rather than at a site boundary
- Some local dispersion would occur at the leak site, with standard breathing rate and an assumed personnel exposure time
- The typical reduction in exposure associated with meteorological dispersion and distance is chi/Q (approx. 2E-6 sec/(Ci*m^3))
- Even though the fission battery is much smaller than a small modular reactor, the increase in dose associated with assessment at the surface of the device versus the site boundary is quite large

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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Overview of U.S. DOE Authorization Pathways

Fission Battery Initiative
Workshop on Safety and Licensing
April 16, 2021

Tom Sowinski
Director
Office of Nuclear Reactor Deployment
DOE Office of Nuclear Energy

Office of Nuclear Energy (NE) Vision and Strategy

Our Mission

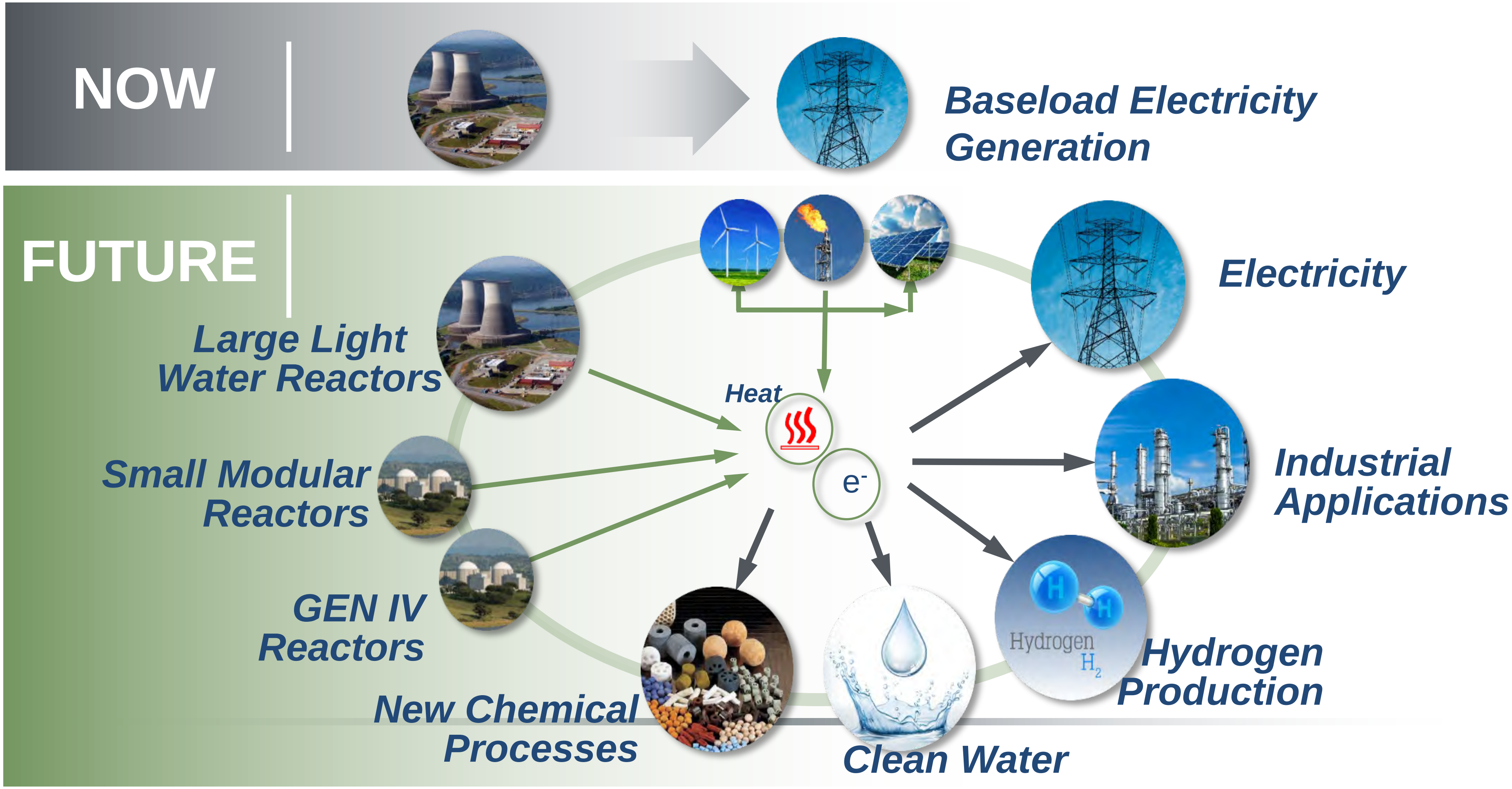
To advance nuclear power to meet the nation's **energy**, **environmental**, and **national security** needs.

Our Priorities

Resolve technical, cost, safety, security and regulatory issues through research, development and demonstration to:

- Enable continued operation of existing U.S. nuclear reactors
- Enable deployment of advanced nuclear reactors
- Develop advanced nuclear fuel cycles
- Maintain U.S. leadership in nuclear energy technology

Sustaining the Present and Shaping the Future of Nuclear



NOW

Baseload Electricity Generation

FUTURE

Large Light Water Reactors

Small Modular Reactors

GEN IV Reactors

Electricity

Industrial Applications

Hydrogen Production

Clean Water

New Chemical Processes

Brief History of U.S. Reactor Regulatory Authorities

- The Atomic Energy Commission (AEC) was authorized under the Atomic Energy Act of 1946, as amended, to regulate activities conducted on its behalf and to license activities of “persons”
  - “Persons” required to obtain a license from the AEC included individuals, corporations, firms, public institutions, etc.
  - **Excluded the AEC**
- The Energy Reorganization Act (1974) split the duties and authorities of the AEC, establishing the roles of the Nuclear Regulatory Commission (NRC) and DOE
  - NRC maintained the primary authority to license activities of “persons” and associated types of nuclear facilities including:
    - Research and test reactors
    - Commercial reactors, including prototypes
  - DOE maintained the more limited authority to regulate facilities and activities conducted on its behalf, except for certain specific facilities (explained in more detail later in presentation), as well as undertake all research and development activities

DOE and NRC Regulatory Process Similarities

- Both regulatory processes are ultimately committed to ensuring the health and safety of the public, workers, and the environment

- Both processes require developers to submit and obtain approval on rigorous and validated safety bases before construction and operation of their nuclear facilities
  - DOE authorization should **<u>not be</u>** misconstrued as “less rigorous” or as a “shortcut” compared to NRC licensing

- Neither process has direct reciprocity for the other
  - Obtaining DOE authorization for construction of a specific reactor design **<u>does not</u>** automatically guarantee it will obtain an NRC license (or vice versa)

DOE Authorization Allowances and Limitations

- In general, DOE (or a private party under an agreement with and subject to oversight of DOE) may construct and operate a research-oriented, non-power reactor at a U.S. Government-owned site/facility under DOE authorization

- Reactors owned, operated, or affiliated with DOE would, however, require an **NRC license** under the following circumstances
  - DOE-affiliated reactor operated by private party on private property outside of DOE oversight and control
  - Reactor operated as part of power generation facilities for electric utility system regardless of siting location
  - Reactor used to demonstrate suitability for industrial/commercial applications regardless of if it is owned by/affiliated with DOE*

*Refers to demonstrating <u>the entire reactor for commercial purposes</u> rather than only portion of a reactor for such purposes

DOE Authorization Allowances and Limitations

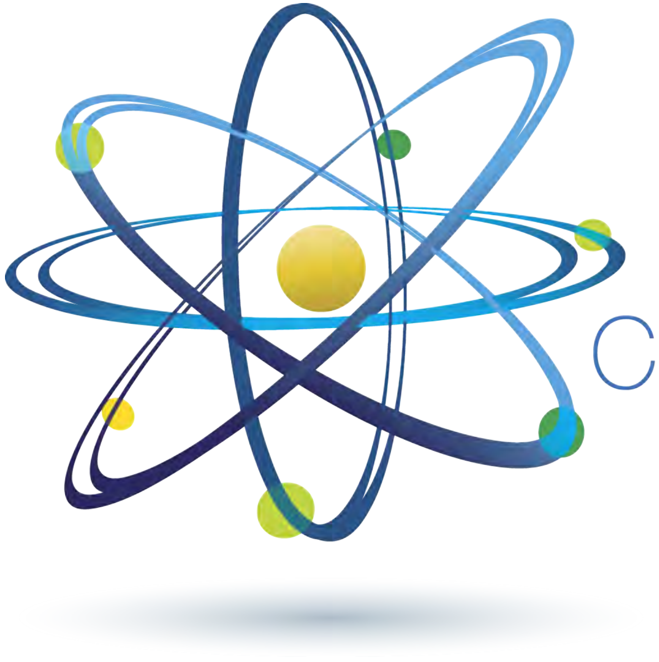
- DOE regulates construction and operation of projects on DOE property for the purpose of developing and testing:
  - New and innovative reactor concepts and technologies
  - Safety/workability of systems or components individually or as part of overall reactor system

- Project cannot rise to level of demonstrating the entire reactor system for commercial suitability.
  - Such a project would require NRC licensing
  - Projects would likely be evaluated by DOE on a case-by-case basis to determine magnitude of reactor commercial demonstration activities

Summary and Path Forward

- DOE maintains the authority to regulate research-oriented, non-power reactor facilities and activities conducted on its behalf (with exceptions)
- Both DOE and NRC regulatory processes are rigorous and ultimately ensure the health and safety of the public, workers, and the environment
- Early engagement with both DOE and NRC is encouraged
  - Assists developers in determining appropriate regulatory pathways for their specific reactor testing and demonstration objectives
- DOE continues its coordination with NRC on regulatory processes
  - NRC invited to observe recent DOE authorization reviews
  - Promotes mutual knowledge sharing and potential future bridging pathways between DOE authorization and NRC licensing

Thank you!



Clean. **Reliable. Nuclear.**

April 16, 2021

Jason Andrus

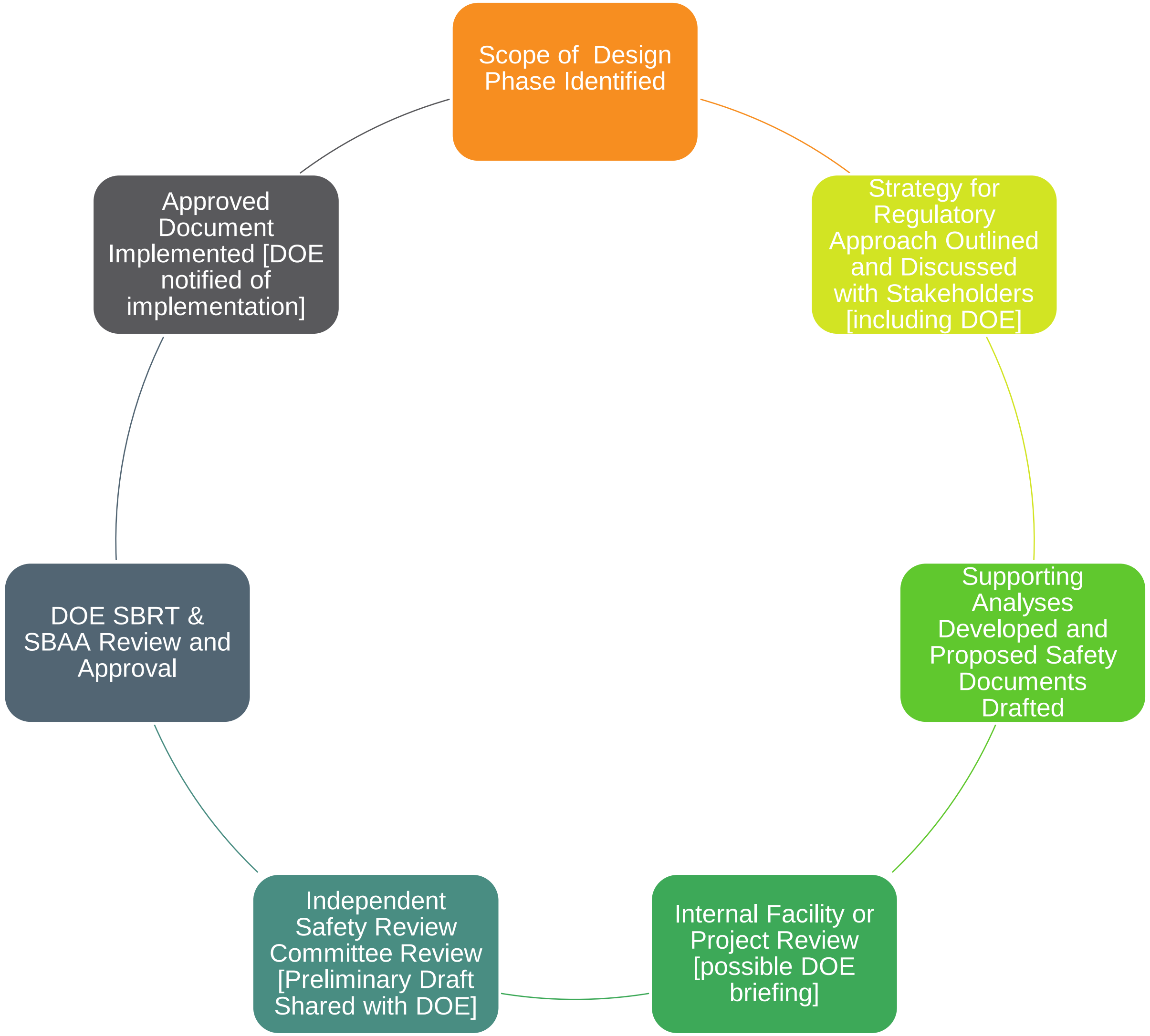
Manager, Advanced
Nuclear Facility Safety
Engineering

Preparation of Safety Basis Documents for DOE Authorization of Fission Batteries

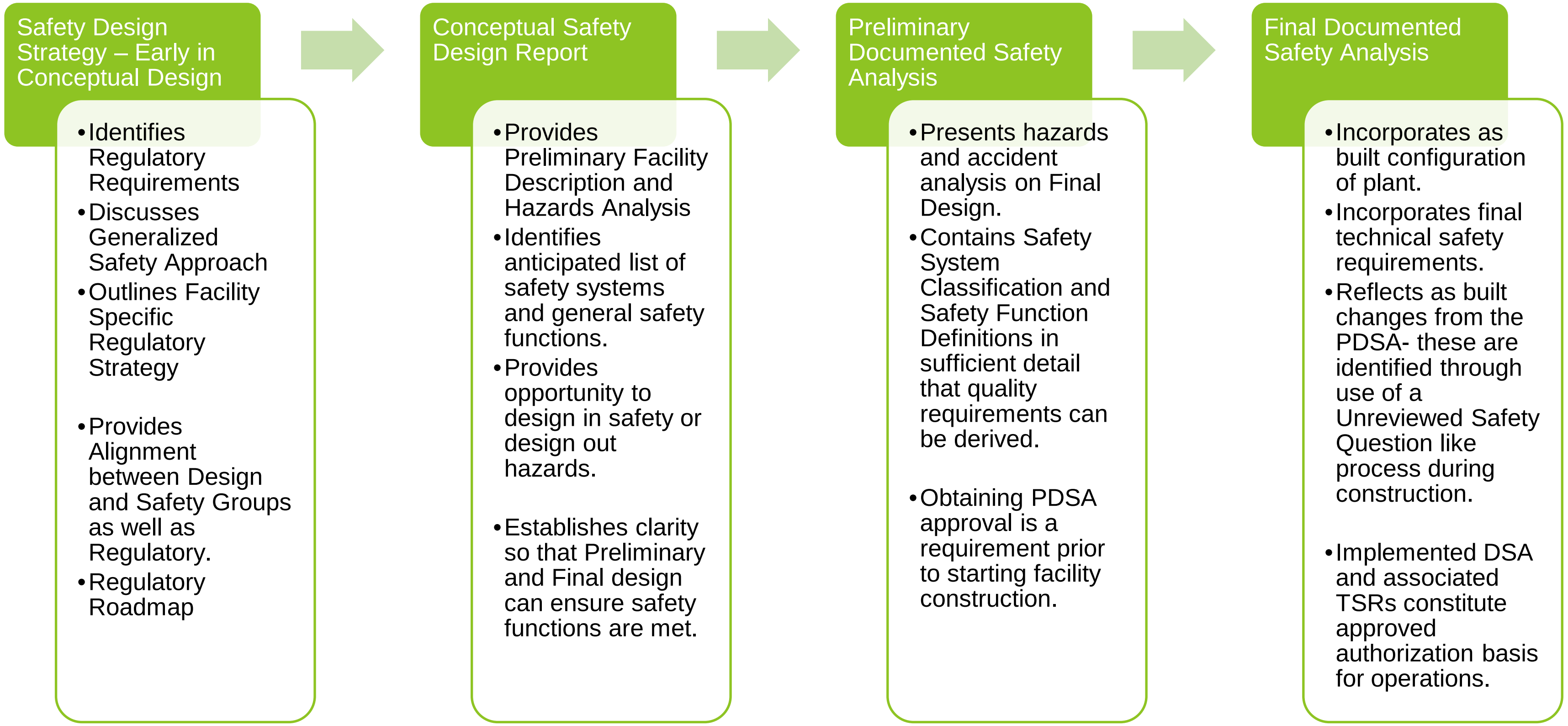
Idaho National Laboratory

Overview of Safety Document Development Process within DOE Authorization

- DOE Process provides for frequent technical interactions with review team to identify key concerns and issues early.
- Technical rigor and quality requirements implemented at the analysis and safety document level.
- Multiple review gates imposed prior to formal submittal for DOE Approval.



Safety Basis Deliverables – Integrating Safety Into Design



Safety Design Strategy – Early in Conceptual Design

- Identifies Regulatory Requirements
- Discusses Generalized Safety Approach
- Outlines Facility Specific Regulatory Strategy

- Provides Alignment between Design and Safety Groups as well as Regulatory.
- Regulatory Roadmap

Conceptual Safety Design Report

- Provides Preliminary Facility Description and Hazards Analysis
- Identifies anticipated list of safety systems and general safety functions.
- Provides opportunity to design in safety or design out hazards.

- Establishes clarity so that Preliminary and Final design can ensure safety functions are met.

Preliminary Documented Safety Analysis

- Presents hazards and accident analysis on Final Design.
- Contains Safety System Classification and Safety Function Definitions in sufficient detail that quality requirements can be derived.

- Obtaining PDSA approval is a requirement prior to starting facility construction.

Final Documented Safety Analysis

- Incorporates as built configuration of plant.
- Incorporates final technical safety requirements.
- Reflects as built changes from the PDSA- these are identified through use of a Unreviewed Safety Question like process during construction.

- Implemented DSA and associated TSRs constitute approved authorization basis for operations.

Safety is Design

- Principles of Inherently Safer Design
- Understanding of Uncertainties and Unknowns
- Margin Management (Design Capability > Safety Limits > Operating Limits)
- Application of Safety Factors

- DOE Integration of Safety in Design ensures these concepts are considered and documented as part of design process.

Fundamental Safety Functions – Fission Batteries

- Reactivity Control
  - Strong negative Temperature Feedbacks designed into the system
  - High Confidence to achieve shutdown and maintain adequate shutdown margins
- Heat Removal –
  - High reliability, simple systems for passive heat removal
  - Thermal capacity to ensure temperature margins
  - Structural performance to protect heat removal transfer boundaries
- Preservation of Radioactive Material Boundaries
  - Fuel Selection
  - Design and operating margins to fuel qualification temperatures
  - Adequate cooling margins to ensure structural materials behavior
- Shielding
  - Sufficient shielding to allow for necessary access during operation and simplified shielding models for transport if necessary.

Technical Elements in a Safety Basis

Internal and External Oversight and Assurance (including Regulatory Oversight)

Technical Safety Requirements and Operating Limits

System Performance Analyses

Maintenance, Testing and Quality Assurance

Safety Management Processes and Procedures

Safety Analysis

Engineered Safety Systems

Administrative Safety Requirements

Facility Design

Facility Operating Parameters

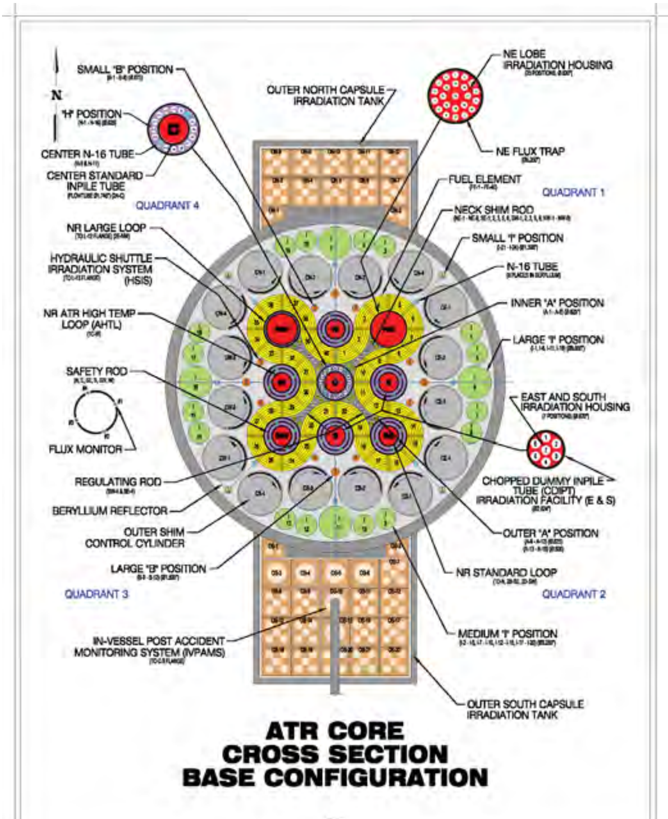
Regulatory Requirements and Approach

Design Goals and Standards

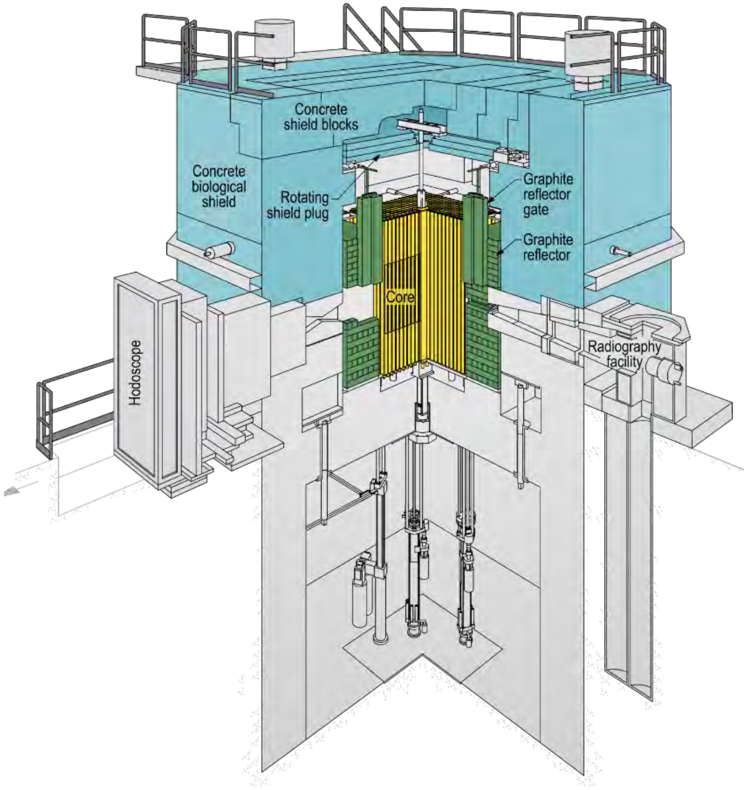
U.S. DEPARTMENT OF ENERGY | Nuclear Energy

DOE Safety Authorization Process for New Reactors

April 2021



ATR CORE CROSS SECTION BASE CONFIGURATION



Historic Context

Admiral James Watkins
(Secretary, 1989-1993)

Key Historic Themes:

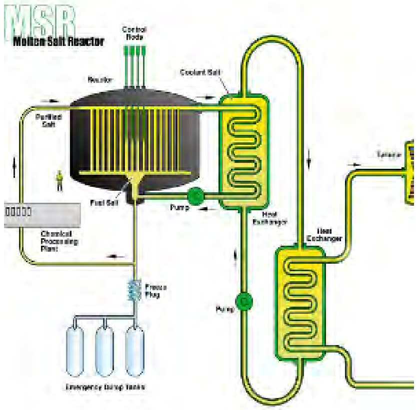
- Culture of Production
- Military/Wartime Mission
- Closed System
- Secrecy vs transparency
- HQ authority vs field autonomy
- Mission vs safety/environment

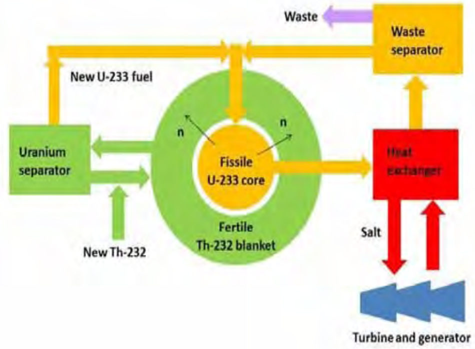
Key Contemporary Themes:

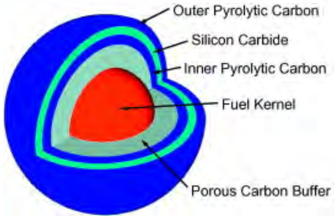
- Technically qualified staff
- Organizational Culture
- Integrated safety management
- Environmental stewardship
- Adoption of commercial nuclear standards
- Community engagement

The Challenge with New Reactor Technology Regulation

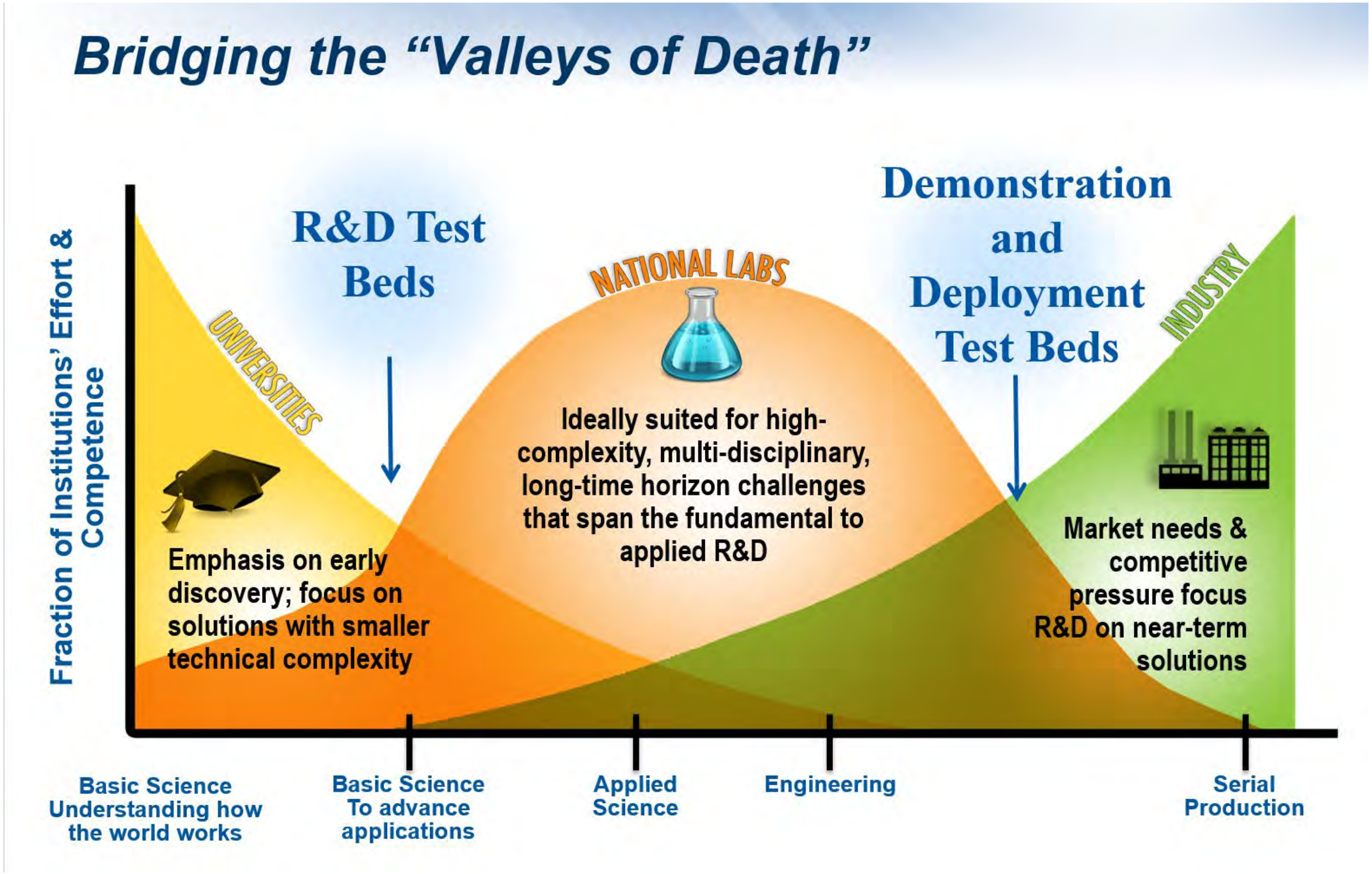
- **Numerous technologies coming into play**
  - Molten salt
  - Gas cooled
  - Unique fuel designs
  - Broad range in size and functionality
- **Rapid pace of progression within the technology lifecycle**
- **Additional data/analysis needed to support NRC licensing for broad application**
- **Regulatory Framework must be:**
  - Technically rigorous
  - Flexible
  - Adaptable







DOE Mission Enables Progressing Ideas to Application



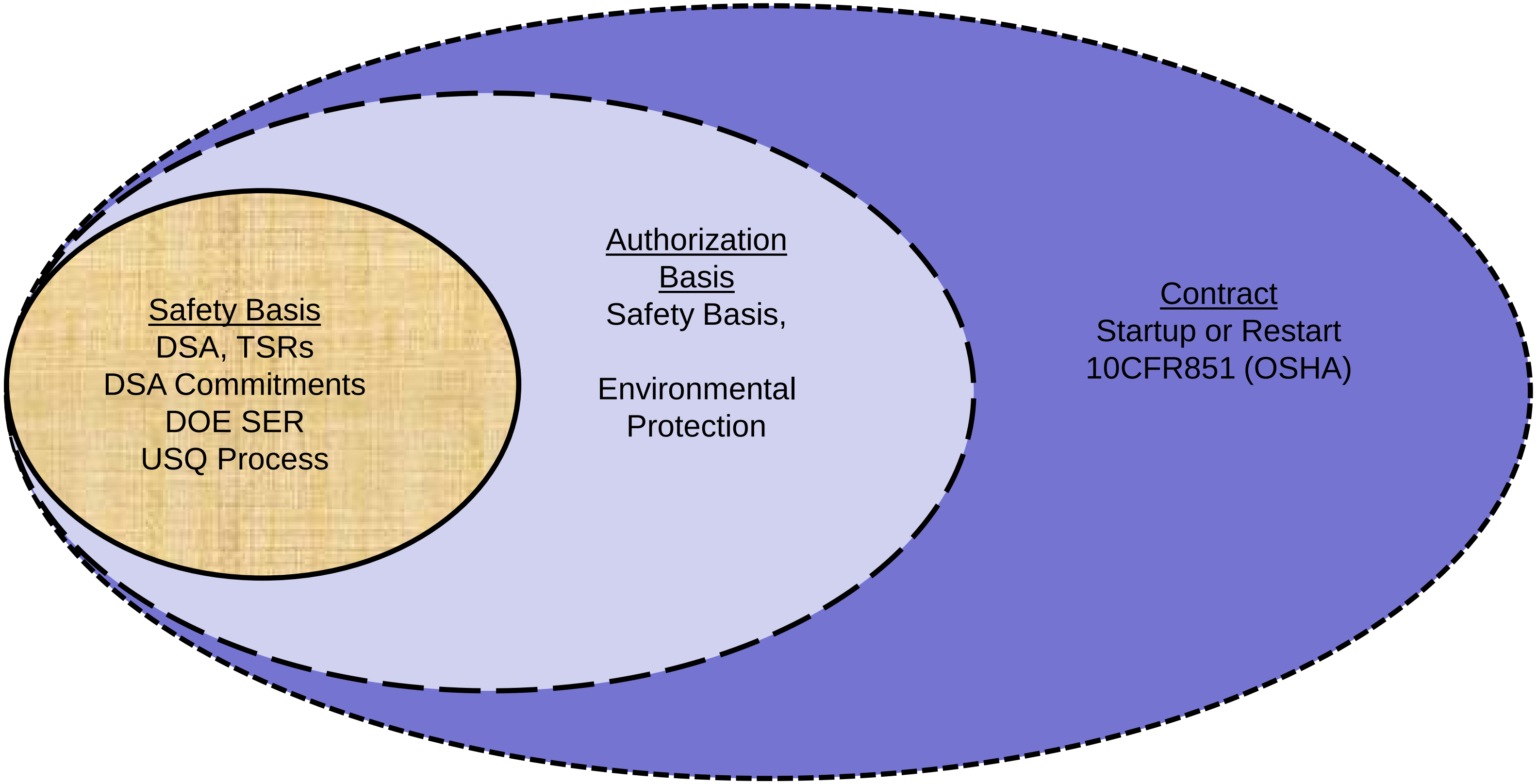
The DOE authorization process readily supports the advancement of nuclear technology

- **Authorization Basis – provides reasonable assurance of worker, public, and environmental protection.**

- **Regulatory environment designed to support broad array of capabilities and needs.**
  - Fuel fabrication, storage/waste, and reactors
  - National security missions and science missions
  - Complex, multi-mission nuclear R&D facilities

- **Technically Rigorous – Flexible – Adaptable**
  - Up front tailoring of approach to best fit the application
  - Allows for real-time evaluation of upcoming technologies
  - Drives thorough understanding of the hazards, accident scenarios and associated development of controls
  - Extensive review, approval and operational readiness mechanisms

Relationships of Regulatory Requirements



Safety Basis
DSA, TSRs
DSA Commitments
DOE SER
USQ Process

Authorization Basis
Safety Basis,

Environmental Protection

Contract
Startup or Restart
10CFR851 (OSHA)

Nuclear Safety – Regulatory Structure

- **10 CFR 830 – Nuclear Safety Management**
  - Subpart A, “Quality Assurance Requirements”
  - Subpart B, “Safety Basis Requirements”

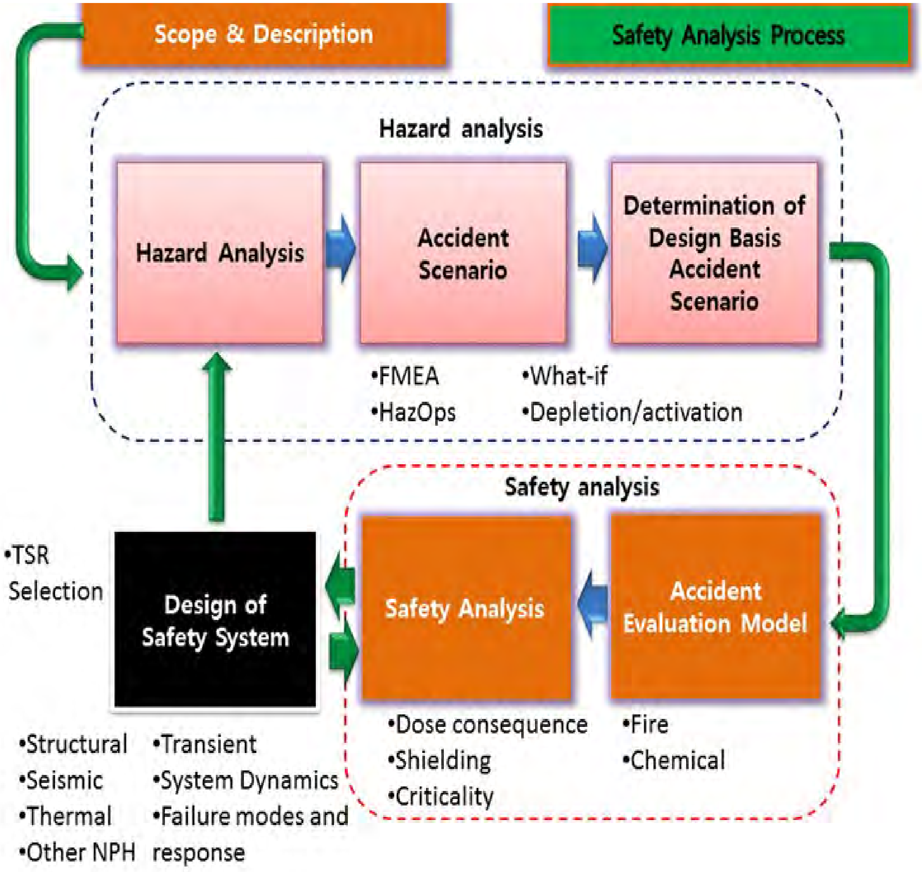
Additional Detail on 10 CFR 830 Subpart B

Defines content of DSA

- Facility description
- Systematic identification of natural and man-made hazards associated with the facility
- Evaluate normal, abnormal, and accident conditions
- Derive adequate controls necessary to ensure adequate protection of the public, workers, and the environment
- Define characteristics of the safety management programs necessary to ensure safe operations

Unreviewed Safety Questions

- DOE has process similar to 10CFR50.59



Scope & Description

Safety Analysis Process

Hazard analysis

Hazard Analysis

Accident Scenario

Determination of Design Basis Accident Scenario

•FMEA
•HazOps

•What-if
•Depletion/activation

Safety analysis

Safety Analysis

Accident Evaluation Model

•Dose consequence
•Shielding
•Criticality

•Fire
•Chemical

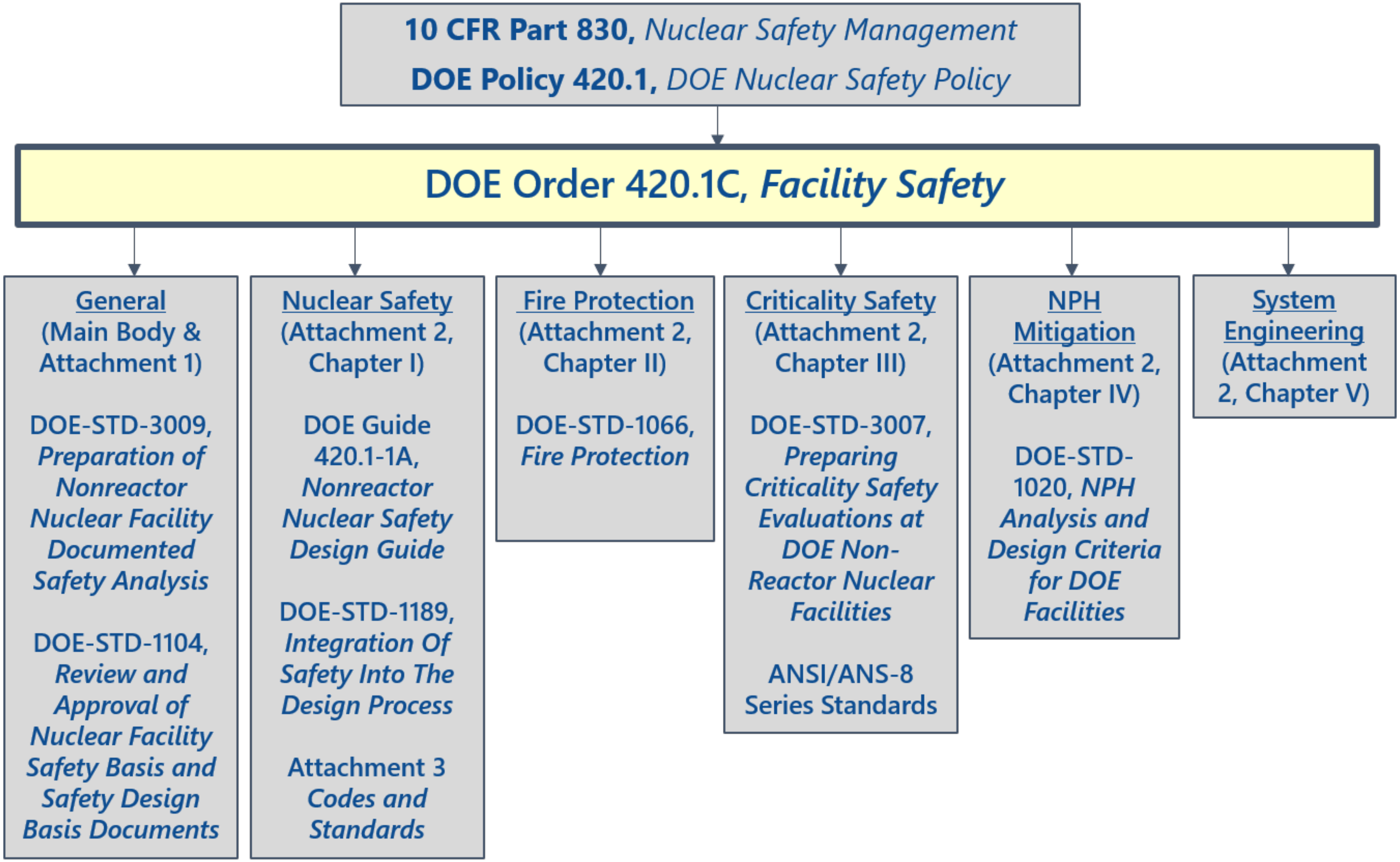
•TSR Selection

Design of Safety System

•Structural
•Seismic
•Thermal
•Other NPH

•Transient
•System Dynamics
•Failure modes and response

Engineering Design Perspective



10 CFR Part 830, *Nuclear Safety Management*

DOE Policy 420.1, *DOE Nuclear Safety Policy*

DOE Order 420.1C, ***Facility Safety***

General
(Main Body & Attachment 1)

DOE-STD-3009, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*

DOE-STD-1104, *Review and Approval of Nuclear Facility Safety Basis and Safety Design Basis Documents*

Nuclear Safety
(Attachment 2, Chapter I)

DOE Guide 420.1-1A, *Nonreactor Nuclear Safety Design Guide*

DOE-STD-1189, *Integration Of Safety Into The Design Process*

Attachment 3 *Codes and Standards*

Fire Protection
(Attachment 2, Chapter II)

DOE-STD-1066, *Fire Protection*

Criticality Safety
(Attachment 2, Chapter III)

DOE-STD-3007, *Preparing Criticality Safety Evaluations at DOE Non-Reactor Nuclear Facilities*

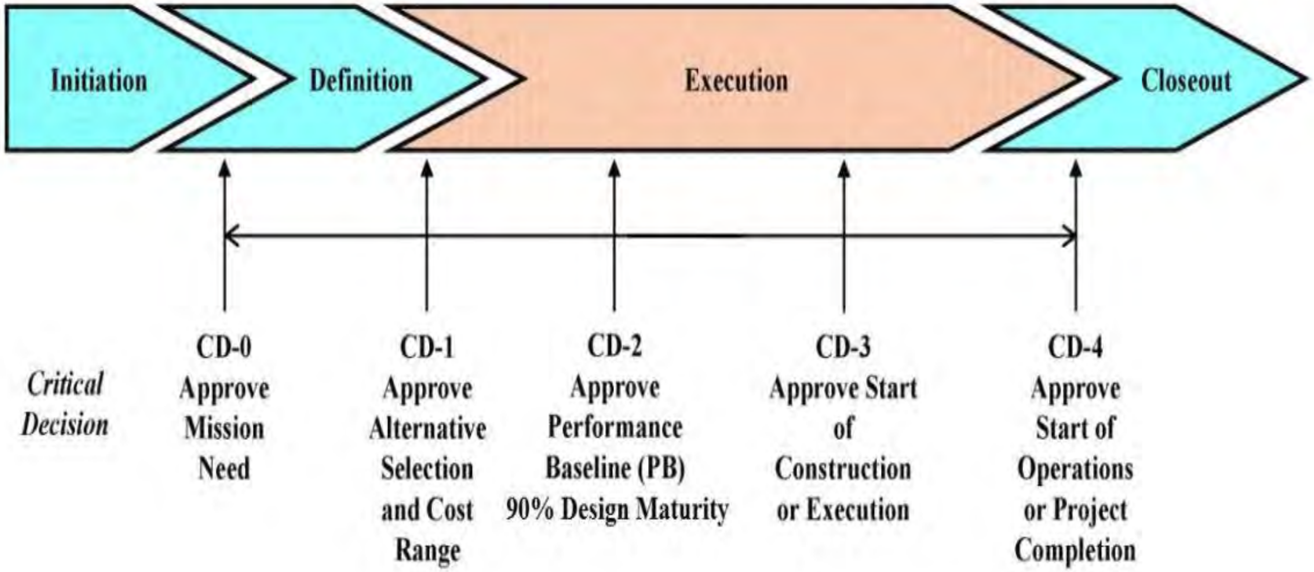
ANSI/ANS-8 Series Standards

NPH Mitigation
(Attachment 2, Chapter IV)

DOE-STD-1020, *NPH Analysis and Design Criteria for DOE Facilities*

System Engineering
(Attachment 2, Chapter V)

DOE-STD-1189 Integration of Safety into the Design Process



SDS & CSDR and Safety Review Letter → Develop Preliminary Safety and Design Results → SDS & PDSA & SER → DSA & SER, ORR

Safety Design Strategy (SDS), Conceptual Safety Design Report (CSDR), Preliminary Documented Safety Analysis (PDSA), Safety Evaluation Report (SER), Operational Readiness Review (ORR)

Summary

- For a test reactor, DOE is uniquely qualified and has the established Authority under the Energy Reorganization Act of 1974 Title II.
- DOE has a codified process to ensure safety in design for new reactors. NRC regulations have been adopted by the DOE process.
- DOE has the same Adequate Protection Standards for the public, but strives to have very low design basis accident doses at the public boundary.

Thank you for attending today’s workshop!

- Send additional questions, comments, or suggestions to:
  - Jason Christensen: Jason.Christensen@inl.gov
  - Maria Avramova: mnavramo@nscu.edu
  - Vivek Agarwal: Vivek.Agarwal@inl.gov

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