ARPA-E
CHANGING WHAT'S POSSIBLE

Nuclear and ARPA-E: Activities and Opportunities

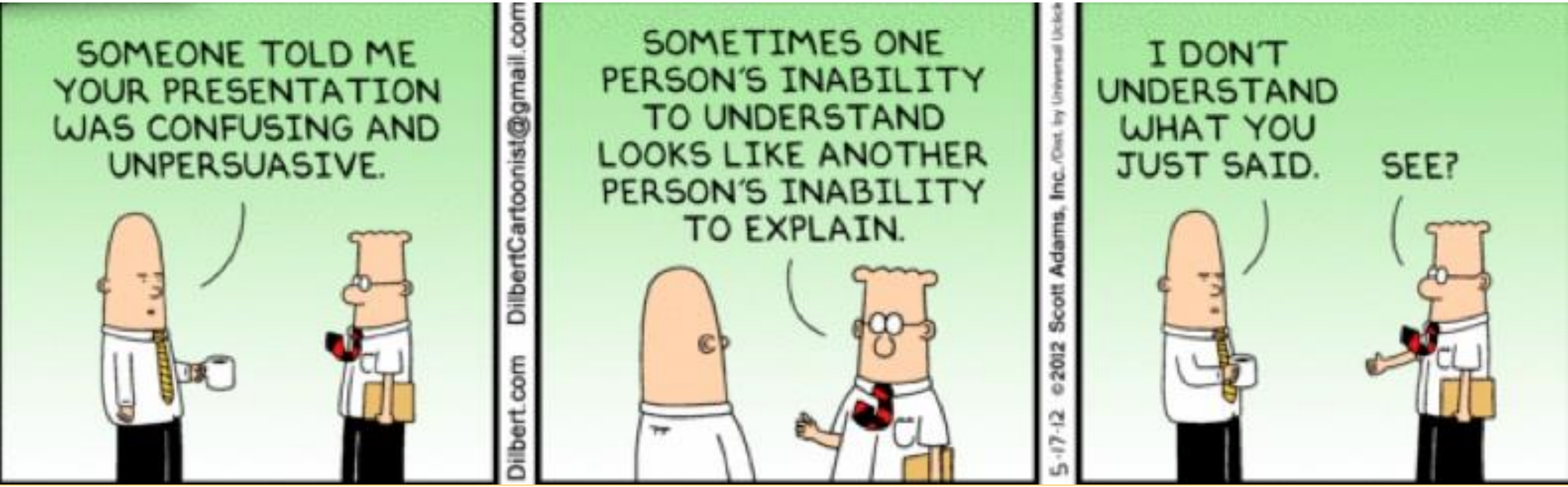
Rachel Slaybaugh

NUC Workshop: Innovations in Advanced Reactor Design, Analysis, and Licensing

18 September 2019

Outline

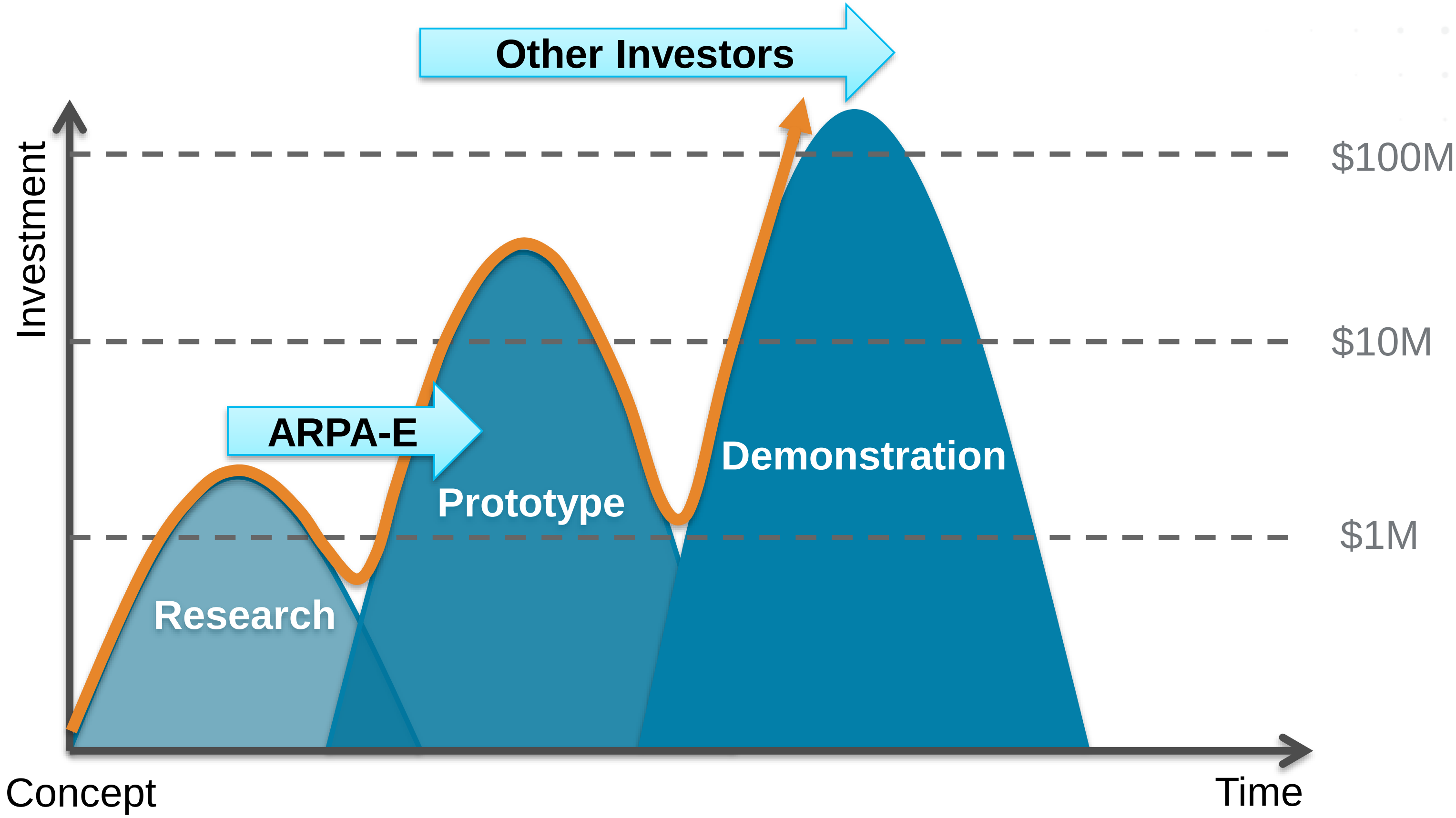
- ARPA-E quick overview
- MEITNER
- OPEN+ Materials Cohort
- LISE
- What might be next?



ARPA-E Mission

Mission: To overcome long-term and high-risk technological barriers in the development of energy technologies

ARPA-E: Strategic De-Risking for Investment



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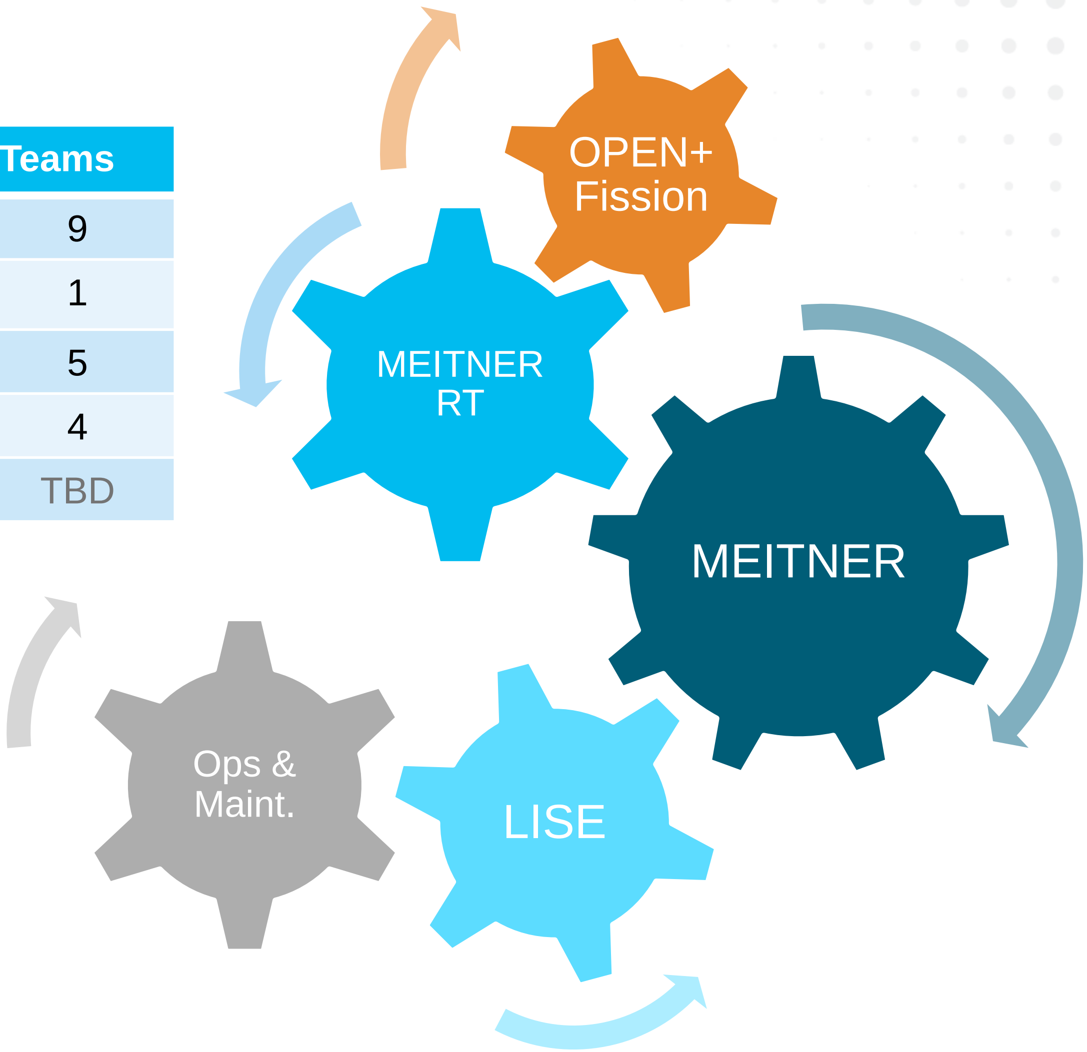
ARPA-E Nuclear Fission Landscape

Program/Cohort	Budget	Teams
MEITNER	~$30M	9
MEITNER Resource Team	~$10M	1
OPEN + Fission	~$12M	5
LISE	~$8M	4
Optimal O&M	~$35M	TBD



Multiple groups of fission teams, all managed together to achieve economically viable nuclear power

MEITNER

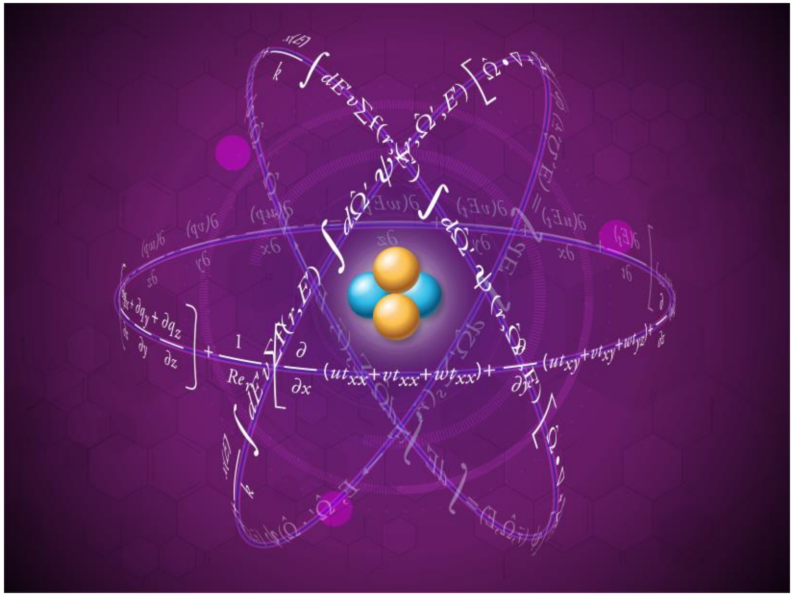
(Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration)

- 1st fission program from ARPA-E
- $30M available for 9 selected teams
- $10M for Resource Team to provide key technical support

MEITNER Objective

Identify, characterize, and develop <u>enabling technologies</u> that support moving existing advanced reactor designs from concept to products that are:

- "Walkaway" safe
- Quickly deployable
- Safeguardable
- Cost competitive
- Commercially viable



MEITNER: Primary Design Target Areas

- **Goal:** Develop and demonstrate technologies that improve advanced reactor performance

ID	Metric	Units	State-of-the-Art	With New Technology
1	Overnight construction cost	$\$/W_e$	2-7	< 2
2	On-site construction time	Months	> 60	< 24
3	Total staffing level (on-site & off-site)	FTE/GW_e	450-750	< 50
4	Emergency planning zone (EPZ)$^+$	Miles	10 and 50	0
5	Time before human response required for an accident	Days	3	> 30
6	Onsite backup power	kW_e	> 0 kW	0
7a	Ramp rate without steam bypass	power capacity/min	5%	> 5%
7b	Process heat temperature	ºC	N/A	> 500

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Our Teams Tackle Key Areas

Microreactor

- Westinghouse (INNOVATION YOU CAN BE SURE OF)
- Los Alamos National Laboratory
- Stony Brook University
- HolosGen™

Construction

- moltex energy (safer, cheaper, nuclear)
- University at Buffalo, The State University of New York
- EPRI

Components

- The University of Tennessee Knoxville
- Oak Ridge National Laboratory

Safety

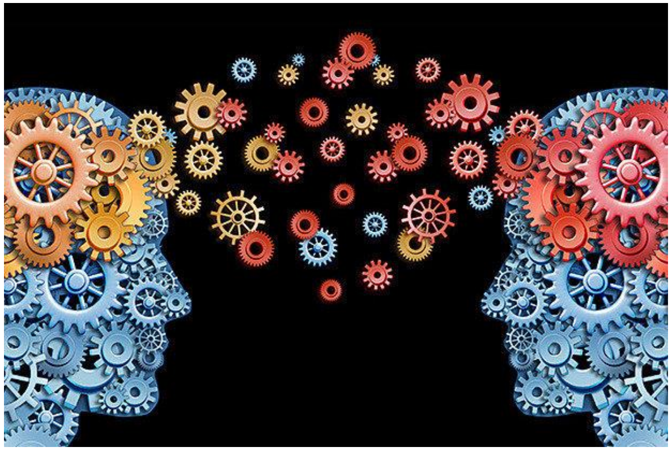
- Yellowstone Energy
- NC State University
- Zachry

Load Following

- Illinois

Resource Team Provides Extra Boost

Team (mostly) in the laboratory complex provides specialized, high-value capabilities



1. Modeling & Simulation
2. Subject Matter Experts
3. Techno-Economic Analysis

Result: leverage U.S. national resources for strategic technology improvement and economics feedback into design

Meet the Resource Team




Principal Investigator
Matthew Jessee (ORNL)

Deputy Principal Investigator
Temi Taiwo (ANL)

SME Lead
Steve Zinkle (UT-K)

M&S Lead
TK Kim (ANL)

Techno-Economic Analysis Team
Eric Ingersoll
Kirsty Gogan
Andrew Foss
John Herter
(Lucid Catalyst)

Jason Quinn (CSU)

Advisors
Kord Smith (MIT)
Jess Gehin (INL)

DOE Lab Leads
Jim Wolf (INL)
Topher Matthews (LANL)

Design Team Points of Contact (POCs)
Lou Qualls (ORNL) : UIUC, Moltex
Topher Matthews (LANL) : WEC
Rick Vilim (ANL) : NCSU
Jim Sienicki (ANL) : HolosGen
Bob Salko (ORNL) : Yellowstone Energy
Justin Coleman (INL) : SUNY/Buffalo

DOE Lab, University, and Industry Subject Matter Experts
M&S Codes and DOE Computing Centers
Access to Experimental Facilities

Enhance Design Teams' capacity through access to subject matter experts (SME), high-fidelity modeling and simulation (M&S) tools, and techno-economic analysis (TEA)

Market Study re Load Following (RT TEA)

Study to assist MEITNER DTs to understand **in quantitative terms** (e.g. $/MW and $/MWh) the value that a reactor with flexible power output could earn from grid operators

1. Identify market mechanisms for capturing the value of flexibility/reliability
2. Identify the required performance attributes of “flexible” reactors
3. Identify alternative forms of providing system flexibility apart from flexible reactors
4. Model selected ISO scenarios with PROMOD (specialized power system software)
5. Prepare report and deliver presentations
6. Discuss findings and design implications one-on-one with MEITNER participants

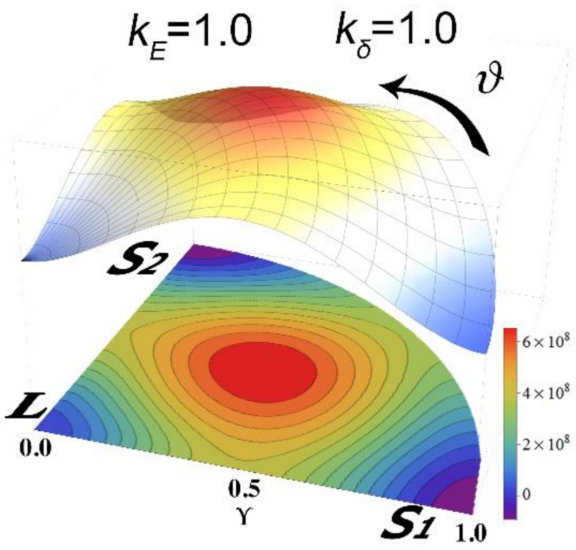
OPEN+ 2018: Nuclear Cohort

- First time creating "cohorts" to focus on particular topics in energy where ARPA-E sees significant opportunities to innovate and create new communities

- This first cohort focuses on ways to enable advanced nuclear energy by overcoming challenges in high performance materials science

OPEN+ 2018: Faster Nuclear Materials Dev

- CMU: Additive manufacturing of spacer grids for nuclear reactors
- LBNL: MEMS RF accelerators for nuclear energy and advanced manufacturing
- LANL: Advanced manufacturing of embedded heat pipe nuclear hybrid reactor
- MIT: Multimetallic layered composites for rapid, economical advanced reactor deployment
- UW-Madison: Accelerated materials design for molten salt tech. using innovative high-throughput methods



Leveraging Innovations Supporting nuclear Energy (LISE)

- It is clear that a substantial reduction of construction cost, O&M cost, and construction time, in combination with targeting reactor plant operation for commercial viability, is required to fundamentally enhance the competitiveness and attractiveness of nuclear energy
- The ARPA-E MEITNER Program is already investigating several innovative technologies that forward this goal
- But the problem is large
- LISE teams complement the MEITNER teams to round out the portfolio for enabling technologies

LISE: Four Teams $7.5M Fed

- NC State University: A data-driven approach to high precision construction and reduced overnight cost and schedule
- Southern Research Institute: Machine learning for automated maintenance of future MSR
- National Energy Technology Laboratory: Distributed nuclear reactor core monitoring with single-crystal harsh-environment optical fibers
- Idaho National Laboratory: Next-generation metal fuel

What's coming next?

U.S. Reactors are Shutting Down from O&M

Category	Fuel	Capital	Operating	Total
All U.S.	6.44	6.64	20.43	33.50
Single-Unit	6.42	8.92	27.32	42.67
Multi-Unit	6.44	5.99	18.46	30.89

- Table in 2017 $/MWh
- Minimal staffing across best performing plants: ~750 FTEs
- Operations and Maintenance are the largest addressable categories

FTEs at a 1 GWe Reactor

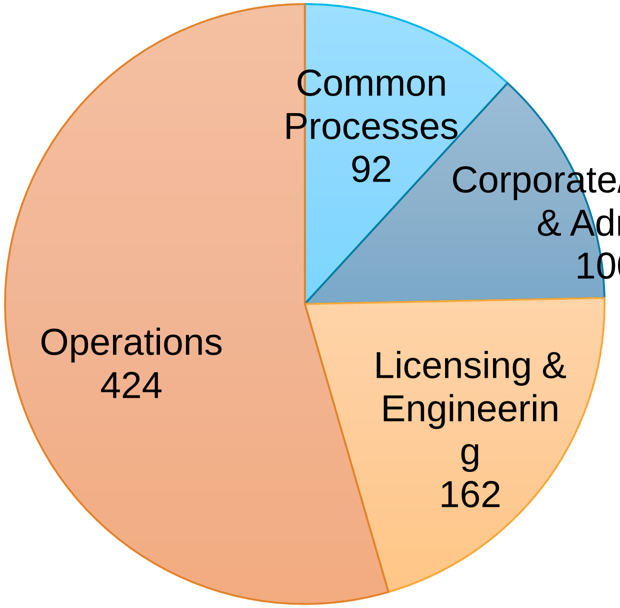


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Table: https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/nuclear-costs-context-201810.pdf
Pie chart: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1052_prn.pdf

Advanced Reactors Need New O&M Paradigm

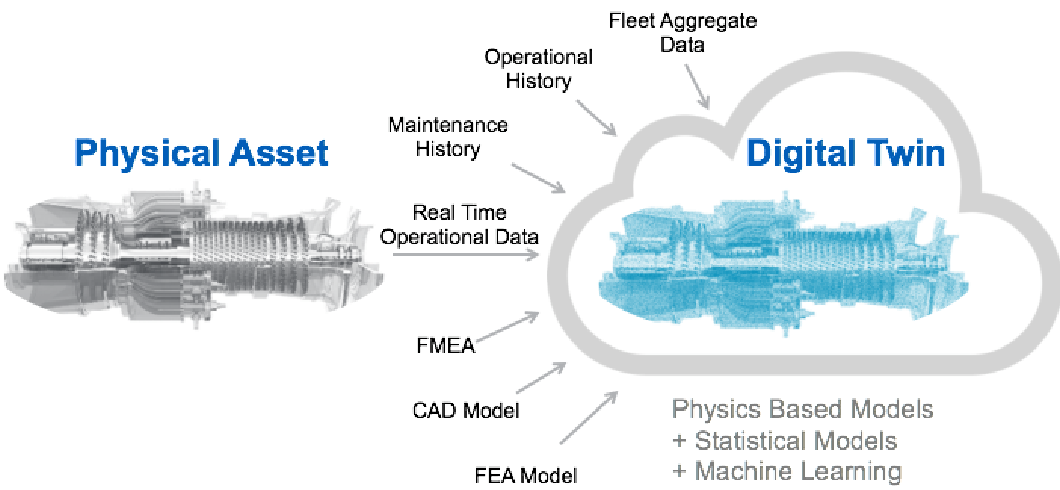
- Advanced reactor development has emphasized:
  - Avoiding mega-projects requiring large capital outlays
  - Reducing construction uncertainty

- For small modular reactors, O&M costs are likely to play an even more crucial role than for existing fleet
  - Reactors make fewer GWe: lose economy of scale
  - O&M costs become a larger fraction of total cost

- Have Gen IV reactors improved in terms of O&M?
  - Moltex (~1 GWe) $44/MWh estimate uses the same O&M costs as proposed for the current UK PWRs
  - NuScale (multiple 50 GWe) 0.7 FTEs/MWe is not radically different either

Digital Twins for Reactor Ops & Maintenance

- Digital Twin:
  - "A 'digital twin' is a physics-based, or data science-based, model of an asset that exists in real life. It should mirror digitally the exact characteristics and operating performance of the real device, so that operators can understand the…asset"



We'd like to use a digital twin of the reactor plant systems to directly support operations and maintenance

Enables better design, training, flexible operations, faster learning curves, regulator interactions, and plant autonomy

Requires

- Combining multiple pieces of existing software and models to simulate any reactor scenario and build a database
- Developing an AI-based tool that takes real-time plant state and identifies issues, advises the operator/staff on actions, etc.
- Investigating rigorous details of how to use digital twins correctly and reliably

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BNEF, Digital Twin Edition, Nov 7 2018, https://www.bangkokbankinnohub.com/digitaltwin/

What If Reactors *Could* Be Autonomous?

- Lower direct personnel costs
- Eliminate radiation to workers
- Reduce cost / amount of maintenance
- Reduce risk of human error
- Increase operational excellence
- Increase margin / safety envelope

However,

- Increase cost of sensors / equipment / software?
- Dealing with low or no training data?
- Need to fill gaps in physical tools (sensors, robots, etc.) and data for software

What Might an ARPA-E Program Look Like?

1. Develop autonomous operations algorithms and Test on cyber-physical test systems
   - Investigates what sensors are needed
   - Investigates what data and simulations are needed
   - Provides verification data
   - Provides cost basis information
   - Feedback into design
2. Specific topics for “filling in the gaps”
   - Materials performance data
   - Robotics and autonomy algorithms
   - Sensors

If it works…

will it matter?

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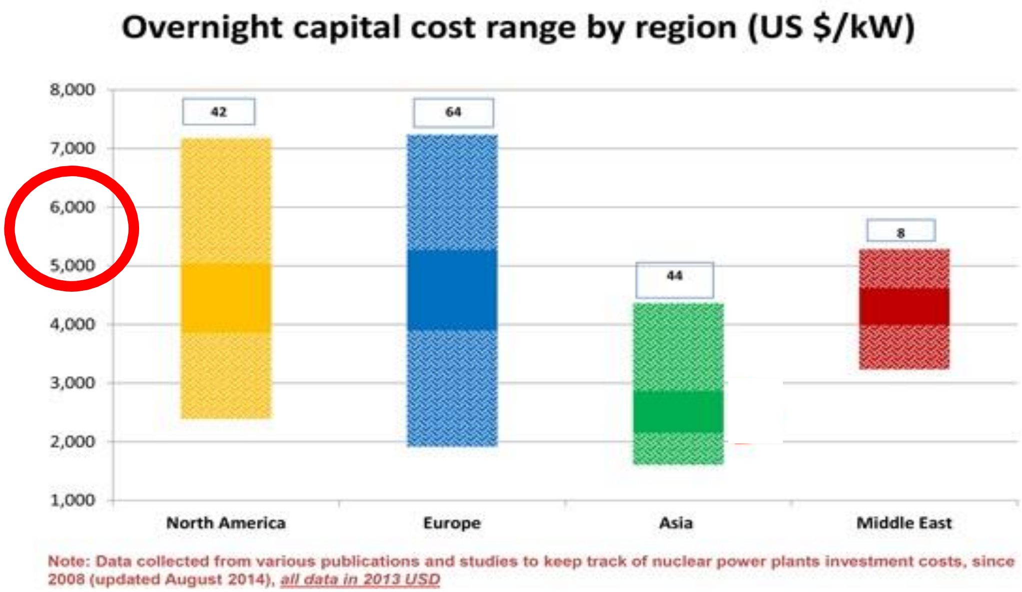
Motivation



- New build construction costs and times are large and unpredictable
- O&M is the bulk of operating cost

Avg. plant operating expenses (2015 $/MWh)

Plant Type	Operation	Maintenance	Fuel	Total
Nuclear	11.17	7.06	7.48	25.71
Fossil Steam	5.16	5.41	26.70	37.26
Gas Turbine	2.34	2.68	28.22	33.24

MEITNER Motivation

- A substantial reduction of construction cost, O&M cost, and construction time is required
- We often only focus on the nuclear core, despite the fact that this may not drive these factors
- Early design choices throughout the entire system impact the rest of the system in terms of functionality, cost, and constructability
- ARPA-E targeted development of enabling technologies that require understanding the inter-relatedness of design choices
- Sets up success in many futures

What Is the Current State?

- Deterministic
  - Standards-based
  - Heavy regulatory burden
  - Hesitation to adopt new technologies or change approach
  - Driven almost exclusively by physics-based models

- Human-work driven (e.g., physically inspect items, take readings, etc.)
- Data collection is difficult and use is inefficient

From a survey of 350 nuclear industry experts as reported in
Market Report: the future of nuclear digitalization (Nuclear Energy Insider, 2017)

Technical Gaps and Challenges

- Making the leap from model to digital twin:
  - **Per-asset** functionality: twin must accept periodic or continuous updates from physical system to update models
  - **Real-time** decision-making support:
    - Fully coupled multi-physics models are too CPU-intensive to execute in real-time; surrogate models (likely AI) trained on offline sims could
    - System must handle physics simulation uncertainty, using synthetic data, rare events, corner cases, sensor uncertainty
    - Potential opportunities for Machine Learning and Artificial Intelligence
- Designing for maintenance
  - Define **optimal sensor set**—balance tradeoff between lots of instrumentation (rich data-stream) and associated costs (sensors are expensive and must be maintained themselves; penetrations into core complicate design and construction; etc.)

Why is this ARPA-E Hard?

- Disparate communities need to come together
- In a radiation environment
- System and Multiphysics complexity
- Uncertainty in models and physics
- Safety and Security are essential
- Low-probability events with high impact
- Gap between current state and current state of the art

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This is the way the world is moving…

Let's show leadership in this area and put nuclear energy at the forefront of low-cost operational excellence

ARPA-E Nuclear Energy Team

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Physics PhD

Colleen Nehl,
Physics PhD

Geoffrey Short,
Mech Eng PhD

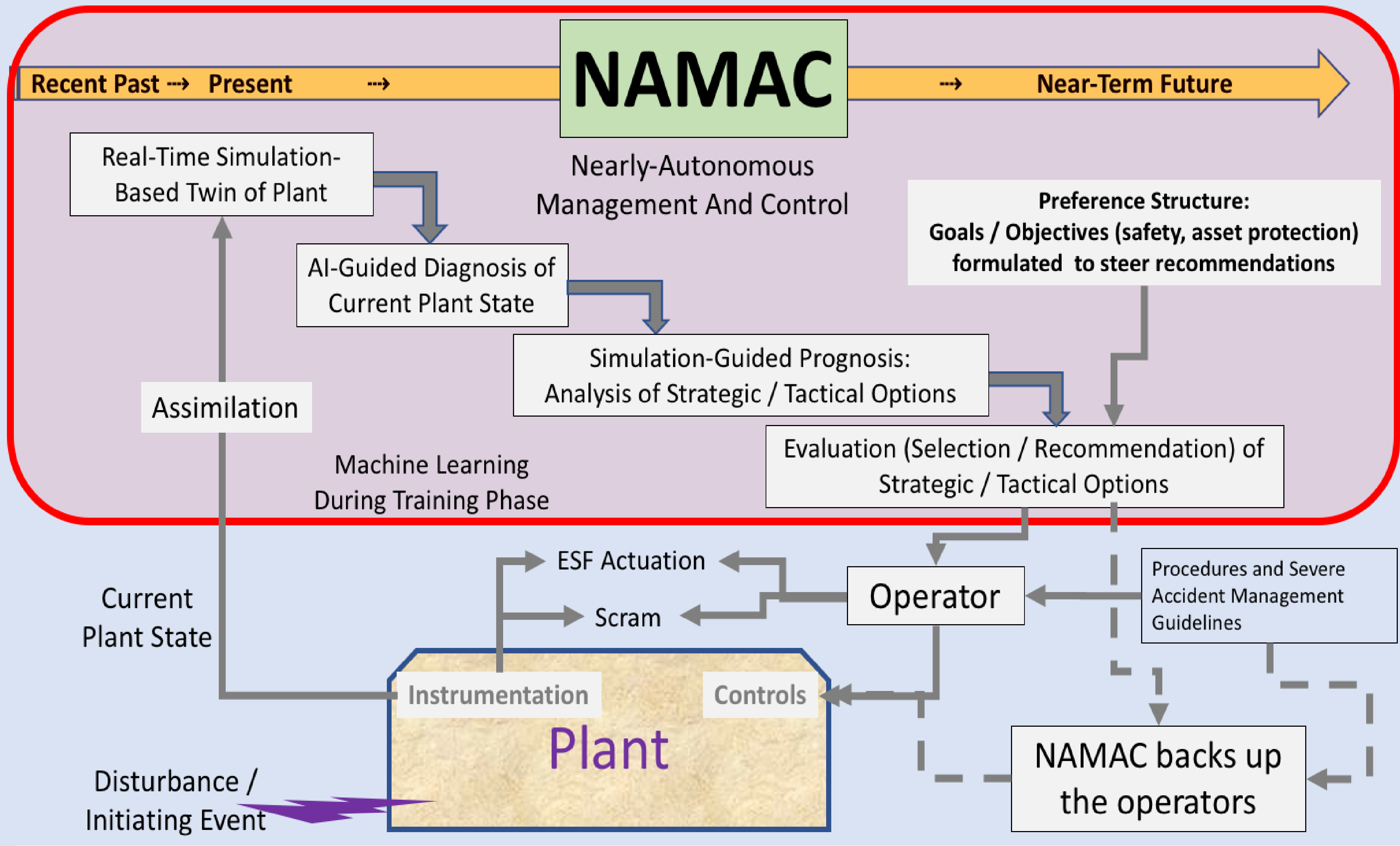
Lakshana Huddar,
Fellow

Victoria Chernow,
Fellow

Zia Rahman,
Mech Eng PhD

Caitlin Zoetis,
Proj. Manag. SETA

Autonomous Reactors?



N. T. Dinh, North Carolina State; Collaborators: OSU, NMSU, ORNL, INL, ZNE and TerraPower

Tech To Market Approach

SCOPE

Provide strategic market insights necessary to create innovative, commercially relevant programs

MANAGE

Manage project teams' T2M efforts through T2M plans and jointly developed milestones

ADVISE

Support project teams with skills & knowledge to align technology with market needs

PARTNERSHIPS

Engage third-party investors and partners to support technology development towards the market