DEQ ENERGY

North Carolina Energy Policy Council

AGENDA

10:00 a.m. Wednesday May 15, 2019
Archdale Building, Ground Floor Hearing Room
512 N Salisbury St, Raleigh, NC 27604

Nuclear Generation
(90 min)

Overview and Update on the U.S. Nuclear Industry (30 min)

Bradley Williams, Senior Advisor, Office of Nuclear Energy, U.S. Department of Energy

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

Clean. Reliable. Nuclear.

Nuclear Energy Overview

May 15, 2019

Bradley Williams

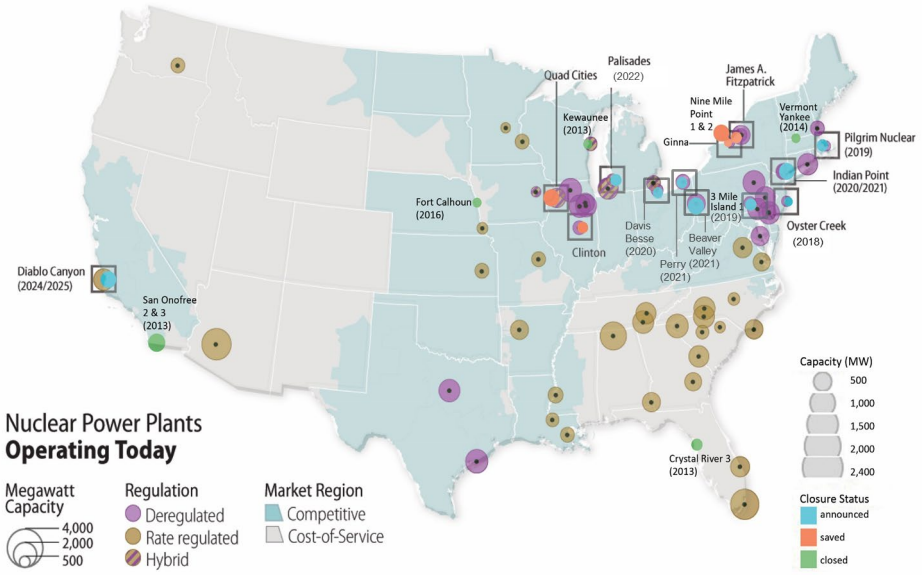
Senior Advisor to the Assistant Secretary for Nuclear Energy

Office of Nuclear Energy

U.S. Department of Energy

Nuclear Energy: A National Strategic Asset

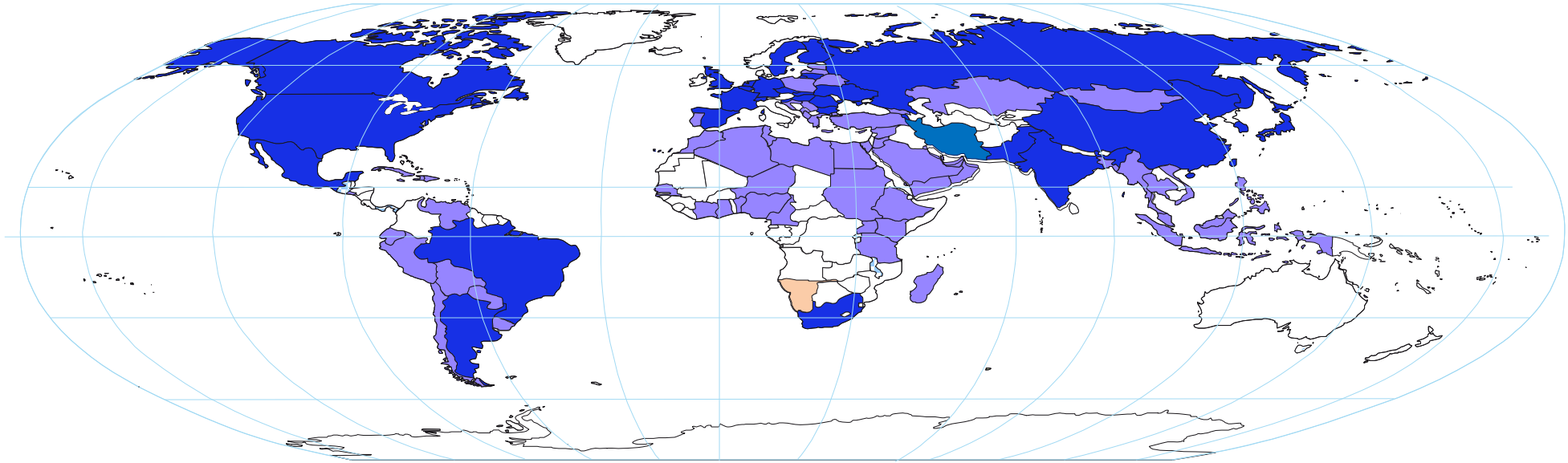
- Recognition of the importance of nuclear – today and in the future
  - Energy Security
  - National Security
  - Economic Prosperity
  - Environmental Sustainability
- Concern about the financial viability of some currently operating plants, yet benefits from keeping them running
- Increased interest in nuclear in domestic and international markets to address climate change and ensure reliable, resilient power
- Innovators and utilities looking at advanced nuclear as a way to move beyond electricity
- **<u>Secretary Perry: Make Nuclear Energy Cool Again!</u>**
- **<u>President Trump: Revive, Revitalize and Expand</u>**



- **20% of electricity (56% of non-emitting)**
- **92% capacity factor**
- **Supports 475,000 jobs**
- **$10B in federal & $2.2B in state taxes annually**

> *"If you really care about this environment that we live in… then you need to be a supporter of this [nuclear energy] amazingly clean, resilient, safe, reliable source of energy."*
>
> ***Secretary Rick Perry***

Global Growth and Market Opportunity



Potential Nuclear Power Expansion

- **35 countries taking steps to develop nuclear power**
- **30 countries with operating reactors developing expansion plans**

~450 reactors operating

11% of electricity / 40% of clean electricity

Source: IAEA/PRIS & WNA

- ~60 reactors under construction in 15 countries (20 in China)
- ~170 reactors planned in over 25 countries, worth as much as $700 billion over the next 5-10 years
- ~370 reactors proposed in 36 countries, worth as much as $1.6 trillion over the next 10-25 years

Nuclear Power Plants Shutting Down Prematurely

Year	Retirements	MW	Operator	State	License Expiration
2013	Crystal River 3	890	Duke	FL	2016 (40)
	San Onofre 2 & 3	2,254	SoCal Edison	CA	2023 / 2024 (40)
	Kewaunee	560	Dominion	WI	2033 (60)
2014	Vermont Yankee	563	Entergy	VT	2032 (60)
2016	Fort Calhoun	502	Omaha Power	NE	2033 (60)
2018	Oyster Creek	610	Exelon	NJ	2029 (60)
	Total Closed since 2013	**5,276**			
2019	Pilgrim	678	Entergy	MA	2032 (60)
	Three Mile Island 1	803	Exelon	PA	2034 (60)
2020	Davis-Besse*	908	FirstEnergy	OH	2037 (60)
	Duane Arnold	601			
2021	Perry*	1,268	FirstEnergy	OH	2026 (40)
	Indian Point 2 & 3**	2,061	Entergy	NY	2013 / 2015 (40)
	Beaver Valley 1 & 2*	1,872	FirstEnergy	PA	2036 / 2047 (60)
2022	Palisades	789	Entergy	MI	2031 (60)
2024-25	Diablo Canyon 1 & 2	2,240	PG&E	CA	2024 / 2025 (40)
	Total Pending Closures	**11,220**			
2017	FitzPatrick***	852	Entergy	NY	2034 (60)
	Ginna***	582	Exelon	NY	2029 (60)
	Clinton***	1,065	Exelon	IL	2026 (40)
2017-18	Nine Mile Point 1 & 2***	1,937	Exelon	NY	2029 / 2046 (60)
2018	Quad Cities 1 & 2***	1,819	Exelon	IL	2032 (60)
	Total Saved	**6,255**			

* Pending review and approval by PJM

** One reactor will shut down in 2020, and the other will shut down in 2021.

*** Closures averted by state policy actions.

Combined Construction and Operating Licenses (COLs)

SITE/LOCATION		UTILITY	REACTOR TECHNOLOGY/ NO. UNITS		COLA DATES			
					Submitted	Docketed	Issued	
Vogtle	GA	Southern Nuclear	AP1000	2	3/28/2008	5/30/2008	2/10/2012	
V.C. Summer	SC	SCE&G	AP1000	2	3/27/2008	7/31/2008	3/30/2012	Construction Stop (7/31/17)
Fermi	MI	DTE Energy	ESBWR	1	9/18/2008	11/25/2008	5/1/2015	
South Texas Project	TX	STPNOC	ABWR	2	9/20/2007	11/29/2007	2/12/2016	Terminated (7/12/18)
Levy	FL	Duke Energy	AP1000	2	7/30/2008	10/6/2008	10/26/2016	Terminated (4/26/18)
William States Lee	SC	Duke Energy	AP1000	2	12/13/2007	2/25/2008	12/19/2016	
North Anna	VA	Dominion Energy	ESBWR	1	11/27/2007	1/28/2008	6/2/2017	
Turkey Point	FL	Florida Power and Light	AP1000	2	6/30/2009	9/4/2009	4/5/2018	

- 18 COLs have been docketed by the NRC since 2007
- 8 (totaling 14 reactors) have been approved
- 10 (totaling 14 reactors) were suspended and or withdrawn
- 6 Licensees currently hold COLs

American Innovation Can Capture the Global Market

Advanced Nuclear Industry: Next Generation

third way
fresh thinking

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Congressional Support for Nuclear Energy – Strong and Bipartisan

Current Fleet

- Investment Tax Credit
- Support to local communities impacted by nuclear power plant closures

Advanced Reactor Concepts

- Production Tax Credit
- Micro-reactors for national security locations
- Versatile Fast Neutron Source
- Advanced Reactor Demo Projects
- High Assay-Low Enriched Uranium (HALEU) fuel

Streamline Innovation

- Regulatory reform
- Licensing cost-sharing for advanced reactor concepts
- Accessibility to DOE facilities
- Export control reform

- **Since 2015, over 20 bills have been introduced, 4 reported out of committee, 5 passed the House or Senate, and 4 were signed into law. 6 of the bills are related to waste.** *(updated 1/22/19)*

- **Support also includes appropriating the largest funding ever for DOE-NE in FY 2019 ($1.3B)**

Office of Nuclear Energy Mission Pillars

Existing Fleet

Advanced Reactor Pipeline

Fuel Cycle Infrastructure

Global Competitiveness

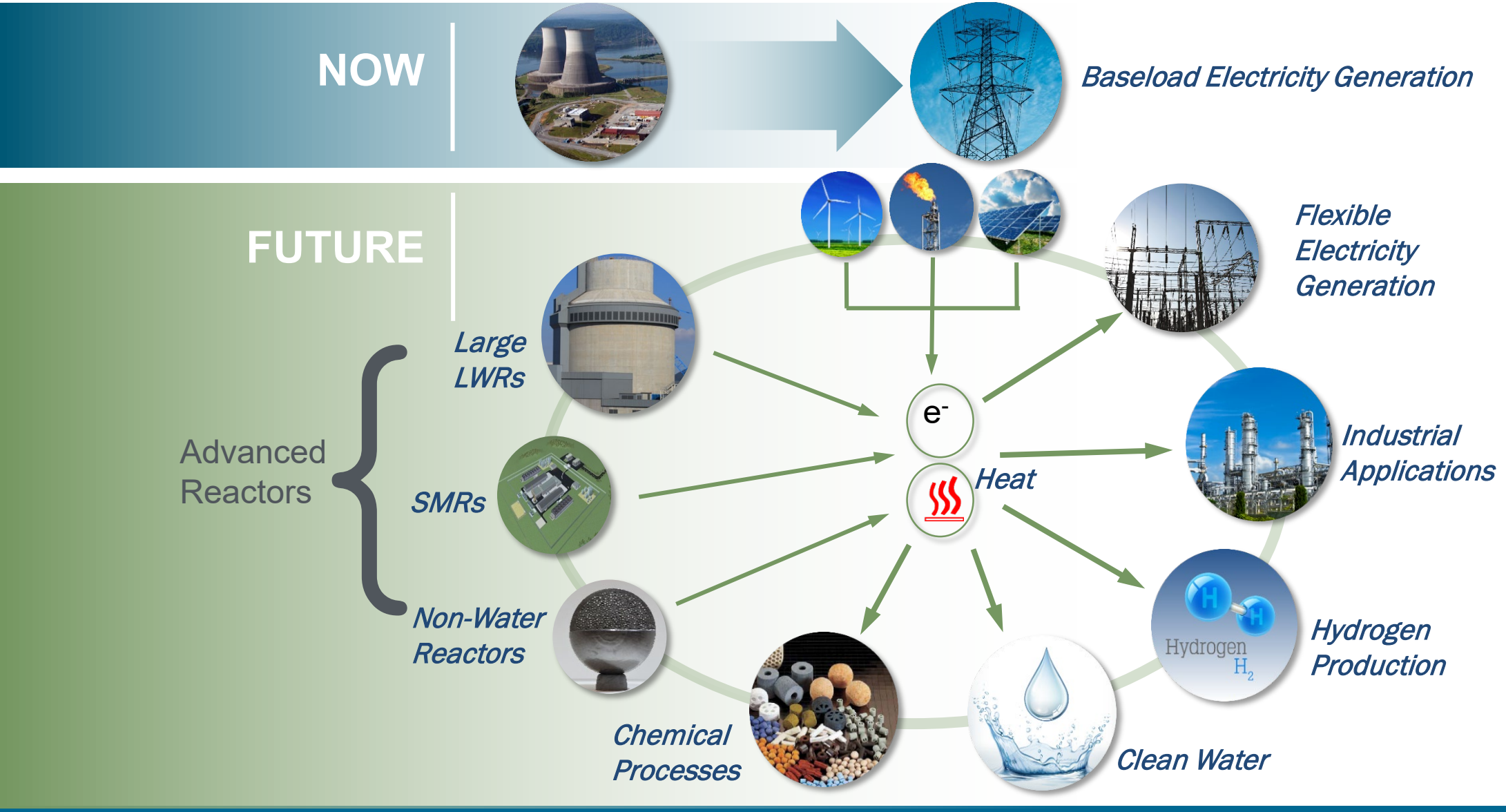
Sustaining the Existing Fleet

- **Improving Performance and Reducing Costs**
  - LWRS – subsequent license renewal and technical improvements
  - Accident Tolerant fuel – enhanced performance and safety
  - CASL – Energy Innovation Hub for M&S
  - Non-electric applications to improve flexibility and increase revenue generation

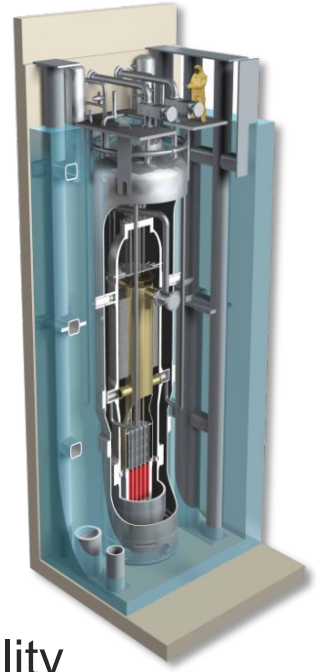
- **Policy and Market Reform Support**
  - Level the playing field with technology neutral policies
  - Ensure critical attributes are properly valued
  - Risk-informed, performance-based regulation

- **State and Local Technical Assistance, Education and Outreach**

Nuclear Beyond Electricity – Advanced Reactors



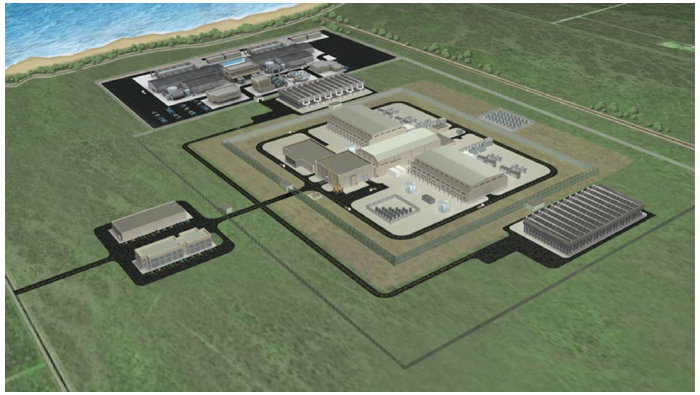
Small Modular Reactors



Greater affordability

- Easier financing for public power entities
- Lower capital investment
- Factory fabrication, shorter construction times

New standard of passive nuclear safety



Energy and environmental benefits

- Greenhouse gas and air pollution avoided
- Grid benefits: stability, security, quality, availability, reliability
- Siting flexibility
- Hybrid energy systems and flexible integration with renewables

Importance to National Security

Economic development and job growth

- Manufacturing jobs and supply chain opportunities in the United States

Micro Reactors

Designed for Specialized Applications

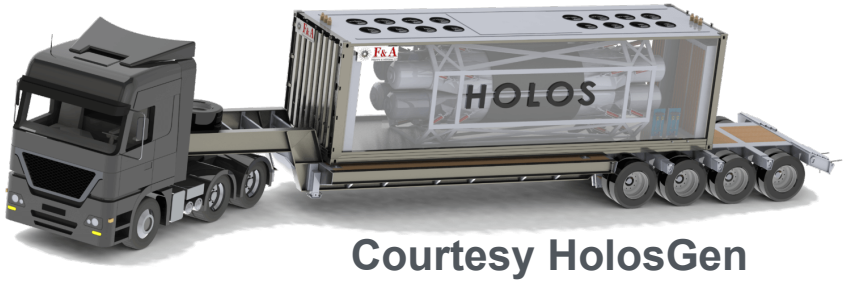
- Siting flexibility including near population centers
- Micro-grids
- Remote Operating Bases
- Data Centers
- Disaster Relief (FEMA)
- Specialized Non-electric Applications

OKLO

Westinghouse

eVinci™ Micro Reactor

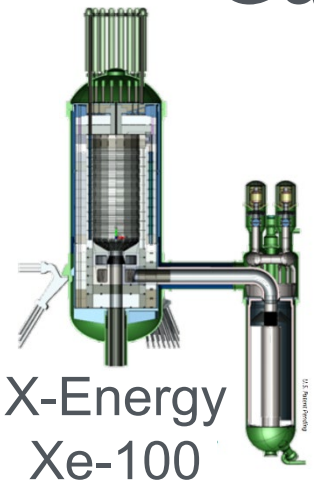
FEMA



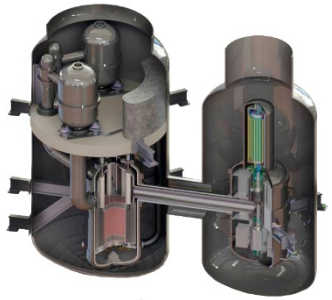
Courtesy HolosGen

Examples of Non-Water Advanced Reactors

Gas Reactors



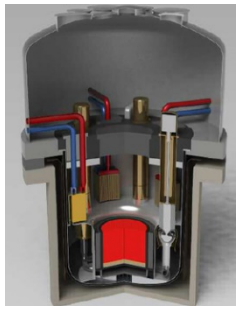
X-Energy
Xe-100



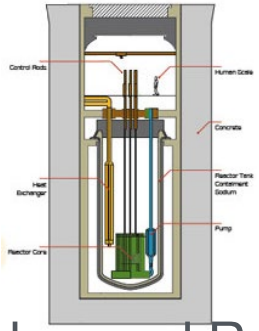
General Atomics
Energy Multiplier Module, EM2

Fast Reactors

GE Hitachi
PRISM

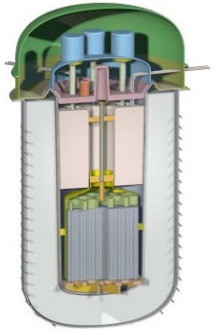


TerraPower
TWR

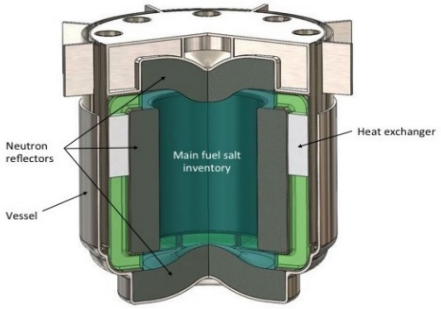


Advanced Reactor
Concepts LLC
ARC-100

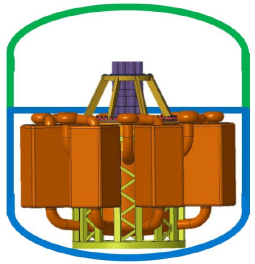
Molten Salt Reactors



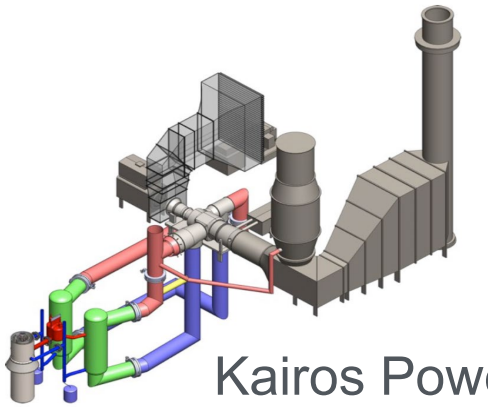
Terrestrial Energy
USA IMSR



TerraPower
MCFR



Elysium USA
MCSFR



Kairos Power
UCB PB-FHR

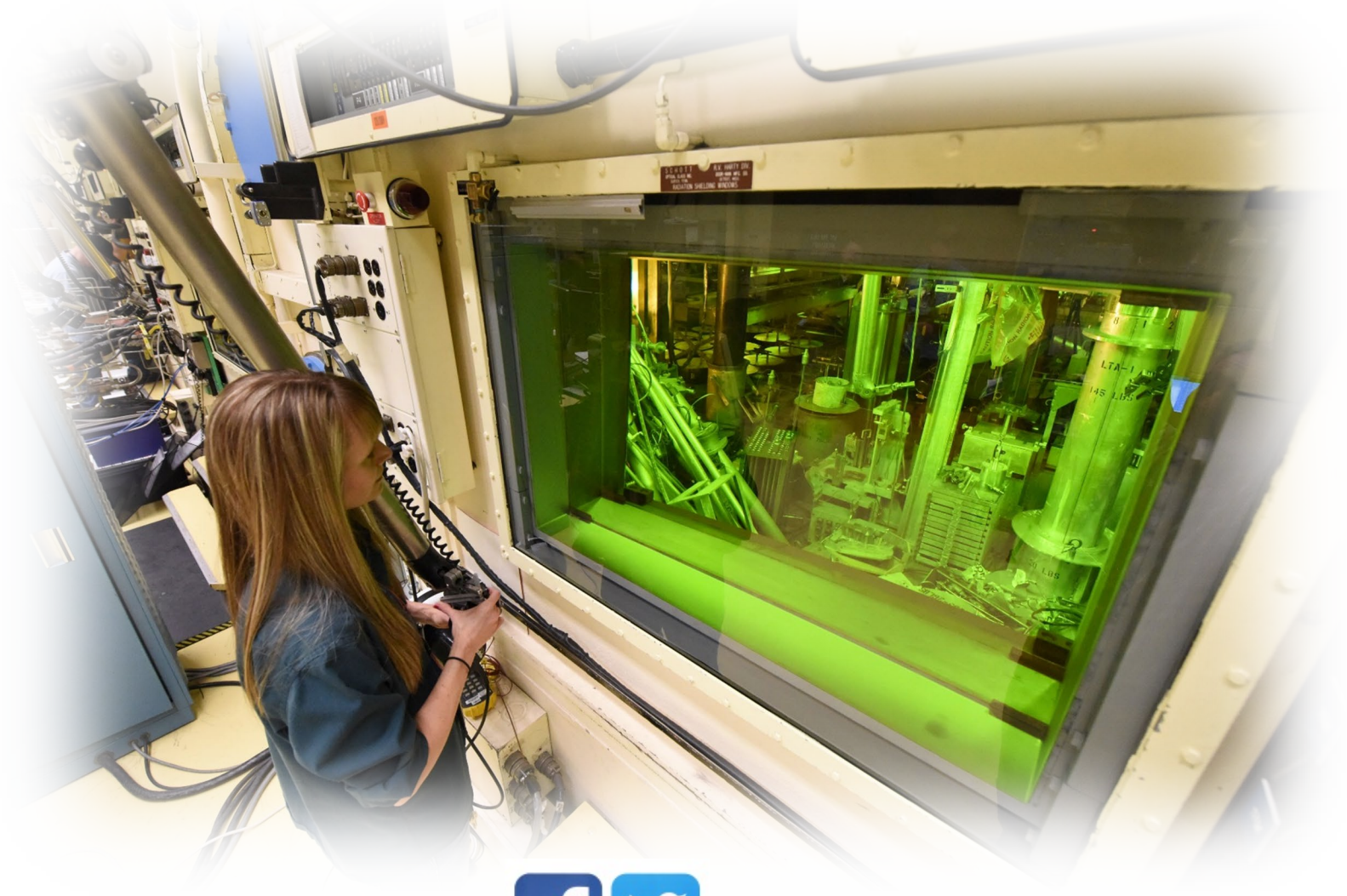
Gateway for Accelerated Innovation in Nuclear (GAIN)

GAIN Gateway for Accelerated Innovation in Nuclear

A private-public partnership framework aimed at rapid and cost-effective development of innovative nuclear energy technologies towards market readiness

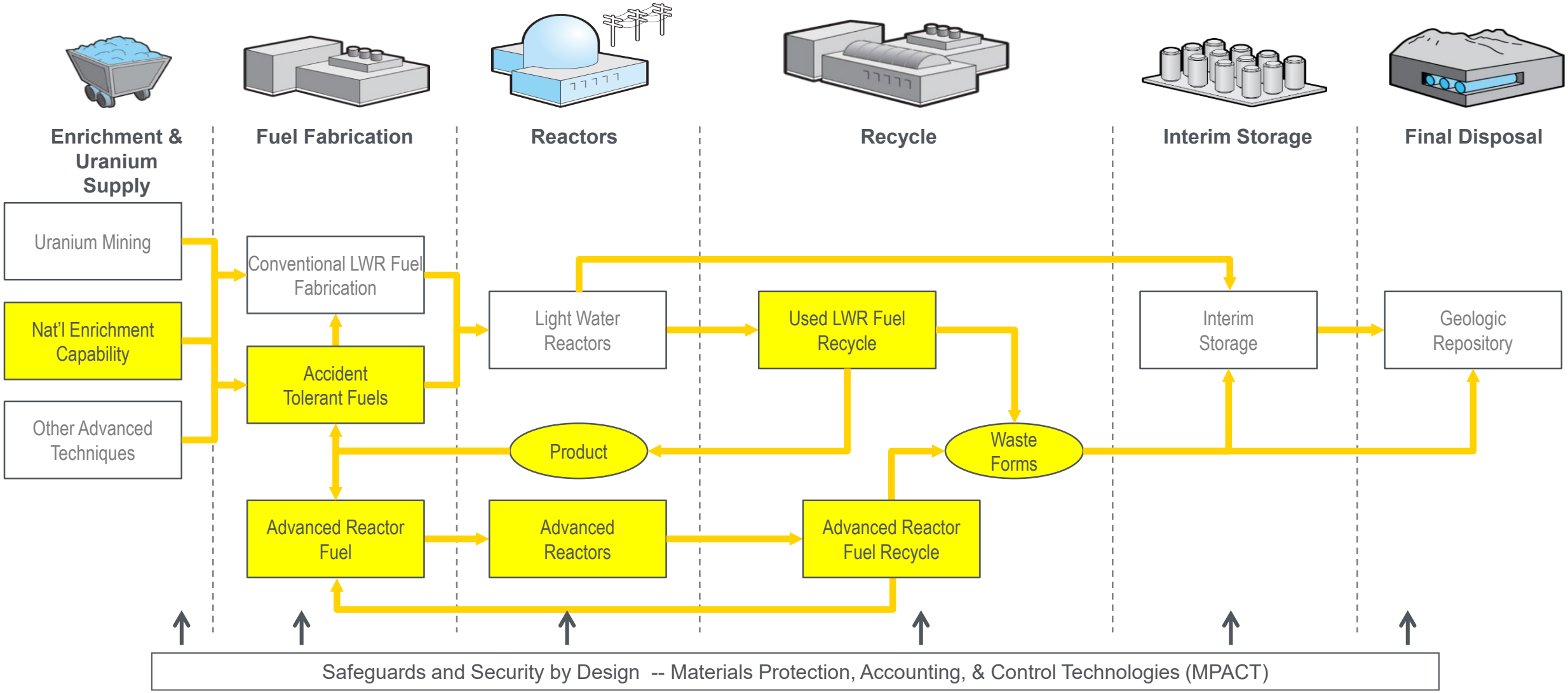
Mission

Provide the nuclear energy industry with access to technical, regulatory and financial support necessary to move innovative nuclear energy technologies toward *commercialization* in an accelerated and cost-effective fashion.

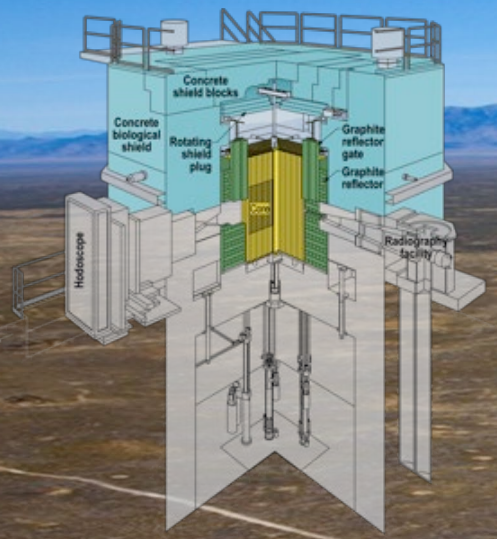


@GAINnuclear https://gain.inl.gov

Fuel Cycle Infrastructure



Transient Reactor Test (TREAT) Facility



- 100 kW Steady-state power with 19 GW Peak Transient Power
- Core: ~1.2 m high x 2 m. dia.; surrounded by 0.25 m graphite reflector
- 19 x 19 array of 10 x 10-cm. fuel and reflector assemblies
- Fuel: 0.2 wt.% high enriched UO2 dispersed in graphite
- 12 steady-state and 8 transient control rods
- Instantaneous, large negative temperature coefficient (self protecting driver core)

TREAT Experimental Facility Restarted in 2017

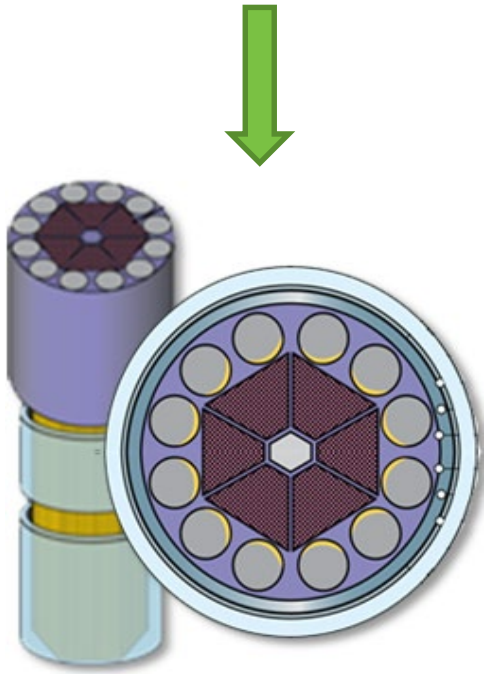
Versatile Advanced Test Reactor

- **Goal:** An Operational Versatile Advanced Test Reactor by 2026, to support accelerated development of advanced fuels and materials for U.S. advanced reactor vendors, as well as to provide the capability for testing those fuels and materials to support licensing by the Nuclear Regulatory Commission.

- A Versatile Advanced Test Reactor with a high fast neutron flux will revitalize our research infrastructure and remove a critical impediment for U.S. developers of advanced nuclear energy technologies.

Addressing Need for High-Assay Low Enriched Uranium (HALEU)

- Most advanced reactor concepts require HALEU for startup cores (15-19.75% - u-235)
- Expected demands for HALEU are very significant
  - A typical start-up core requires 4 MT HALEU
- In addition, there are other national missions that require a reliable supply of enriched uranium
- DOE-NE is working towards addressing these needs



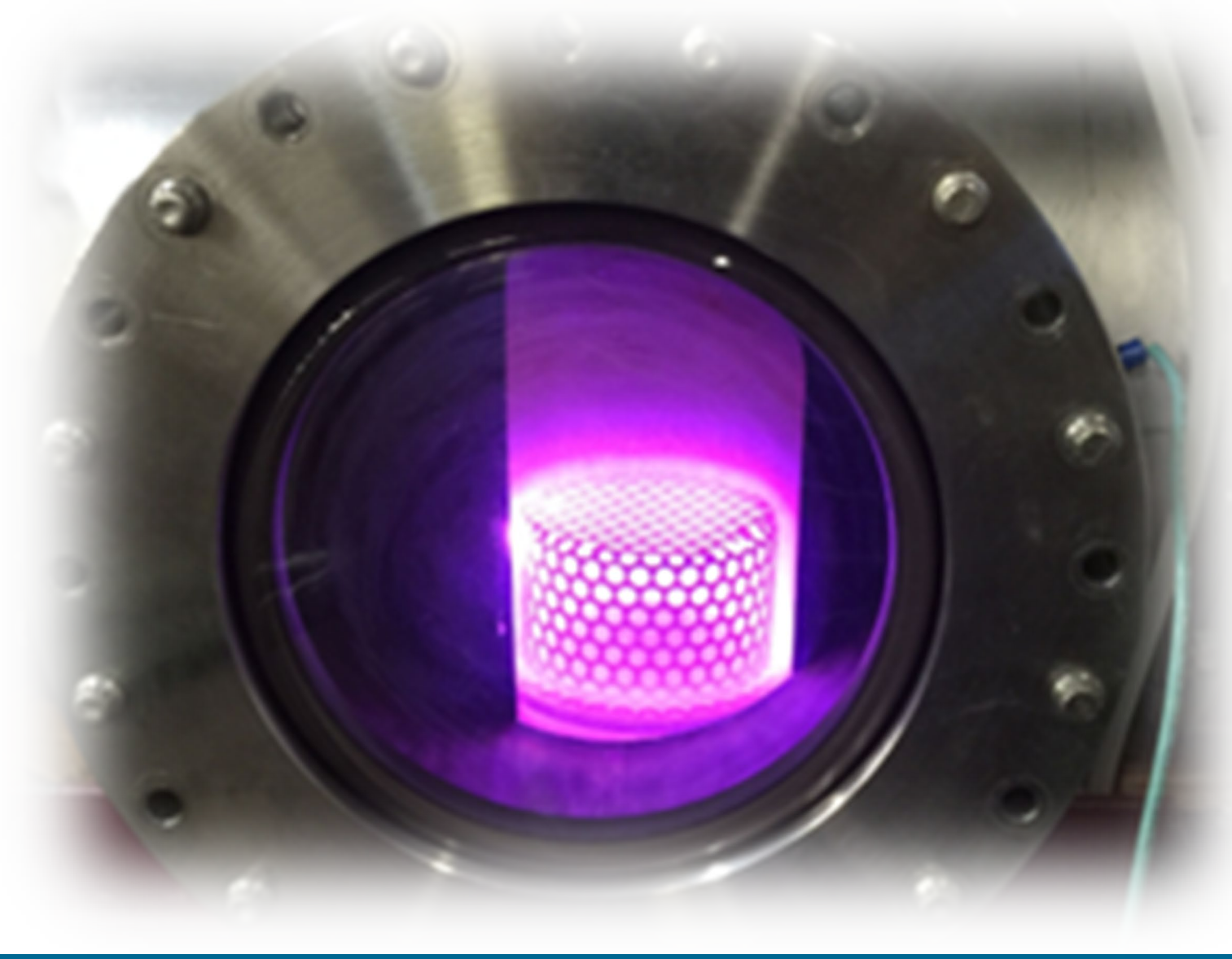
Advanced Manufacturing

Vision

- To improve the methods by which nuclear equipment, components, and plants are manufactured, fabricated, and assembled by utilizing practices found in industries such as oil, aircraft, and shipbuilding

Goal

- To reduce cost and schedule for new nuclear plant construction
- To make fabrication of nuclear power plant (NPP) components faster, cheaper and more reliable



Bilateral, Multilateral and Commercial International Cooperation

- **Bilateral Engagement**
  - R&D coordination and integration with advanced fuel cycle countries, e.g., bilateral action plans, International Nuclear Energy Research Initiatives (I-NERIs), and R&D agreements
  - Technical and policy support for civil nuclear energy working groups and bilateral MOUs

- **Multilateral Engagement**
  - Coordination and leadership for NE's engagement in multilateral organizations such as the International Atomic Energy Agency (IAEA), Generation IV International Forum (GIF), the International Framework for Nuclear Energy Cooperation (IFNEC), OECD's Nuclear Energy Agency (NEA), and the International Energy Agency (IEA)

- **International Commercial Engagement**
  - Promotion of U.S. civil nuclear energy policy and technical objectives through engagement on international commercial nuclear matters
  - Advancement of issues associated with developing commercial options for the safe and secure management of used fuel, including regional and international disposal, to support the growth of nuclear power

Nuclear Innovation: Clean Energy Future (NICE Future)

CLEAN ENERGY MINISTERIAL

Accelerating the Global Clean Energy Transition

Lead Participants:

USA, CANADA, JAPAN

Participants

ARGENTINA, POLAND, ROMANIA, RUSSIA, UAE, UK

Official Launch:

At the 9th Clean Energy Ministerial (May 2018, Denmark) NICE Future was launched by the United States, Canada and Japan to spotlight nuclear energy in the international clean energy community.

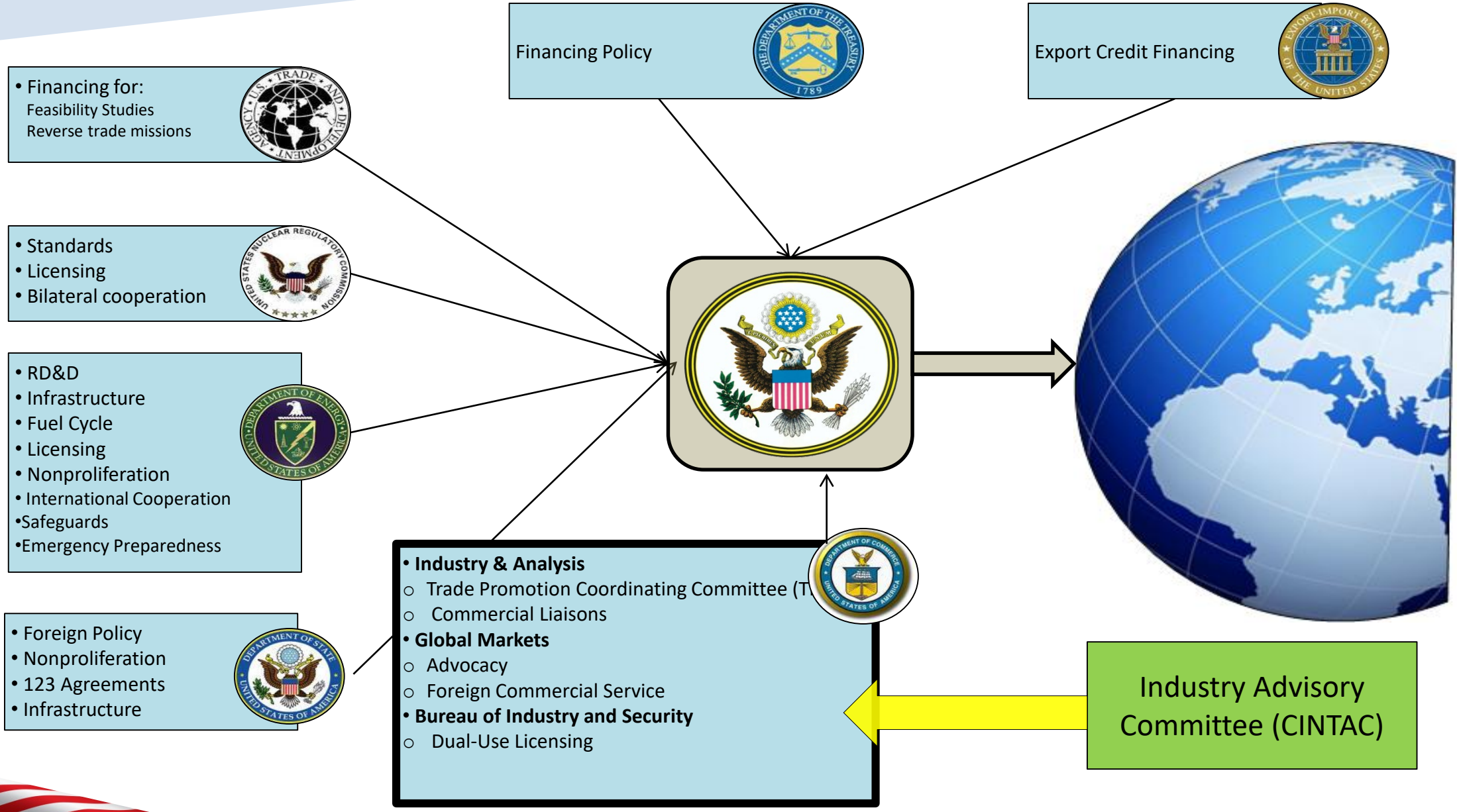
Overview:

NICE Future focuses on nuclear power as a clean energy option for reliable and resilient baseload electricity, and non-electric applications especially when deployed as hybrid nuclear-renewable systems.

Areas of Work:

1) Evaluations of innovative systems, technology, storage, uses
2) Policy-maker and Stakeholder Engagement
3) Economics
4) Communicating nuclear energy's role in clean energy systems

Team USA: Whole-of-Government Strategy



Summary

- The demand for domestically-generated, reliable, resilient and clean sources of baseload electricity will continue to drive many countries toward nuclear energy as part of their energy security and national economic and environmental calculus.

- Profound opportunity for new nuclear growth exists:
  - Strong global market interest
  - Growing need for increased global access to electricity
  - Support energy security, economic and environmental goals
  - U.S. leadership to ensure safety & nonproliferation are as important as ever

- The Administration is committed to advancing nuclear energy in the U.S. and abroad.

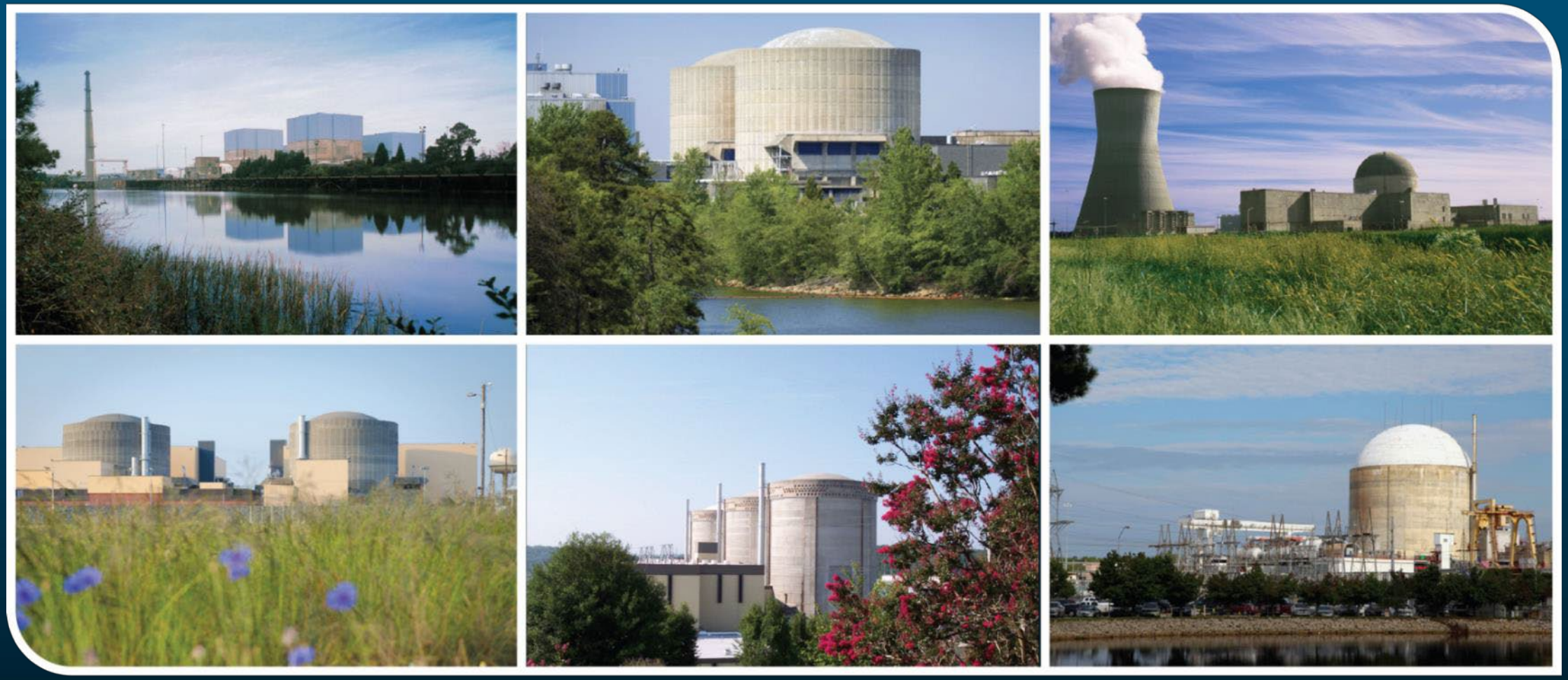
Questions?

Clean. **Reliable. Nuclear.**

Nuclear Generation at Duke Energy in North Carolina (30 min)

Preston Gillespie, Senior Vice President and Chief Nuclear Officer

Duke Energy



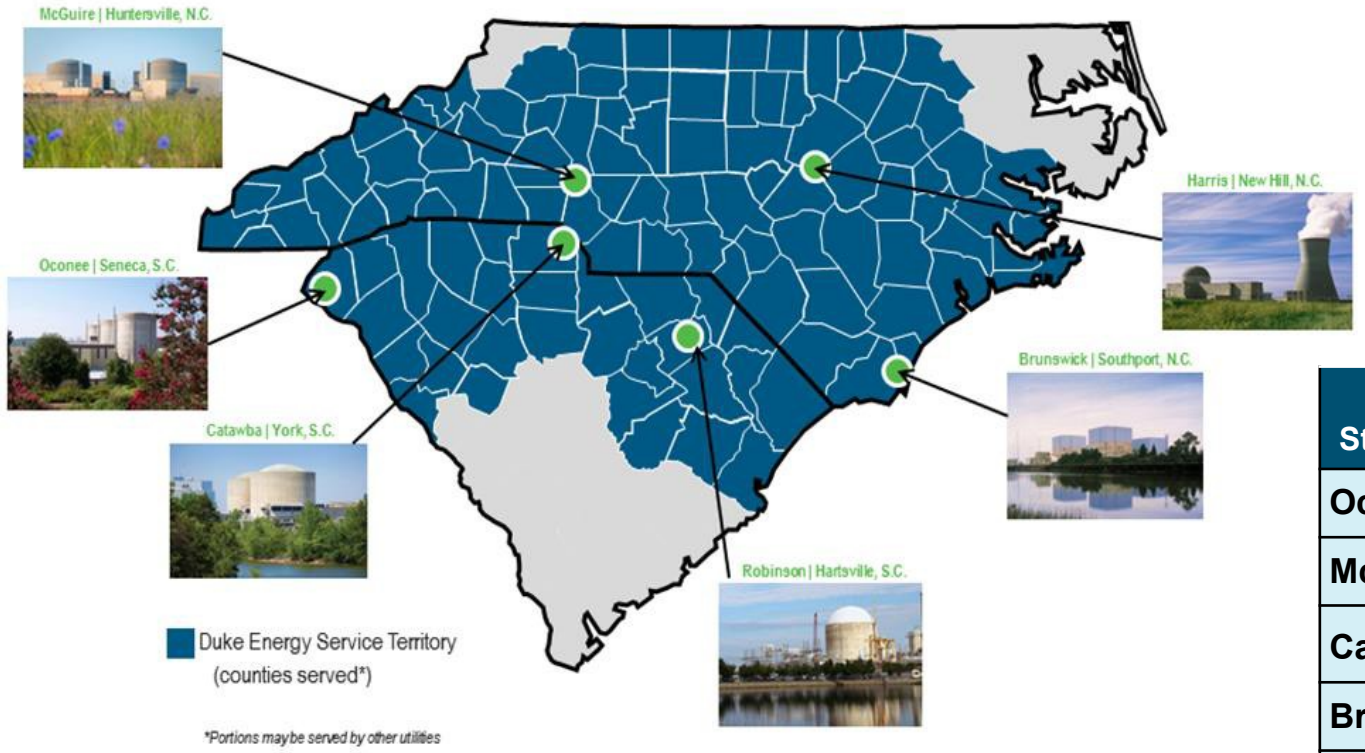
Duke Energy Nuclear Generation

Preston Gillespie, Senior Vice President and Chief Nuclear Officer

North Carolina Energy Policy Council – May 15, 2019

DUKE ENERGY®

Duke Energy Nuclear Fleet



Station	Capacity (MW)	Units	Commercial Operation	License Extension
Oconee	2,618	3 PWRs	1973	2033, 2034
McGuire	2,386	2 PWRs	1981	2041, 2043
Catawba*	2,370	2 PWRs	1985	2043
Brunswick	1,963	2 BWRs	1975	2034, 2036
Harris	980	1 PWR	1987	2046
Robinson	795	1 PWR	1971	2030
Total	11,112	11		

Catawba is jointly owned by North Carolina Municipal Power Agency Number One, North Carolina Electric Membership Corporation, Piedmont Municipal Power Agency and Duke Energy

Nuclear Energy Facts

CLEAN ENERGY

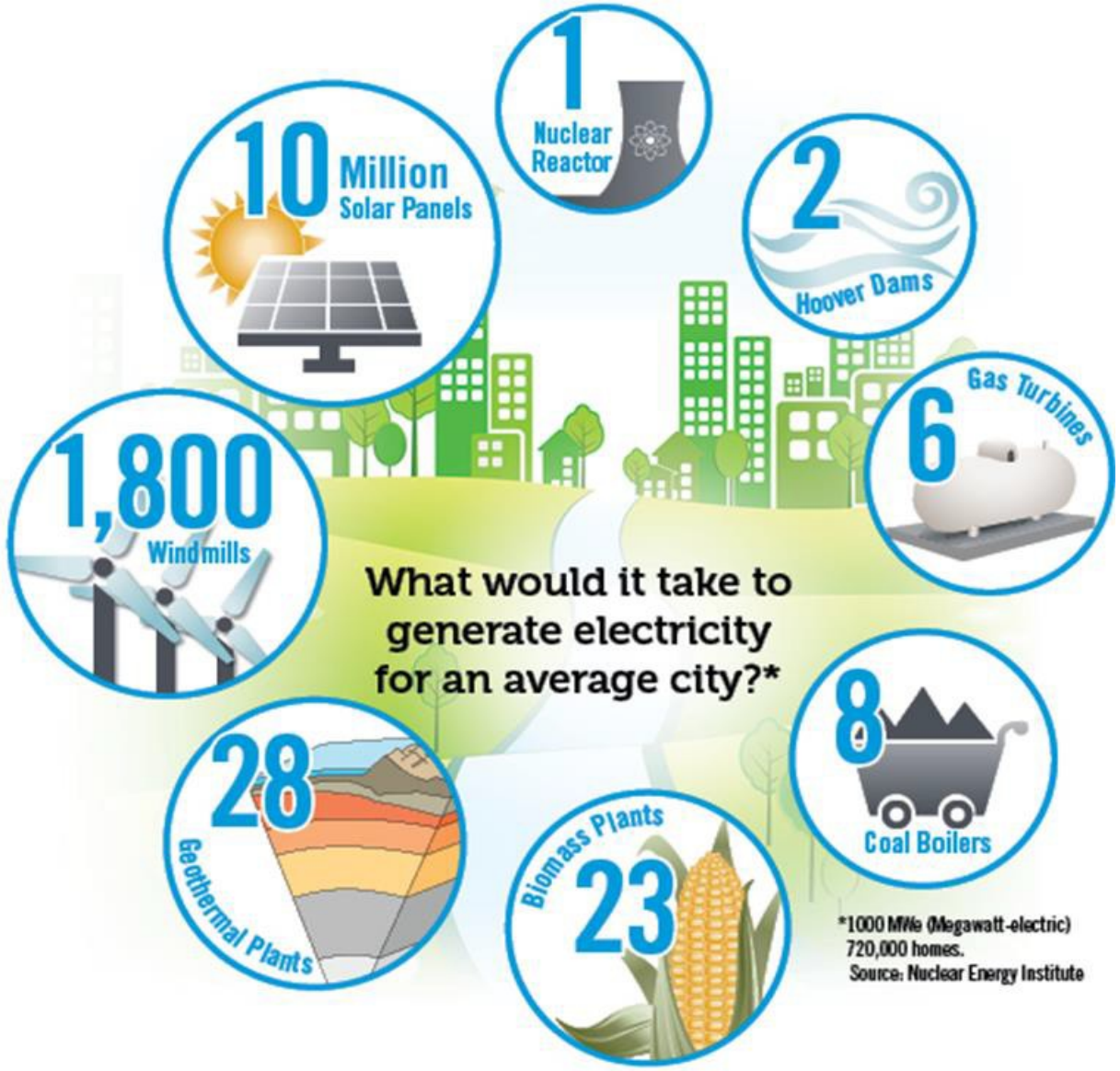
Provide more than 55% of U.S. carbon-free generation

CONSISTENT BASELOAD GENERATION

Nuclear units run 24/7, over 90% of time

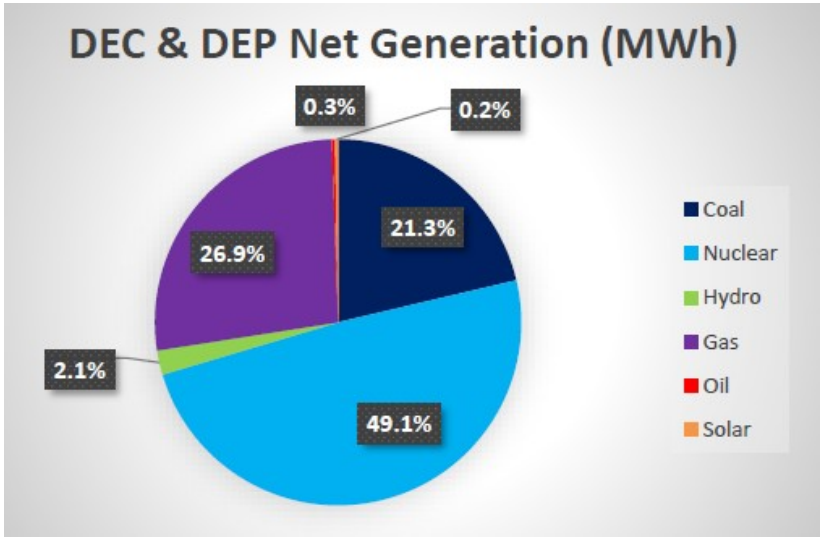
Employ thousands; Provide

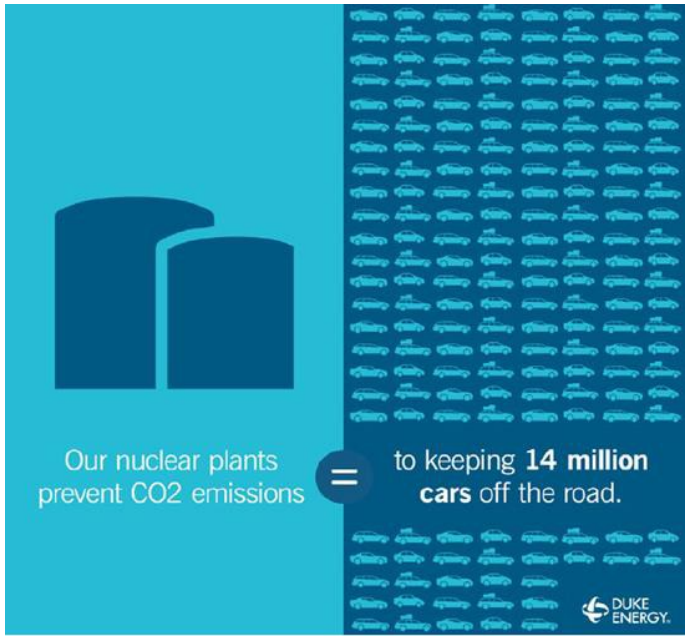
Diverse Resources



2018 Duke Energy Nuclear Fleet Performance

- Capacity factor = 93%
  - 20th consecutive year with capacity factor > 90%
- Provided nearly half of Duke Energy's generation in the Carolinas
- Avoided carbon dioxide emissions equal to keeping 14 million cars off the road
- Employed more than 5,000 at Carolinas nuclear stations
- Paid more than $308 million in property and payroll taxes
  - N.C. nuclear payroll = $153 million
  - N.C. nuclear property = $20 million





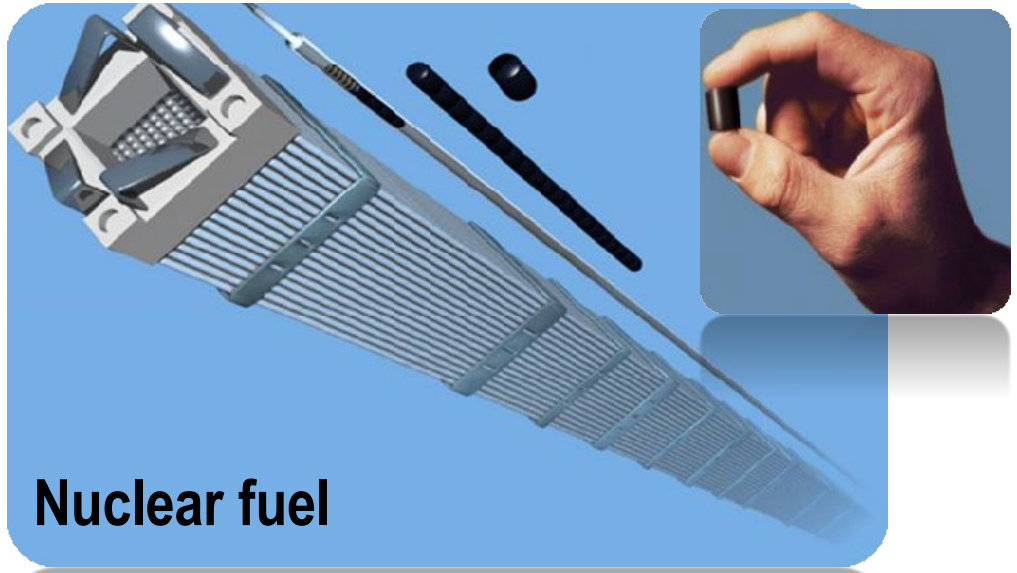
2018 North Carolina Nuclear Plant Superlatives

- Brunswick Nuclear Plant
  - Provided more than 14.5 million megawatt-hours of electricity
  - Industry-recognized for exemplary performance

- Harris Nuclear Plant
  - Generated 7.6 million megawatt-hours
  - Completed more than 369 days of continuous operation
  - Industry-recognized for exemplary performance

- McGuire Nuclear Station
  - Unit 1 set an annual generation record of more than 10 million megawatt-hours
  - Unit 2 completed a 510-day breaker-to-breaker run
  - Continues as the longest running exemplary plant in U.S.

Nuclear Fuel



Used Nuclear Fuel – Safe and Secure

Used fuel pool

Dry fuel storage

Shared Values

- Nuclear energy is a sustained success story for the Carolinas providing safe, clean, reliable electricity that customers depend on all day, every day
- Our employees are both proud and passionate about their work, and are honored to be part of many service and volunteer efforts in their communities
- We recognize it is a privilege to operate in our local communities – this is something we never take for granted

DUKE ENERGY®

*BUILDING A **SMARTER** ENERGY FUTURE℠*

Nuclear Energy Technology Update (30 min)

Dr. Mohamed Bourham,
Alumni Distinguished Graduate Professor of Nuclear Engineering,
North Carolina State University

Department of NUCLEAR ENGINEERING

NC STATE UNIVERSITY

Nuclear technology trends and updates, including small modular reactors (SMR) and other new initiatives/enhancements

Mohamed Bourham, Kostadin Ivanov

Nuclear Engineering Department, NC State University

Energy Policy Council Meeting

State Energy Program, North Carolina Department of Environmental Quality

May 15, 2019

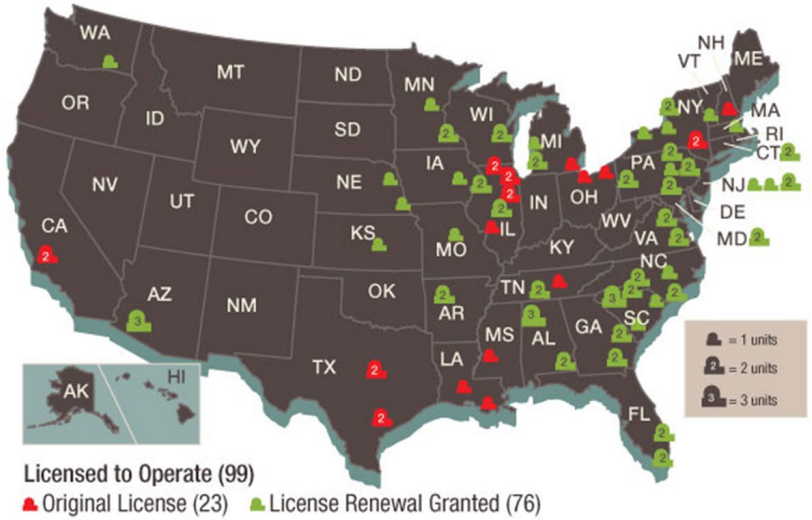
Raleigh, North Carolina

Introduction

- This presentation summarizes current nuclear technology trends and updates
- Special attention is devoted to small modular reactors (SMRs)
- Other new initiatives/enhancements are presented also
- The Nuclear Engineering Department (NED) at NCSU is introduced outlining:
  - the NED contributions to the manpower production, technology advancement, and national/international leadership in nuclear energy;
  - the strong connections of NED to the industrial, national laboratories and regulatory segments of nuclear energy.
- Proposal is made on how to strengthen the cooperation between NED, NCSU and other nuclear energy-related entities in the state with the NC State Energy Program

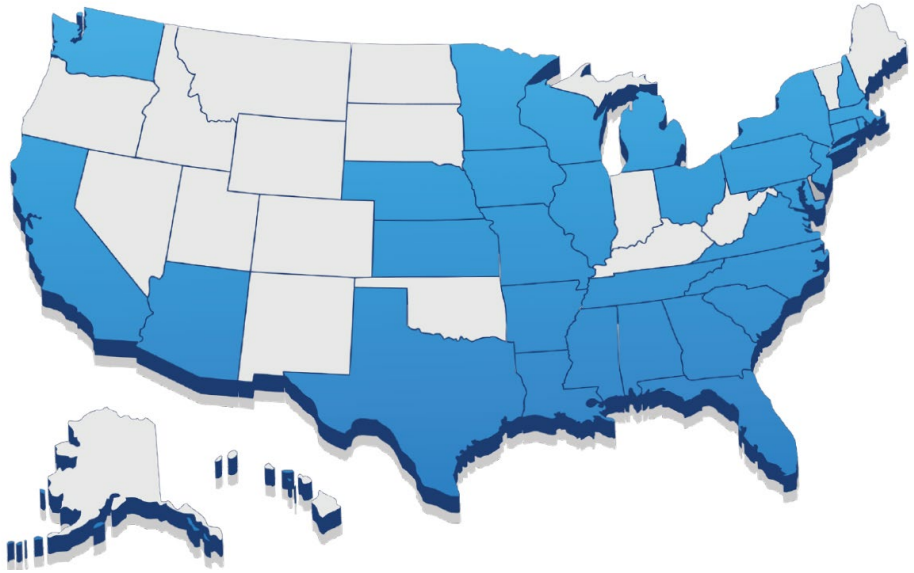
Nuclear Energy Trends and Updates

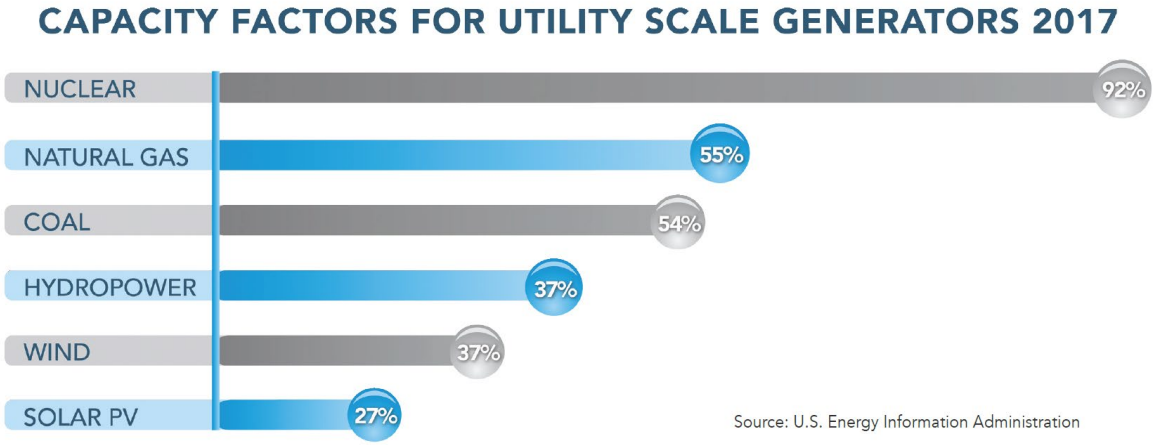
- With 70 new reactors under construction worldwide, the nuclear industry is currently experiencing moderate growth
- Nuclear power is a critical energy source that provides 19 % of the electricity in U.S., and 56 % of the nation's carbon free electricity
- In U.S. majority of operating nuclear power reactor (Generation II) licenses are renewed from 40-years to 60-years
- New reactor (Generation III and III+) licensing in the U.S. is ongoing and 2 AP1000 are being built
- Government (DOE) and industry support for Small Modular and Advanced Reactor Designs

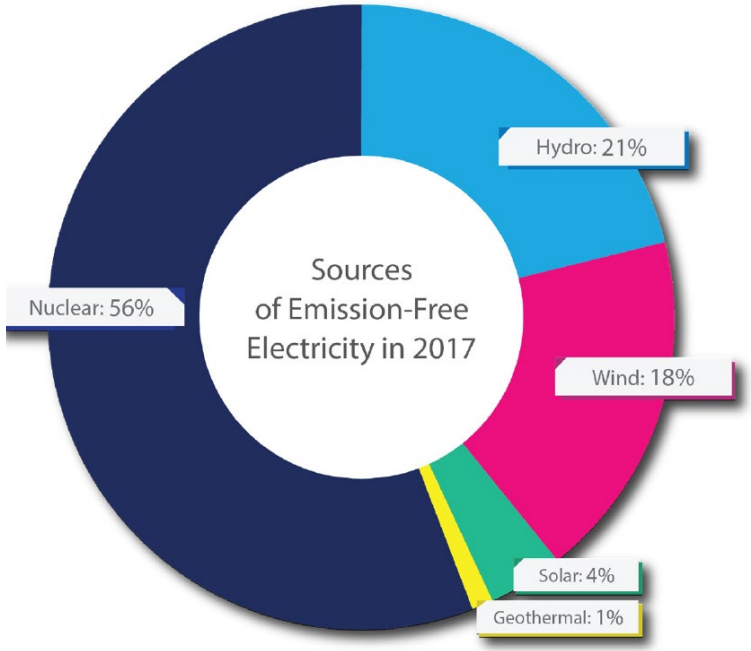


Nuclear Energy Trends and Updates

- Nuclear power provides 56% of America's clean energy
- Nuclear power is the most reliable energy source in America
- Nuclear helps power 30 U.S. States
- Nuclear energy is clean and sustainable







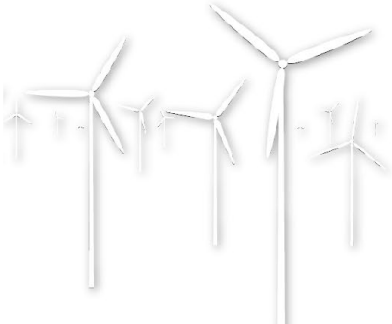
Nuclear Energy Trends and Updates

- The major problem is the economic competitiveness of the existing fleet as compared to the very inexpensive pipeline natural gas, resulting from hydraulic fracturing ("fracking")
- As a result, some of the U.S. nuclear capacity has been shut down prematurely and many other reactors are threatened with the same fate
- Only two large reactors are under construction in the U.S. and these have been plagued by delays and cost overruns
- Policy changes are necessary on federal and state levels to assure survival of the existing fleet of U.S. commercial nuclear plants:
  - Continued early shutdowns of operating plants are jeopardizing the entire domestic commercial nuclear industry and threaten to have extremely severe repercussions on national security and the integrity of the national electricity grid;
  - Without policy changes, reductions in operating costs and improved efficiencies utilizing advances in technology will not be sufficient to address the crisis in short-term economic sustainability.

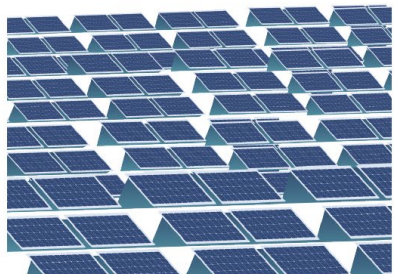
A typical reactor produces around 1 gigawatt of power or the same amount of power as:

100 million
LED bulbs

431 utility-scale
wind turbines

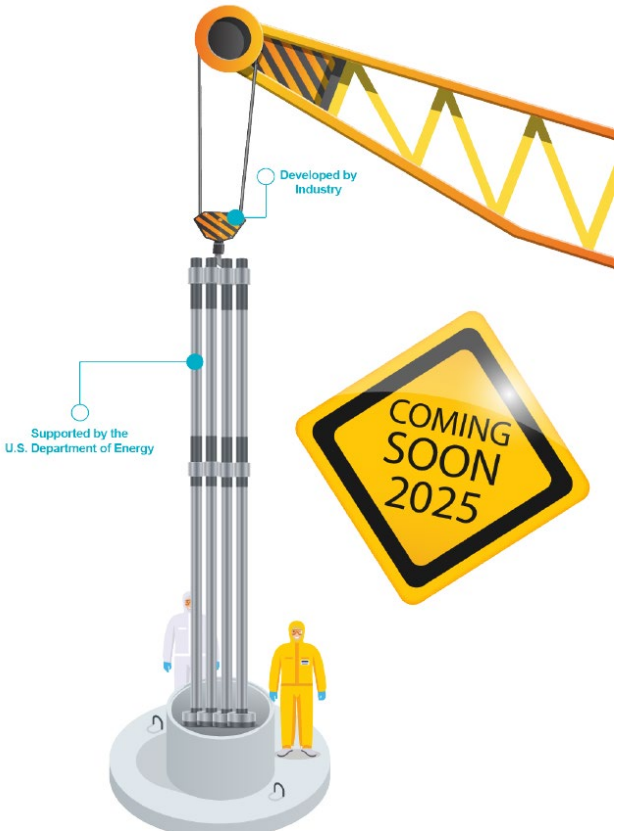


3.125 million
PV panels



Accident Tolerant Fuel (ATF)

- The U.S. Department of Energy is working with industry to quickly develop new fuels with enhanced accident tolerance
- These nuclear fuels will not only increase the safety of today's light-water reactors but also improve plant performance at a crucial time for the U.S. nuclear industry
- These fuel concepts will perform better and withstand extreme heat and steam for longer durations than the current fuel
- Accident tolerant fuels will be able to last longer and operate more efficiently in a reactor core. This could potentially extend the time between refueling from 1.5 years to 2 years or more and use roughly 30% less fuel
- In addition to lasting longer, accident tolerant fuels are also designed to have higher burnup



Small Modular Reactors (SMRs)

- Within the next decade, advanced small modular reactors (SMRs) could change the way we think about reliable, clean and affordable nuclear power
- Instead of going big, scientists and engineers went small developing mini reactors that are roughly a third of the size of a typical nuclear power plant
- That means the America's largest clean energy source could be coming to a market near you - making nuclear more scalable and flexible than ever before
- There are several SMR designs currently being developed:
  - NuScale SMR design, which is the most matured;
  - Holtec SMR-1600 design;
  - X-Energy Xe-100 SMR design;
  - Rolls-Royce SMR design.

FOUR KEY BENEFITS TO SMRS

LESS PREP

SMR modules require limited on-site preparation -- which could significantly reduce up-front capital costs and construction times compared to large scale reactors.

MORE OPTIONS

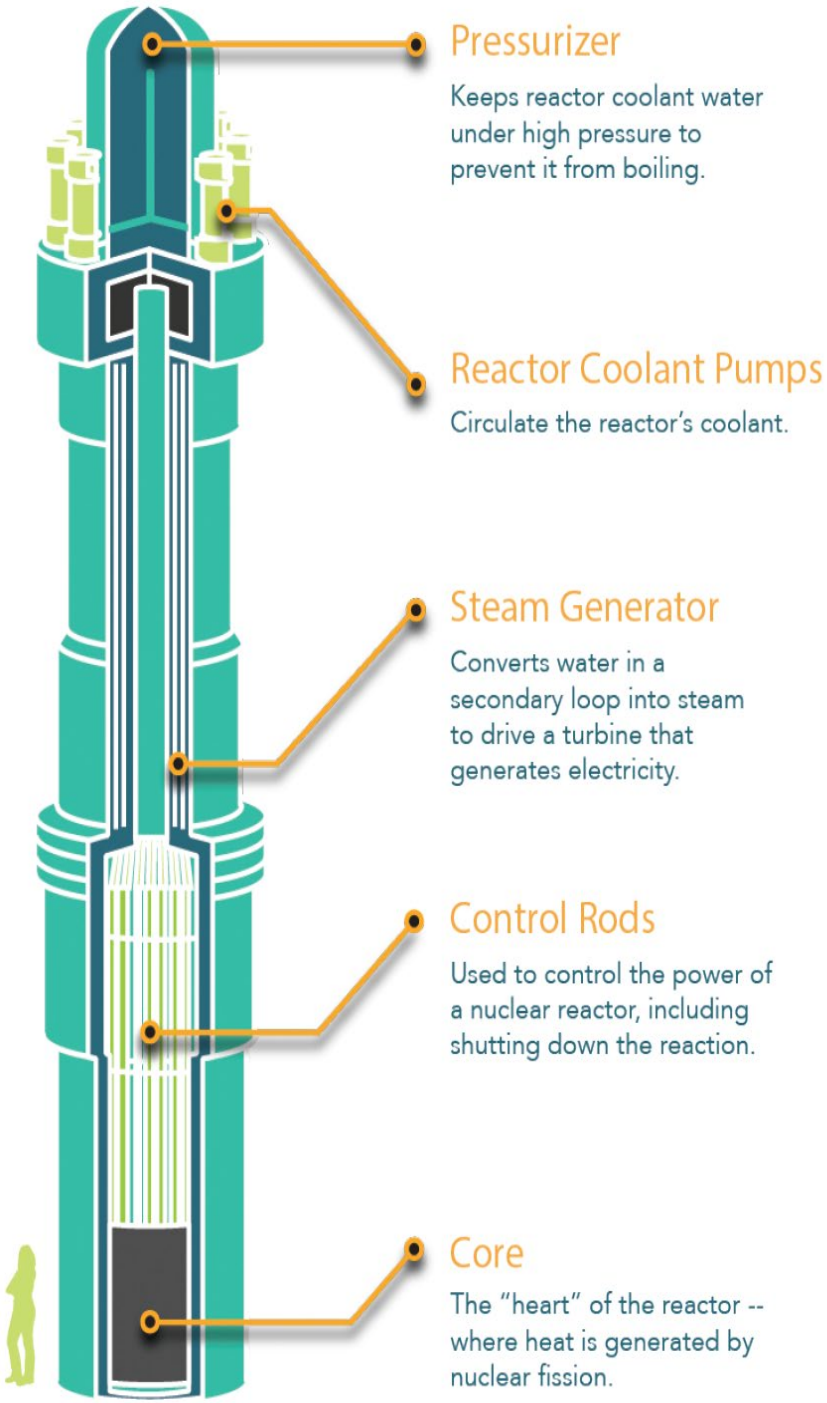
SMRs could increase nuclear technology options -- their smaller size makes them ideal for locations that cannot support large reactors.

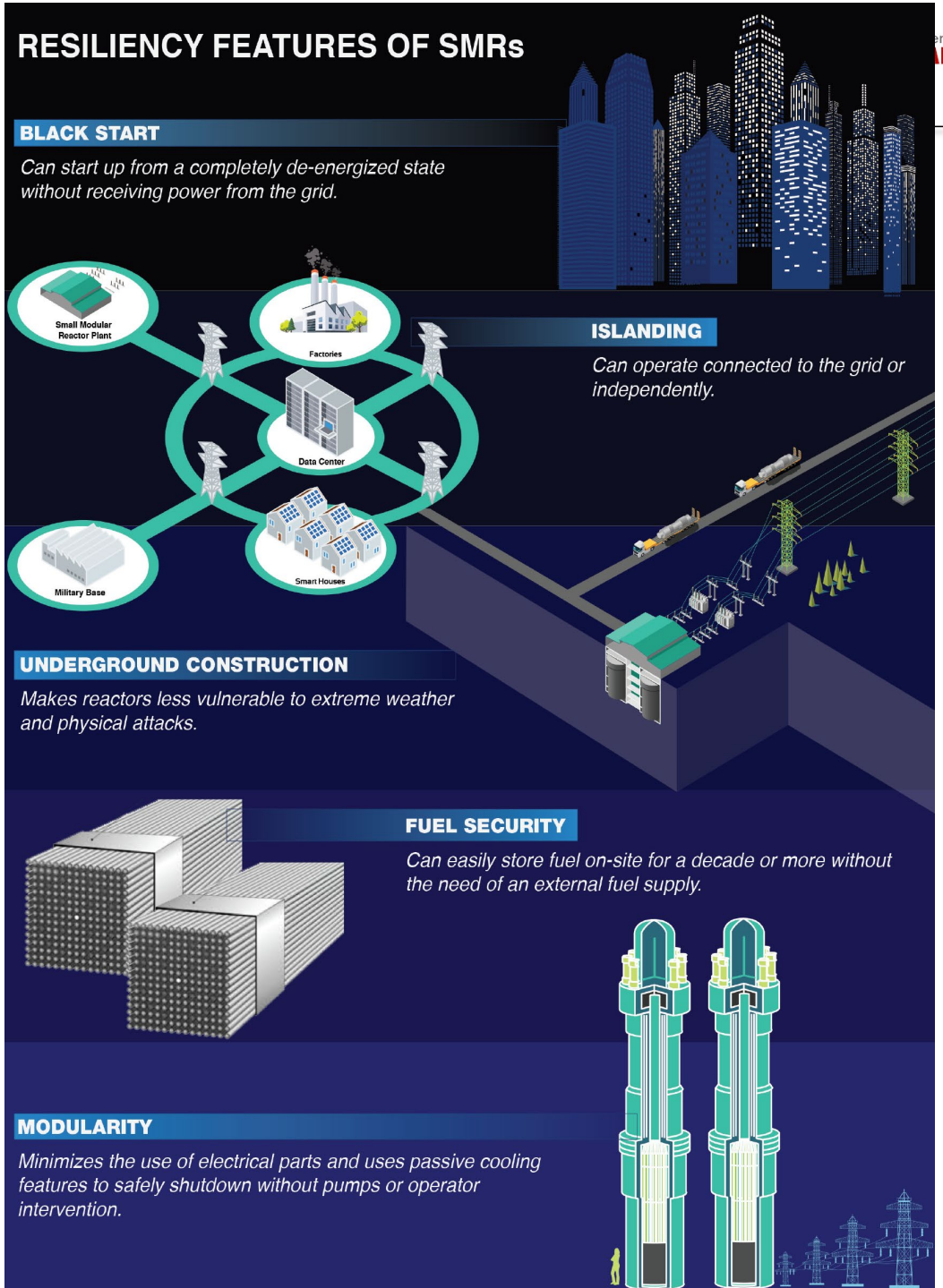
FLEXIBILITY

As energy demand increases, additional SMRs can be added to provide more power at a site.

NEW BUSINESS

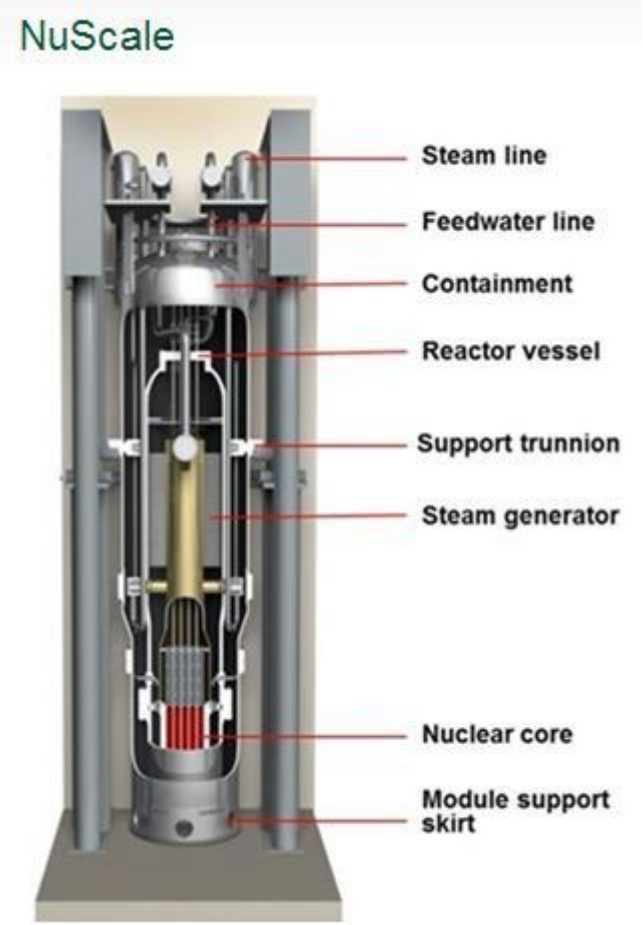
SMRs could strengthen U.S. leadership in nuclear energy worldwide -- creating new domestic jobs and businesses, and global export opportunities.


Pressurizer
Keeps reactor coolant water under high pressure to prevent it from boiling.
Reactor Coolant Pumps
Circulate the reactor's coolant.
Steam Generator
Converts water in a secondary loop into steam to drive a turbine that generates electricity.
Control Rods
Used to control the power of a nuclear reactor, including shutting down the reaction.
Core
The "heart" of the reactor -- where heat is generated by nuclear fission.


RESILIENCY FEATURES OF SMRs
BLACK START
Can start up from a completely de-energized state without receiving power from the grid.
Small Modular Reactor Plant
Factories
Data Center
Smart Houses
Military Base
ISLANDING
Can operate connected to the grid or independently.
UNDERGROUND CONSTRUCTION
Makes reactors less vulnerable to extreme weather and physical attacks.
FUEL SECURITY
Can easily store fuel on-site for a decade or more without the need of an external fuel supply.
MODULARITY
Minimizes the use of electrical parts and uses passive cooling features to safely shutdown without pumps or operator intervention.

NuScale SMR Design

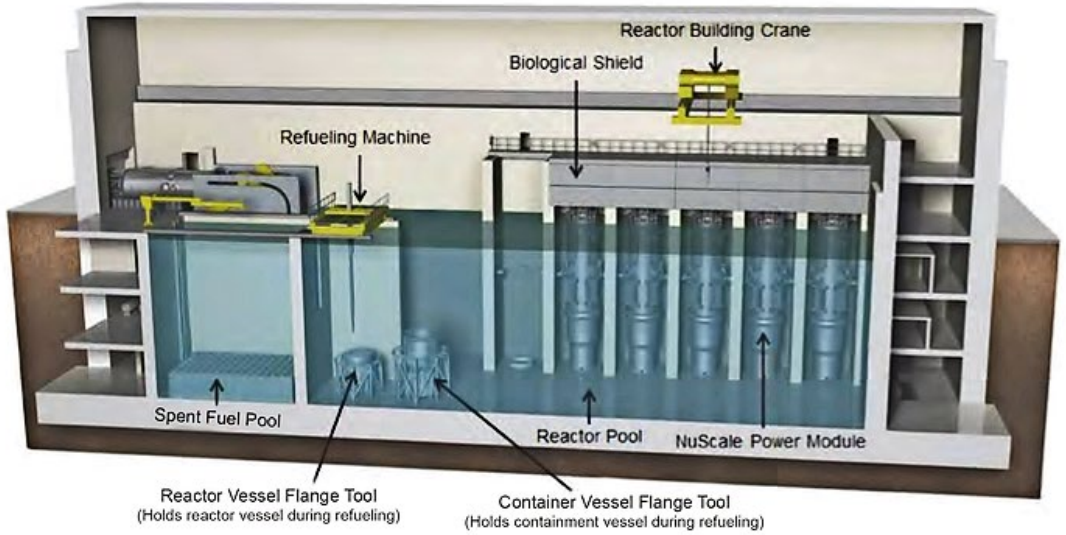
- NuScale's self-contained SMR design houses the reactor core, pressurizer and steam generator inside a single containment vessel
- A single module can generate 50 MWe (gross) of electricity and at just under 25 meters in length, 4.6 meters in diameter and weighing 450 tones, incorporates simple, redundant, diverse, and independent safety features
- A power plant could include up to 12 modules to produce as much as 720 MWe (gross)



NuScale SMR Design

- NuScale's SMR is undergoing design certification review by the US Nuclear Regulatory Commission (NRC), the first and so far only SMR to do so
- The NRC completed the first phase of its review in April last year, and the regulator is scheduled to complete its safety evaluation report in August 2020
- NuScale expects the application to be approved by the commission the following month
- Utah Associated Municipal Power Systems plans the development of a 12-module demonstration NuScale plant at a site at the Idaho National Laboratory, with operation expected by 2027
- The US Department of Energy in December signed an MoU on the use of power from two of the 12 modules

Inside a NuScale Small Modular Reactor Building



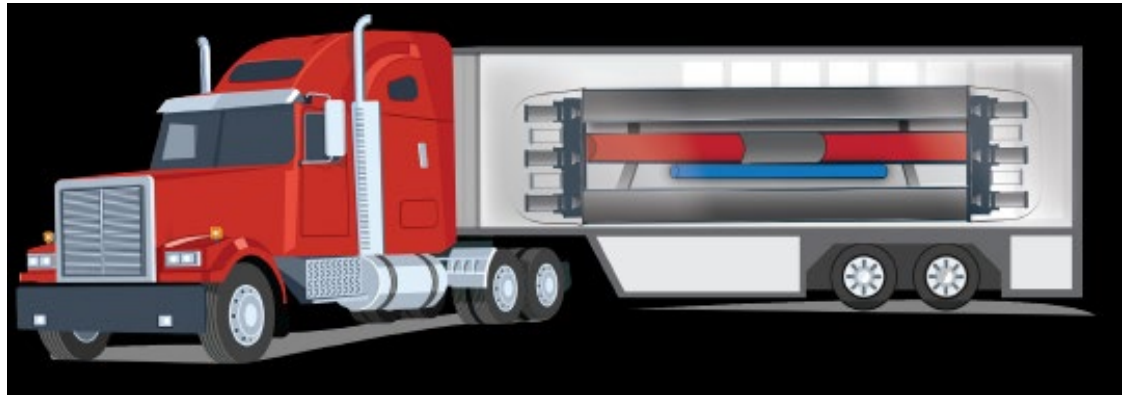
Source: NuScale Power LLC

A BNA Graphic/reac13g1

Nuclear Microreactors

Microreactors have three main features:

- Factory fabricated;
- Transportable;
- Self-regulating.



Other facts and benefits include:

- Seamless integration with renewables within microgrids;
- Can be used for emergency response to help restore power to areas hit by natural disasters;
- A longer core life, operating for up to 10 years without refueling;
- Can be quickly removed from sites and exchanged for new ones;
- Micro reactors will produce 1-20 megawatts of thermal energy that could be used directly as heat or converted to electric power;
- They can be used to generate clean and reliable electricity for commercial use or for non-electric applications such as district heating, water desalination and hydrogen fuel production;
- The U.S. Department of Energy supports a variety of advanced reactor designs including gas, liquid metal, molten salt and heat pipe-cooled concepts;
- American microreactor developers are currently focused on gas and heat pipe-cooled designs that could debut as early as the mid-2020s.

Nuclear Energy and Technology Updates

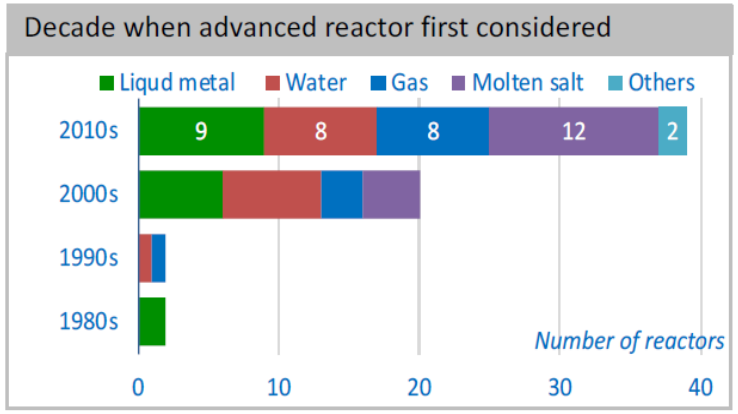
- The U.S. government and congress have considered initiatives to support the American nuclear industry to compete with state-owned or state-sponsored developers in rival nations – especially China and Russia:
  - Department of Energy Research and Innovation Act
  - Nuclear Energy Innovation Modernization Act (NEIMA) with focus on NRC-related activities
  - Nuclear Energy Innovation Capabilities Act (NEICA)
  - Nuclear Utilization of Keynote Energy Act, Production Tax Credit Extension, and National Defense Authorization Act
  - Nuclear Waste Legislation
  - Nuclear Energy Leadership Act (NELA)
- Bills are introduced in different states to provide support for the operating nuclear power plants and to avoid closures – Illinois, New York, Ohio, Pennsylvania, Connecticut, etc.

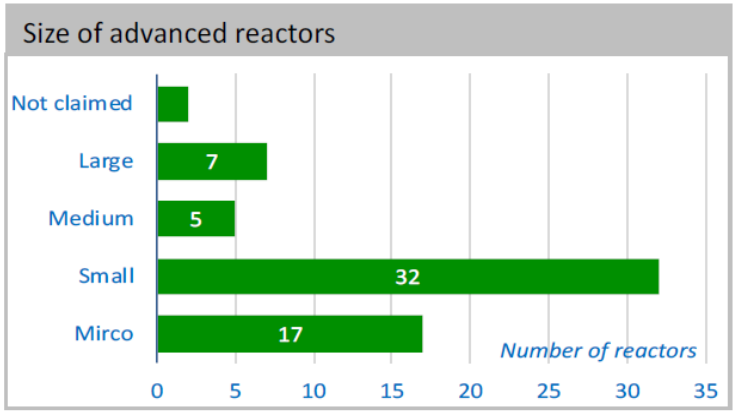
Nuclear Energy and Technology Updates

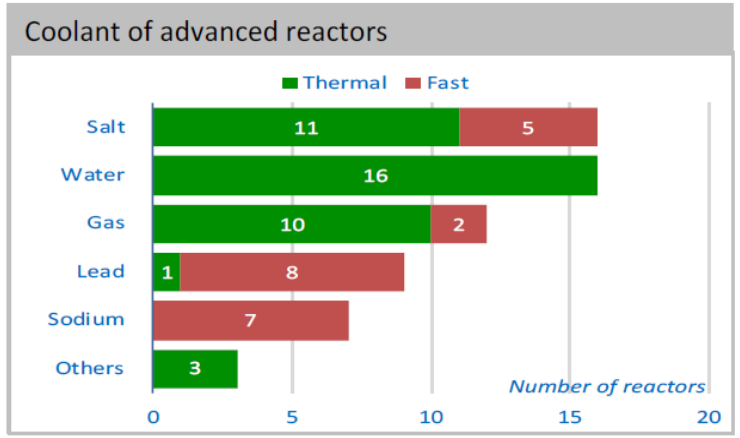
- The Nuclear Energy Innovation Capabilities Act (NEICA):
  - authorizes DOE to partner with industry to create a cost-sharing program to help defray the cost of reactor licensing
  - directs DOE to expand high-performance computer capability focusing on advanced reactor modeling & simulation capability
  - establishes the National Reactor Innovation Center
- The Nuclear Energy Innovation Capabilities Act (NEICA) introduces:
  - Authorization of Long-Term Power Purchase Agreements
  - Long-Term Nuclear Power Purchase Agreement Pilot Program
  - Advanced Nuclear Reactor Research and Development (R&D) Goals - to re-establish U.S. as a global leader in nuclear technology.
  - Requirement for a 10-year strategic plan that supports advanced nuclear R&D goals to be developed by the DOE's Office of Nuclear Energy
  - Facilities Required for Advanced Reactor R&D – construct Versatile Test Reactor (VTR) Based Fast Neutron Source.
  - Provision of domestic High-Assay Low-Enriched Uranium (HALEU) availability
  - Creation of University Nuclear Leadership Program to develop a highly-skilled workforce

Trends in Advanced Reactor Development in U.S.

- The U.S. Department of Energy and its national labs are supporting research and development on a wide range of new advanced reactor technologies that could be a game-changer for the nuclear industry
- These innovative systems are expected to be cleaner, safer and more efficient than previous generations
- In North America, 48 companies, backed by more than $1.6 billion in private capital, are developing plans for advanced nuclear reactors
- DOE invests in public-private partnerships to fund cost-shared development of advanced reactor designs







- **Advanced reactor concepts has been increasing since 2000**
  - Wide range of reactor types being proposed
  - Being accelerated recently in the U.S. because of investment of private capital through entrepreneurs and various initiatives of DOE-NE
- **More than 70% reviewed in this study are small or micro reactor concepts**
  - Affordable construction cost through modular and factory construction, applications in small grids, harsh locations, and special purposes
- **Various coolants and fuel forms are adopted**
  - Traditional assumptions of coolant materials for fast and thermal reactors have been changed

Versatile Test Reactor (VTR)

Why a Test Reactor ?

The *mission of the VTR program* is to provide leading edge capability for accelerated testing and qualification of advanced fuels and materials enabling the U.S. to regain and sustain technology leadership in the area of advanced reactor systems.

INDUSTRIAL INTEREST

- Fuels/Materials/Instrumentation &Sensors Testing
  - Sodium-cooled reactors
  - Lead/LBE-cooled reactors
  - Gas-cooled reactors
  - Molten salt reactors
- Accelerated testing for reactor materials

Domestic deployment for clean energy transition

Global market share

- Some concepts may be ready for a demonstration unit within 10 years
- VTR will help with continuous improvements in operations and economics beyond initial demonstration within 10 years
  - E.g. LWR technology evolution history (progress from 60 to 90% availability)

NATIONAL SECURITY/SCIENTIFIC INTERESTS

- State-of-the art knowledge of fast reactor technology
  - Global safety and security policies
  - Safeguards technologies
- Research on long-term fuel cycles
- Potential scientific research on
  - Fusion materials
  - Neutrino science/detector development

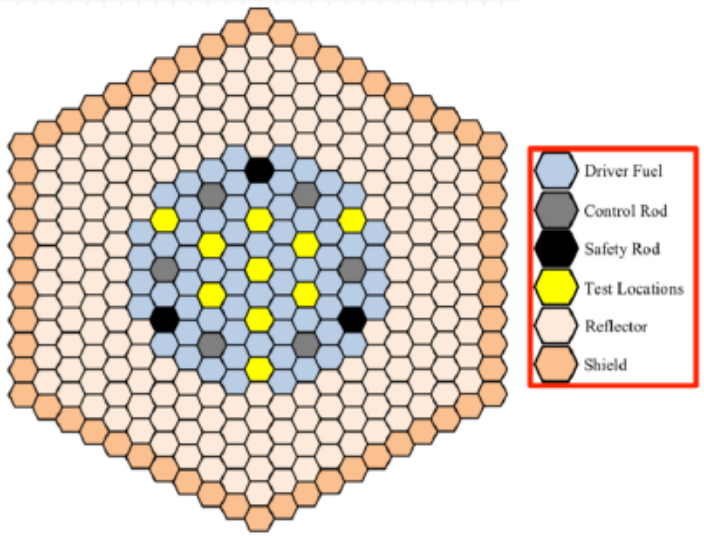
Science and technology leadership with strong influence on international standards and policies for the civilian use of nuclear energy and associated fuel cycles.

*) K. Pasamehmetoglu, Versatile Test Reactor Overview, Advanced Reactors Summit-VI, Jan 31, 2019

Versatile Test Reactor (VTR)

Preliminary requirements/assumptions for VTR

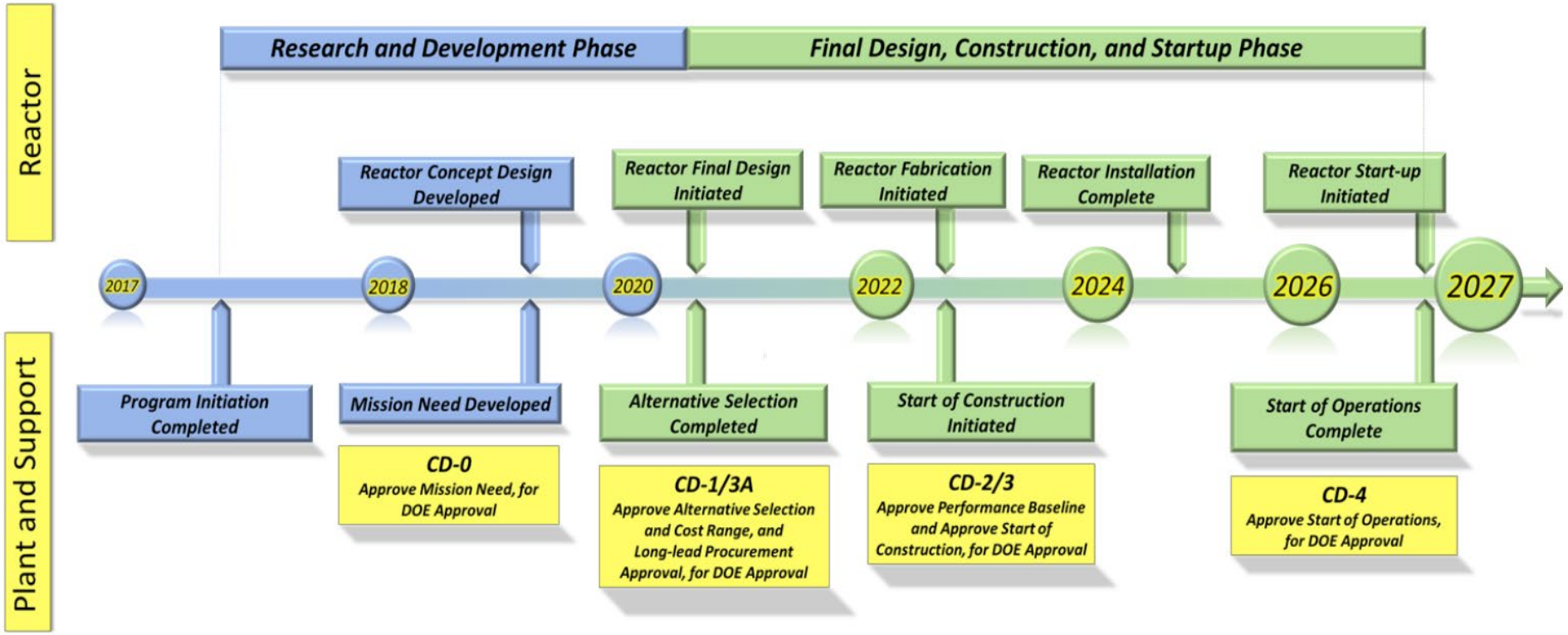
Parameter	Target
High neutron flux	≥ 4 x 10^{15} n/cm^2-s
High fluence	≥ 30 dpa/yr
High test volume in the core	≥ 7 L (multiple locations)
Representative testing height	0.6 ≤ L ≤ 1 m
Flexible test environment	Rabbit & Loops (Na, Pb, LBE, He, Salt)
Advance instrumentation & sensors	In-situ, real time data
Experiment life cycle	Proximity to other infrastructure
Driver fuel life cycle management	Existing facilities as much as possible



ASSUMPTIONS:

- Mature Technology: Sodium-cooled pool type reactor
- Metallic alloy fuel (HALEU, LEU+Pu, DU-Pu)
- Novel testing capabilities
- Start date: 2026

VTR Program Timeline



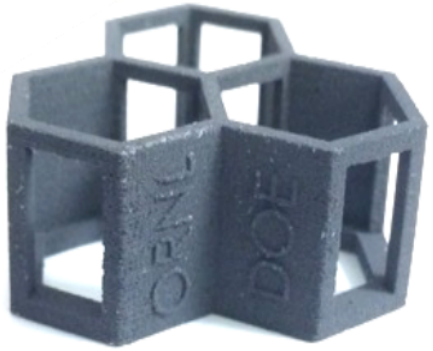
APRA-E/MEITNER Program

- **MEITNER (Modeling-Enhanced Innovation Trailblazing Nuclear Energy Reinvigoration)**
  - MEITNER seeks innovative technologies that can enable designs for lower cost, safer advanced nuclear reactors
  - ARPA-E provides capabilities on advanced modeling and simulation, techno-economic analysis, and subject matter expertise through Resource Team and project teams (awardees) will leverage these resources for modeling and simulation support, design assistance, and information on the state of the art in relevant areas
- **Awarded projects (2-3 years)**
  - HolosGen, LLC -*Transportable Modular Reactor by Balance of Plant Elimination*
  - Yellowstone Energy - *Reactivity Control Device for Advanced Reactors*
  - North Carolina State University - *Development of a Nearly Autonomous Management and Control System for Advanced Reactors*
  - State University of New York at Buffalo - *Reducing Overnight Capital Cost of Advanced Reactors Using Equipment-based Seismic Protective*
  - University of Illinois at Urbana-Champaign - *Enabling Load Following Capability in the Transatomic Power MSR*
  - Westinghouse Electric Company, LLC - *Self-regulating, Solid Core Block "SCB" for an Inherently Safe Heat Pipe Reactor*
  - MOLTEX – *Rigid Elastic Composite Civilworks (RECC) in Advanced Reactors*
  - Stony Brook University - *Technology Enabling-EPZ Micro Modular Reactors*
- **Additional ARPA-E Solicitation on "Leveraging Innovations Supporting Nuclear Energy" in following topics;**
  - Advanced control, high-performing moderator for gas-cooled reactor, ultra-high temperature power conversion, flexible power production, and advanced construction techniques.

Transformational Challenge Reactor (TCR) Program

- The Transformational Challenge Reactor (TCR) is not a 'new' reactor, but rather a demonstration of a very innovative approach to additive manufacturing through 3-D printing.
- The TCR approach has the potential to make SMRs more price competitive with other current energy options

- TCR program targets a new approach to boost nuclear energy development and deployment made possible by the effective combination of advanced manufacturing technologies with materials and computational sciences
- The program aims to provide answers to fundamental questions in four key areas:
  - Advanced designs
  - High performance materials
  - Accelerated qualification
  - Enhance sensing towards autonomy
- The output and insights gained from this program may be adopted by the advanced reactor community to accelerate their pace of technology deployment into the market



3D printed high-purity SiC heat exchanger and grid structure

NCSU Nuclear Engineering Department

Department of NUCLEAR ENGINEERING
NC STATE UNIVERSITY

- First university reactor and nuclear engineering program in USA
- Currently the largest stand-alone NE department with research reactor in the Southeast
- 19 tenured/tenure-track, 3 research & 1 teaching faculty
- 2 open faculty positions for this 2018-2019 academic year
- 4 Distinguished & Endowed Professorships, 2 Distinguished Alumni Graduate Professors & 1 Distinguished Alumni Undergraduate Professor
- 4 Joint Faculty Appointments (JFAs) with ORNL & 3 JFAs with INL
- 130 (100 PhD) graduate & 111 undergraduate students

NCSU Nuclear Engineering Department

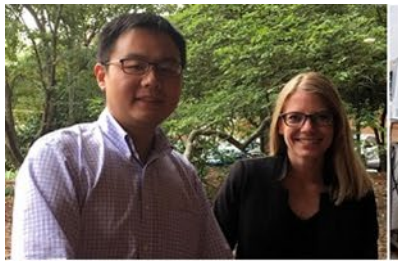
Department of NUCLEAR ENGINEERING
NC STATE UNIVERSITY

Research Areas

- Nuclear Power Design & Safety Analysis
- Radiation Science & Engineering
- Plasma Science & Engineering
- Nuclear Materials, Waste Forms & Storage
- Nuclear Computational Science
- Nuclear Security & Nonproliferation

Research Facilities, Consortia & Centers

- Nuclear Reactor Program - 1 MW (2 MW) PULSTAR Reactor & Research Facilities
- Consortium for Advanced Simulation of LWRs (CASL)
- Consortium for Nonproliferation Enabling Capabilities (CNEC)
- Consortium for Engineering Applications of Radioisotopes (CEAR)
- Participation in the Center for Critical Infrastructure Protection & Facility Decommissioning (CNEFS)
- Consortium for Nuclear Power (CNP) on the basis of Reactor Dynamics and Fuel Modeling Group (RDFMG) & CTF Users' Group



NCSU Nuclear Engineering Department

Department of NUCLEAR ENGINEERING

NC STATE UNIVERSITY

- **NC State's Nuclear Engineering programs are recognized and respected nationally and internationally**
- **NC State's Nuclear Engineering Graduate Program Ranked #3 by US News & World Report in 2019**
- **NC State's Online Master of Nuclear Engineering is ranked #1 by Best College Reviews**
- **National Research Consortia Leadership**

  Palmtag: CASL Chief Technologist

  Azmy: CNEC Director ♦ Mattingly: CNEC Chief Scientist
- **Special Faculty Appointments**

  Gilligan: Director, US-DOE's Nuclear Energy University Program (NEUP)

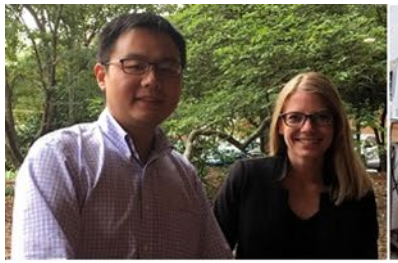
  Turinsky: Presidential appointment to the Nuclear Waste Technical Review Board (NWTRB)
- **International Programs Leadership**

  Ivanov & Avramova: Coordinators of OECD/NEA LWR UAM Benchmark activities

  Ivanov: IAEA CRP on HTGR UAM Coordinator

  Avramova: CTF Users Group Coordinator
  (60 global organizations from industry, research institutes, regulators & academia)

  Ivanov: Member of the Nuclear Science Committee (NSC) of the Nuclear Energy Agency (NEA)-OECD and Chair of Working Party on Scientific Issues of Reactor Systems (WPRS) at NSC, NEA-OECD



Undergraduate Program

Department of NUCLEAR ENGINEERING
NC STATE UNIVERSITY

ANS Student Conference 2019
April 4-6 at Virginia Commonwealth University

Student Participation: **Seven** Senior Design Teams & **Five** CASL Student Researchers Presented. **Thirty-Five** NCSU students in attendance. **Four** Faculty & Staff Representatives.

4 Winners in Designated Categories

'ISOTOPES & RADIATION' CATEGORY WINNER - *Design and Optimize Molybdenum-99 Production Capability*

Faculty: Drs. Ayman Hawari and Jason Hou; External Sponsors: Dr. Ugur Mertyurek (Oak Ridge National Laboratory)

'FUEL CYCLE & WASTE MANAGEMENT' CATEGORY WINNER - *Core Design using PRISM and Coupling Formosa to PRISM*

Faculty: Dr. Jason Hou; External Sponsors: Drs. John Strumpell and Joseph Deciantis (Framatome)

'REACTOR PHYSICS' CATEGORY WINNER - *Design of a Critical Benchmark Experiment for Molten Sodium Coolant*

Faculty: Dr. John Mattingly; External Sponsors: Dr. Jesson Hutchinson (Los Alamos National Laboratory)

'OPERATIONS & POWER' CATEGORY WINNER - *BWRX-300 Load Follow*

Faculty: Dr. Robert Hayes; External Sponsors: Dr. Christer Dahlgren (GE Power)

NCSU awarded bid to host ANS Student Conference 2020
April 5-7, 2020

ANS Student Organizing Committee Co-Chairs:
Jonathan Crozier & Ishita Trivedi
ANS Student Chapter Co-Advisors:
Robert Hayes & Lisa Marshall

Graduate Program

Future Fall 2019 Profile

**Subject to change*

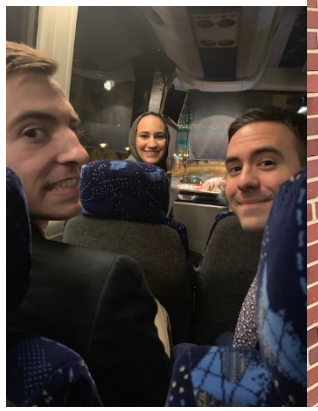
Incoming Students: 35

- PhD: 17 *(12 funded including 5 fellowships, 5 self-funded)**
- MS: 7 *(1 funded, 6 self-funded)*
- MNE-ABM: 4 *(4 funded)*
- MNE-Distance: 7

** 3 Current students awarded NEUP Fellowships beginning Fall 2019*

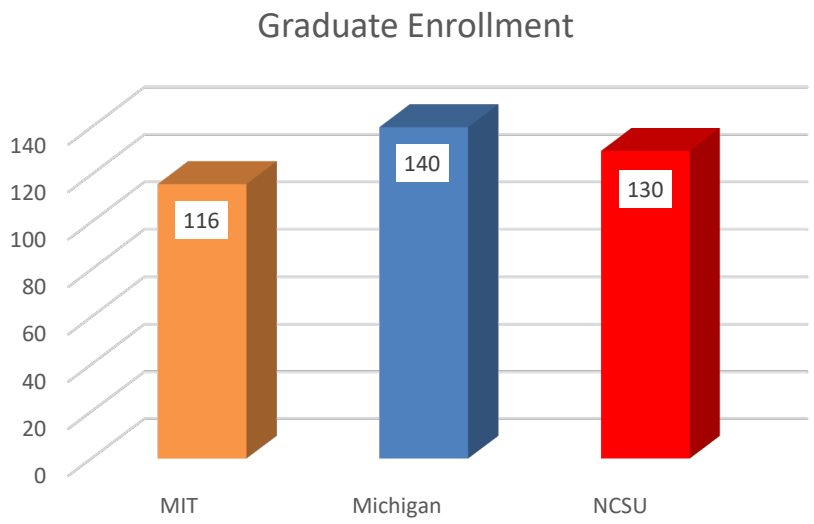
Expected Fall 2019 Graduate Population: 145*

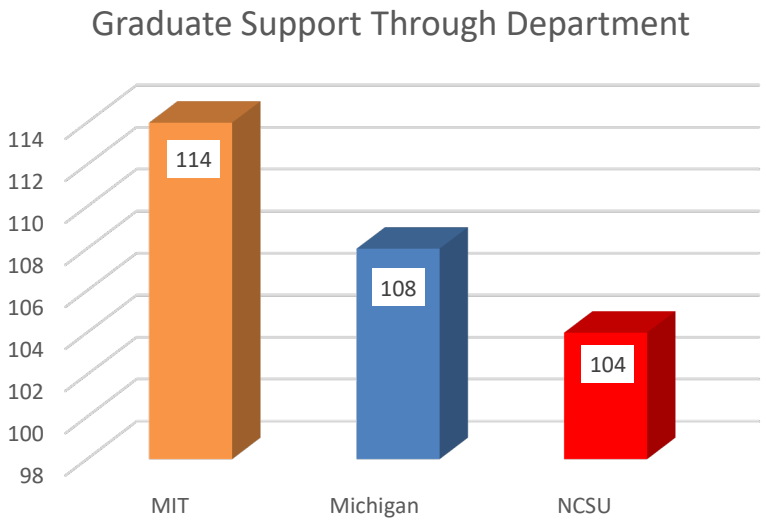
- PhD: 106
- MS/MNE: 16
- MNE-Distance: 23

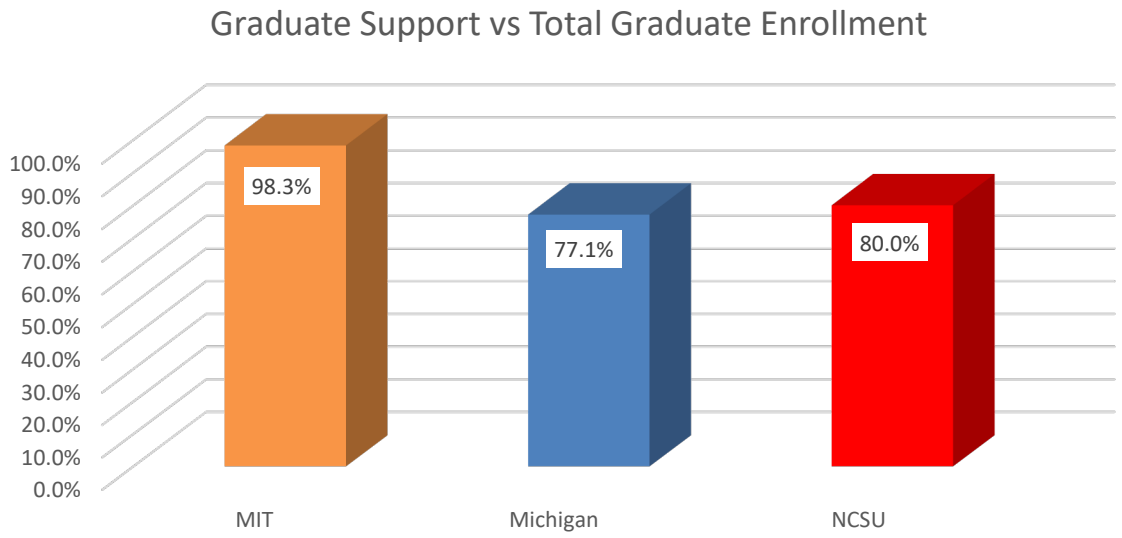


Graduate Program

Comparison with other Nuclear Engineering Departments







Graduate Support Includes:

- RA
- TA
- Internal/External (U.S)
- Fellowships

Nuclear Reactor Program

UNC Board of Governors Center

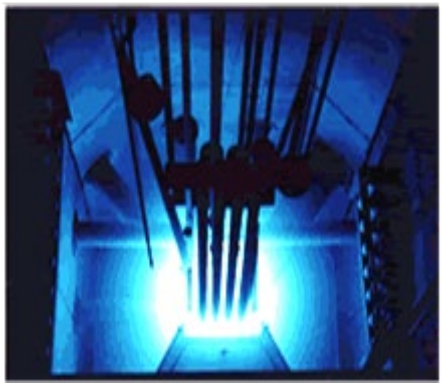
Department of NUCLEAR ENGINEERING

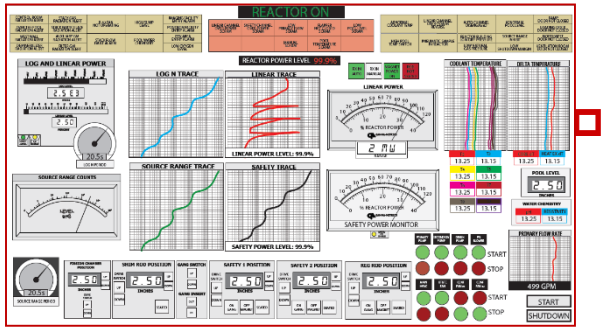
NC STATE UNIVERSITY

NRP

https://www.ne.ncsu.edu/nrp/

- **Operations**
  - Director: Ayman Hawari
  - 30 operating and technical staff
  - $2.5 M average annual expenditures
- **PULSTAR Reactor**
  - Critical in 1972
  - 1-MWth power (2-MWth upgrade pending with NRC)
  - UO2 fueled (4% & 6% enriched in U-235)
  - Open pool design
  - Light water moderated and cooled
- **Utilization**
  - 10,000 user hours annually
  - Support 24/7 3-shift operation
  - Utilization costs can be covered by the DOE's NSUF user system and the NSF's RTNN user network





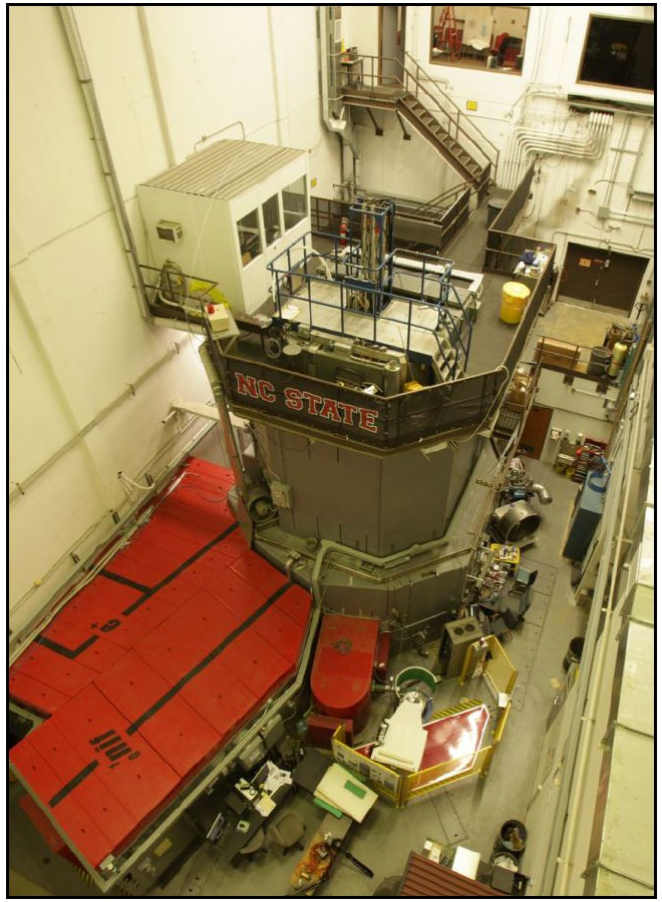
Mission

- **Education and Training**
  - Provide understanding of the physics and operations of nuclear reactors to the next generation of nuclear engineers
  - Training in radiological science and engineering
- **Research and Discovery**
  - Multidisciplinary center of radiation physics, interaction, and detection
  - State-of-the-art facilities for materials pre and post irradiation examination
    - Includes in-pool and ex-pool studies
- **Outreach, extension, service**
  - Support the national infrastructure through the use of nuclear methods in various aspects including medical and industrial

PULSTAR Reactor Bay
Major facilities

Major Facilities & Capabilities

- Neutron powder diffractometer (Upgraded)
- Neutron imaging (real time dynamic radiography and tomography)
- Intense positron beam
- Ultracold neutron source (ex-core testing)
- Fission gas release loop (beamport testing)
- Neutron activation analysis
- In-pool irradiation testing facilities
  - Facilities offer filtered thermal and meV monochromatic neutron beams, and monoenergetic keV positron beams



National & International Partnerships

- **Partner in the DOE/INL NSUF**
  - Experiments conducted at PULSTAR
- **Partner with DOE NE (and Labs)** to develop international educational programs
  - **Internet reactor laboratory**
- **Partner in NSF RTNN** (Research Triangle Nanotechnology Network)
- **Member of the NNSA Nuclear Data Advisory Group**
- **Lead of OECD/NEA WPEC SG42** TSL data group
- **Partner with IAEA** in various activities
  - Host of IAEA Fellows
- **Host of international scholars**
- **Organizer team for ICPA 2018 and IGORR 2019 meetings**

Representative publications

- A. Datta, Ayman I. Hawari, "Investigation of A Model Based Reconstruction Technique for Neutron Tomography at the PULSTAR Reactor," Nuclear Instruments and Methods in Physics Research A, 2019.
- K. K. H. Leung et al (as part of the nEDM collaboration), "The neutron electric dipole moment experiment at the Spallation Neutron Source," European Physical Journal, 2019.
- H. Zhou et al "Radiation-induced Changes of Point Defects in Ferroelectric Capacitors as Revealed by Doppler Broadening Positron Annihilation Spectroscopy," J. Applied Physics, vol. 124, no. 24, 2018.

CASL mission: Through usage of high performance computing, develop and apply the Virtual Reactor Simulator (VERA) to address 3 critical performance goals for nuclear power

1

Reduce capital and operating costs per unit energy by:

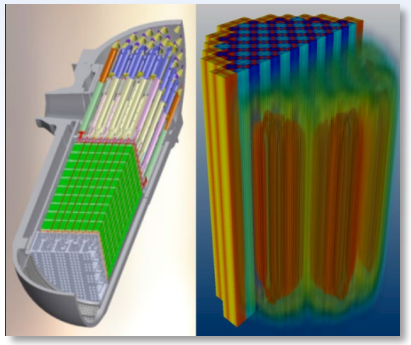
- Power uprates
- Lifetime extension

2

Reduce nuclear waste volume generated by enabling higher fuel burnups

3

Assure nuclear safety by enabling high-fidelity predictive capability for component and system performance from beginning of life through failure



CASL

NC STATE UNIVERSITY

The CASL Team

Core partners

Oak Ridge National Laboratory

Electric Power Research Institute

Idaho National Laboratory

Los Alamos National Laboratory

Massachusetts Institute of Technology

North Carolina State University

Sandia National Laboratories

Tennessee Valley Authority

University of Michigan

Westinghouse Electric Company

Current Individual contributors

CD-adapco

Rensselaer Polytechnic Institute

Texas A&M University

University of Tennessee – Knoxville

University of California – Santa Barbara

UCLA

Notre Dame University

Anatech Corporation

Core Physics Inc.

G S Nuclear Consulting, LLC

University of Texas at Austin

AREVA

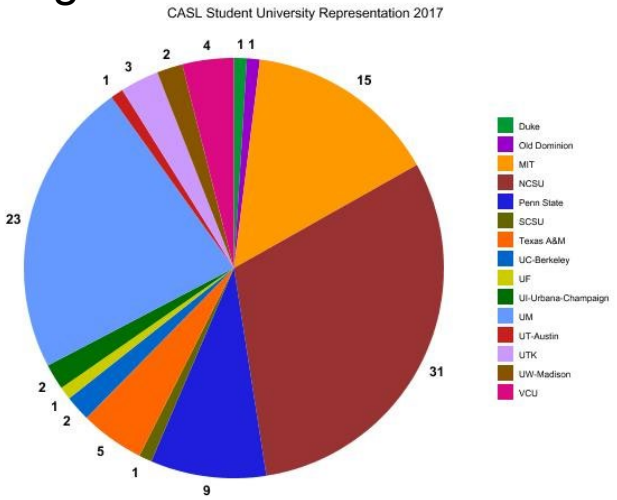
NC State Engagement in CASL

- Participants: 39
  - *9 faculty*
  - *1 staff*
  - *2 Post Docs*
  - *18 Grad students*
  - *(5 positions supported by Dean of Engineering)*
  - *6 UG students (Scholars)*
- Leadership Roles
  - *Chief Technologist (Palmtag)*
  - *Education Program Director (Doster)*
- Departments
  - *Nuclear Engineering (NE)*
  - *Material Science & Engineering (MSE)*
  - *Mathematics (MA)*
  - *Mechanical & Aerospace Engineering (MAE)*
- Joint Faculty Appointments (ORNL)
  - *Igor Bolotnov*

CASL Education Program led by NCSU

Program Charter:

- Integrate CASL technology into undergraduate and graduate curricula
- Develop a plan to educate industry users
- Encourage diversity of participation in CASL activities
- Advise Chair on educational development activities
- Review and recommend education curricula and programs



Program Activities:

- Recruiting at ANS Student Conference
- Undergraduate Research Scholars Program
- CASL Institute/Certificate Program 2016-2019
- CASL Summer Research Experience for Undergraduate (REU) 2015-2018

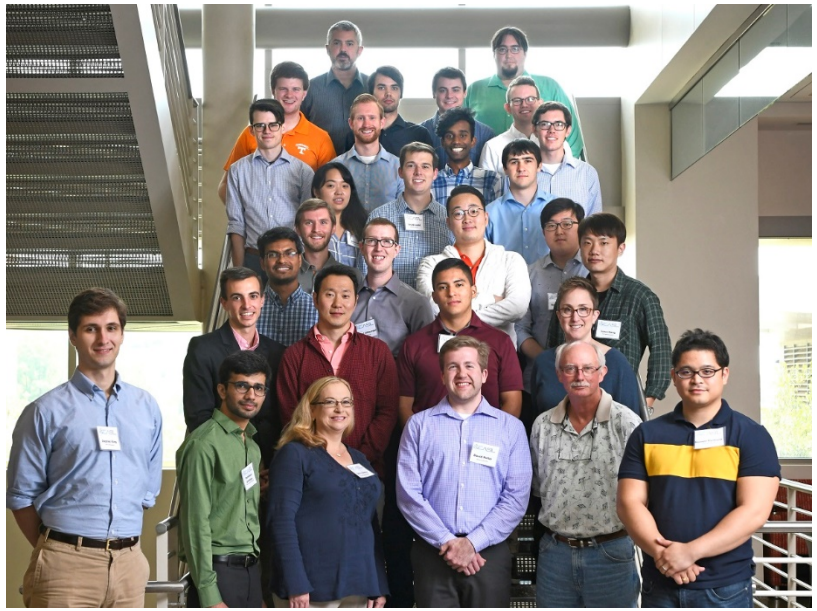
CASL Summer Institute (NCSU)

- The CASL Institute introduces participants to CASL and the VERA framework.
- Record lectures and instruction on the VERA codes including hands-on examples and projects.
- Served as first successful deployment of VERA training in an Open University environment with students logging over 6,000 core-hours in HPC usage (NCSU Henry 2 Cluster)
- 28 application accepted from over 40 applicants. 26 accepted invitation. 22 participants completed the 2-week course, earning a certificate based on a team project
- 2019 CASL Summer Institute planned for August at NCSU

CASL Institute serves as a model for future VERA deployments for the post-CASL user community

- NCSU IT personnel created unique scripts which allowed domestic and international students to run the software with no performance penalties while addressing Export Control concerns

- Qualifies for PE Continuing Education Credits



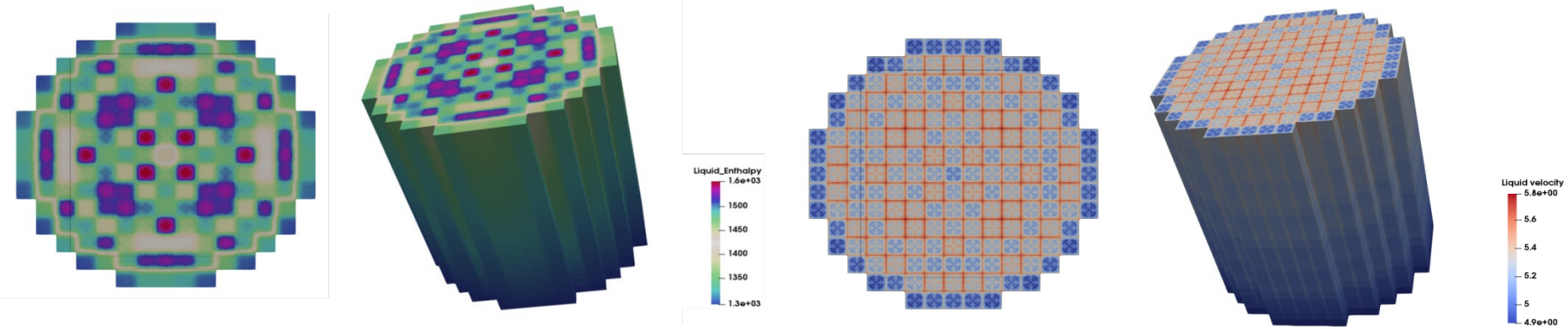
Consortium for Advanced Simulation of LWRs CASL

Department of NUCLEAR ENGINEERING

NC STATE UNIVERSITY

Signature capabilities that have been established through CASL:

- Reactor physics and multi-physics research with VERA (VERA is the most advanced 3D PWR reactor simulator in the world) – *Scott Palmtag*
- Thermal-hydraulics research in the area of DNS simulations applied to reactor design and safety analysis – *Igor Bolotnov*
- Single and multi-physics verification and validation as well as data driven modeling and validation – *Nam Dinh*
- Single and multi-physics uncertainty quantification and propagation – *Paul Turinsky*
- CTF sub-channel developments, verification and validation and uncertainty quantification; CTFFuel developments as well as Hi2Lo research using CFD to inform CTF for spacer grid effects – *Maria Avramova*



Consortium for Nuclear Power (CNP)

Consortsium for Nuclear Power
CNP

The *CNP mission* is to promote research and development, innovation, education, and training as well as provision of technical support/expert advice/consultancy services that benefit the nuclear industry and its regulation.

Established in July 2017

CNP major goals:

- Increase research output;
- Attract new sources of funding;
- Address grand challenges of nuclear power;
- Find and develop new collaborations;
- Develop new and novel areas of research;
- Become an internationally recognized entity for partnership;
- Increase outreach and public awareness;
- Provide excellence in education, mentoring and training;
- Manage the software UGs such as: CTF UG (core thermal-hydraulic simulator), Core design and fuel cycle optimization UG, HTGR software UG, V&V and UQ software UG, Nodal Simulator UG, etc.

Industry Advisory Board:

- *Southern Company Services, Inc., USA*
- *Tractebel Engineering S.A., Belgium*
- *Rolls-Royce Power Engineering plc, UK*
- *Global Nuclear Fuel - Japan Co, Ltd.*
- *Framatome, France-USA-Germany*

University Members:

- *Penn State, USA*
- *University of Cambridge, UK*
- *Imperial College London, UK*
- *Hacettepe University, Turkey*
- *University of Florida*

Consortium for Nuclear Power (CNP)

Department of NUCLEAR ENGINEERING

NC STATE UNIVERSITY

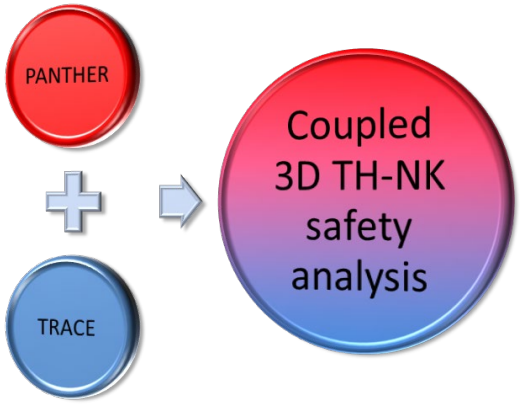
Industry Advisory Board

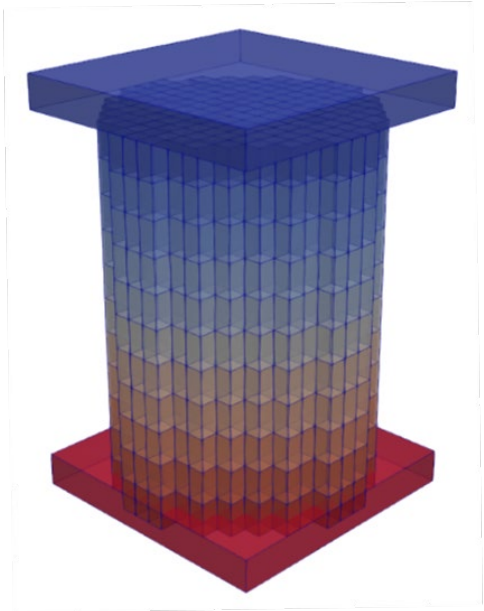
Southern Company, TRACTEBEL, ENGIE, NC STATE UNIVERSITY, framatome, ROLLS ROYCE, GNF

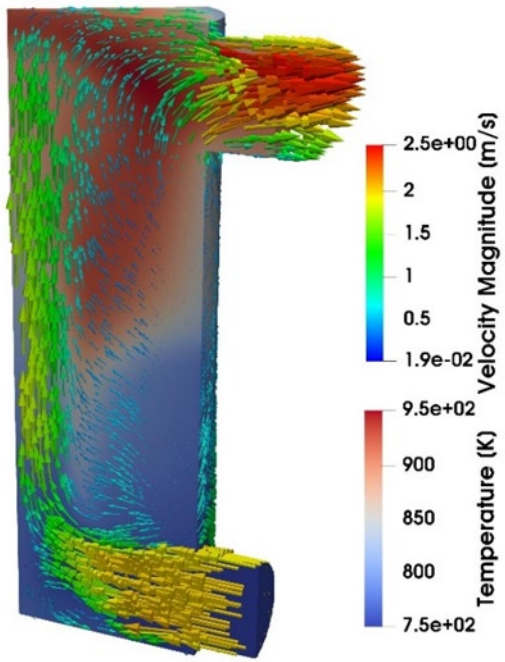
CNP exists as a five-tier member supported mechanism for its funding

Core and enhancement research projects, approved by Industry advisory board (IAB)

Projects are conducted by a faculty member as a PI, research associates, post-docs and graduate students in cooperation with industry/lab partners







CNP current projects:

- Multi-physics modelling and simulation for design and safety analysis of a Liquid Fuel Molten Salt Reactor using Gen-Foam;
- TRACE/PANTHER coupling ;
- Reduced Order Model for Transient Fuel Gap Properties;
- Developing a user guidance for lower and upper plenum modelling with CTF;
- Coupling CTF (core) with RELAP5-3D (system);
- Advanced nodal codes developments regarding efficiency and numerical stability improvements.

Consortsium for Nuclear Power
CNP

CTF code - modern and robust thermal-hydraulics reactor core simulator

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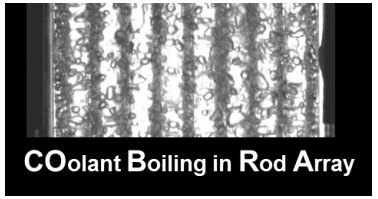
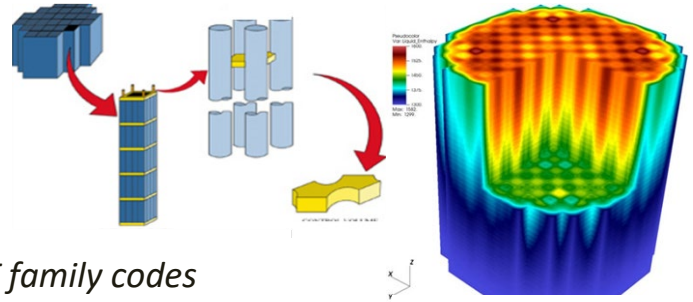
CTF provides the best available sub-channel methods to the scale of an entire reactor core

Two-fluid three-field two-phase flow model

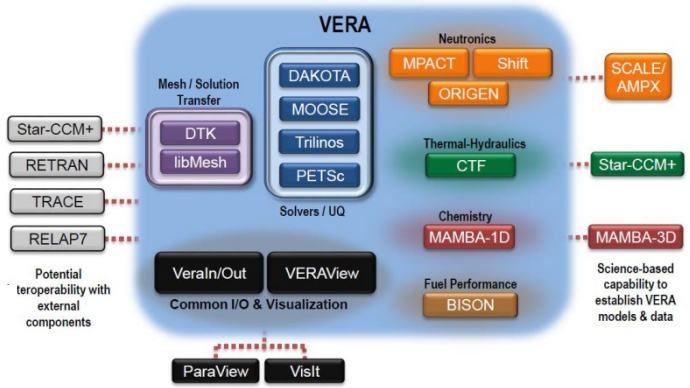
Current CTF is being jointly developed by RDFMG-NCSU and ORNL within DOE CASL project



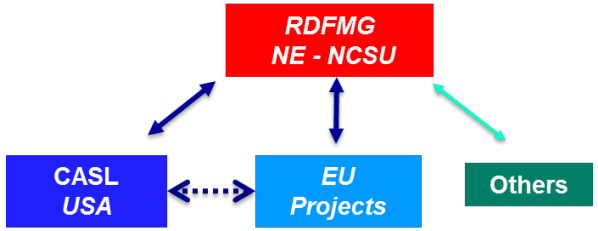


CTF originates from COBRA-TF family codes

Subchannel Resolution



CTF User's Group – more than 50 active members



Leverage and combine all non-proprietary developments, improvements, modifications and error fixes; and the available verification and validation database and application experience of CTF from different organizations and activities.

CTF -5 Meeting: May 14-15, 2018, NINE, Lucca, Italy

NCSU leads in Nuclear Engineering Applications of Data Science and Analytics and Artificial Intelligence

- Data science, data analytics and artificial intelligence techniques have been utilized in three applications in nuclear engineering including experiment design, uncertainty scaling, and plant control
- There is a unique opportunity to integrate a modern data technology platform (Data Science Methods, and Data Analytics - Big Data, Deep Data and Smart Data) in advanced modeling and simulation of nuclear power plants including verification, validation and uncertainty quantification
- Data analytics on large data sets can provide insights for decision-making as well as better prediction of equipment performance and maintenance requirements
- NCSU leads on nuclear energy applications of data analytics coupled with artificial intelligence
- Two related projects with DOE led currently by NCSU (PI – Nam Dinh, Co-PIs – Maria Avramova and Igor Bolotnov):
  - *Development and Application of a Data-Driven Methodology for Validation of Risk-Informed Safety Margin Characterization Models – NEUP IRP*
  - *Development of a Nearly Autonomous Management and Control System for Advanced Reactors – APRA-E MEITNER*

Conclusions

- Nuclear Engineering Department, NCSU is well established and nationally and international recognized as a premier department:
  - High relevance of our capabilities to national agenda
  - Credibility in the commercial power sector and strong international connections
  - We are ready to assist and support the NC Energy Policy Council in the area of nuclear energy
- Advances are being made that will make nuclear energy a more viable energy source
- NC can economically (vendors, engineering service companies and utilities located in NC) and environmentally benefit from further development of nuclear energy in the state
- The NCSU Nuclear Engineering Department is well established and positioned to assist and provide support in such development

Conclusions

- We propose to create NC Nuclear Energy Consortium similar to the Virginia Nuclear Energy Consortium (VNEC)

  http://virginianuclear.org/about-vnec/
- In 2013, the Governor and General Assembly created the Virginia Nuclear Energy Consortium Authority
- In accordance with the founding statute, VNEC was created to represent stakeholders invested in the development of nuclear energy.
- These stakeholders include the state of Virginia, institutions of higher education, nuclear energy companies, suppliers, and local organizations who support the advancement of the nuclear industry
- Each of VNEC's members is represented on the Board of Directors for VNEC
- VNEC Membership is open to any organization that seeks to strengthen and advance nuclear energy in Virginia.