Development of Advanced Nuclear Technologies

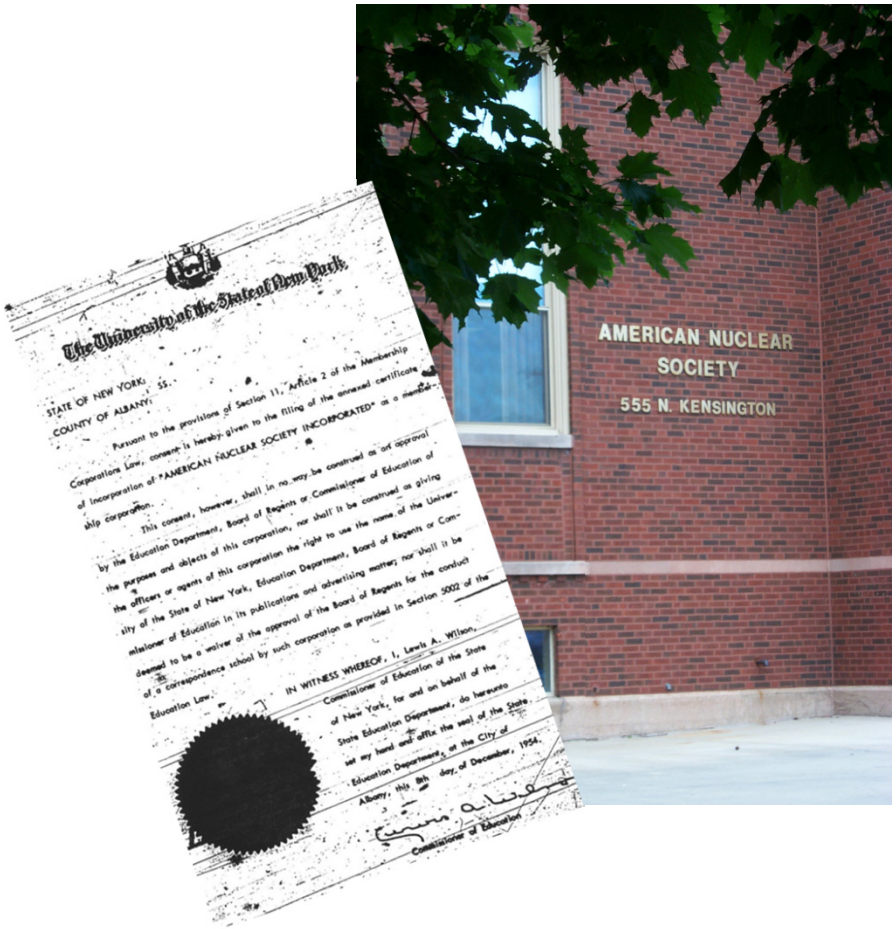
American Nuclear Society

Andrew C. Klein, PhD, PE

Vice-President/President-Elect of ANS
Editor, *Nuclear Technology*
Professor of Nuclear Science and Engineering
Oregon State University

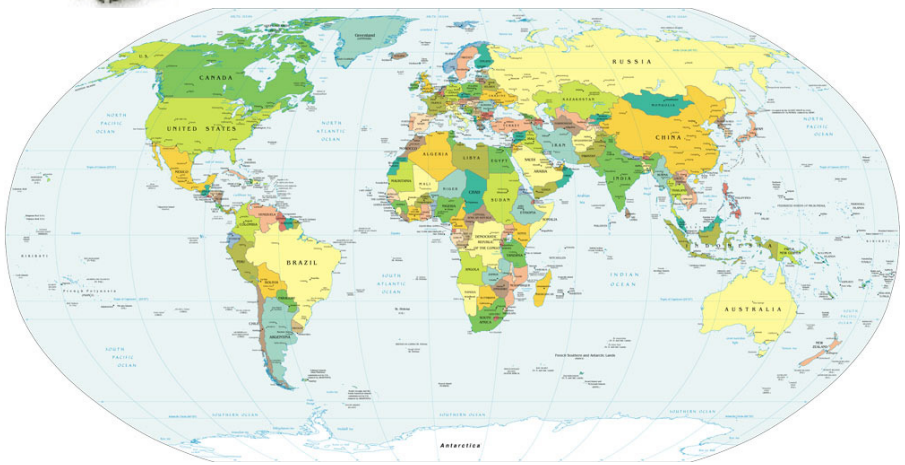
April 2016

About ANS



- Founded in December 1954
- Creates a forum for knowledge sharing
- Convenes countless conferences
- Stimulates discussion and debate among professionals
- Fosters interest in the profession
- Provides recognition for excellence
- Influences the conversation about nuclear with those outside the field

Some Vital Statistics



- About 11,000 individual members
- Nearly 100 organizational members
- International alliances, bilateral agreements with some 30 nuclear societies outside the U.S.
- Over 60 local sections
  (including 9 outside the U.S.)
- 20 specialty professional divisions and technical groups including the Young Members Group
- More than 30 local student sections

Nuclear Energy: Still Going Forward

ANS

The Importance of Nuclear Energy

Evolution of Nuclear Power

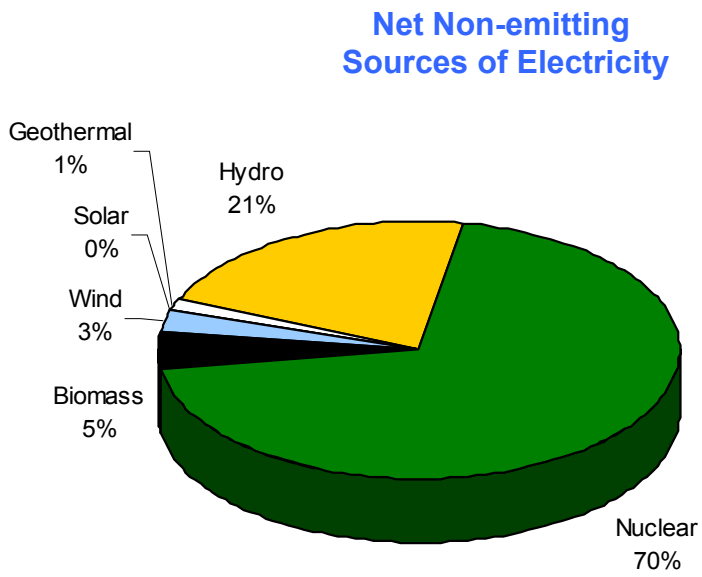
Small Modular Reactors

Advancing Advanced Reactors

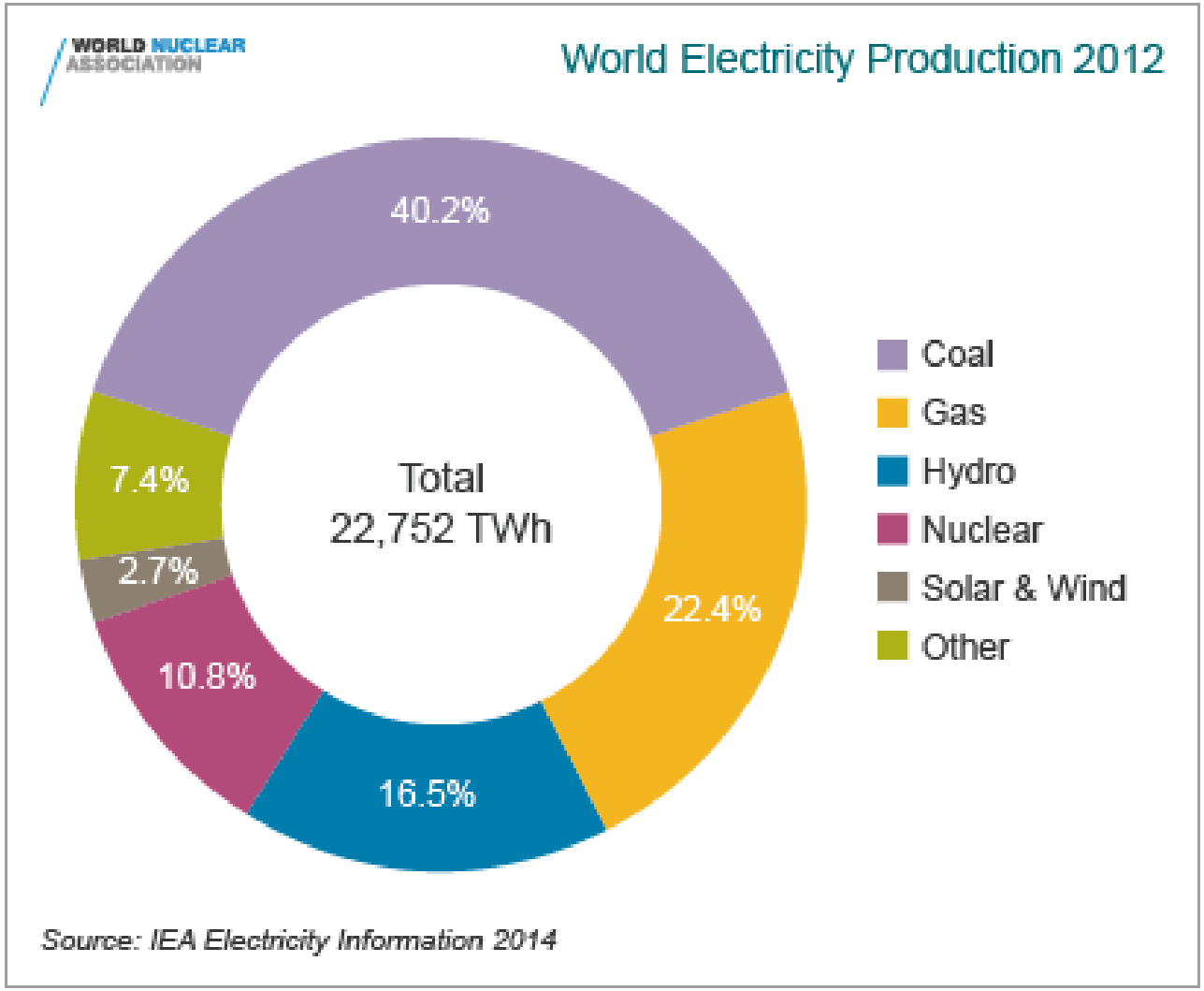
What can you do?

Nuclear – Important, Clean Energy Source

- **Nuclear power is the clean, reliable, expandable base load energy source**
  - **Provides over 70% of U.S. emission-free electricity**
  - **Avoids about 600 MMTCO$_2$ each year**
  - **Helps reduces overall NOx and SOx levels**

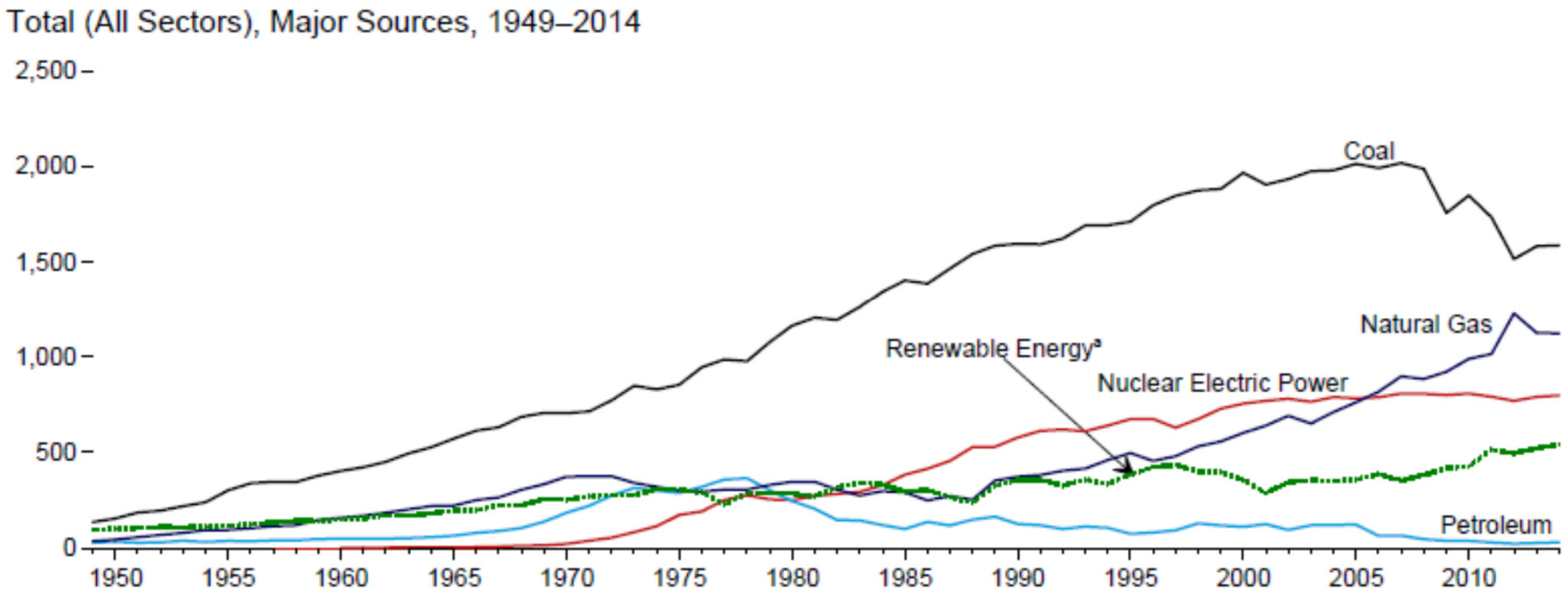


Current Energy Consumption is Carbon Based



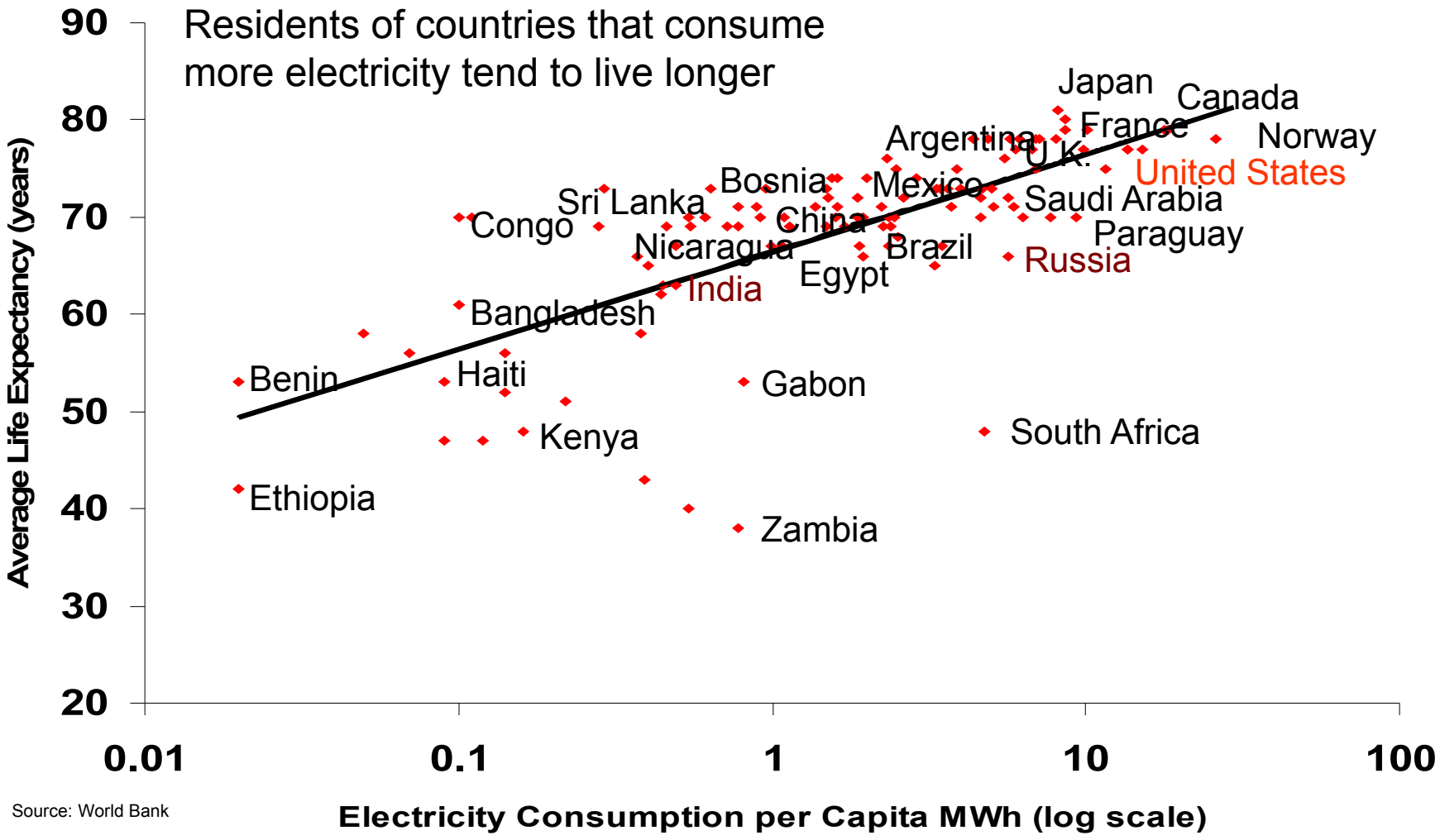
WNA, 2014

Electricity Net Generation (Billion kW-Hrs)



Source: Monthly Energy Review, US Energy Information Administration, March 2015

Cross Country Comparisons of Life Expectancy & Electricity Consumption

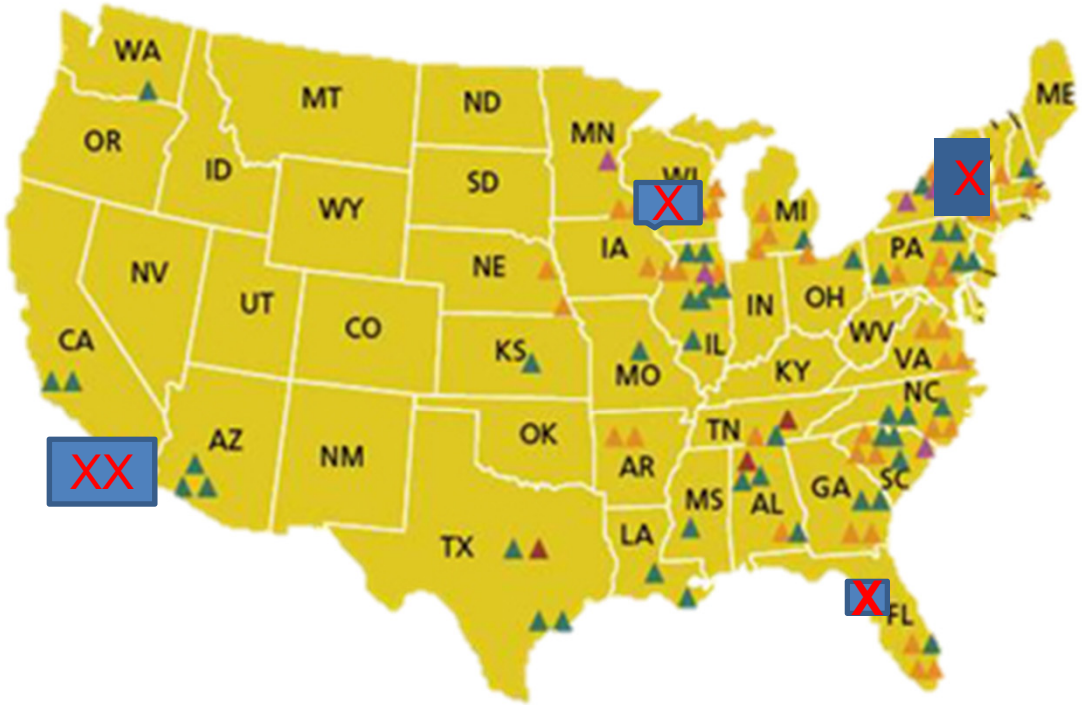


Source: World Bank

So, What's Happening?

- Deregulated markets in US do not recognize emissions reduction or even capacity factors
- Price of natural gas
- Overall slowing of demand growth
- Five units in US shut down since 2013
- Three more already scheduled
- More operating units at risk
- No credit for operating plants in the EPA CPP
- Only five new units presently under construction
- Little recognition of the vital role nuclear plays in reducing emissions

US nuclear units shut down since 2013



Fitzpatrick scheduled to close January 2017
Pilgrim to shut down in 2019
Oyster Creek scheduled to close in 2019

Some Glimmers of Rationality?

- EPA CPP does provide credit for new nuclear
- White House Summit (November 2015); clear declaration of the need for nuclear and innovation
- Wisconsin and Kentucky Legislatures repeal of nuclear prohibition
- NY State PUC staff statement

Fight to Save US Nuclear Plants

Include something on

- ANS Nuclear In the States Toolkit
- Upcoming DOE-NE Workshop
- Save US Nuclear activities
  - Environmental Progress
  - Third Way
  - Breakthrough Institute
  - Clean Air Task Force
  - Others

Nuclear In the States Toolkit

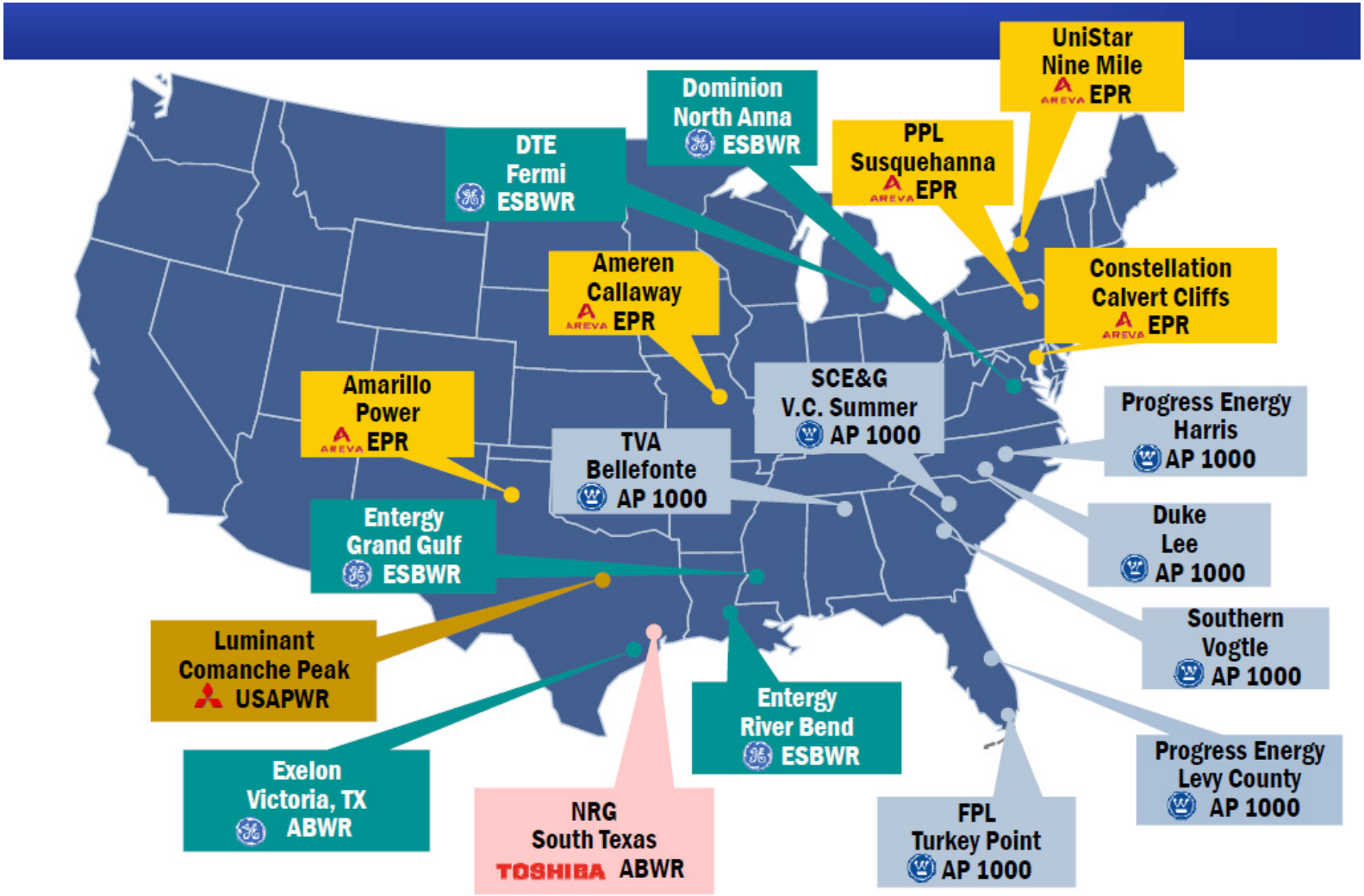
Policy options for States considering the role of nuclear power in their energy mix

- Policy pathways to support the current nuclear fleet
- Prevent early retirement
- Comprehensive overview of a wide range of policy and other options
  - Federal-level initiatives such as federal tax credits
  - Community-level options like public hearings
  - Policy tools
  - Market-based tools
- State policymakers determine methods to best fit their goals
  - Policy
  - Environmental
  - Energy
  - Economic
- Each State faces a different set of circumstances regarding nuclear power.

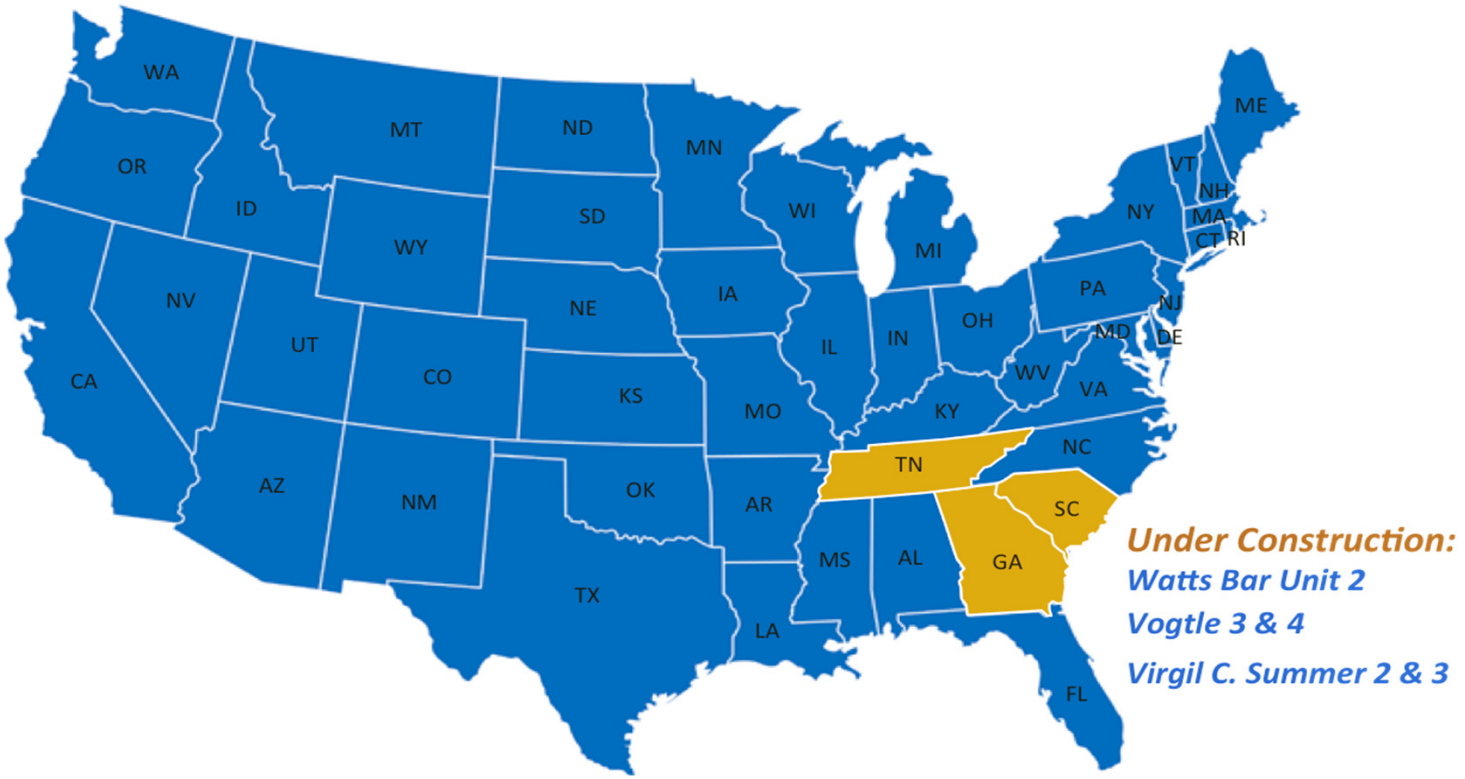
Toolkit Elements

- **Increase Nuclear Plant Revenue/Revenue Certainty**
  - **Power Contracts**
  - **Low-Carbon Portfolio Standard**
  - **Carbon Tax**
  - **Nuclear Portfolio Standard**
  - **Clean Air Portfolio Standard**
- **Public Hearings/Meetings**
- **Clean Power Plan**
- **Industry Consolidation**
- **Public/Government Ownership**
- **Lower Costs**
- **Capacity Markets**
- **Electricity Markets**
- **Return to Economic Regulation**
- **Others**

Outlook on New Construction



Five New Units Under Construction



Source: NEI - Nuclear Units Under Construction Worldwide

Challenges to New Construction

- High capital costs ($8-12 billion)
- Used fuel issues
- Availability of nuclear qualified components
- Availability of skilled personnel
- Lengthy licensing and construction schedule
- Cost and schedule performance
- Public concerns/misunderstandings
- Price/availability of natural gas

Advanced Nuclear Technologies

Opportunities

- Highly Efficient Technologies
- New Instrumentation and Control Strategies
- Modular Construction
- Preapproved Sites
- Dramatically Reducing Waste Production
- Proliferation Resistant
- New Markets

Challenges

- Turning the Economy of Scale on it's Head?
- Different Operations and Industry Comfort?
- New Licensing Strategies/Requirements?
- Inexperience with New Technologies?
  - Industry?
  - Regulator?
  - Workforce?

Evolution of Nuclear Power

ANS

Generation I

Early Prototype Reactors

- Shippingport
- Dresden
- Fermi I
- Magnox

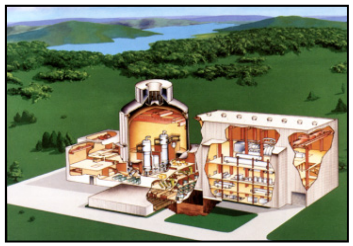
Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- VVER/RBMK

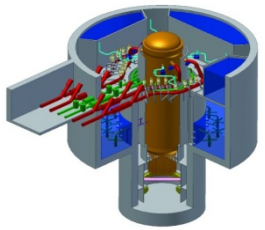
Generation III

Advanced LWRs



- ABWR
- System 80+
- AP600
- EPR

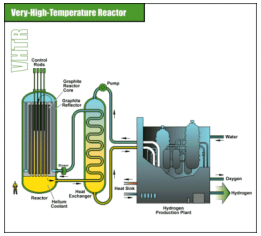
Generation III+



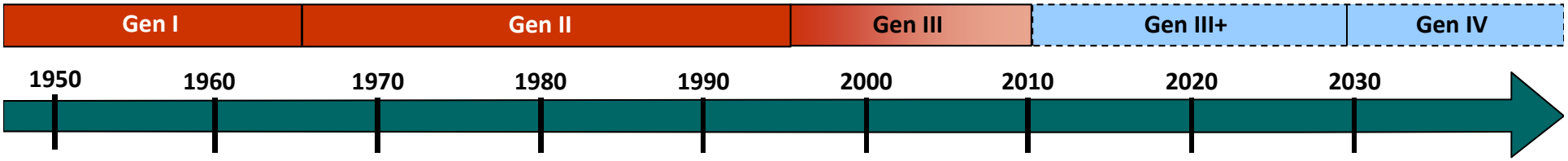
Near-Term Deployment

- AP1000
- PBMR
- SWR-1000
- ABWR-II

Evolutionary Improved Economics



- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant



1. U.S. Department of Energy Gen-IV Roadmap Report

U.S. DEPARTMENT OF ENERGY

Advanced Nuclear Technologies

Many recent new and old ideas

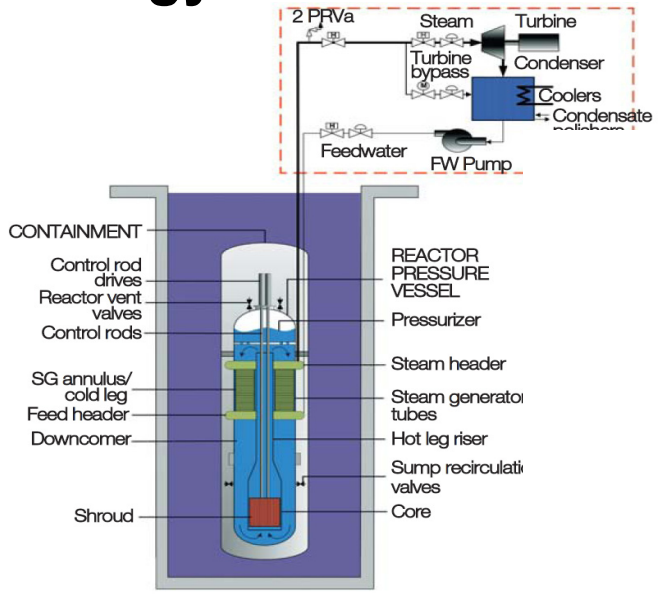
- ❑ Small Modular Reactors
- ❑ Advanced Reactors
- ❑ Innovative Nuclear Concepts
- ❑ Innovative Development Constructs
- ❑ Innovative Nuclear Business Models

Small, Modular Reactors

- Small Modular Reactors (SMRs) are being developed for deployment around the world
  - Offer enhanced passive safety features and promise lower construction and financing costs
  - Domestic market focused on replacement of 600+ smaller, aging coal fired plants
  - Export market focused on emerging economies with smaller grids

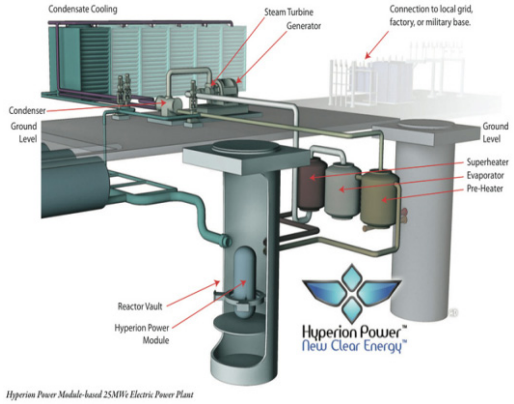
Benefits of SMRs

- **SMRs potential for changing social and energy supply paradigms is compelling**
  - **Jobs**
  - **US goods and services**
  - **National Security and energy policy**
  - **Climate change benefits**
  - **Complement large reactor programs**

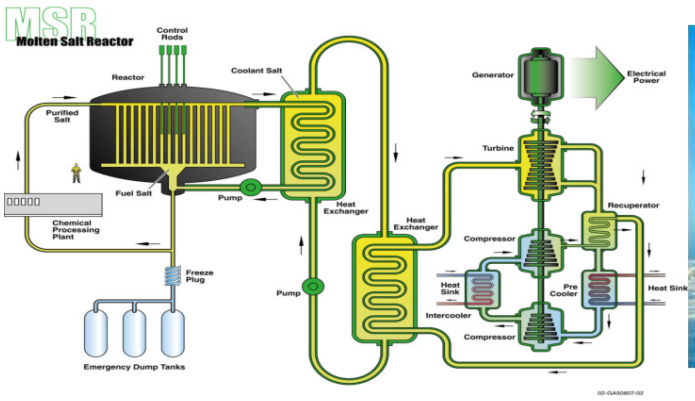


NuScale Integral PWR

SMR licensing must address technology-neutral Issues

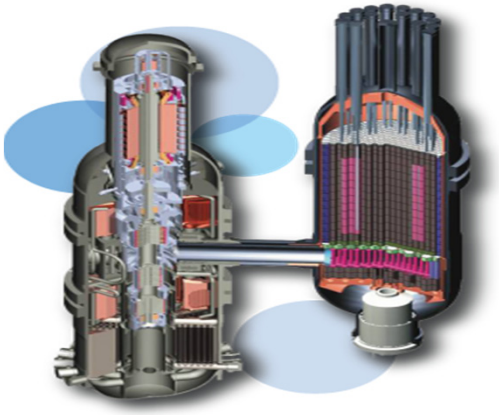


Hyperion Reactor

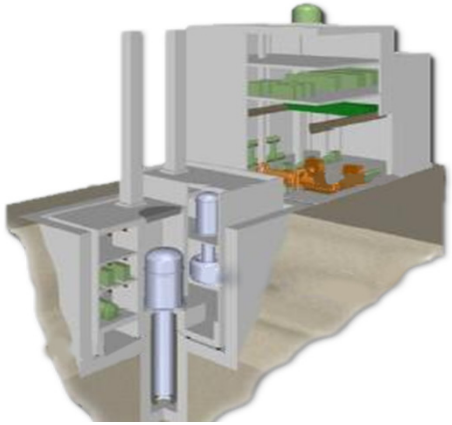


Molten Salt Reactor

KLT-40 Icebreaker Reactor
(35 Mwe floating nuclear power plant)



General Atomics MHR

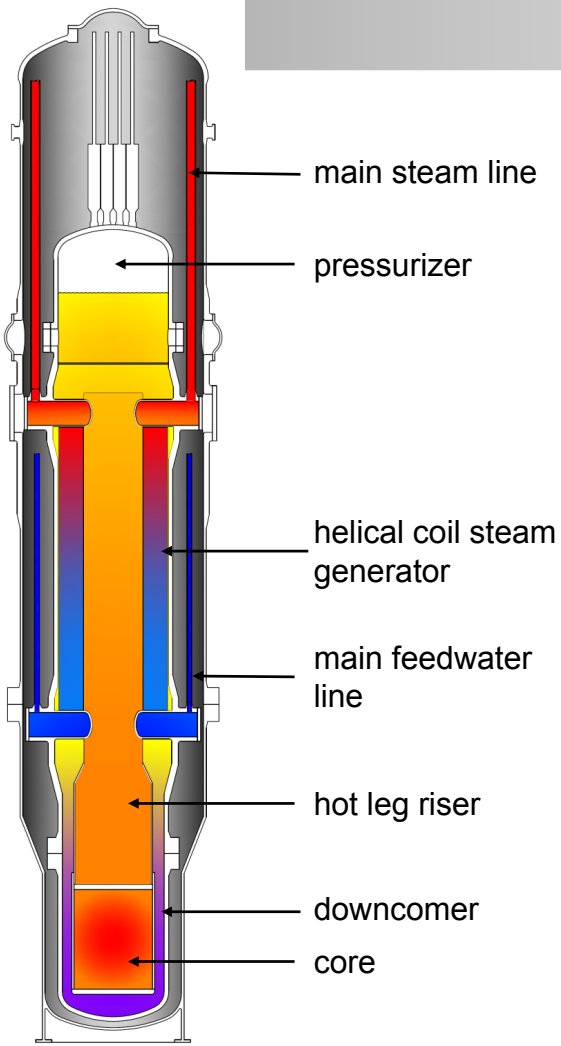


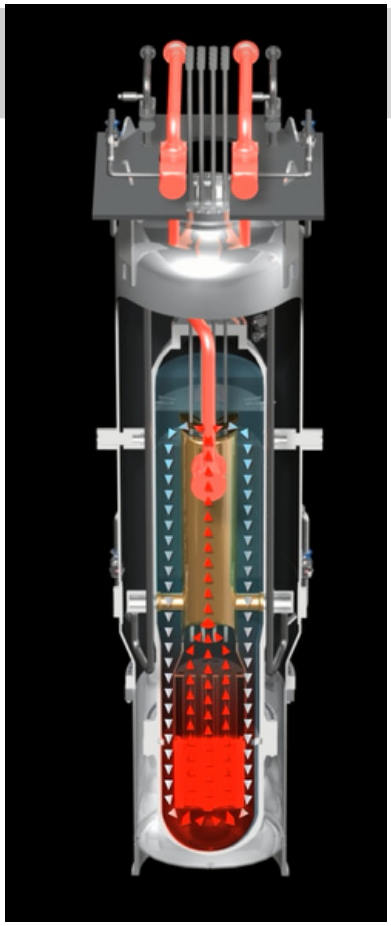
Toshiba 4S (10 to 50 MWe) Sodium-cooled

PBMR (165 MWe)

NuScale Reactor Design Features

- Primary side
  - natural circulation
  - integral pressurizer
  - No Reactor Coolant Pumps
- Secondary side
  - feedwater plenums
  - two helical steam generators with large surface area per volume to maximize thermal efficiency
  - steam plenums



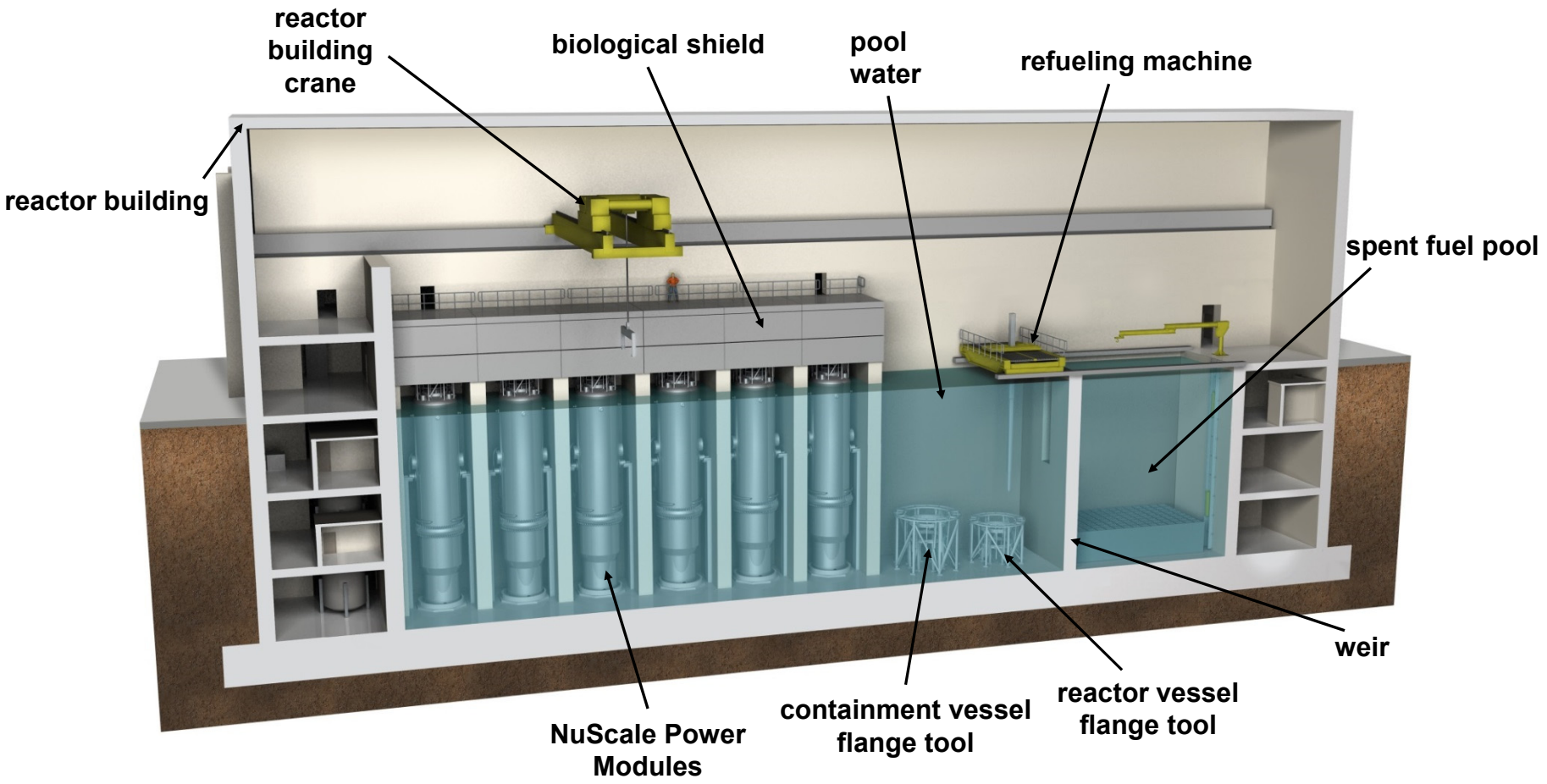


primary coolant flow path

NuScale Power™

Reactor Building Cross-Section

Reactor building houses reactor modules, fuel pool, and reactor pool

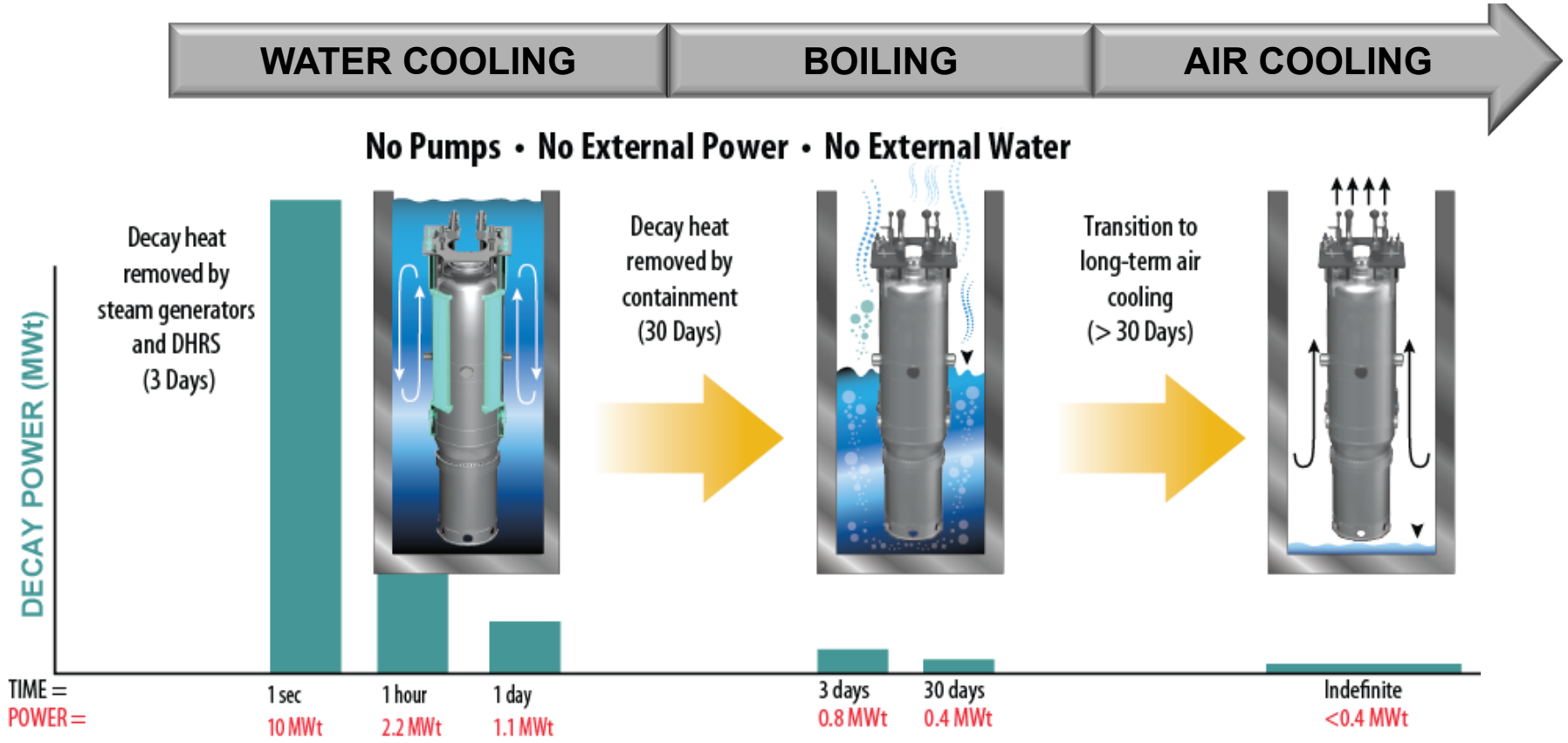


NuScale Power™

Response to Loss of All Power

Stable Long-Term Cooling Under all Conditions

Reactor and nuclear fuel cooled indefinitely without pumps or power



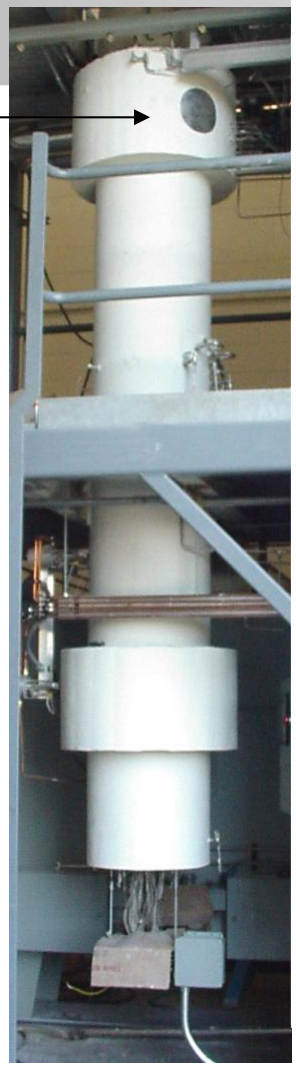
** Based on conservative calculations assuming all 12 modules in simultaneous upset conditions and reduced pool water inventory*

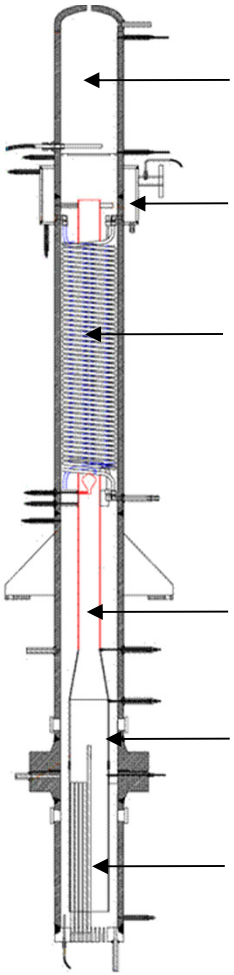
NuScale Integral System Test Facility

reactor pressure vessel

reactor building pool

containment vessel





NuScale Power™

Advancing Advanced Reactors

Generation IV Designs and Concepts

- US Department of Energy
- International Development
- Large Companies – Private Investments
- Startup Companies – Venture Capital

Advanced Reactor Missions

- Process heat applications including cogeneration
- Actinide management to extend fuel resource utilization
- Reduce the nuclear waste burden
- Integration of with intermittent energy sources for reliable energy systems
  - Hybrid Energy Systems

Technology Innovations

- Reduction of capital cost and improvement of thermal energy conversion
- Incorporation of passive safety features
- Advanced fuels
  - Dissolved
  - Particle
  - Metallic
  - Ceramic
- Cladding innovations enabling high burnup, extensive actinide destruction, and enhanced accident tolerance
- Advanced power conversion systems (Brayton, supercritical CO_2) to improve overall energy conversion efficiency and reduce water usage

Advancing Advanced Reactors

High Temperature Gas Reactors

General Atomics http://www.ga.com/energy-multiplier-module

Areva http://us.areva.com/EN/home-3225/areva-inc-areva-htgr.html

Hybrid Power Technologies
http://www.hybridpowertechnologies.com/

Molten Salt Reactors

Transatomic Power http://www.transatomicpower.com/

Terrestrial Energy http://terrestrialenergy.com/

Oklo (formerly UPower) http://oklo.com/

ThorCon Power http://thorconpower.com/

Liquid Metal Reactors

TerraPower http://terrapower.com/

General Electric http://gehitachiprism.com/

Advanced Reactor Concepts
http://www.arcnuclear.com

Gen4 Energy http://www.gen4energy.com/

Westinghouse http://www.westinghousenuclear.com/

Fusion Reactors

Helion Energy http://www.helionenergy.com/

Tri Alpha Energy http://www.trialphaenergy.com/

General Fusion http://www.generalfusion.com/

Gateway for Accelerated Innovation in Nuclear (GAIN)

GAIN Gateway for Accelerated Innovation in Nuclear

ANS

U.S. DEPARTMENT OF ENERGY | Office of Nuclear Energy

- New DOE-NE approach
- Provide the nuclear community with access to the technical, regulatory, and financial support necessary to move innovative nuclear energy technologies toward commercialization
- Ensure continued safe, reliable, and economic operation of the existing nuclear fleet

DOE-NE Demonstration & Test Reactor Assessment Program

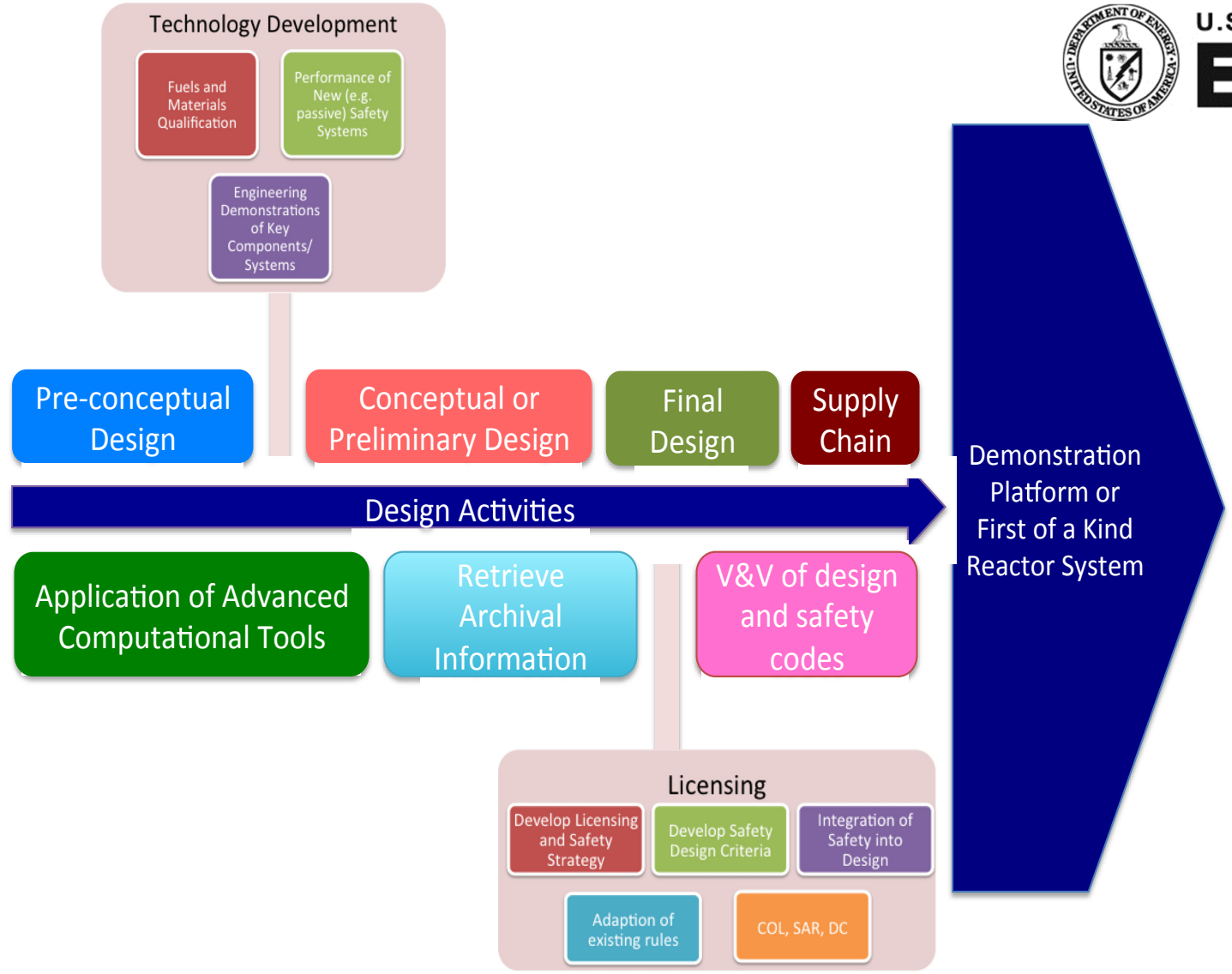
Demonstration Reactor Concepts

- Sodium-Cooled Fast Reactor
- High Temperature Gas-Cooled Reactor
- Lead-Cooled Fast Reactor
- Molten Salt-Cooled Reactor

Test Reactor Concepts

- Sodium-Cooled Fast Test Reactor
- Helium-Cooled Thermal Test Reactor

Technical, Licensing and Design Readiness



International Advanced Reactor Developments

Sodium fast reactor demonstration reactor projects

- Russia (880 MWe BN-800)
- India (500 MWe PFBR)
- China (Experimental Fast Reactor (CEFR) in operation since 2010)
- Japan (restart of Japan Experimental Fast Reactor (JOYO) test reactor and Monju demonstration reactor)

Sodium fast reactor design projects

- Korea (150 MWe PGSFR)
- France (300 MWe ASTRID)

High temperature gas-cooled reactor projects

- China (building two-unit 250 MW pebble bed)
- Eastern Europe (ALLEGRO fast-spectrum gas-cooled reactor study)

International Advanced Reactor Developments

Lead-cooled fast reactor project

- Russia (BREST-300 design project, aiming for 2020 operation)

Subcritical accelerator-driven test projects

- Belgium (85MWth Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) design project)
- Russia (study phase)
- European Union (study phase)

Molten salt reactor projects

- China (2 to 10 MW molten salt pebble bed reactor)
- Europe (study phase)
- Russia (study phase)

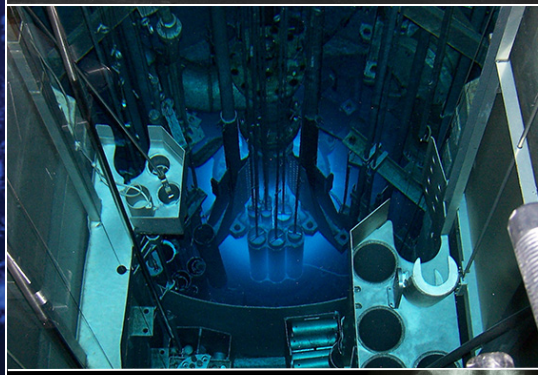
What Can You Do?

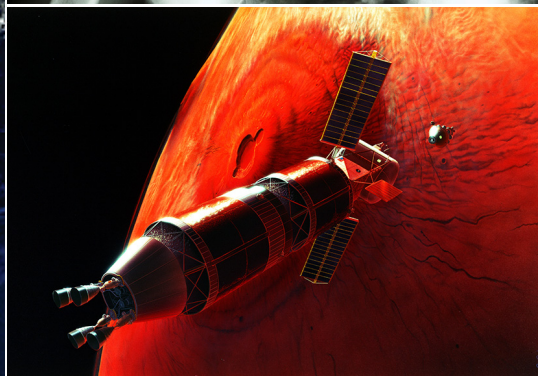
- Share the message: social media, letters to editor, etc.
  - The World Needs Nuclear!
- Share the link: www.nuclearconnect.org
- Be involved:
  - Washington Internships for Students of Engineering (WISE)
- Be a part of the public discussion:
  - Why is your energy future not part of the current election debate?
- Challenge bad science wherever you encounter it
- Be proud of who you are and what you do
- Join, renew and recruit for ANS!

The WORLD needs NUCLEAR

NUCLEAR needs the American Nuclear Society

ANS





Washington Internships for Students of Engineering (WISE)

Nine-week program in Washington, D.C. sponsored by a consortium of professional societies

- Focus: Technology policy—i.e., the intersection between technology and the political process
- Primary audience – rising seniors, but grad students (especially first year) will be considered, too
- Seminars and meetings at government agencies in the Washington area
- Individual research project on a technology policy issue of the intern's choice—20 page paper and end-of-program presentation on Capitol Hill
- Intern class of about 12-15 students, led by Faculty-Member-in-Residence

ANS sponsors two interns each summer

- Office space and support provided by Nuclear Energy Institute
- Stipend of $2100; housing provided by WISE Program in George Washington U. dormitories
- ANS Student Membership required for sponsorship by ANS
- Application deadline: December 31

Washington Internships for Students of Engineering (WISE)

WISE participation can help open a wide variety of opportunities: grad school, industry and national laboratory internships, and jobs

ANS News articles on the program appear twice each year

ANS WISE Coordinator: Dr. Alan Levin, DOE, alevin@alum.mit.edu

WISE website: www.wise-intern.org

"The summer I spent in the WISE program was extremely influential on my career path. After completion of my service time with the U.S. Navy and Master's Degree, I decided on a career path that would use my engineering background and interest in public policy gained from the WISE program and had the opportunity to join the U.S. Nuclear Regulatory Commission."

--Chris Henderson, U.S. NRC resident inspector and 1998 ANS WISE intern

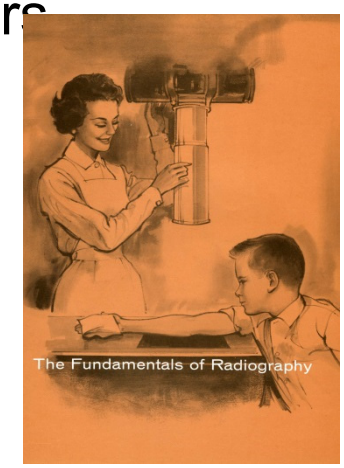
Oregon State University

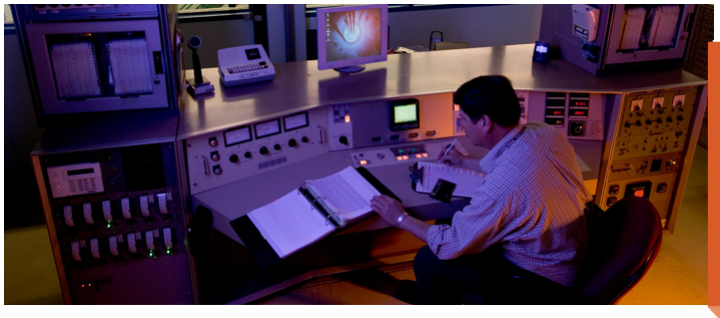
School of Nuclear Science and Engineering

OSU's Nuclear History

- Nuclear Engineering at OSU for > 50 years
- New Name
  - School of Nuclear Science and Engineering
- TRIGA reactor at OSU for > 40 years
- Research spans multiple areas:
  - Fundamental nuclear science
  - Nuclear reactor design
  - Radiation safety
  - Radiochemistry
  - Medical applications
  - Environmental protection
  - National security and defense


AGN-201 Nuclear Training Reactor

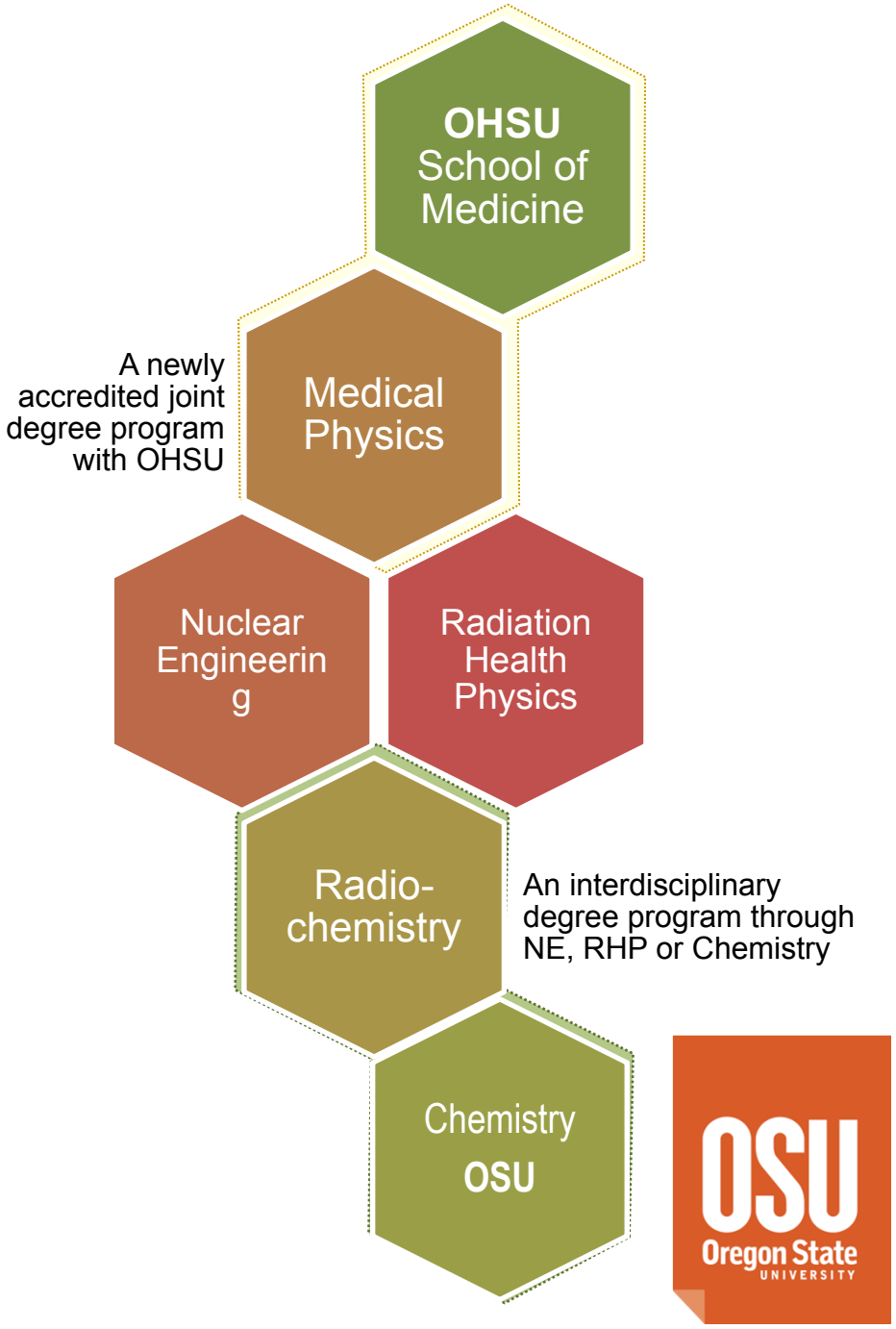




OSU Oregon State UNIVERSITY

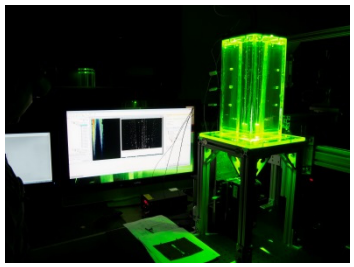
NSE Today

- One of 8 U.S. institutions to offer complete suite of degrees (B.S., M.S., and Ph.D.) in both NE and RHP
- Research areas:
  - Nuclear engineering
  - Medical applications
  - Radiation protection
  - Non proliferation
  - Environment



NSE Research Facilities

- ***Built with research funding***
- Integral Test Facilities
  - –APEX (AP1000) scaled model
  - –ATHRL (NuScale Prototype)
  - –ANSEL
    - High temperature gas reactor test facility
    - Hydro-mechanical Fuel Test Facility
- LIFT – Laser Imaging of Fluids & Thermal
- Transuranic radiochemistry labs
- Radioecology facilities



OSU Oregon State University

OSU Radiation Center

User Facilities:

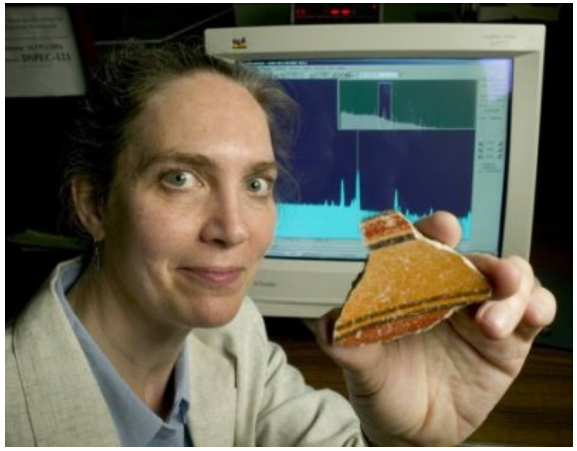
- 1.1 MW TRIGA Reactor
- Spectroscopy laboratories
- Radiochemistry laboratories
- Irradiators

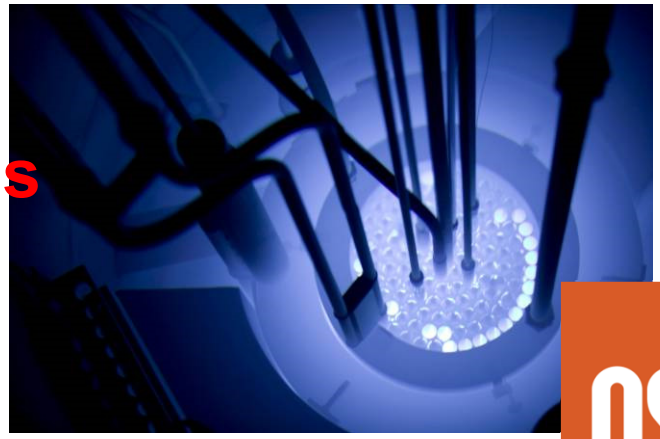
Instruction

- Reactor operator training

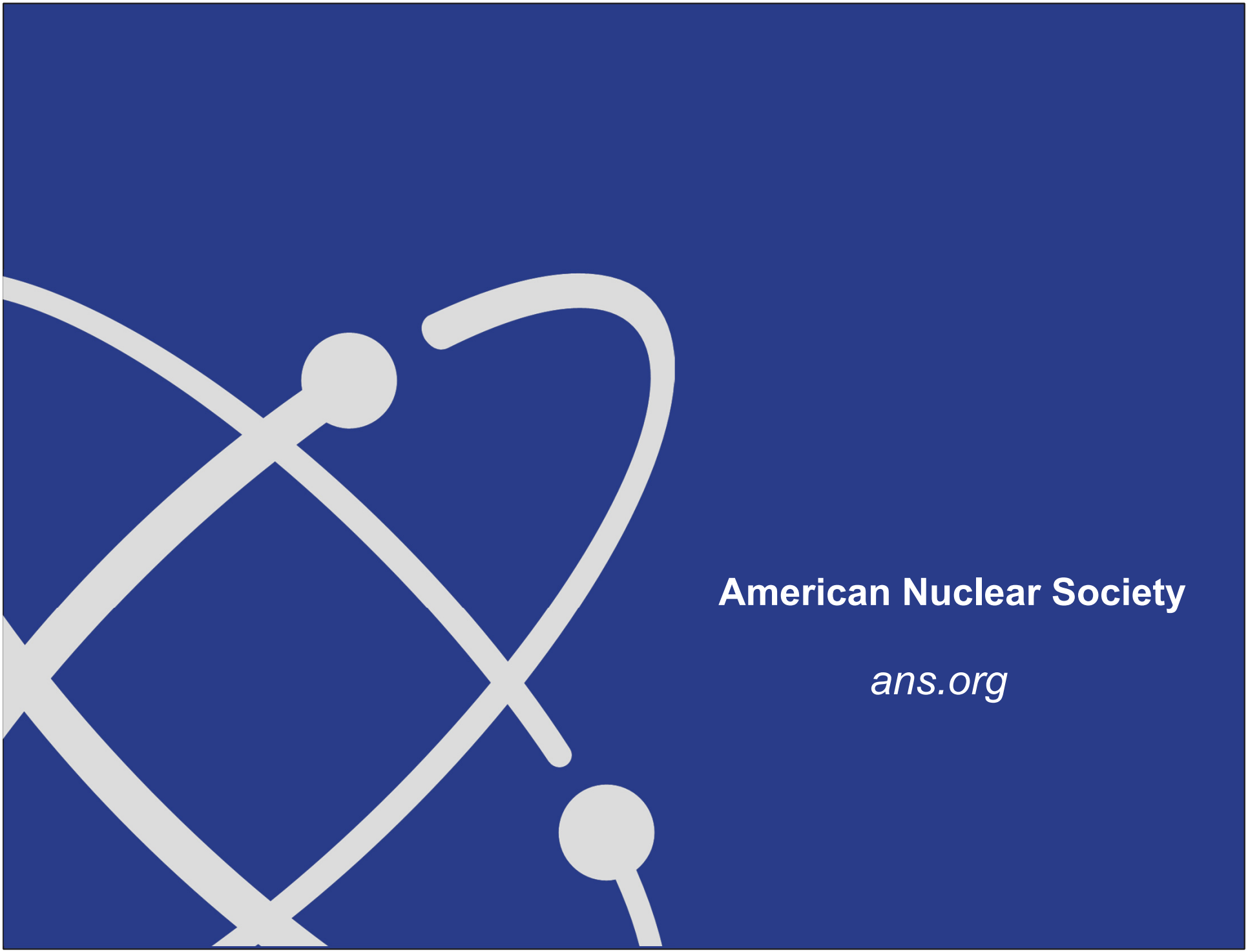
Activities:

- **Neutron activation analysis**
- ***Geological age dating***
- **Neutron radiography**
- ***Isotope production***





OSU Oregon State University


American Nuclear Society
ans.org