U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Nuclear Energy
Past, Present and Future

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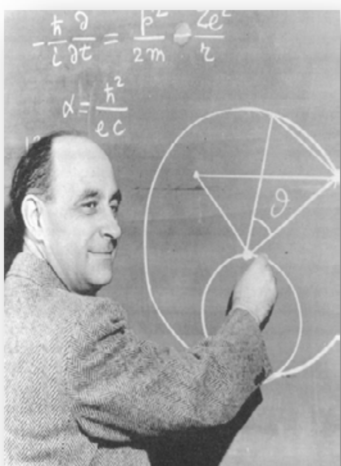
October 16, 2014

Outline

- History of nuclear energy development
- Nuclear energy today
- Challenges to nuclear energy expansion
- DOE's research and technology development
- Nuclear energy in space
- Building a clean energy future
- Conclusions

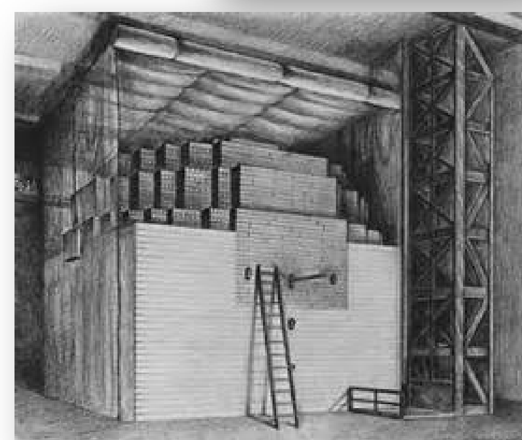
The Early Years

- **1939 – Uranium atom split in Germany and fear that Germany was working on an atomic bomb**
  - Einstein signs Leo Szilard Letter to President Roosevelt relaying possibility of chain reaction
  - Briggs Committee appointed to study chain reactions



- **1941 – Fermi and Szilard suggest possible design for uranium chain reactor**

- **1942-** First controlled, self-sustaining nuclear chain reaction at University of Chicago



Chicago Pile–1, Dec 2, 1942 at 3:20 pm for 33 minutes

The Early Years (cont.)

- **1942 – Army Corps of Engineers District "Manhattan Project" at Los Alamos, NM**
  - Brigadier General Leslie Groves – US Army Corps of Engineers
  - Scientific research led by Physicist Robert Oppenheimer

- **Three primary research and production sites**
  - Los Alamos, NM – Weapons research and design laboratory
  - Hanford Site, WA – Plutonium production
  - Oak Ridge, TN – Uranium enrichment

- **1946 – President Harry Truman**
  - Established Atomic Energy Commission (AEC)
  - Argonne National Lab was created as the successor of Metallurgical Lab of Univ. Chicago

The Early Years (cont.)

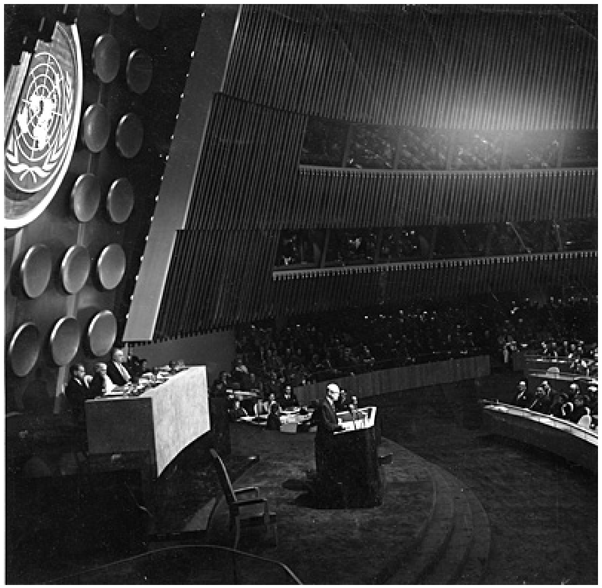
- **1947 – Atomic Energy Commission (AEC) established**
  - Lewis Strauss appointed as one of five Commissioners
  - 1953 – President Eisenhower appoints him as chairman of the AEC

- **1949 – Hyman Rickover assigned to dual role as Atomic Energy Commission's Division of Reactor Development and made Director of the Naval Reactors Branch**
  - Leads efforts to develop Nautilus and oversee development of Shippingport Atomic Power Station

- **Experimental Breeder Reactor I (EBR-I) – Idaho National Lab**
  - December 20, 1951, world's first electricity generated from nuclear power

Atoms for Peace

The First Wave of Nuclear Power Deployment

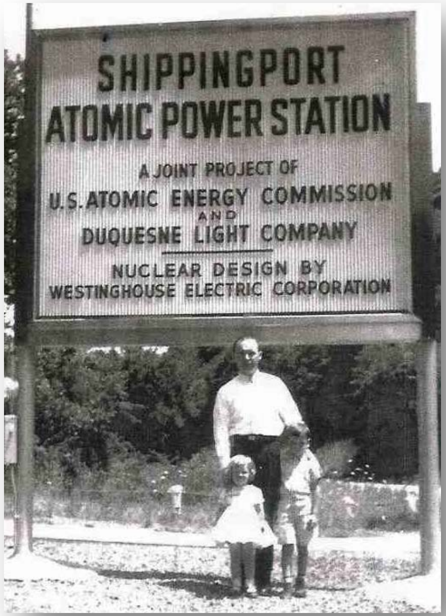


"Peaceful power from atomic energy is no dream of the future. That capability, already proved, is here – now – today."

President Dwight D. Eisenhower
December 8, 1953
United Nations General Assembly

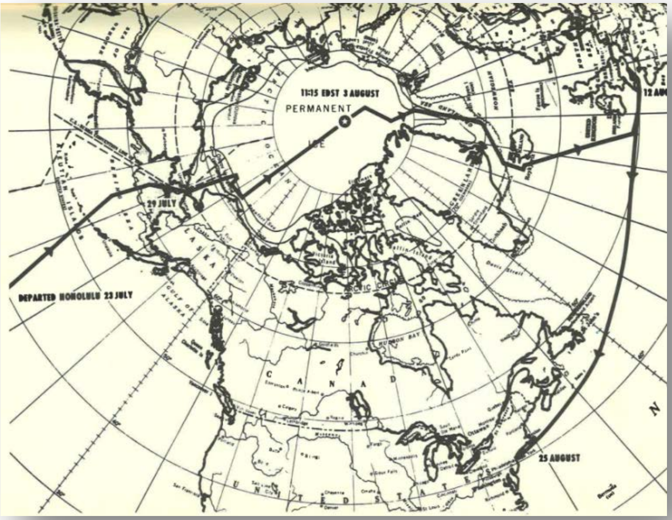
- **President Eisenhower signs the Atomic Energy Act of 1954**
  - Private ownership of nuclear reactors
  - Leasing of nuclear fuels for private use
  - Industrial access to classified data needed for nuclear power development
  - Encouraged international development of nuclear power

Nuclear Power "Firsts"



- **Shippingport Atomic Power Station – World's first full scale nuclear power plant**
  - 1954 – Construction begins
  - 1957 – Plant becomes operational distributing to the Duquesne Light Company grid

- **USS Nautilus - World's first operational nuclear-powered submarine**
  - 1955 – USS Nautilus maiden voyage
  - 1958 – Operation Sunshine, submerged transit to North Pole
  - 1979 – final voyage



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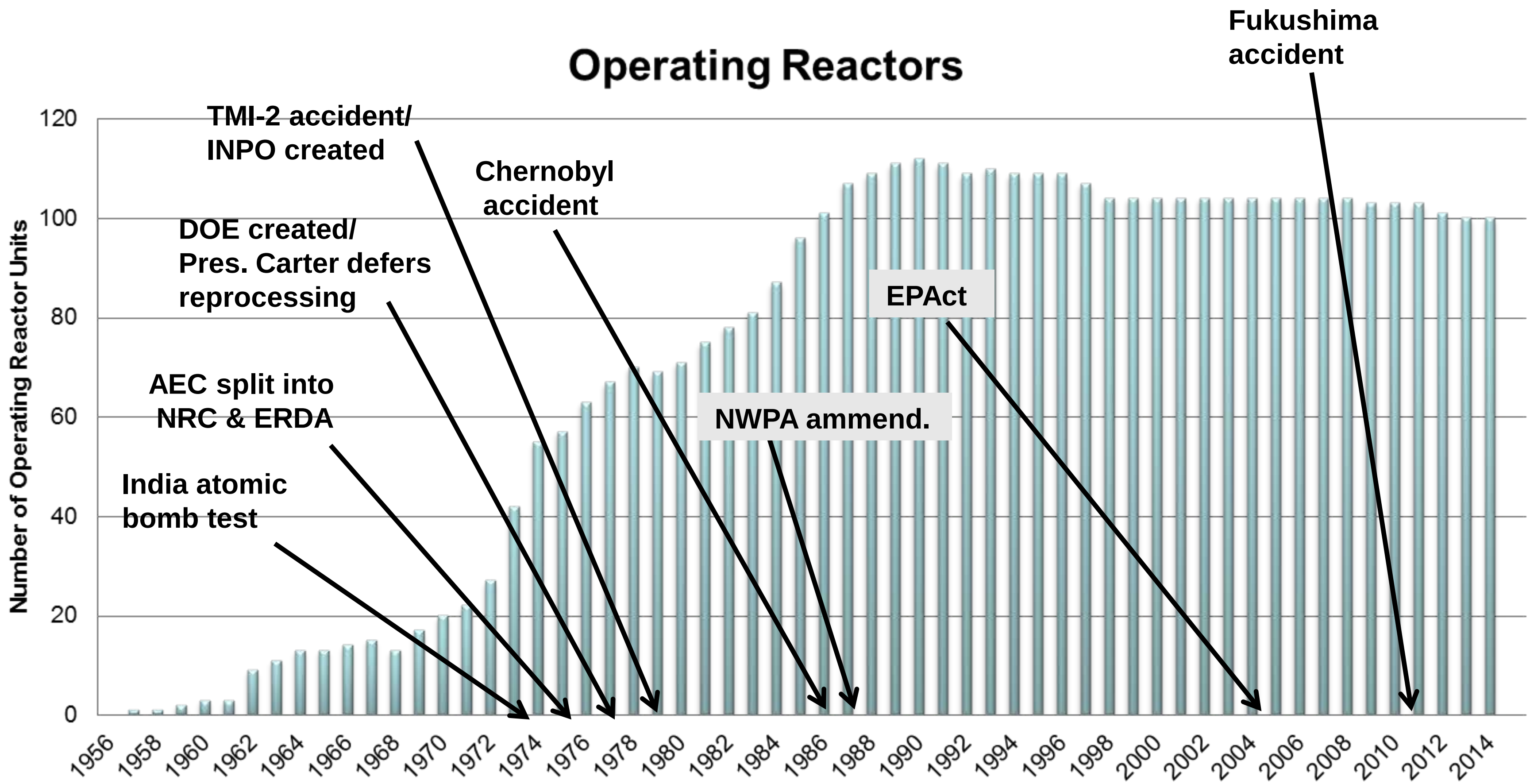
Key Events Influencing Commercial Nuclear Power



United States Committed to *"All of the Above"* Clean Energy Strategy

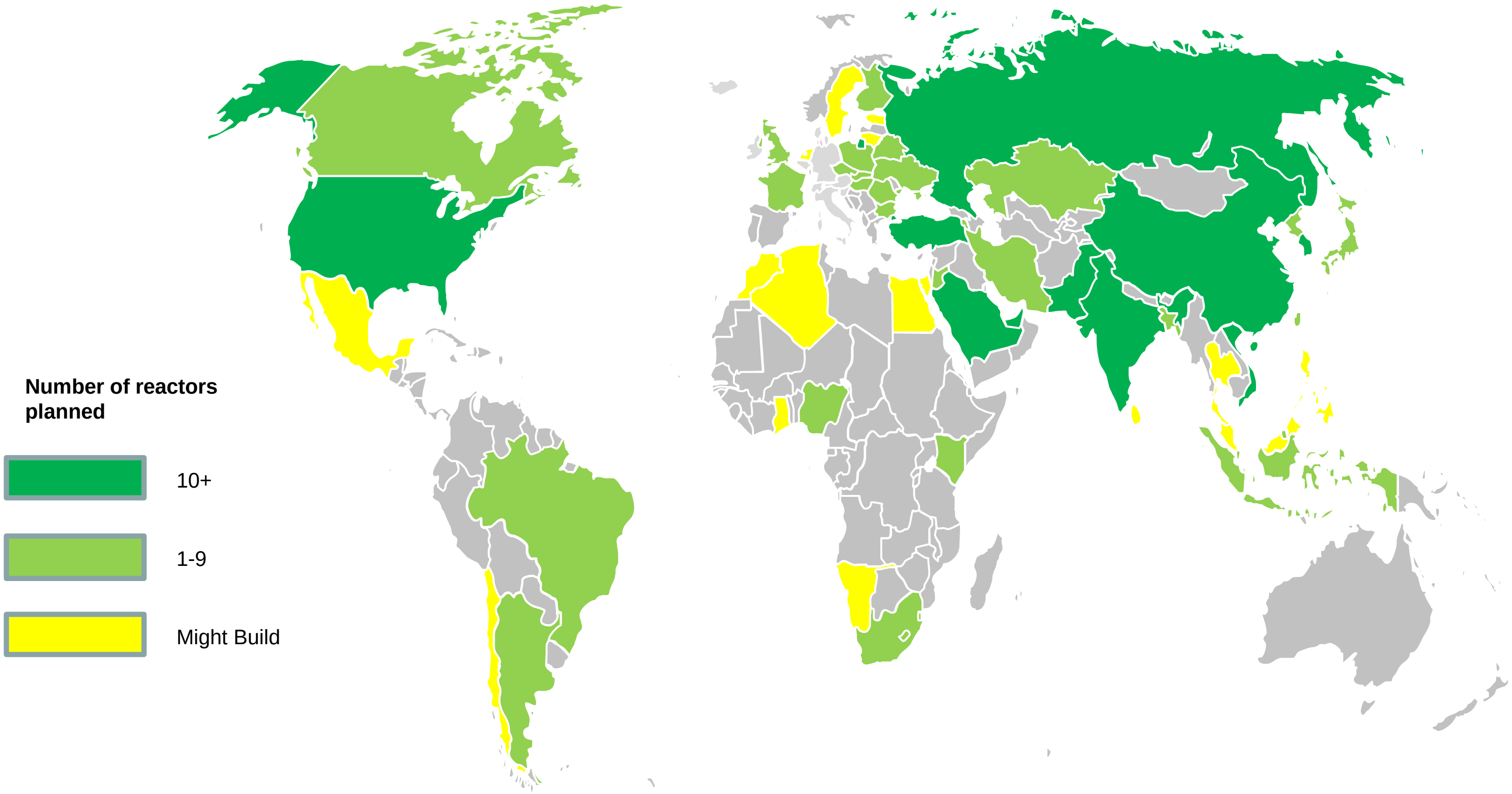
"By 2035, 80% of America's electricity will come from clean energy sources. Some folks want wind and solar. Others want nuclear, clean coal and natural gas. To meet this goal we will need them all."

~2011 State of the Union

"All-of-the-above is not merely a slogan, but a clear-cut pathway to creating jobs and at the same time reducing carbon emissions, which recently stood at their lowest level in 20 years… President Obama has made clear that he sees nuclear energy as part of America's low carbon energy portfolio. And nuclear power is already an important part of the clean energy solution here in the United States."

~Secretary of Energy, Dr. Ernest Moniz at National Press Club, February 19, 2014

Global Nuclear Projections



- **434 nuclear reactors are operable in 31 countries**
- **73 reactors currently under construction in 14 countries**
- **More than 300 reactors are proposed in 36 countries over the next 15 years**

--- World Nuclear Association as of June 1, 2014

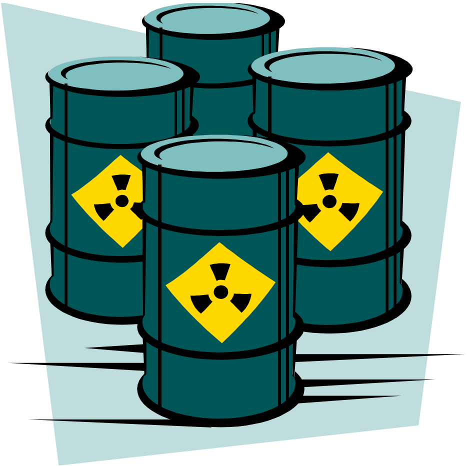
Role of U.S. Department of Energy for Sustainable and Innovative Nuclear Energy

Conduct Research, Development, and Demonstration to:

- Reduce technical risk
- Reduce financial risk and improve economics
- Reduce regulatory risk
- Used fuel management
- Minimize the risks of nuclear proliferation and terrorism
- Foster international and industry collaboration

Potential Challenges to Global Nuclear Power Expansion

- Safety / Public Acceptance
- Economics
- Nuclear Waste
- Proliferation risk



Light Water Reactor Sustainability (LWRS) Program

LWRS Program Goal

- Develop fundamental scientific basis to allow continued long-term safe operation of existing LWRs (beyond 60 years) and their long-term economic viability

LWRS program is developing technologies and other solutions to

- Enable long term operation of the existing nuclear power plants
- Improve reliability
- Sustain safety

LWRS focus areas

- Materials Aging and Degradation
- Advanced Instrumentation and Controls
- Risk-Informed Safety Margin Characterization
- Reactor Safety Technology

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Status of New Builds in U.S.

- **First new reactors being built in U.S. in 30 years**
- **V.C. Summer Units 2 & 3**
  - Substantial Completion forecast:
    - Unit 2 (late 2018/early 2019)
    - Unit 3 (12 months after Unit 2)
  - Cost per unit ($4.5 billion 2007 $) pending adjustment
- **Vogtle Units 3 & 4**
  - Commercial operations Unit 3 (2017) & Unit 4 (2018)
  - Estimated construction cost $5.3 billion/unit (CY $)

"The cost and schedule performance of the new reactors being built in South Carolina and Georgia will be very critical."
-Secretary Moniz, April 10, 2014

VC Summer Unit 2 – SCE&G

Vogtle Unit 4 - Georgia Power Company

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Government Incentives for Nuclear

Standby Support Delay Risk Insurance

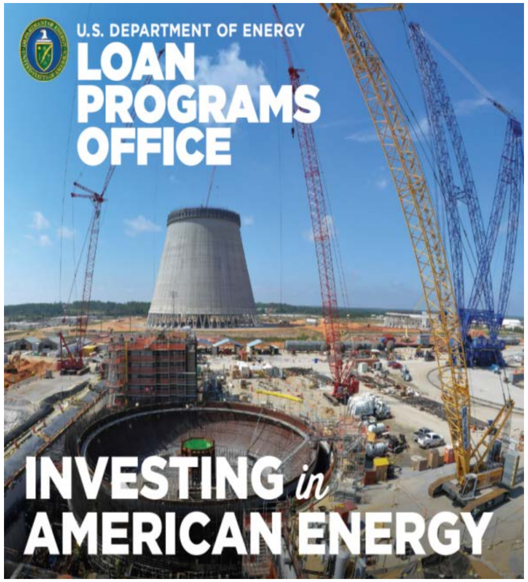
- Designed to reduce risk of licensing delays caused by NRC failing to meet its own schedules or by certain litigation

Production Tax Credit

- Provides $0.018/kWh with a maximum of $125M per year per each 100MW allocated for 8 years
- Only those plants that began construction by 2014 and placed into service by 2021 are eligible

Loan Guarantees

- Reduces cost to build a nuclear power plant by reducing the cost of financing
- In February 2014, DOE provided $6.5 B in guarantees to support the construction of Vogtle Units 3 and 4 in Georgia
- In September, DOE announced plans for another $12.6B in guarantees for advanced nuclear reactors; small modular reactors; uprates and upgrades at existing facilities; and advanced nuclear facilities for the front-end of the nuclear fuel cycle



Accident Tolerant Fuel Behavior

High temperature during loss of active cooling

Slower Hydrogen Generation Rate
- Hydrogen bubble
- Hydrogen explosion
- Hydrogen embrittlement of the clad

Improved Reaction Kinetics with Steam
- Heat of oxidation
- Oxidation rate

Improved Fuel Properties
- Lower operating temperatures
- Clad internal oxidation
- Fuel relocation / dispersion
- Fuel melting

Improved Cladding Properties
- Clad fracture
- Geometric stability
- Thermal shock resistance
- Melting of the cladding

Enhanced Retention of Fission Products
-Gaseous fission products
-Solid/liquid fission products

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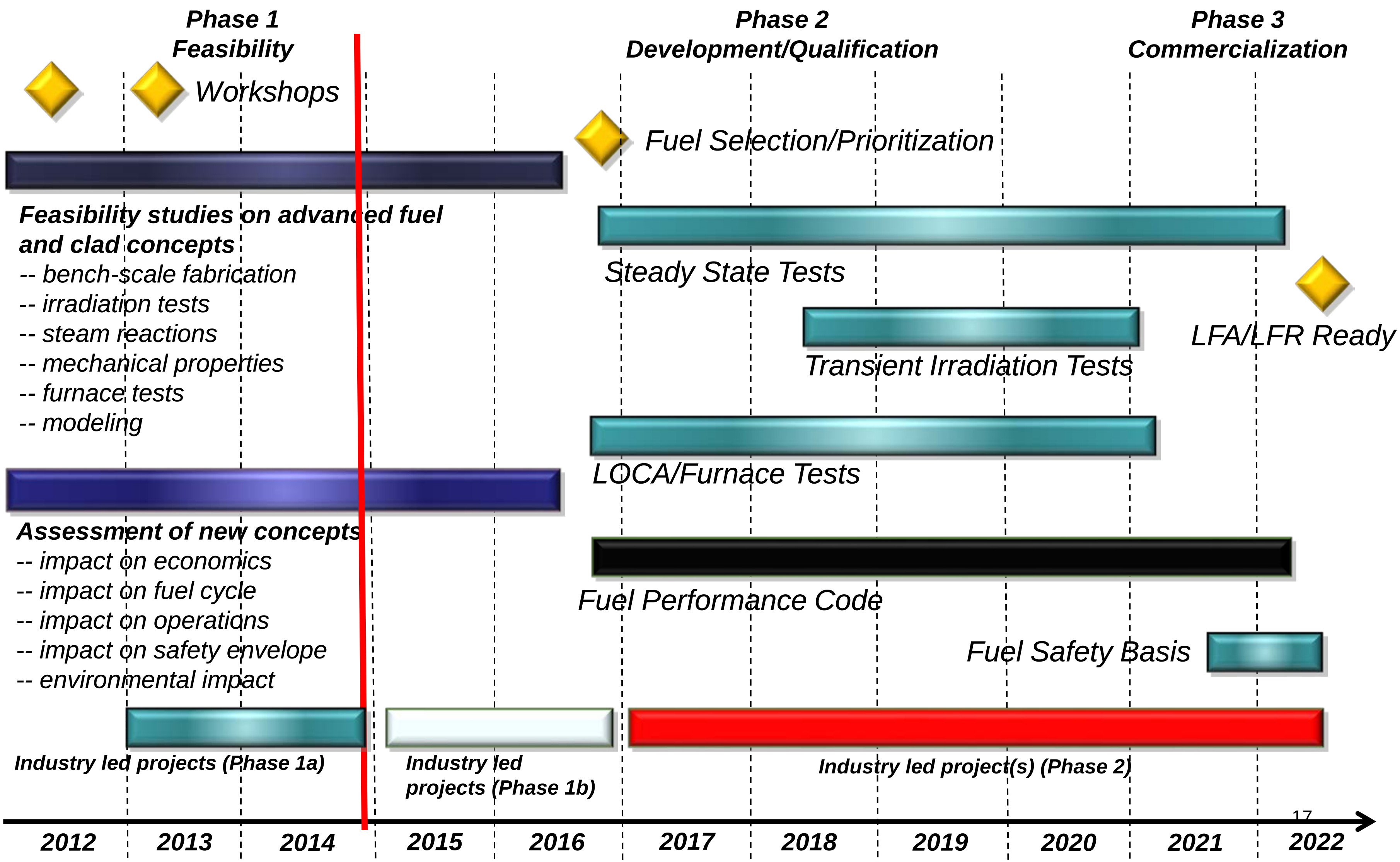
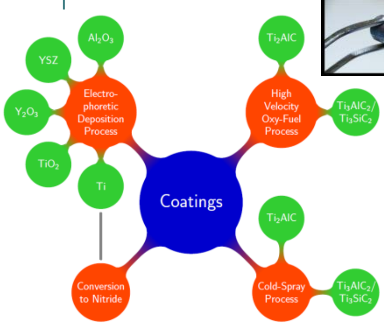
RD&D Strategy For Enhanced Accident Tolerant Fuels – 10 Year Goal



Advanced Fuels – Industry Teams

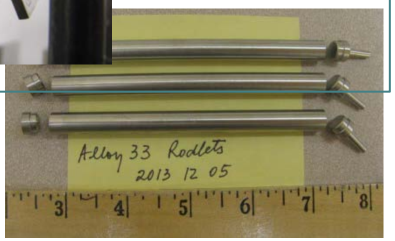
AREVA

- Develop coated Zr-alloy cladding for improved accident performance
- Increased fuel pellet conductivity: Fuel with reduced stored energy that must be accommodated during DBE
- Additives achieved:
  - SiC powder or whiskers
  - Diamond
  - Chromia dopant



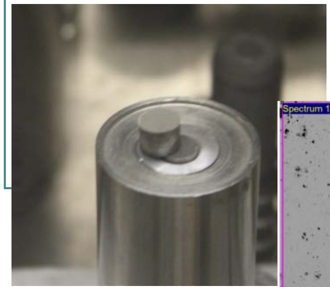
GE

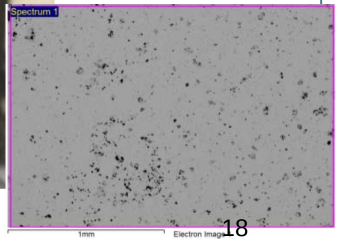
- Develop advanced ferritic/martensitic steel alloys (e.g., Fe-Cr-Al) for fuel cladding to improve behavior under severe accident scenarios
- Objectives:
  - Characterize candidate steels
  - Study tube fabrication methods, neutronics, fuel economy, thermo-hydraulic calcs, reg approval path
  - Initiate ATR testing with UO_2 and two cladding materials.



Westinghouse

- Develop and test cladding concepts: SiC and SiC ceramic matrix composites; coated Zr alloys
- High density/high thermal conductivity fuel pellets (e.g., uranium nitride/silicides)
- First batch of U_3Si_2 pellets were sintered using finely ground powder
- Pellets were pressed using pressures of 6,000-10,000 psi and sintered at temperatures of 1400°C





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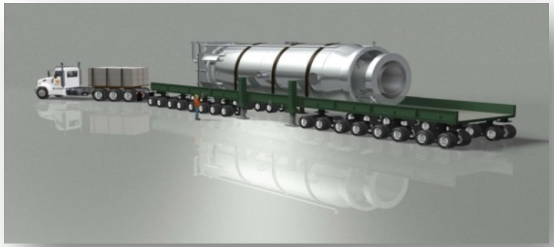
Small Modular Reactors

SMRs: reactor units with less than 300 MWe and are able to have large components or modules fabricated remotely and transported to the site for assembly.

- **Potential Benefits**
  - Enhanced safety and security
  - Reduced capital cost makes nuclear power feasible for more utilities
  - Shorter construction schedules due to modular construction
  - Improved quality due to replication in factory-setting
  - Meets electric demand growth incrementally
  - Regain technical leadership and advance innovative reactor technologies and concepts
- **Potential Markets**
  - Domestic and international utility markets
  - Non-electrical (process heat/desalination) customers



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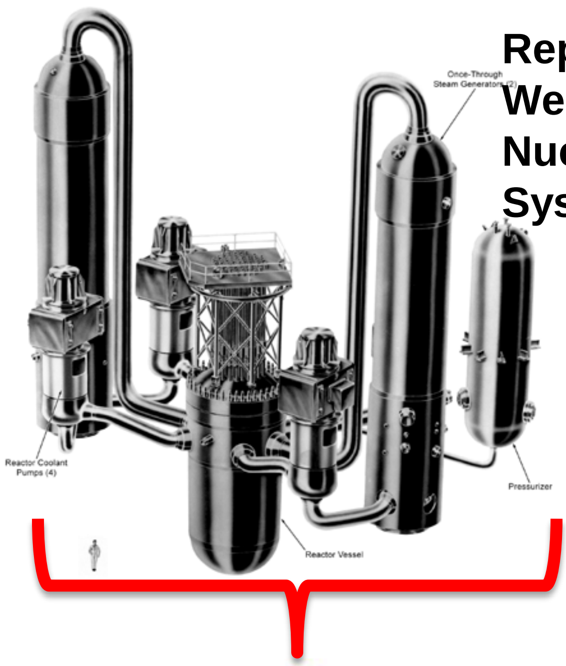
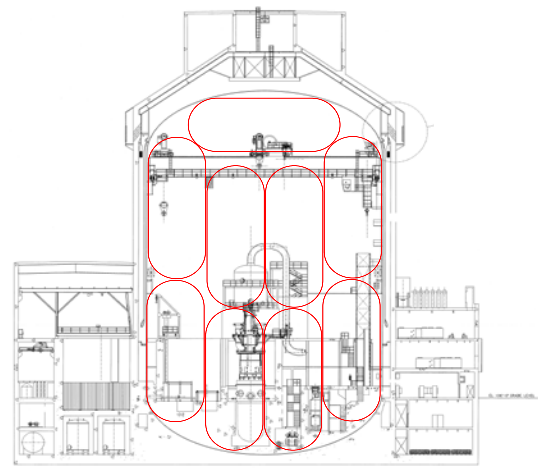
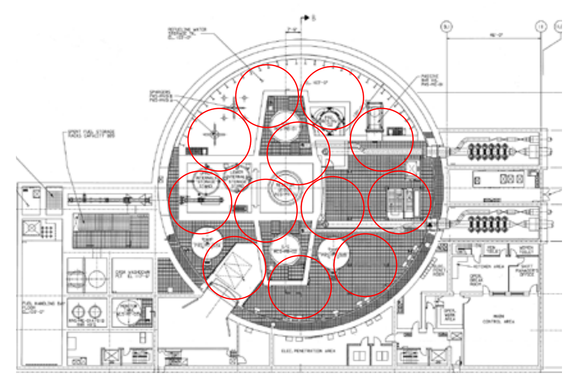
Size Comparison of Conventional Large LWR and SMR



Representative Westinghouse Nuclear Steam Supply System

Westinghouse SMR Integral Nuclear Steam Supply System





25 Westinghouse SMR Containment Vessels fit into single AP1000 Containment Vessel

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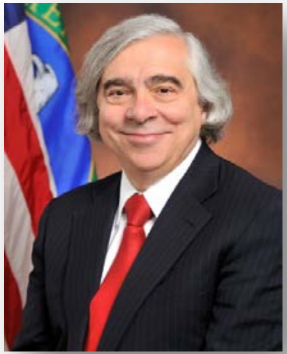
SMR Licensing Technical Support Program

- **Major challenge for commercialization is completing the NRC licensing process**
- **In 2012, DOE initiated the SMR Licensing Technical Support program – Currently a 6 year/$452 M program**
- **Accelerate commercial SMR development through public/private arrangements**
  - Deployment as early as 2022
- **Exploring additional mechanisms for SMR fleet deployment**



"I believe small modular reactors could represent the next generation of nuclear energy technology, providing a strong opportunity for America to lead this emerging global industry."

-- Secretary of Energy, Dr. Ernest Moniz

Status of SMR Licensing Technical Support Program

B&W mPower America

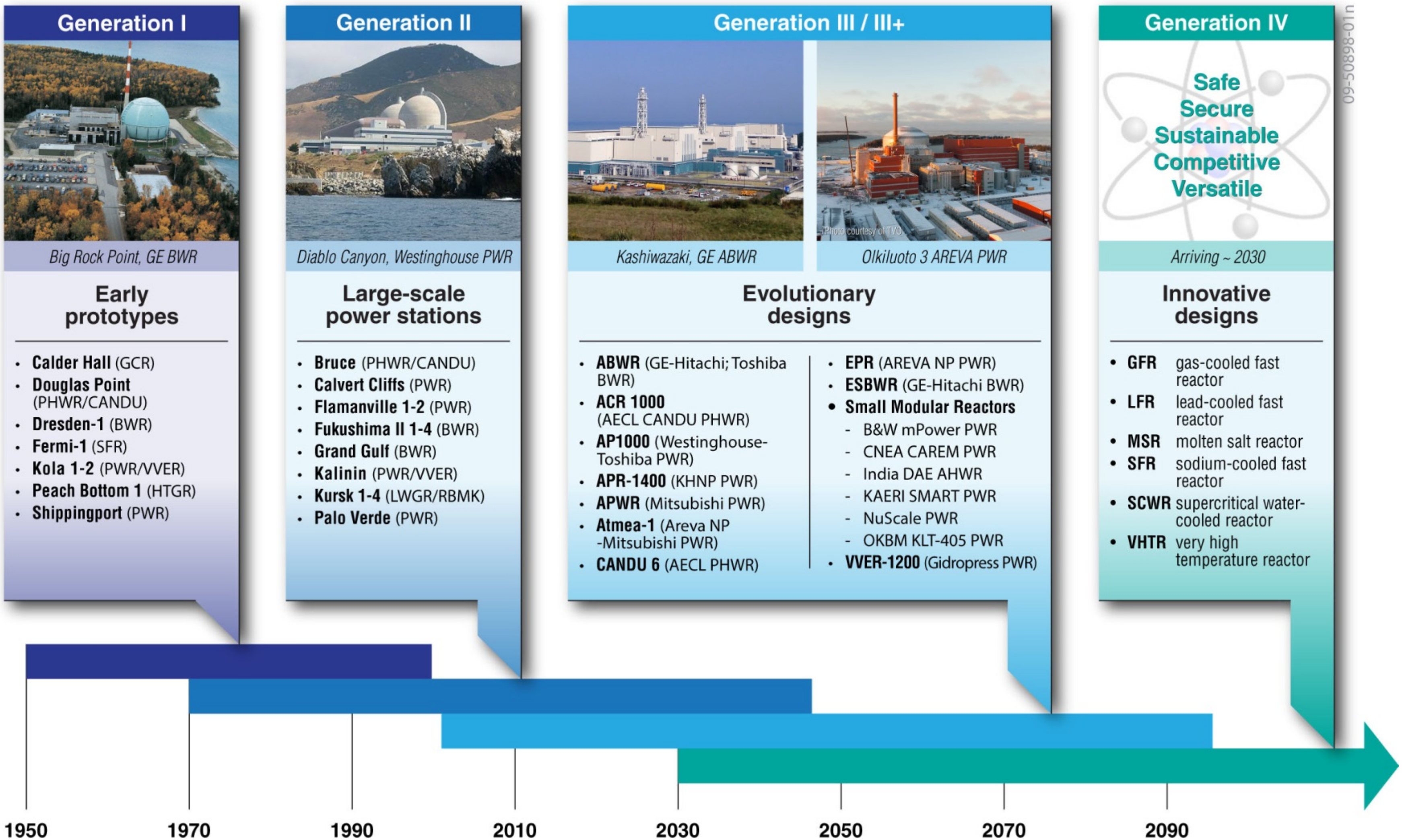
- Cooperative Agreement established with team consisting of B&W, Bechtel, and TVA in April 2013
- Initial DOE commitment of $115 M through Nov 2014
- DOE is working with B&W to establish a path forward for the mPower project

NuScale Power

- Selection of NuScale announced on December 12, 2013
- Cooperative Agreement signed May 27, 2014
- DOE to fund up to $217 M for NuScale SMR development
- DCA submittal currently planned for 2nd half of 2016

The U.S. Government wants to support the safest, most robust SMR designs that minimize the probability of any radioactivity release

Overview of Reactor Developments



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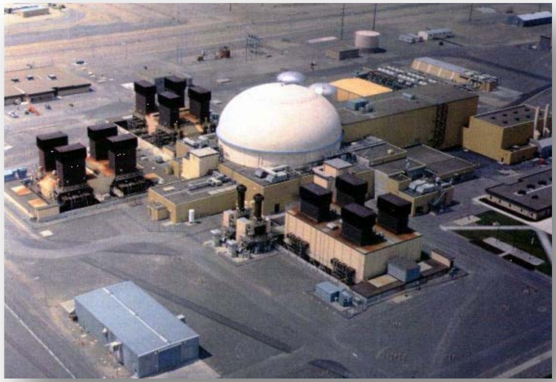
Sodium Fast Reactor Development

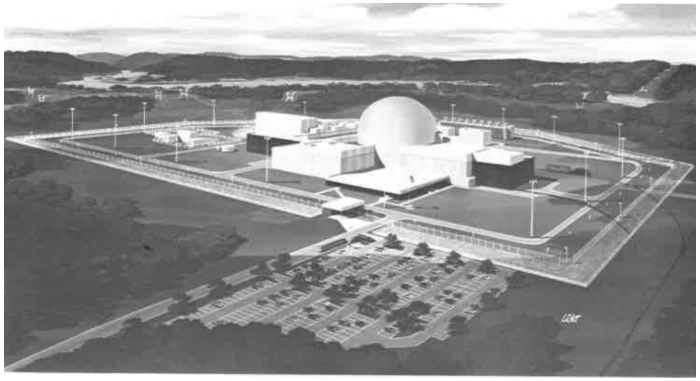
Experimental Breeder Reactor - II

- 62.5 MWt, pool-type, sodium-cooled fast reactor
- Successfully operated over 30 years from 1964 to 1994



Fast Flux Test Facility

- 400 MWth sodium-cooled fast test reactor, located at Hanford, WA
- World class testing capabilities, operated from 1982-1992



Clinch River Breeder Reactor

- 1000 MWth commercial prototype SFR
- Project started early 1970s
- Terminated in 1983 by Congress

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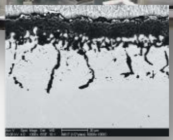
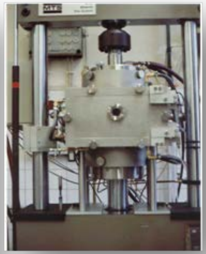
High Temperature Gas Cooled Reactor Technology Development

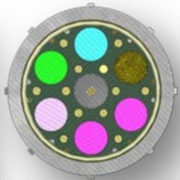
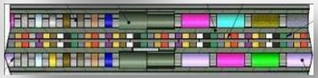




High Temperature Materials Characterization, Testing and Codification



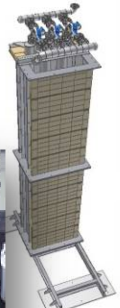
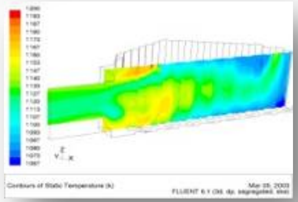
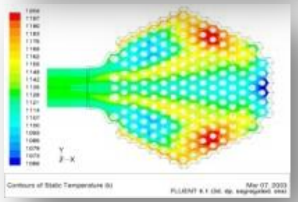

Fuel Fabrication, Irradiation, and Safety Testing

Graphite Characterization, Irradiation Testing, Modeling and Codification

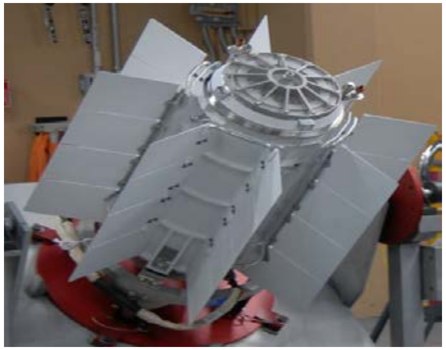
Design and Safety Methods Development and Validation

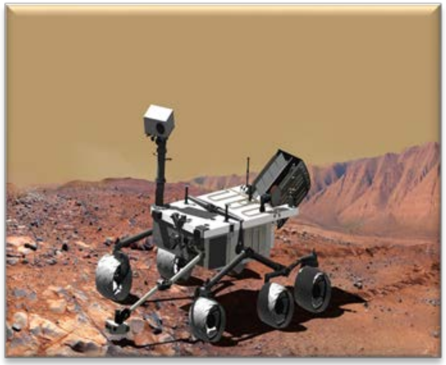


Space and Defense Power Systems

- **Programmatic Goals**
  - Design, develop, build and deliver radioisotope power systems for space exploration and national security applications
  - Support research, development and design of fission power systems for space exploration and national security needs
- **Benefits**
  - Enable NASA and national security missions in locations and environments where other power systems such as chemical batteries and solar power systems do not work
- **Long history of use in space**
  - First launched in 1961, used safely and reliably on 28 missions for over 50 years
  - Enabled exploration of Moon, Mars, Venus, Jupiter, Saturn, Uranus, Neptune and the Sun.
  - And since August of 2012, we have been exploring interstellar space with the Voyager 1 spacecraft launched 37 years ago





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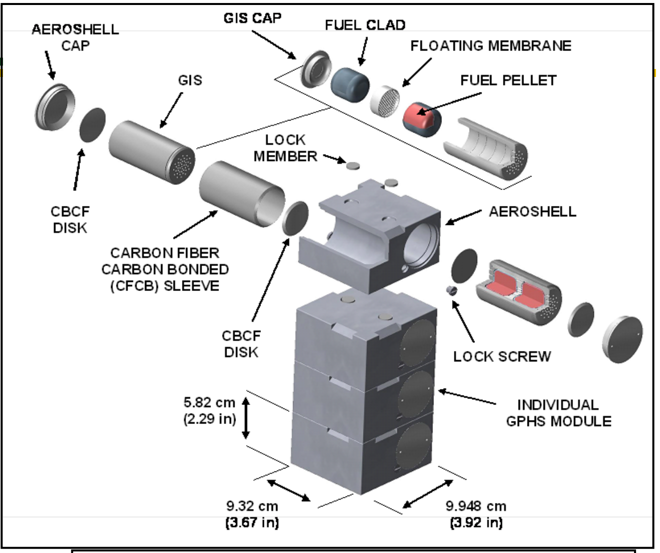
Radioisotope Power Systems

Basic Features

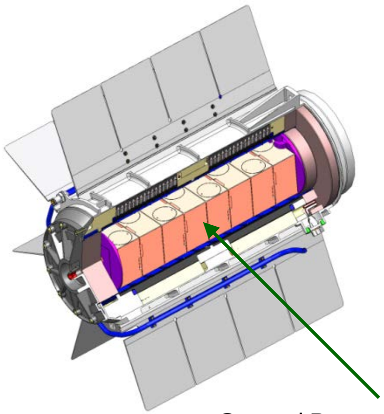
- General Purpose Heat Source Module
  - Plutonium-238 – heat from alpha decay, easily shielded
  - High-strength cladding to encase the fuel
  - Layers of graphite components for insulation and impact protection
  - Each module provides ~250 Wth
- Convertor – heat to electricity
  - All systems flown to date have used thermoelectric conversion
  - Also exploring dynamic conversion for higher efficiency

Multi-Mission Radioisotope Thermoelectric Generator

- Current design - operates in vacuum of space and Mars atmosphere
- Uses eight GPHS modules to produce ~115 W e
- First used on Mars Curiosity Rover in 2011

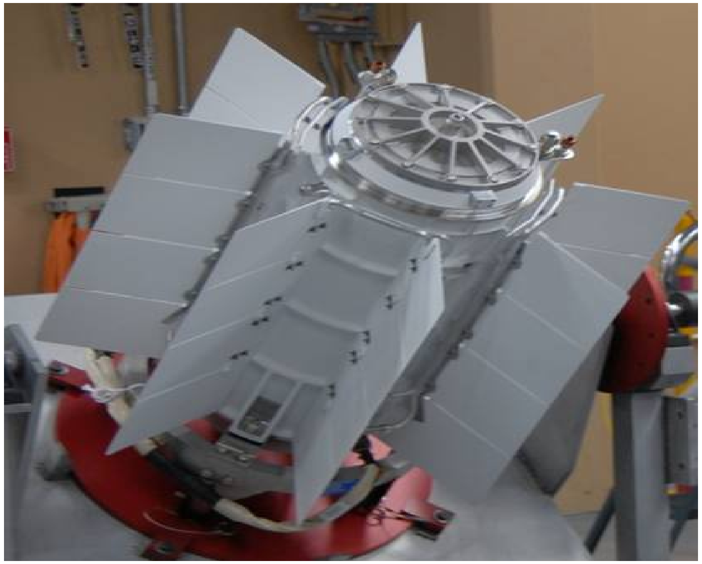


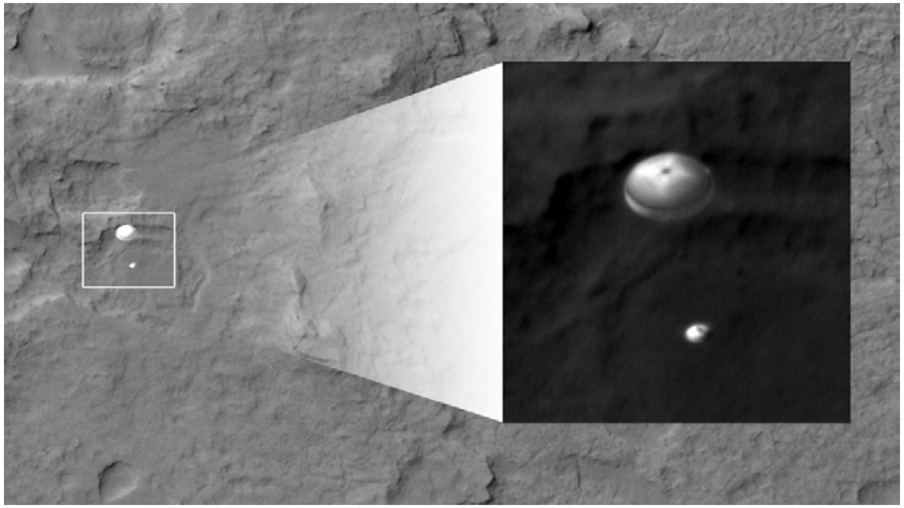
General Purpose Heat Source Module



Multi-Mission Radioisotope Thermoelectric Generator

Mars Science Laboratory





National Laboratory Support to Nuclear Energy

Argonne NATIONAL LABORATORY

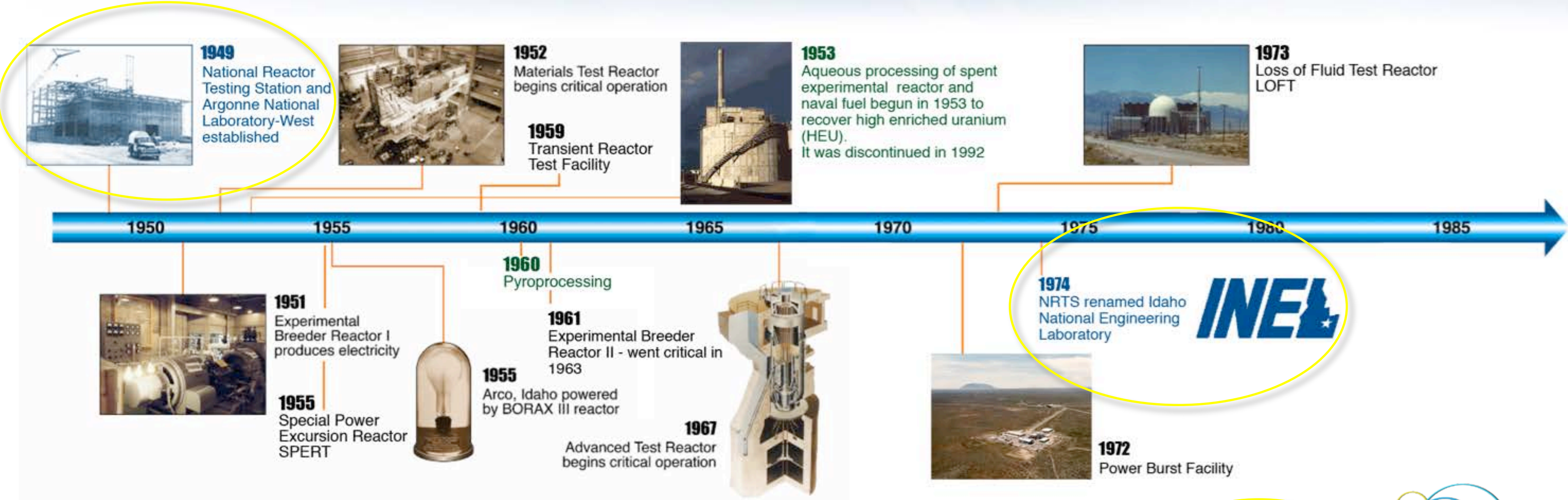
Pacific Northwest NATIONAL LABORATORY

INL Idaho National Laboratory

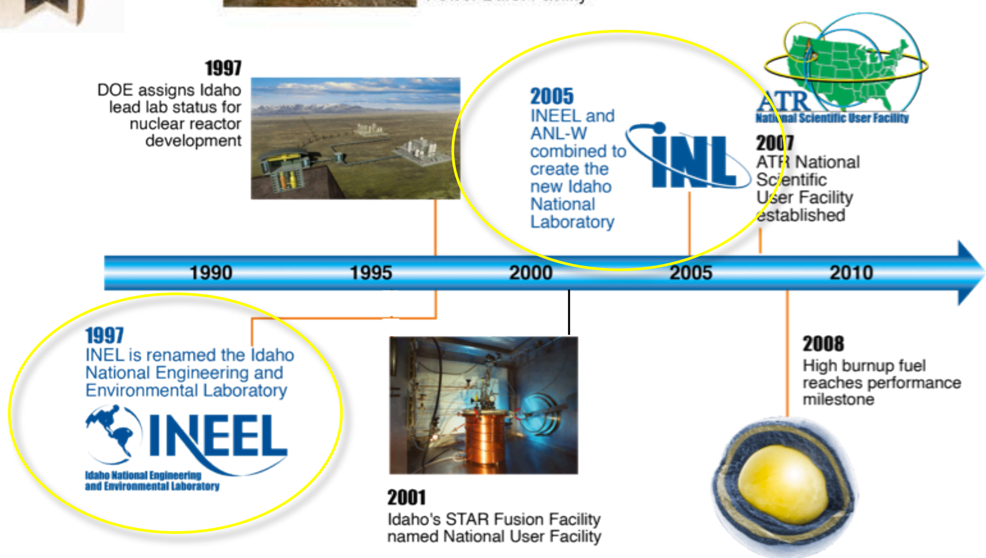
OAK RIDGE National Laboratory

Sandia National Laboratories

Idaho National Lab History



- Nuclear Energy in the U.S.
  - 1940's and 1950's from concept to prototype
  - 1960's from prototype to commercialization
  - 1970's an industry is launched
  - 1980's ensuring safety
  - 1990's laying the foundation for a new generation of nuclear power plants
  - 2000 & beyond a new generation of nuclear power and advanced fuel cycle technologies



Nuclear Energy Leadership –
A Key Component in A Robust Clean Energy Future

Optimized Use of LWRs

- Plant Sustainability
- Used Fuel Disposition
- Accident Tolerant LWR Fuels

Optimization of Nuclear Systems in The Modern Context

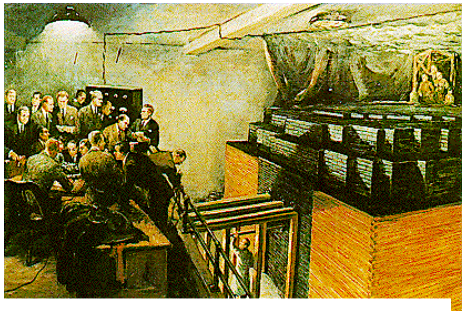
- Improved economics, safety, security and non-proliferation
- Advanced Designs, Fuels, and Fuel Cycles
- Process Heat Applications
- Hybrid Energy Systems/Load Following

Rapid Translation of Innovation to Industry

- Engineering-scale High-performance Computing
- User Facilities
- Knowledge Centers
- Risk-informed Safety Approaches

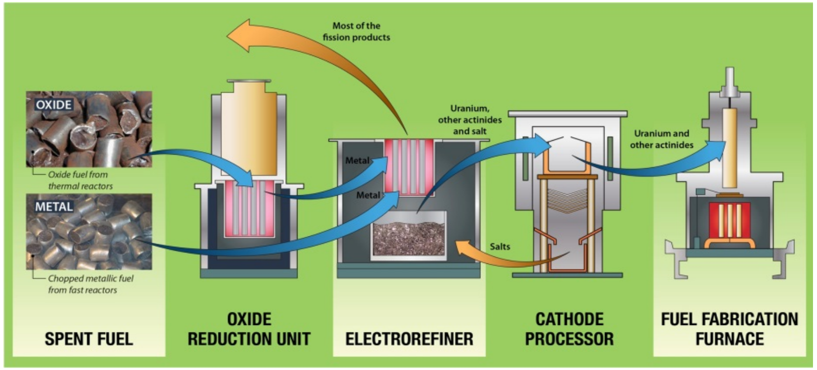
Argonne's Nuclear Program Builds on its Pioneering Achievements

▪ First controlled chain reaction	CP-1 (U. of Chicago)
▪ First electricity generation from nuclear energy ▪ First use of plutonium as fuel ▪ First demonstration of breeding	EBR-I
▪ First prototype BWR power plant	EBWR
▪ First close coupling of reactor operation and fuel recycling ▪ First demonstration of fast reactor inherent safety	EBR-II
▪ Development of metallic fast reactor fuel	
▪ Development of pyroprocessing for nuclear fuel recycle	



Chicago Pile 1 (CP-1)

Experimental Breeder Reactor No. 1 (EBR-I)

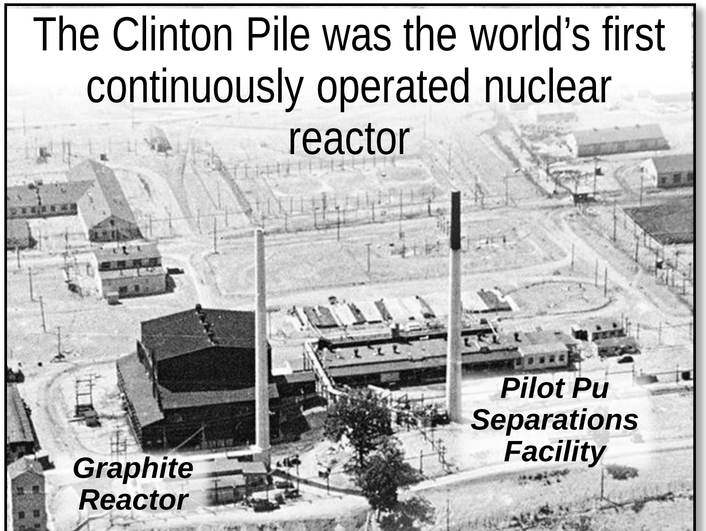


Argonne's Pyroprocessing Technology

Experimental Breeder Reactor No. 2 (EBR-II)

Experimental Boiling Water Reactor

Oak Ridge National Laboratory was founded in 1943 to Develop and Pilot World's First Nuclear Fuel Cycle



The Clinton Pile was the world's first continuously operated nuclear reactor

Chemical processing techniques were developed to separate plutonium from irradiated fuel

X-10 Manhattan Project Mission:

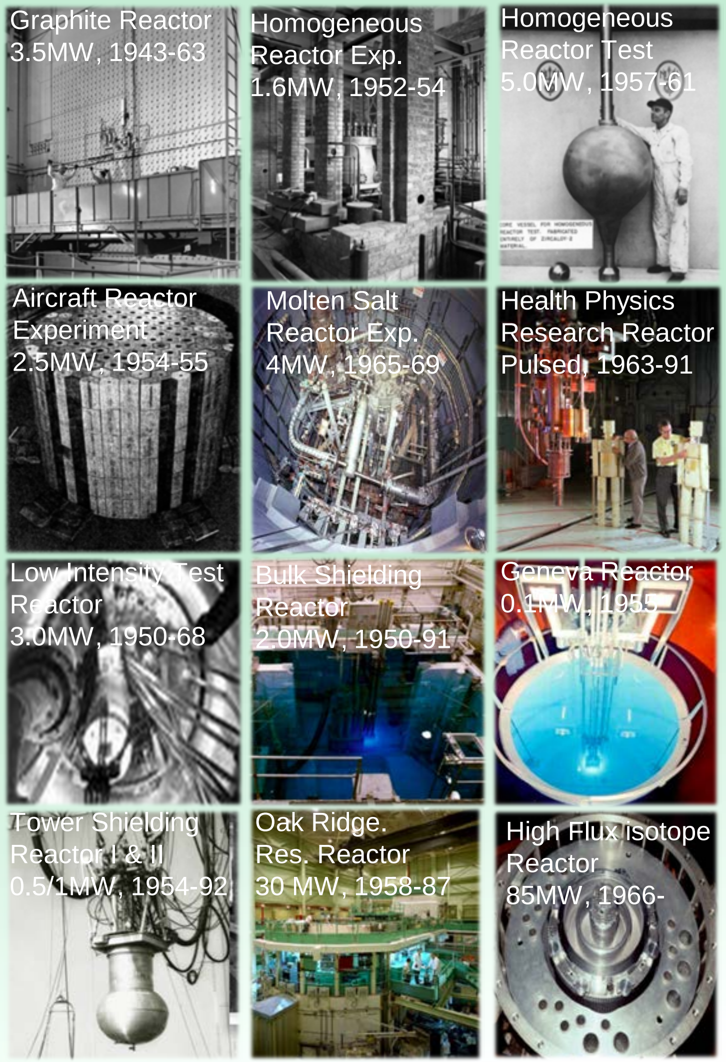
- Pilot reactor-based plutonium production
- Pilot Pu separation from irradiated fuel
- Training Hanford staff
- Fission, reactor, separations R&D

Success led to an expanded mission of basic and applied research:

- Science and engineering for nuclear power
  - Materials and fuels
  - Separations chemistry
  - Reactor safety and technology
- Development of neutron scattering
  - Nobel Prize in Physics
- Development, production, and distribution of radioisotopes for medicine and research
  - Birth of a billion dollar industry

Oak Ridge National Laboratory's Key Contributions to Nuclear Energy Development

ORNL's Thirteen Innovative Nuclear Reactors



Murray W. Rosenthal, *An Account of Oak Ridge National Laboratory's Thirteen Nuclear Reactors, ORNL/TM-2009/181*

Reactor Technology

- Lab Director Weinberg patented LWR
- First proof of electricity generation (1948)
- First zero-power LWR (LITR)
- First Molten Salt Reactor (1954)
- First use of U-233
- Advanced Reactors (gas-cooled reactor, fast breeder reactor development)

Separations

- Development of Purex process
- Development of Thorex process
- Fluorination processing

Reactor Safety

- Criteria for avoiding vessel pressurized thermal shock
- Understanding zirconium-alloy clad behavior in accidents
- Investigation of BWR severe accident phenomena

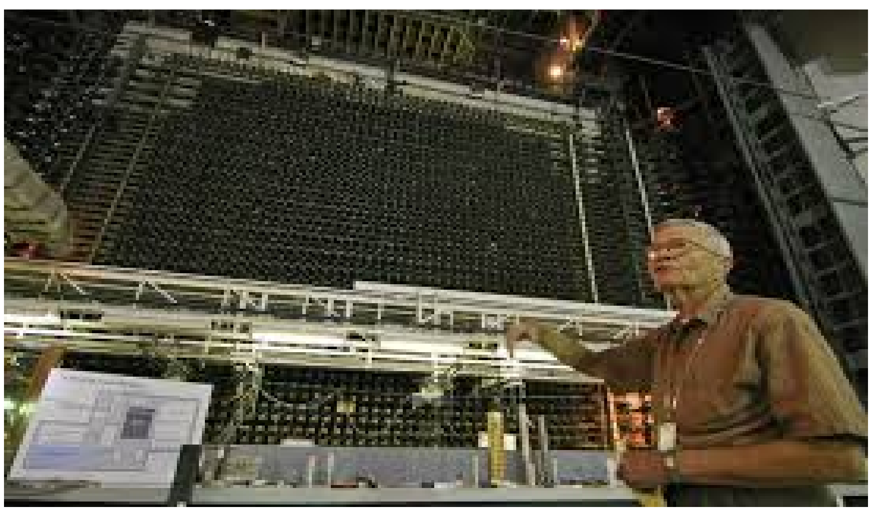
Radioisotopes

- HFIR and REDC developed to produce heavy elements (Cf and above)
- Medical isotopes
- Stable isotopes

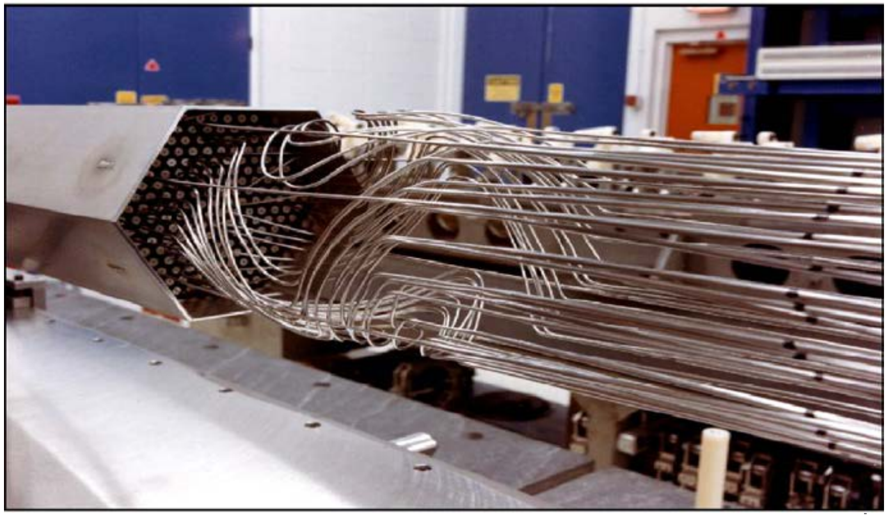
OAK RIDGE National Laboratory

Landmark Reactor Projects at the Hanford Site

B Reactor- 1st large scale nuclear reactor



Fast Flux Test Facility



Sandia National Laboratories

Unique Testing Capability

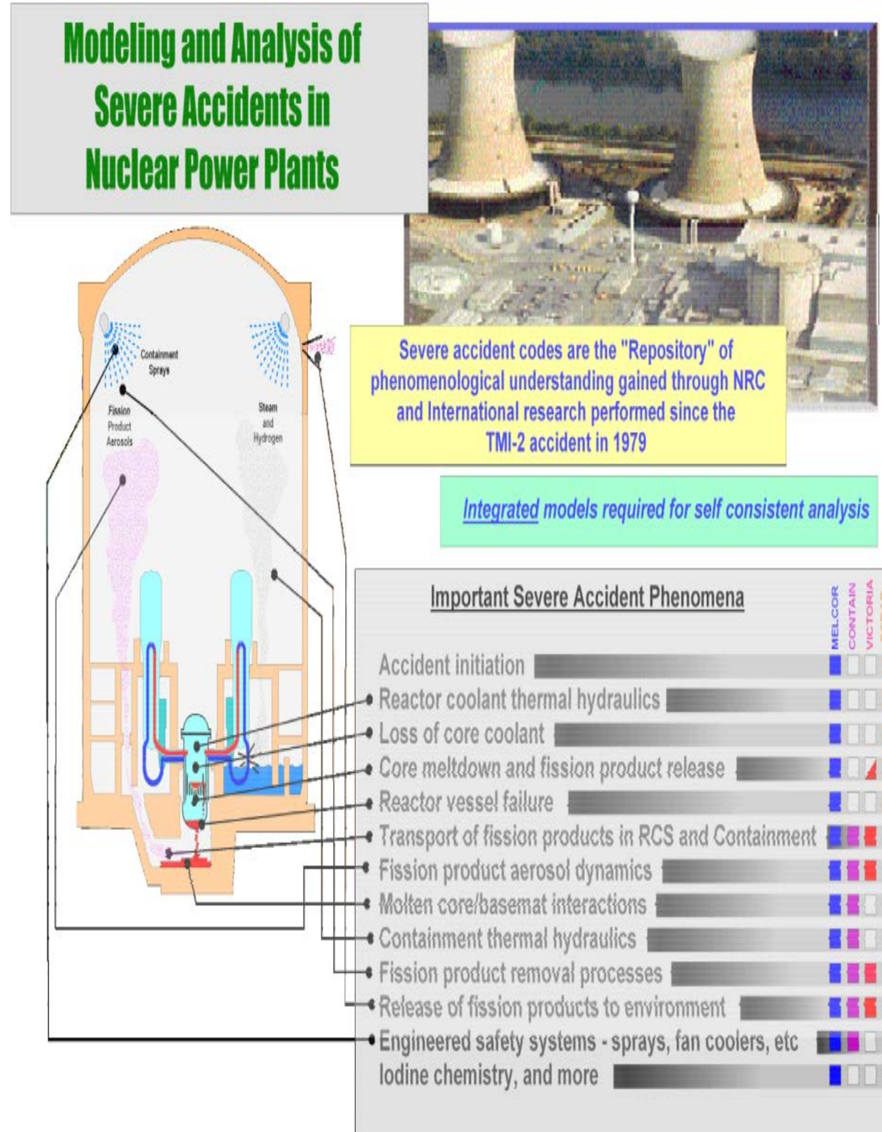
Impact Testing

Fire Testing and Modeling

F4 Crash Test

¼-Scale Prestressed Concrete Containment Vessel Failure Test

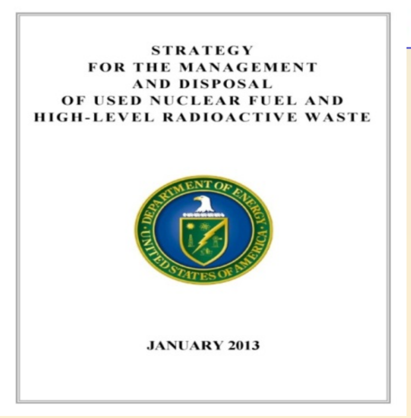
Nuclear Safety



Summary of the Administration's UNF and HLW Strategy

Response to the final report and recommendations made by the Blue Ribbon Commission on America's Nuclear Future

- ***10-year program of work that:***
  - ***Sites, designs, licenses, constructs and begins operations of a pilot interim storage facility***
  - ***Advances toward the siting and licensing of a larger interim storage facility***
  - ***Uses a consent-based siting process***
  - ***Geologic repository operational by 2048***



http://energy.gov/downloads/strategy-management-and-disposal-used-nuclear-fuel-and-high-level-radioactive-waste

Advanced Modeling and Simulation

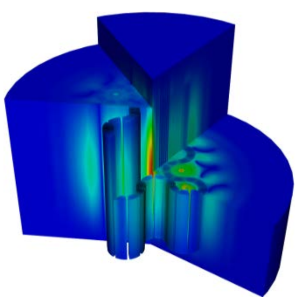
CASL
Consortium for Advanced Simulation of LWRs

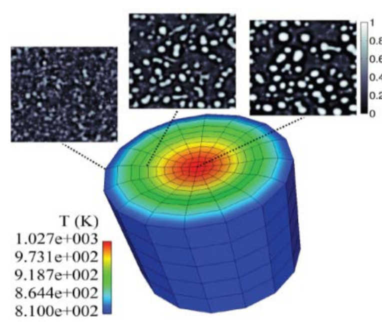
Building a Virtual Reactor to Address Industry Defined Challenge Problems

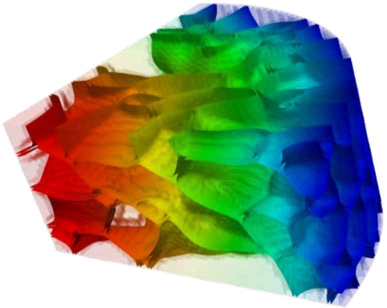
NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

Advanced predictive capability

- mechanistic descriptions of key phenomena
- Simulating phenomena at the appropriate resolution and fidelity
- Coupling multiple phenomena where they compete in real world conditions





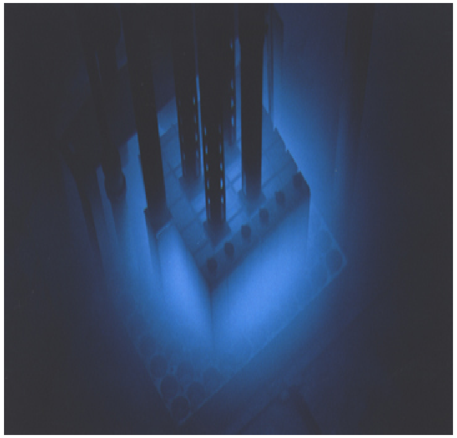


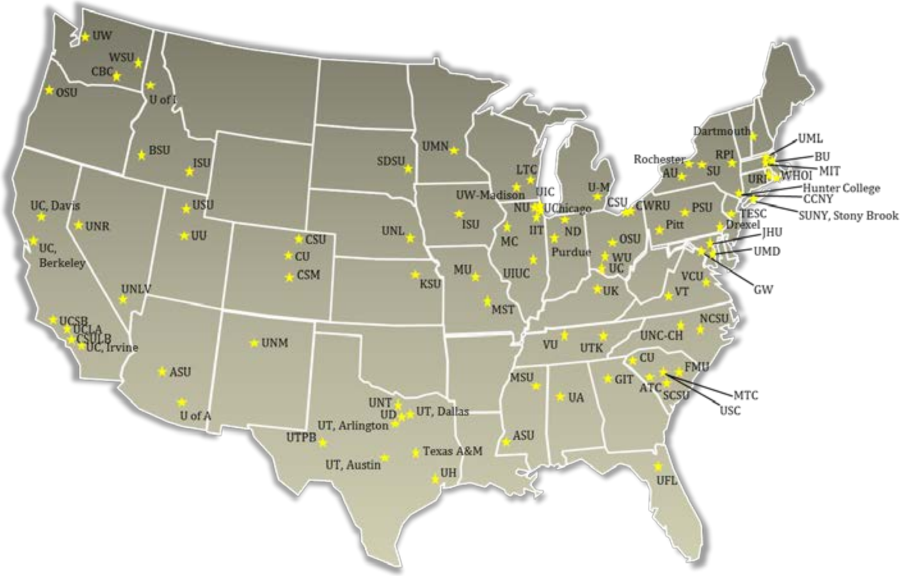
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Nuclear Energy University Programs

- **Competitive process for awarding R&D, infrastructure and scholarships/fellowships**
- **Integrated Research Projects**
  - Multi-University teams
  - Significant scope/budget
- **Since FY09, we have awarded $343M to 97 schools in 38 States**
- **Awards to Purdue University total $5,822,912**
  - R&D projects $3,761,100
  - Infrastructure $1,576,812
  - Scholarships/Fellowships $485,000





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Nuclear Energy

International Cooperation

- **DOE supports technical collaborations through bilateral Action Plans, Working Groups, and the International Nuclear Energy Research Initiative**
- **Bilateral:**
  - Peaceful Uses of Nuclear Energy Agreements (123 Agreements)
  - R&D Agreements
  - International Nuclear Energy Research Initiatives (I-NERIs)
  - Memoranda of Understanding (MOUs)
- **Multilateral:**
  - International Framework for Nuclear Energy Cooperation (IFNEC)
  - Generation IV International Forum (GIF)
  - International Atomic Energy Agency (IAEA)
  - International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)
  - Nuclear Energy Agency (NEA)

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Nuclear Energy

Conclusion

- **Nuclear power is an essential element of our energy mix**
- **Several factors can inhibit the future growth of nuclear energy**
- **DOE is working with the NRC, industry, academia and international partners to overcome these challenges**
- **Expanding nuclear energy can help achieve the Administration's clean energy goals**

"President Obama has made clear that nuclear energy is an important part of our all-of-the-above energy strategy."

"In partnership with our nuclear industry, the U.S. Government is supporting the deployment of passively safe reactors both in the United States and around the world."

U.S. Secretary of Energy, Dr. Ernest Moniz
September *2014 Vienna, Austria*

Useful Websites for Additional Information on Nuclear Energy

DOE Home Page - http://energy.gov

DOE Nuclear Energy (NE) Page - http://energy.gov/ne/office-nuclear-energy

US Energy Information Administration - http://www.eia.gov

American Nuclear Society (ANS) - http://www.ans.org/

International Atomic Energy Agency (IAEA) - http://www.iaea.org

US Nuclear Regulatory Commission - http://www.nrc.gov

Nuclear Energy Agency - http://www.oecd-nea.org

Generation IV International Forum - http://www.gen-4.org

Nuclear Energy Institute - http://www.nei.org

Idaho National Laboratory - https://inlportal.inl.gov/portal/server.pt/community/home/255

Backups

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

FY 2015 Congressional Request Funding Summary

(Dollars in Thousands)

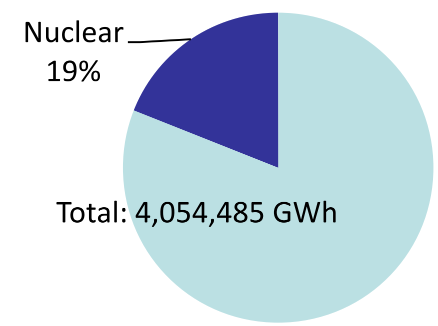
	FY 2014 Enacted[a]		FY 2015 Request
Integrated University Program	5,500		0
SMR Licensing Technical Support	110,000		97,000
Supercritical Transformational Electric Power Generation	--		27,500
Reactor Concepts RD&D	112,822		100,540
Fuel Cycle R&D	186,205		189,100
Nuclear Energy Enabling Technologies	71,109		78,246
Radiological Facilities Management	24,968		5,000
International Nuclear Energy Cooperation	2,496		3,000
Idaho Facilities Management	196,276		185,910
Idaho Safeguards and Security	94,000		104,000
Program Direction	90,000		73,090
Adjustments	-5,000	b	--
Total, Nuclear Energy	**888,376**		**863,386**

a) Reflects application of $814,100 rescission as identified within section 317 of Public Law 113-76.
b) Use of Prior Year Balances.

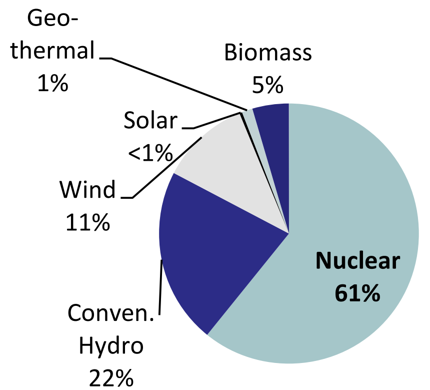
Nuclear Energy Plays an Important Role in US Energy Supply

- **Nuclear power is a clean, reliable base load energy source**
  - Provides 19% of U.S. electricity generation mix
  - Provides 61% of U.S. emission-free electricity
  - Avoids about 700 MMTCO2 each year
  - Helps reduces overall NOx and SOx levels
- **U.S. electricity demand projected to increase ~28% by 2040 from 2011 levels**
- **99 GWe nuclear capacity - 100 operating reactors**
  - Fleet maintaining close to 90% average capacity factors
  - Most expected to apply for license renewal for 60 years of operation

Electricity Production, 2012



Net Non-Carbon Emitting Sources of Electricity, 2012



Source: Energy Information Administration

U.S. DEPARTMENT OF
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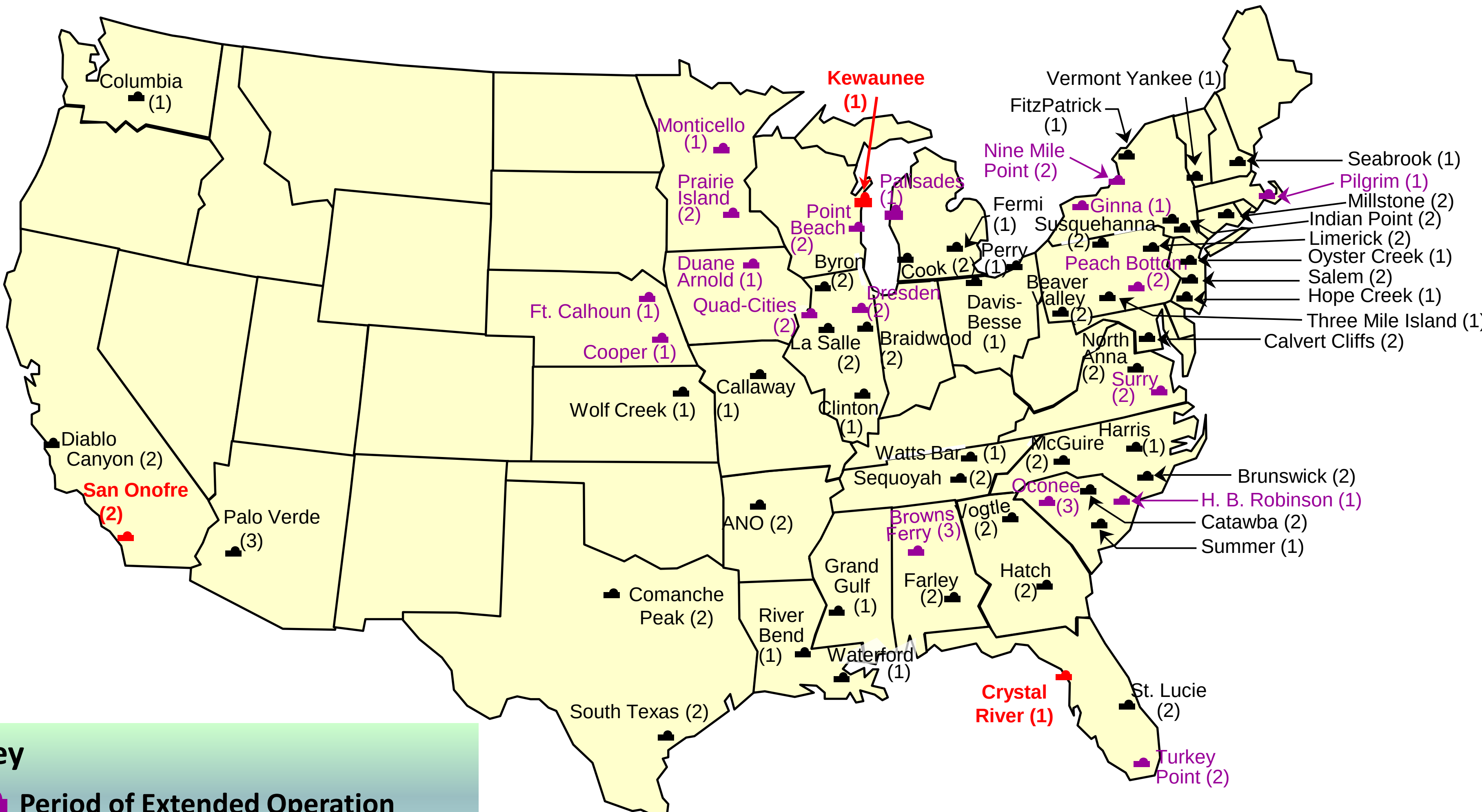
Nuclear Energy

U.S. Nuclear Power Plants in Operation

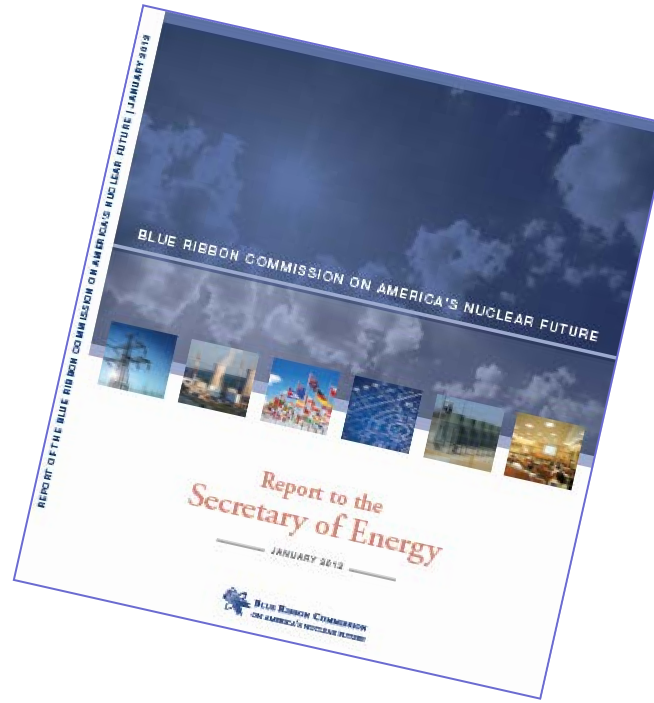


Key

- Period of Extended Operation
- Recently shut-down plants

Blue Ribbon Commission Recommendations

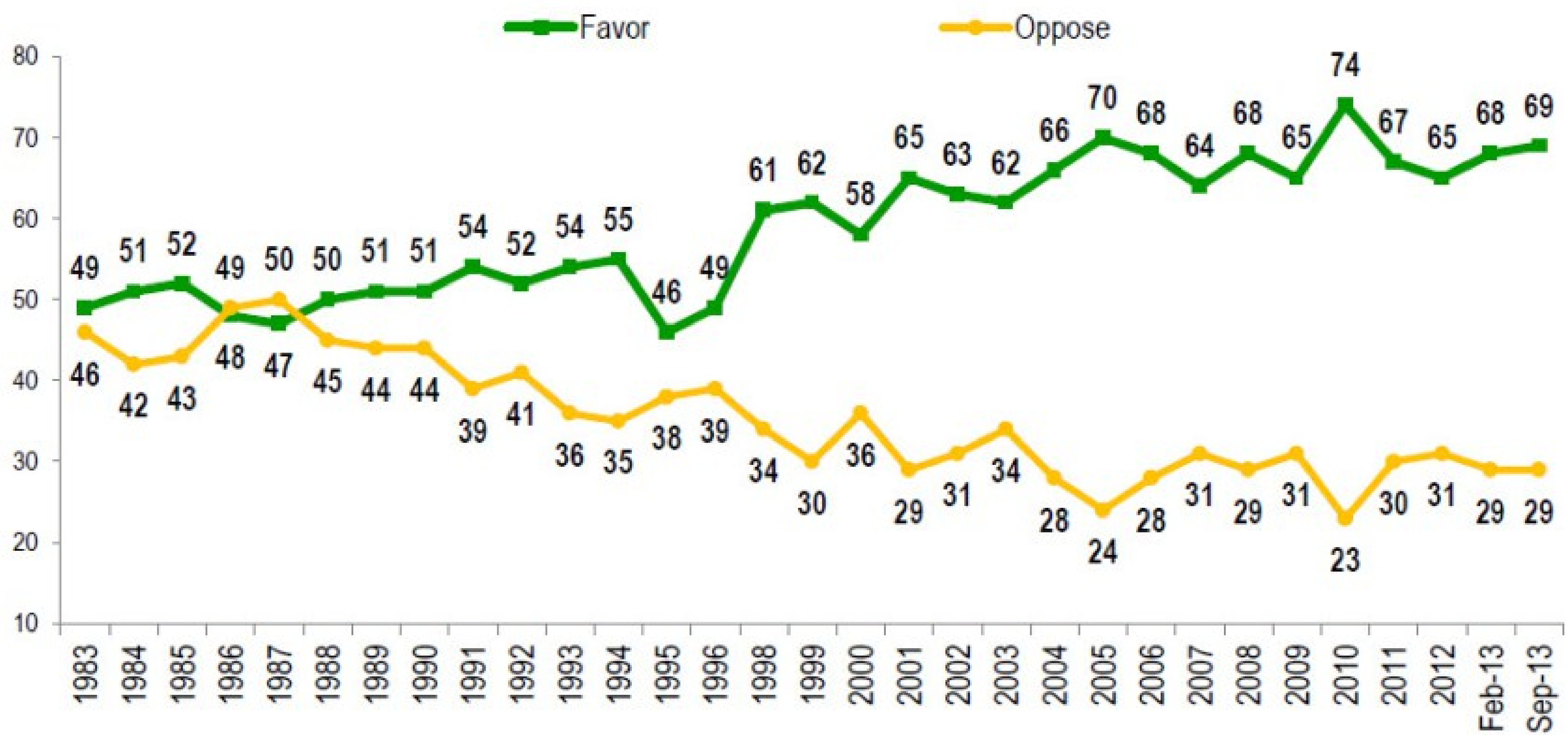
1. A new, consent-based approach to siting future nuclear waste management facilities.
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.
3. Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management.
4. Prompt efforts to develop one or more geologic disposal facilities.
5. Prompt efforts to develop one or more consolidated storage facilities.
6. Prompt efforts to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available.
7. Support for continued U.S. innovation in nuclear energy technology and for workforce development.
8. Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns.



Public Support Increases

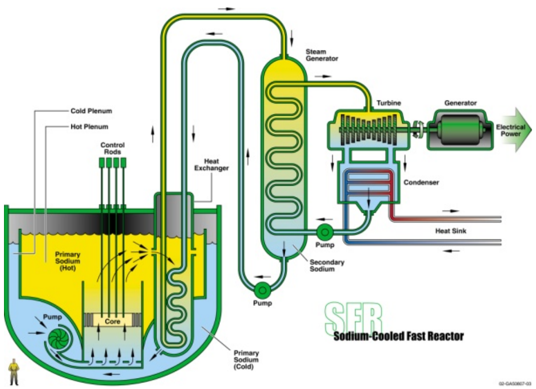
Figure 1. Percent Who Favor and Oppose Nuclear Energy: 1983 to 2013

"Overall, do you strongly favor, somewhat favor, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States?"

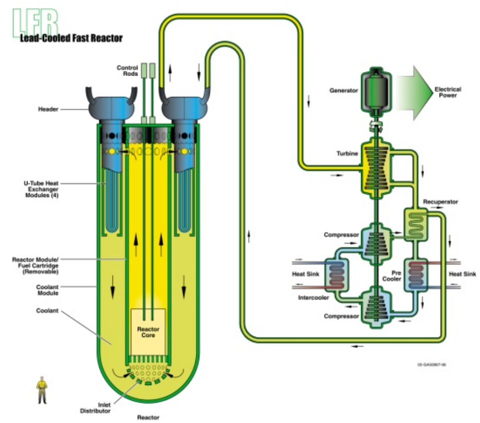


Nuclear Energy Institute-commissioned national public opinion surveys from 1983 to 2013

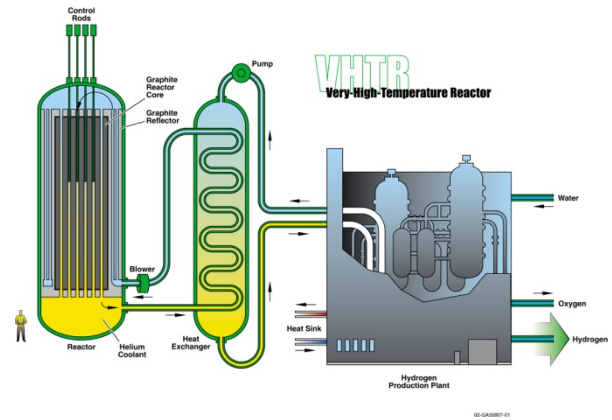
Generation IV Reactor Concepts



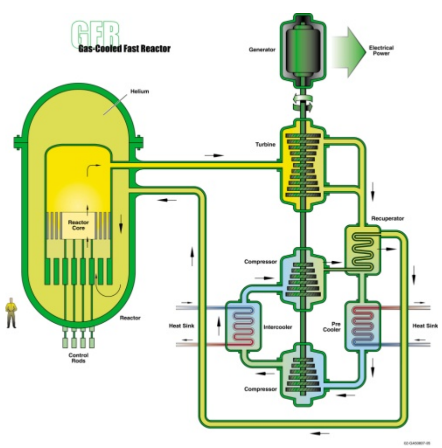
Sodium Fast Reactor



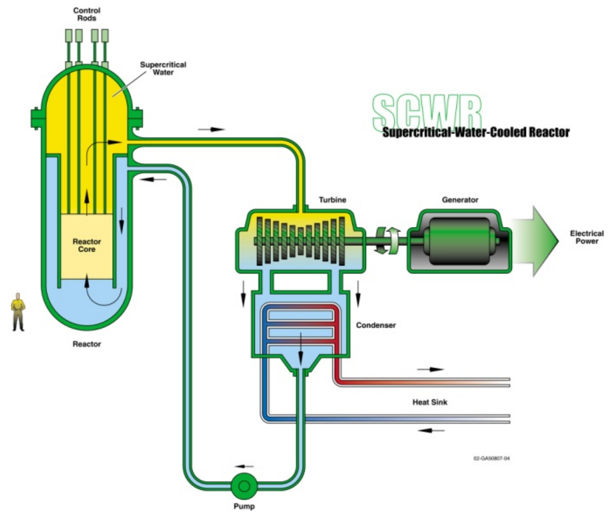
Lead Fast Reactor



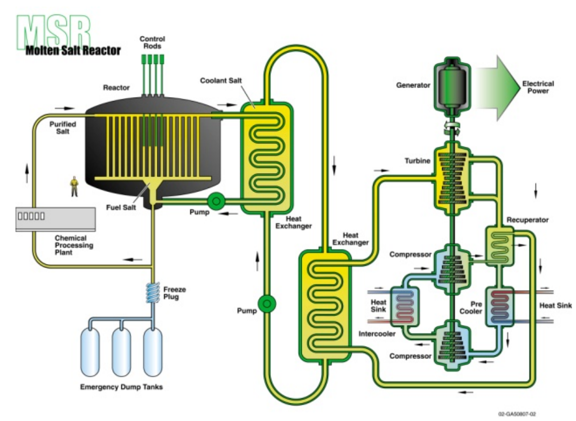
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Fuel Cycle Research and Development: an Integrated Approach

Front End

Back End

Uranium Resources

- *Conventional production*
- *Innovative approaches*
  - *U Seawater*

Fuel Fabrication

- *Safety enhanced LWR fuel*
  - *Accident tolerance*
- *Higher performance*
  - *Improved burnup*

Reactors

Interim Storage

- *Evaluating extended time frames*
- *Transport after storage*

Recycle

- *Separations*
- *Recycled fuel*
- *Secondary waste treatment*

Disposal

- *Alternative geologies*
- *Alternative waste forms*

←----------------Safeguards and Security By Design-------------→

Optimize through Systems Analysis, Engineering, and Integration