U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Perspectives on the Future of Nuclear Power in the United States

DC-ANS Meeting

John E. Kelly
Chief Technology Officer
Office of Nuclear Energy
U.S. Department of Energy

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Nuclear Energy

Nuclear Energy
A Presidential Priority

"Begin a complete review of U.S. nuclear energy policy to secure domestic energy independence and to revive and expand the U.S. nuclear energy sector by preserving the nuclear fleet, paving the way for deployment of advanced nuclear designs, and stimulating exports abroad"

Make Nuclear Cool Again

"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 at Press conference, May 10th***

Near Term Challenges for Nuclear Power in the U.S.

- **Keep current fleet operating**
- **Resolve cost and schedule for new builds**
- **Investment/finance for new builds**
- **Grid of the future**
- **Waste management**
- **Achieving national security objectives thru the supply chain**
- **Advanced SMR deployment**
- **Gen IV development and demonstration**

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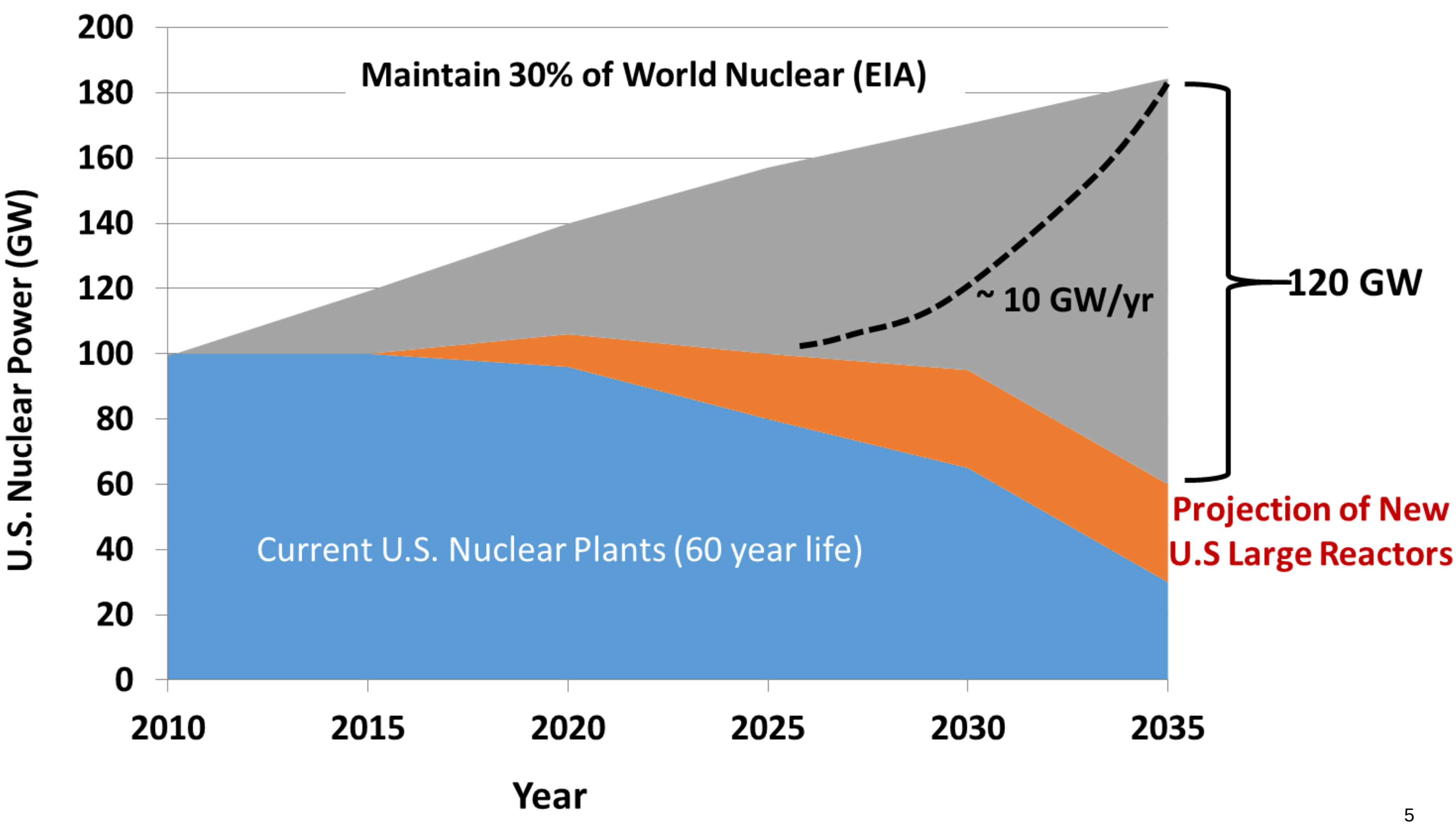
Global Leadership in Nuclear Power Starts with a Strong Nuclear Industry in the U.S.



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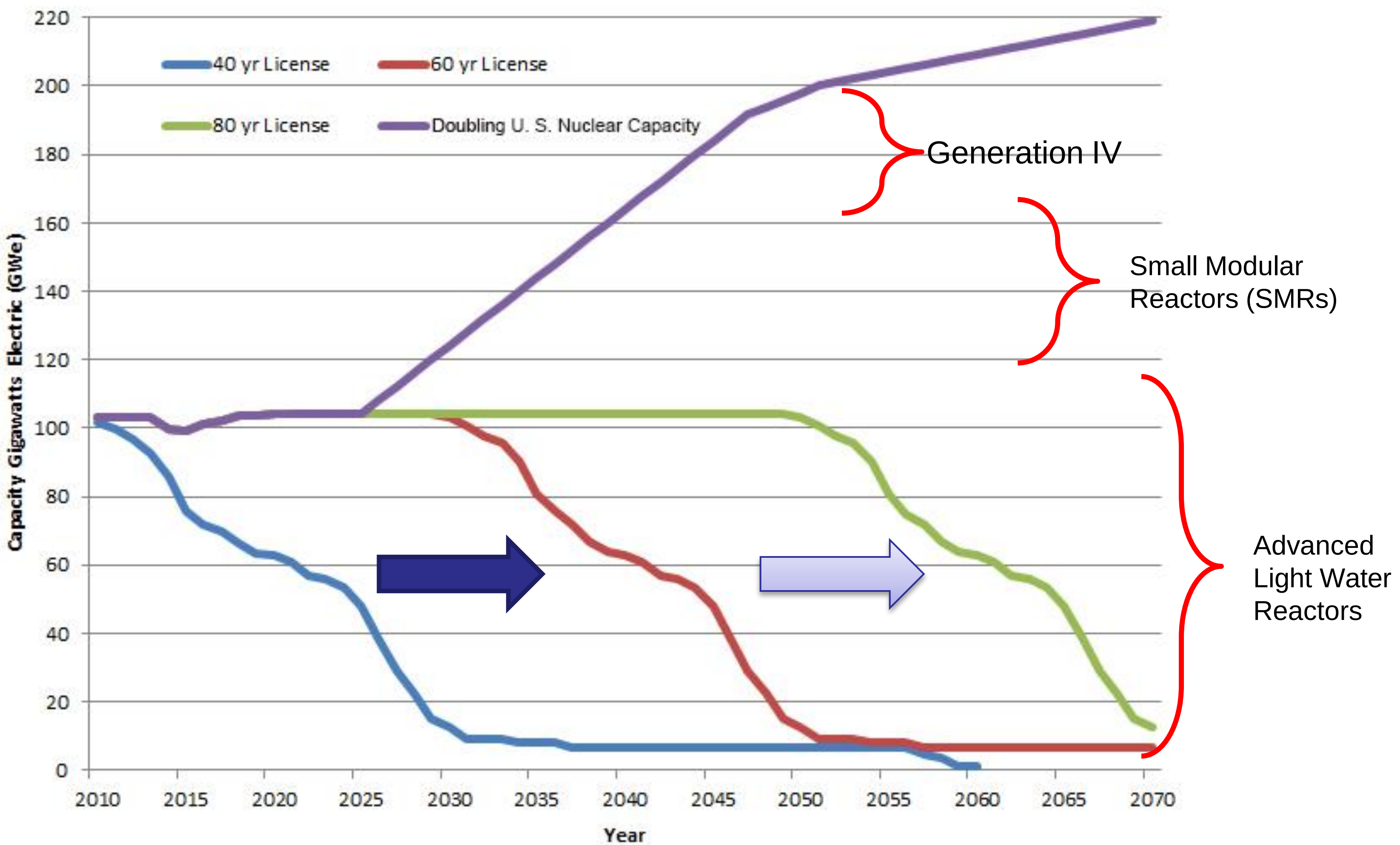
Nuclear Power Capacity Needed to Meet Future Electricity Demand



Keeping the current fleet operating

- **Future of US nuclear industry is very dependent on keeping the current fleet operating**
  - **Revenues**
  - **Sustainability of supply chain**
  - **Workforce development**

- **Complex Situation**
  - **Reform market policies and structure**
  - **Utilities seeking near term support from States**
  - **Reduce operating costs**
  - **Subsequent License Renewal**

Nine Mile Point ~ Courtesy Exelon

Light Water Reactor Sustainability (LWRS) Program

LWRS Program Goal

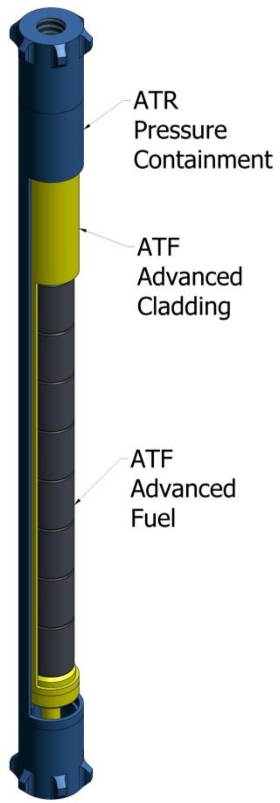
- Develop fundamental scientific basis to allow continued long-term safe operation of existing LWRs (beyond 60 years) and their long-term economic viability

LWRS focus areas

- Materials Aging and Degradation
- Advanced Instrumentation and Controls
- Risk-Informed Safety Margin Characterization
- Systems analysis of emerging issues
- Reactor Safety Technologies

Enhanced Accident Tolerant Fuel

- **Program is developing a new fuel/clad system that would be more tolerant to accident conditions**
  - Eliminate or reduce hydrogen production
  - Withstand higher temperatures
- **DOE is working with 3 vendors**
  - Areva
  - Westinghouse
  - GE
- **Range of concepts**
  - Coatings on Zr
  - New cladding material
  - Higher thermal conductivity fuel
  - Si-C cladding



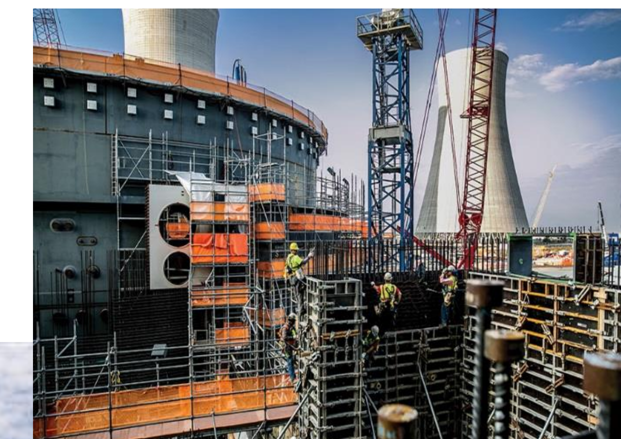
Schematic drawing of the capsule-rodlet assembly for the new accident tolerant fuel experiment in the Advanced Test Reactor (6.2 inches long, 0.4 inches in diameter).

9

New Builds in U.S.

Will these be sufficient to overcome existing plant retirements?

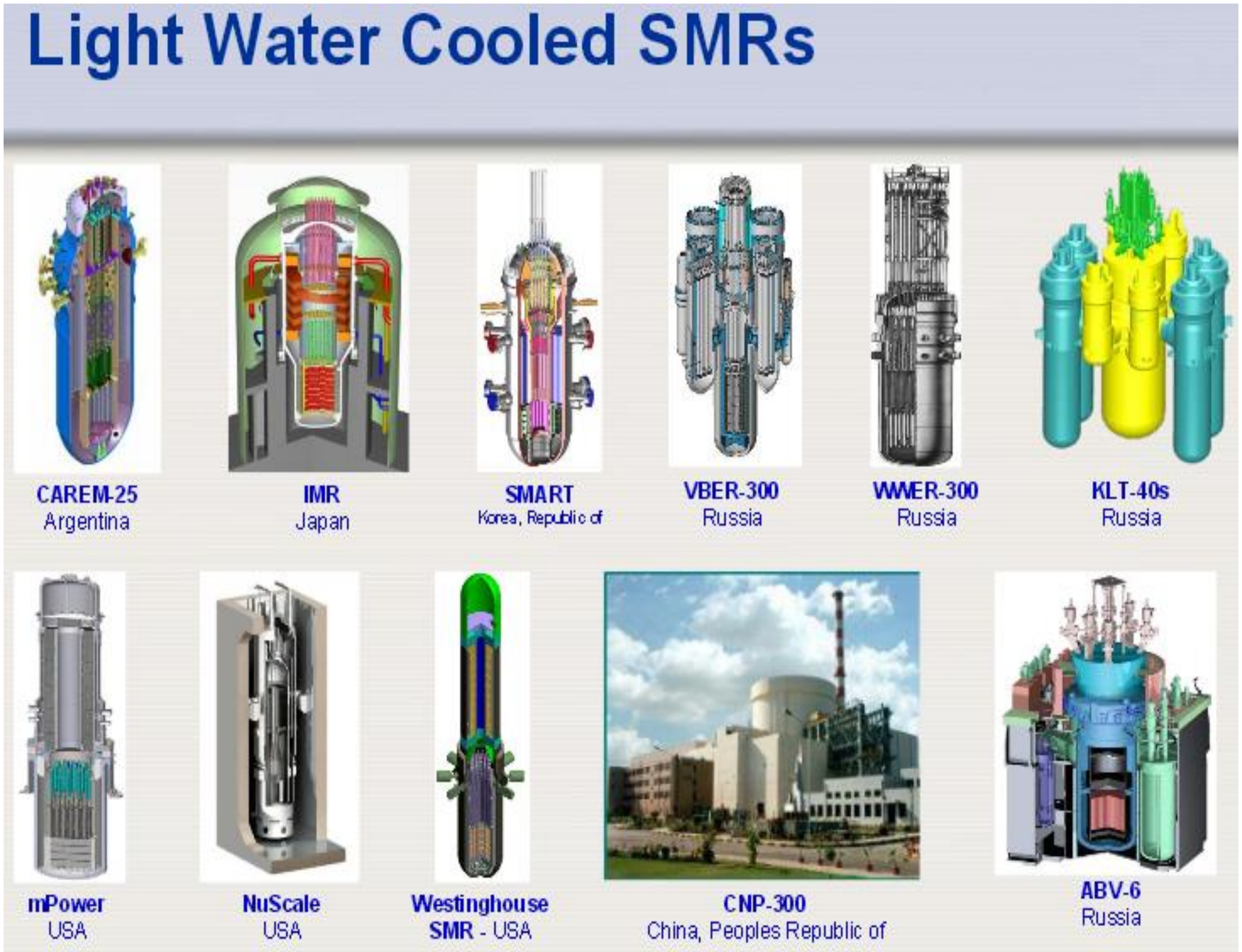
- **First new reactors being built in U.S. in 30 years**
  - **Facing first-of-a kind challenges**
- **Nuclear construction**
  - Vogtle
  - V.C. Summer?
- **Challenges for nuclear deployment**
  - High capital cost
  - Lower electricity demand
  - Low natural gas prices
  - Flawed market structure



Vogtle Unit 3
Courtesy of Georgia Power

V.C. Summer Unit 2
Courtesy of SCANA

Advanced Small Modular Reactors



IAEA definition:

< 300 MWe

Potential Benefits:

- **Factory fabrication**
- **Reduced onsite construction**
- **More flexible siting**
- **Modular expansion**
- **Faster return on investment**

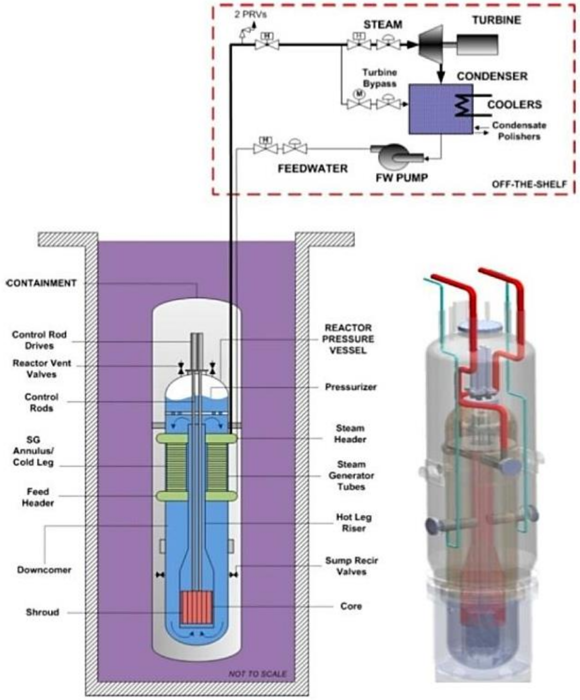
Why is the U.S. Government Interested in Supporting Advanced SMR Technologies?

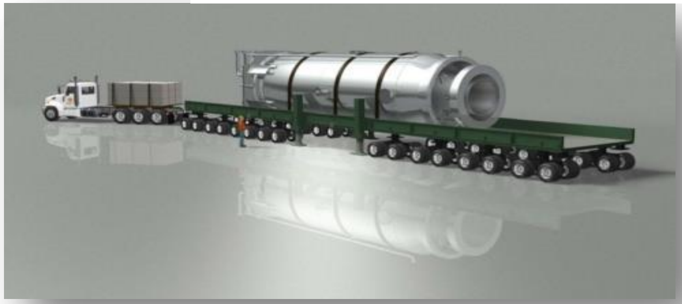
Potential Benefits

- 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
- Domestic job creation potential very high

Potential Markets

- Domestic and international utility markets
- Non-electrical (process heat/desalination) customers





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Current Status of Advanced Small Modular Reactors in the US

NuScale

- **Design Certification Application (DCA) submitted to the NRC in January 2017**
  - NRC accepted and docketed March 2017
  - DCA review and approval within 40 months

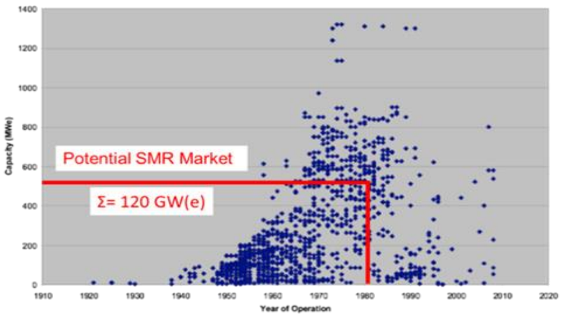
NuScale/UAMPS Siting

- **Site use agreement for a site on the INL**
  - Preferred site identified in August 2016

TVA Siting

- **Submitted Early Site Permit Application to NRC**
  - Review commenced January 2017, completed in approximately 30 months

Clean Energy Option



U.S. Coal Plant Capacity vs. Age

Microgrids

Factory Fabrication

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Growing interest in Micro Reactors

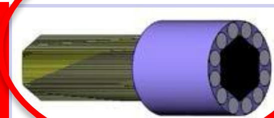
0.5 to 10 kW Non-LWR

Deep Space Power

Military Ops

10 to 100's kW Non-LWR

Space propulsion & planetary surface power; Med Isotopes Military Ops



0.1 to 10 MW Non-LWR

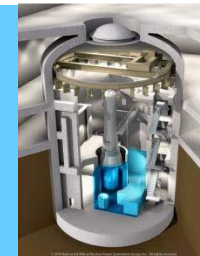
Military Bases; Distributed Hybrid Power; Disaster Relief

Factor built, assembled. Licensing based on prototype.

10 to 50 MW Non-LWR

Power to Grid; Large Military Bases;

Process Heat

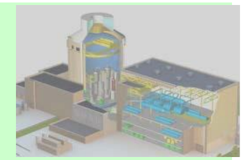


50 to 300 MW

LWR Focus

Power to Grid; Small Cities,

Burning of actinides



1000 MW

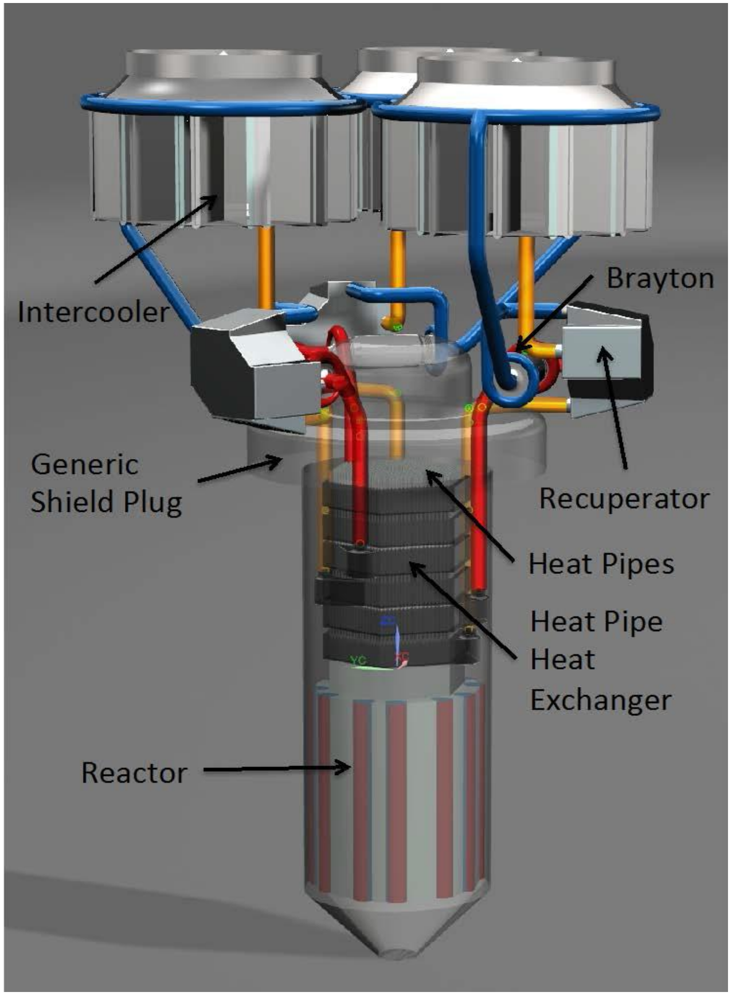
LWR Focus

Power to Grid

4 units under construction in US

Micro Reactors ⟵⟶ **Small Modular**

LANL MegaPower Reactor Design



- 0.5-5 MW electric (DoD Base)
- No moving parts or high pressure
- Heat pipe cooled (no water)
- Encapsulated in armored transport cask
- LE-UO_2 fuel (16-19% enriched)
- Different Power Conversions Systems

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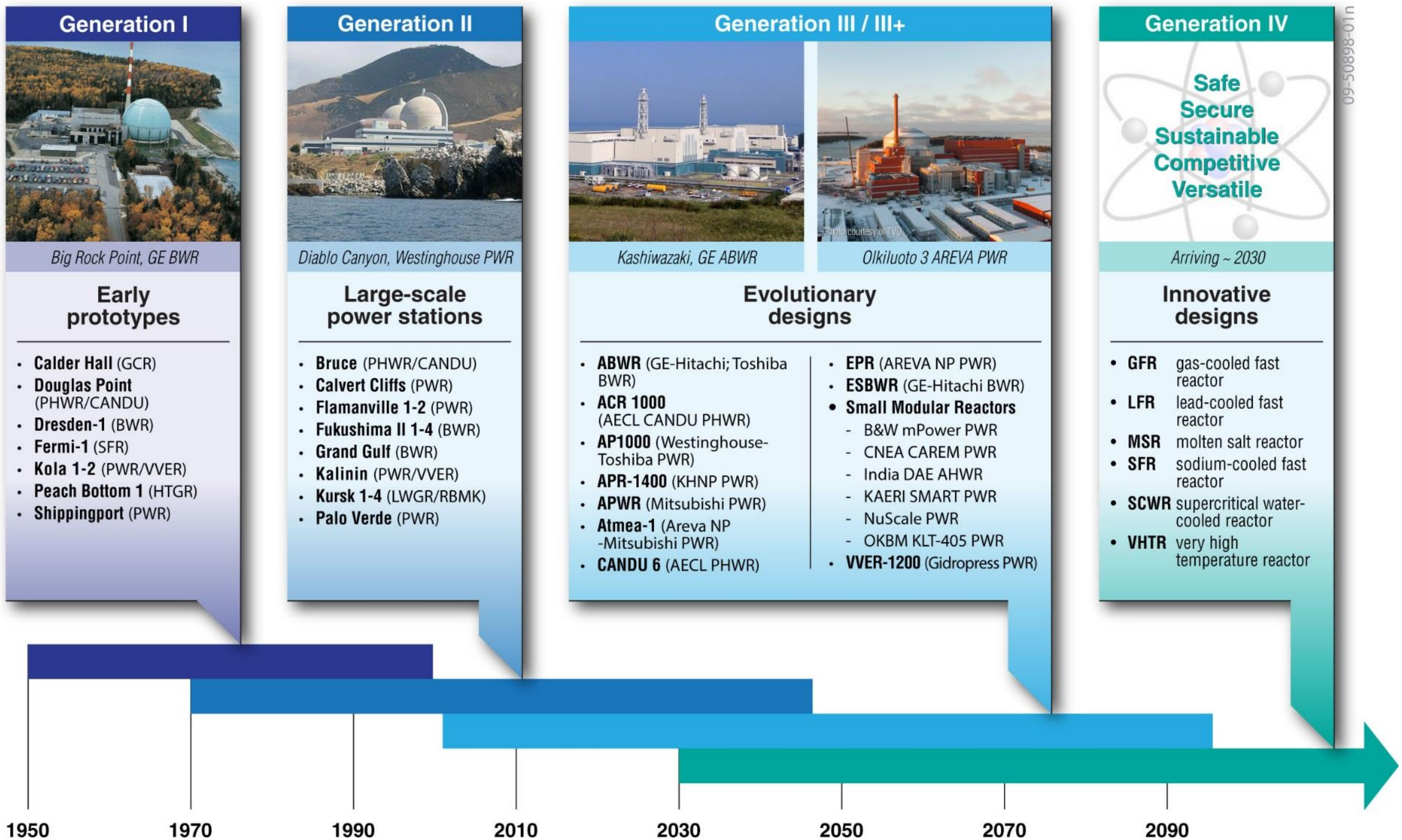
GEN IV International Forum℠



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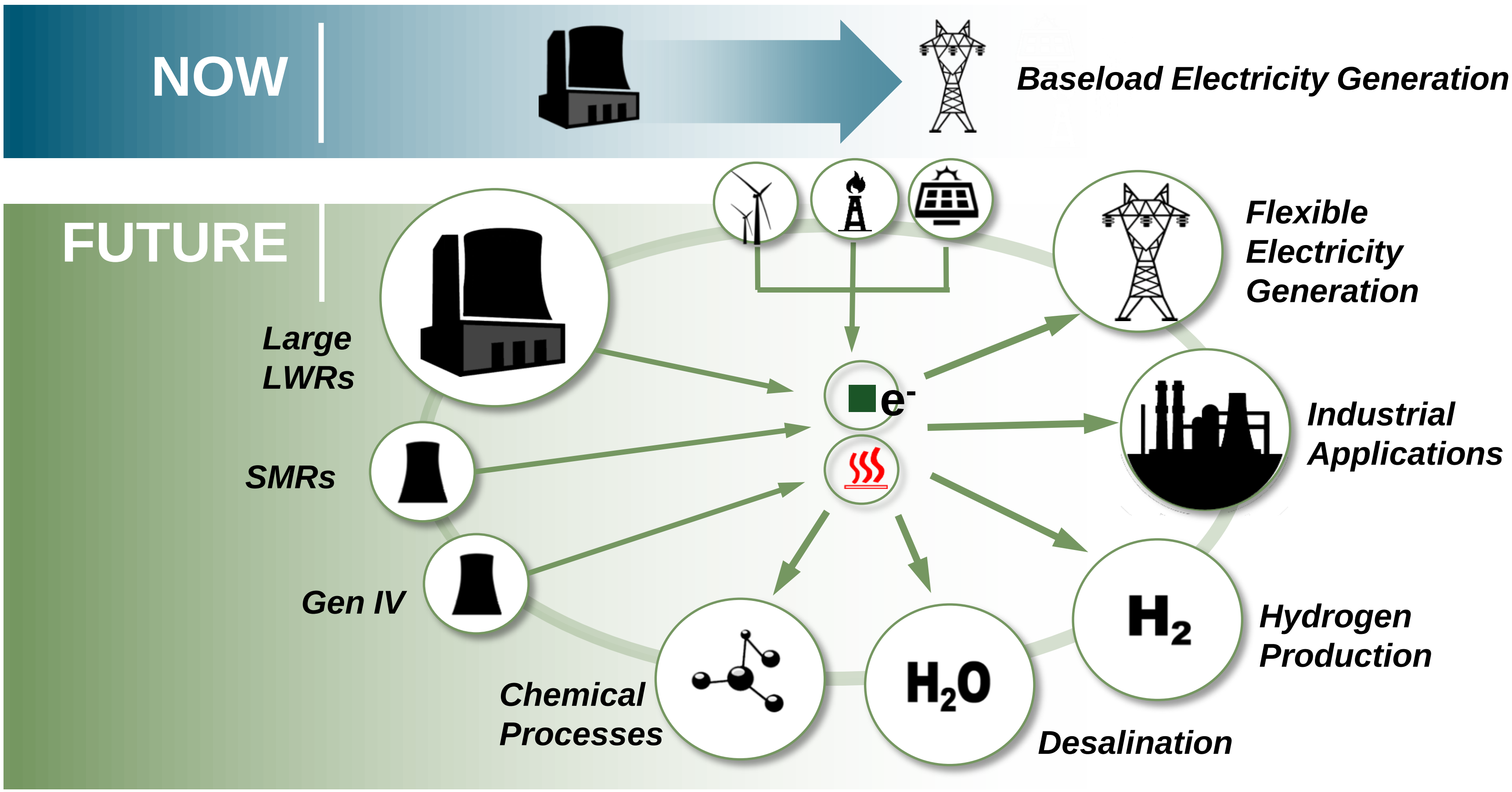
Nuclear Energy Beyond Electricity



Flexible Generators ❖ Advanced Processes ❖ Revolutionary Design

Fourteen Current Members of Generation IV

Argentina *	Japan
Australia *	Korea, Republic of
Brazil *	Russian Federation
Canada	South Africa
China	Switzerland
Euratom	United Kingdom *
France	United States

*Argentina, Australia, Brazil and the United Kingdom are non-active, i.e. they have not acceded to the Framework Agreement which establishes system and project organizational levels for further co-operation. Australia signed the GIF Charter on June 22, 2016, thus becoming the GIF's newest and 14th member.

Generation IV System Development Matrix

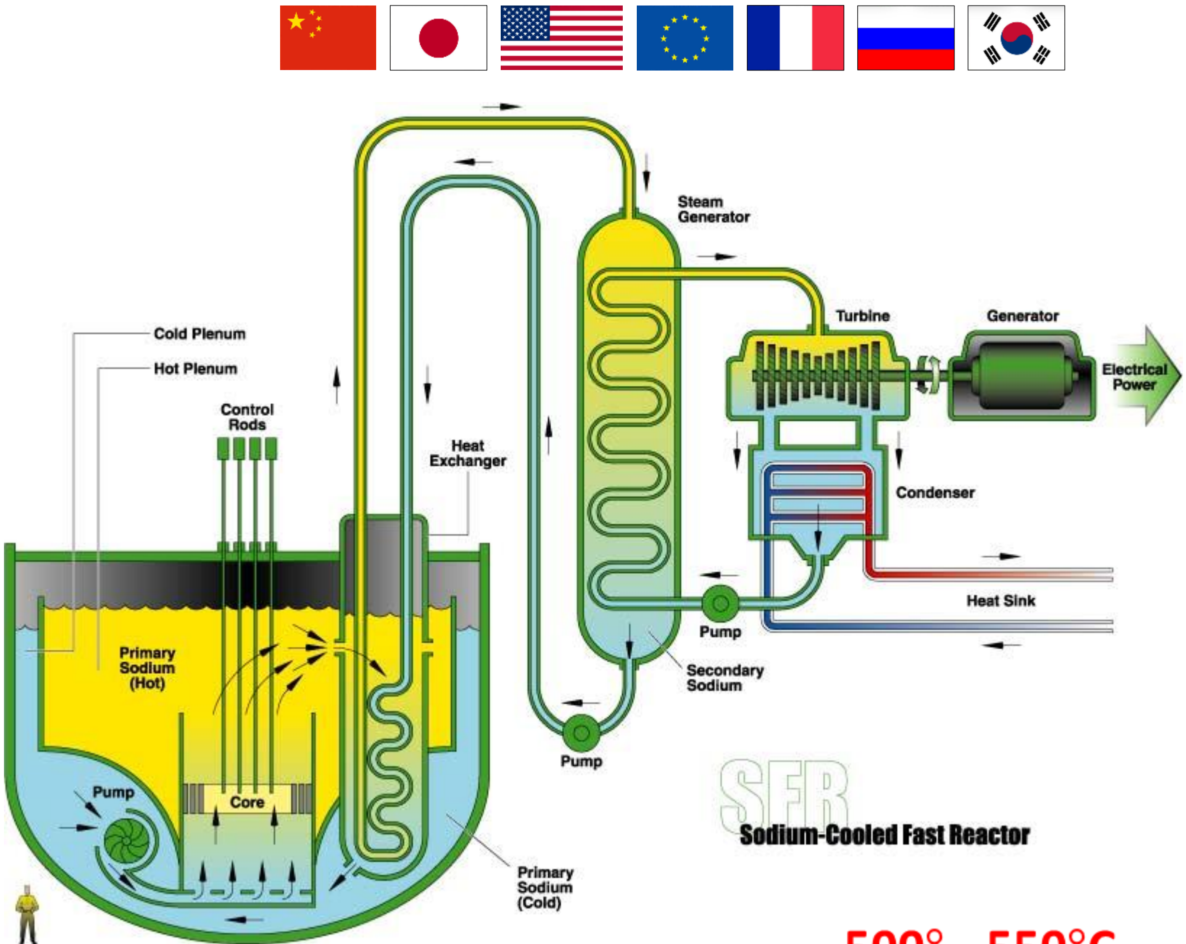
Generation IV Systems	Canada	China	France	Japan	Korea	Russia	South Africa	Switzerland	U.S.A.	EU
Sodium-cooled Fast Reactor (SFR)		●	●	●	●	●			●	●
Very-high Temperature Gas cooled Reactor (VHTR)	●	●	●	●	●	●	●	●	●	●
Gas-cooled Fast Reactor (GFR)			●	●				●		●
Supercritical-water cooled Reactor (SCWR)	●	●		●		●				●
Lead-cooled Fast Reactor (LFR)				●	●	●				●
Molten Salt Reactor (MSR)			●			●			●	●

● *Participating member, signatory of a System Arrangement as of February 2017*

Sodium Fast Reactor

- Major features
  - Fast neutron spectrum
  - Low pressure liquid metal coolant
  - Flexible fuel cycle applications

- SFR design activities
  - ASTRID (France)
  - JSFR (Japan)
  - PGSFR (Korea)
  - BN-1200 (Russia)
  - ESFR (European Union)
  - AFR-100 (United States)
  - CFR-1200 (China)



500° - 550°C

SFR System Status

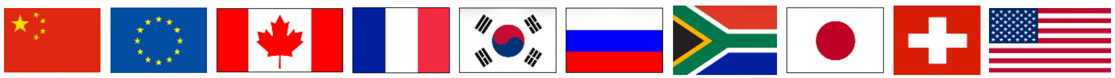
- More than 400 reactor years operating experience since 1951
  - EBR-II, FFTF, Phenix, Superphenix, BOR-60, BN-600, and JOYO
  - BN-800 (Russia) and CEFR (China) started operating in the last decade

- GIF SFR Projects
  - Systems integration and assessment
  - Safety and operation
  - Advanced fuel
  - Component design and balance of plant
  - Global actinide cycle international demonstration project

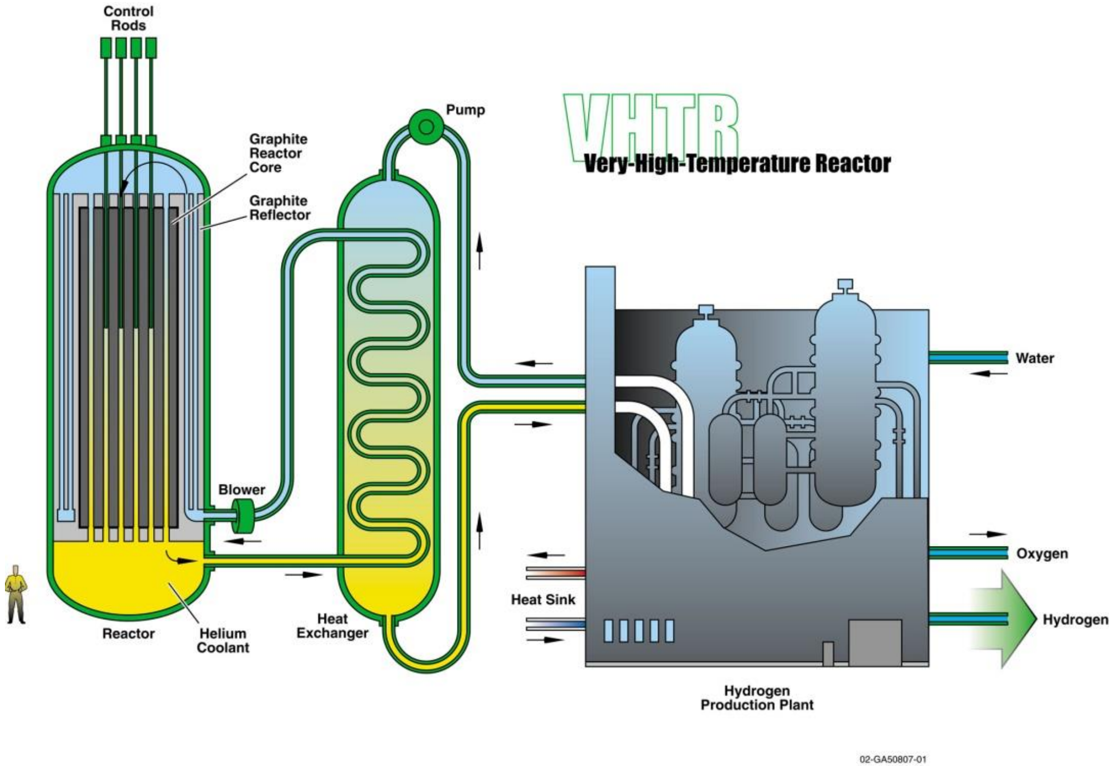
- GIF SFR notable accomplishments
  - Developing, validating and applying safety codes
  - Irradiation and examination of minor actinide fuel samples
  - Under sodium viewing, remote welding, inspection sensors
  - Preliminary irradiations for actinide recycle demonstration

Very High Temperature Reactor

- Major features
  - Inert helium coolant
  - Unique TRISO fuel
  - Thermal neutron spectrum
  - Exceptional safety
  - Very high temperature operation
  - Non-electric applications



- VHTR Design Activities
  - HTR-PM demonstration plant under construction (China)
  - Next Generation Nuclear Plant (United States)
  - Naturally Safe High Temperature Reactor (Japan)
  - Clean Burn High Temperature Reactor (Japan)
  - Multi-purpose HTGR (Japan and Kazakhstan)
  - PBMR (South Africa)

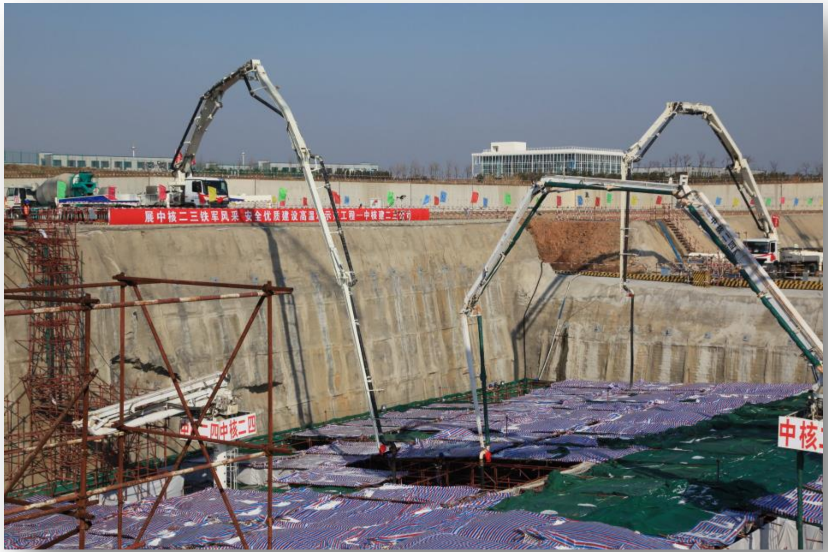


900° - 1000°C

VHTR System Status

- Operating experience gained since 1963
  - AVR and THTR (Germany)
  - Peach Bottom and Fort St. Vrain (United States)
  - HTTR (Japan)
  - HT10 (China)

- GIF VHTR Projects
  - Fuel and fuel cycle
  - Hydrogen production
  - Materials
  - Computation, modeling, validation and benchmarking



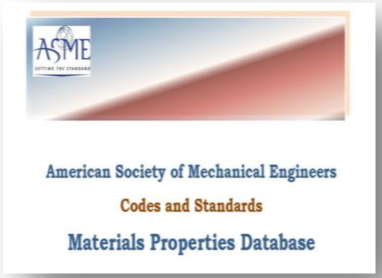
First Concrete poured for China's HTR-PM
~ Courtesy Tsinghua University

- GIF VHTR notable accomplishments
  - Fuel irradiation and examination
  - More than 300 reports uploaded into the Materials Handbook
  - Hydrogen production testing

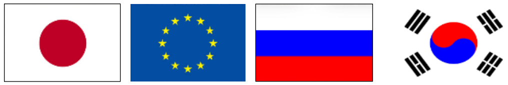
Gen IV Materials Handbook

- **Gen IV Handbook is digital, web-based database system developed to collect and manage all GIF VHTR materials data (>$150M)**
  - **Includes graphite, metals, and ceramics & composites data**
  - **Mandatory usage required by VHTR Materials Project Arrangement**
  - **Includes technical reports, test data, materials pedigree, microstructures, data analysis and comparison tools, etc.**
  - **Very strong access control for individuals, organizations, and data**
  - **Funded by DOE-NE as part of GIF contribution & managed at ORNL**
- **Separate volumes funded for additional DOE and other programs**

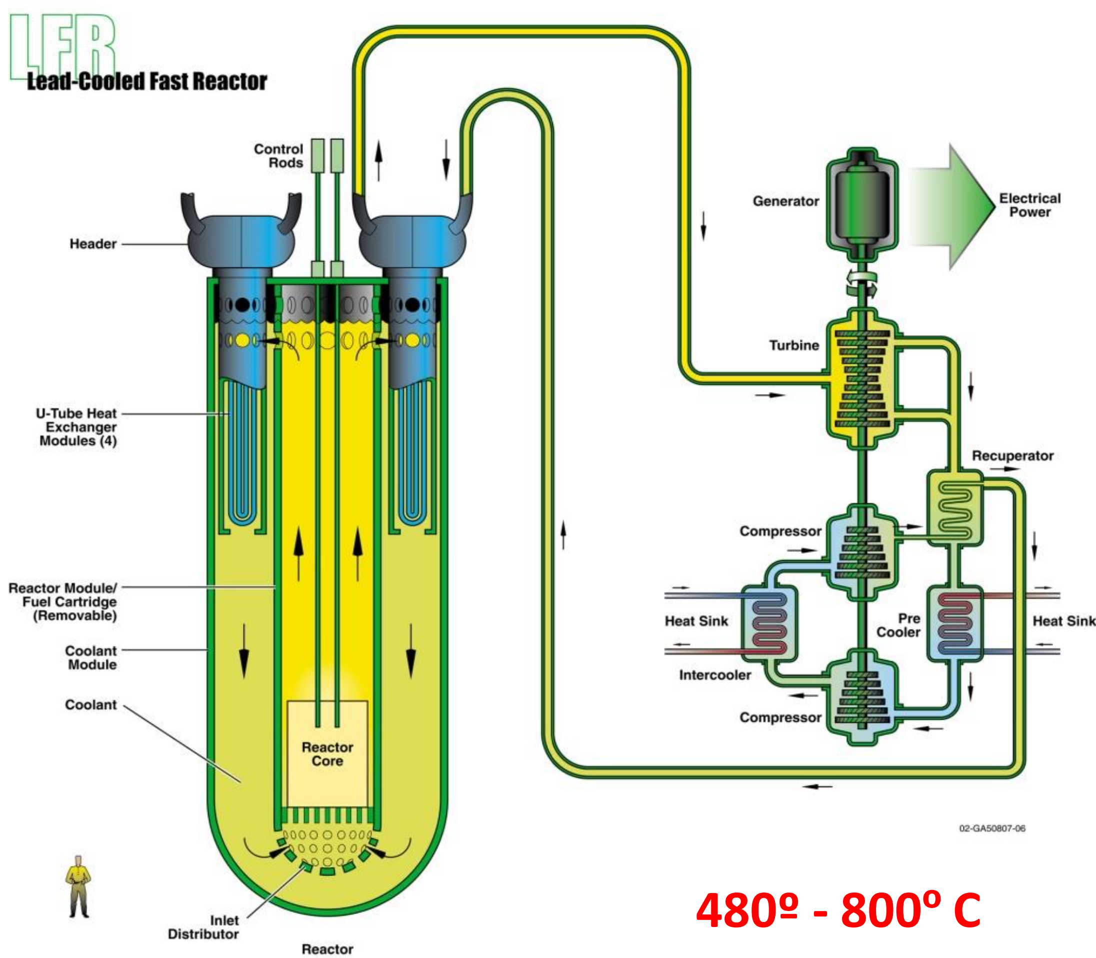
- **ASME has signed contract with ORNL to develop separate volume**
  - **Will contain entire ASME materials data base when complete**
  - **ASME to bear incremental costs**



Lead-cooled Fast Reactor



- Major features
  - Liquid metal coolant that is not reactive with air or water
  - Lead or lead-bismuth eutectic options
  - Fast neutron spectrum
- LFR design activities
  - BREST (Russia)
  - SVBR-100 (Russia)
    - Lead-bismuth
  - ALFRED (European Union)
  - ELFR (European Union)
  - SSTAR (United States)
  - MYRRHA (European Union)
    - Accelerator driven system



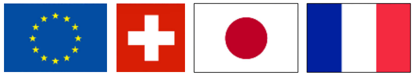
480º - 800º C

LFR System Status

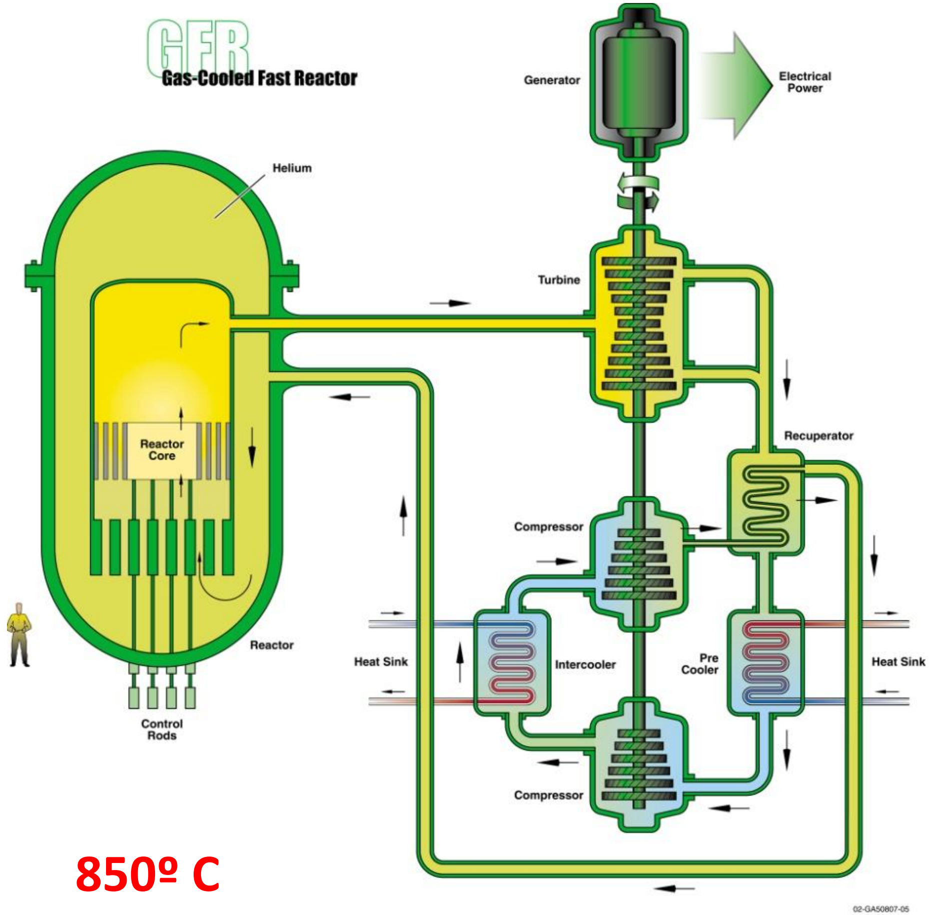
- Operating experience
  - 80 reactor years of Russian submarine LBE reactor operation (15 units)
- GIF LFR Projects
  - GIF has no formal system arrangement for LFR
  - Cooperation conducted under an MOU
- GIF LFR notable accomplishments
  - Developed an international LFR community
  - Developed a provisional system research plan
  - Materials corrosion tests ongoing with lead loops in several laboratories

Gas-Cooled Fast Reactor

GEN IV International Forum



- Major features
  - Fast neutron spectrum
  - Inert helium coolant
  - Very high temperature operation
  - Fuel cycle and non-electric applications
  - Significant development challenges for fuel, safety and components
- GFR design activities
  - Allegro (European Union)



850º C

GFR System Status

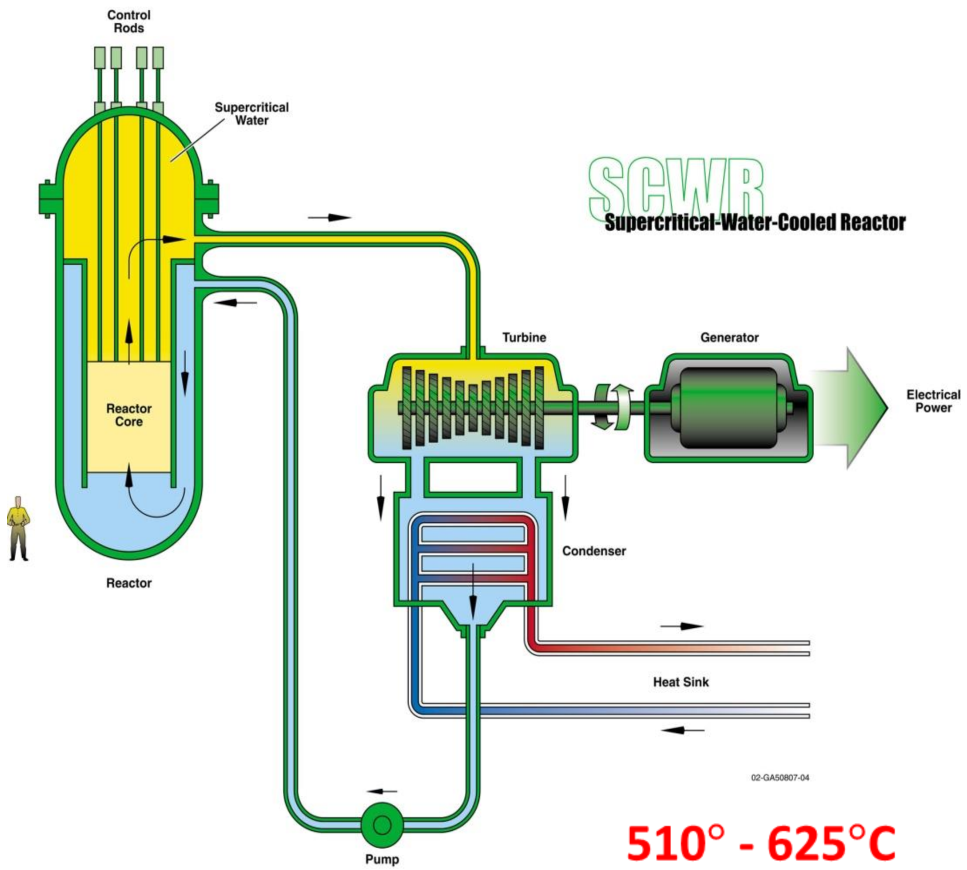
- No operating experience for this challenging concept
  - Development relies on VHTR technology
- GIF GFR projects
  - Conceptual Design and Safety
  - Fuel and core materials
- GIF GFR notable accomplishments
  - Promising fuel concept based on a multi-barrier cylinder
  - Safety system design

GFR reference design

Supercritical Water - Cooled Reactor

- ❑ Major features
  - Merges LWR or PHWR technology with advanced supercritical water technology used in coal plants
  - Operates above the thermodynamic critical point (374º C, 22.1 MPa) of water
  - Fast and thermal spectrum options

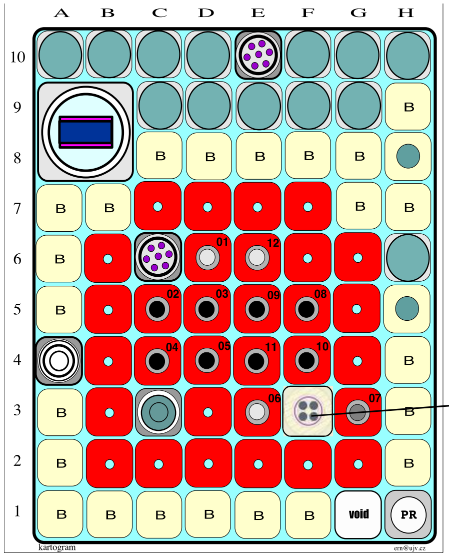
- ❑ SCWR Design Activities
  - First design effort 1957
  - Pre-conceptual design of SC PHWR (Canada)
  - Pre-conceptual SC LWR design activities (Japan and European Union)



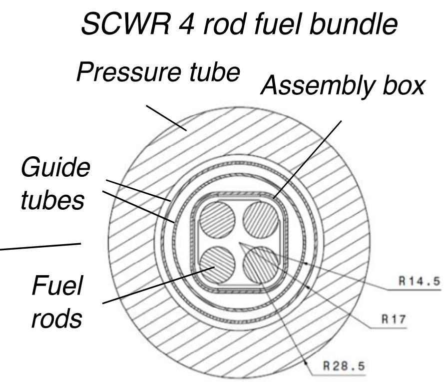
SCWR System Status

- Operating experience
  - No SCWR has been constructed
  - Vast operating experience in supercritical coal plants
- GIF SCWR projects
  - Thermal hydraulics and safety
  - Materials and chemistry
  - Fuel qualification test
  - System integration and analysis
- GIF SCWR notable accomplishments
  - Experiments on heat transfer with supercritical water and other fluids
  - Corrosion testing for different steel alloys
  - Fuel qualification testing planned

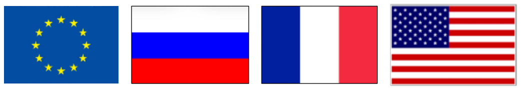
Planned Fuel Qualification Test at UJV in Řež



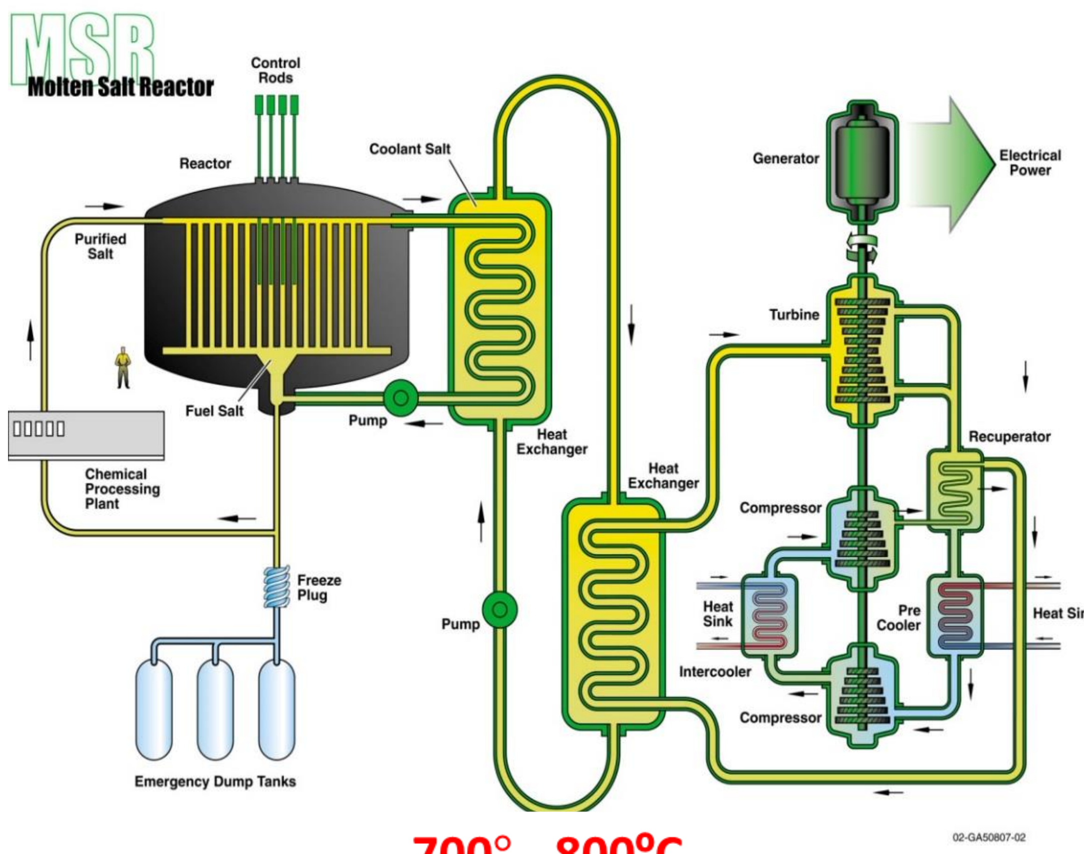
Core of the LVR-15 Reactor



Molten Salt Reactor



- Major features
  - Molten salt eutectic coolant
  - High temperature operation
  - Thermal or fast spectrum
  - Molten or solid fuel
  - On-line waste Management
- Design Activities
  - 2-MWt FHR test reactor (China)
  - Pre-conceptual designs to guide R&D planning
    - Molten Salt Actinide Recycler and Transmuter (MOSART)
    - Molten Salt Fast Reactor (MSFR)



700° - 800°C

MSR System Status

- Operating experience
  - Molten Salt Reactor Experiment (MSRE)
  - Aircraft Reactor Experiment (ARE)

- GIF MSR Projects
  - No formal system arrangement
  - Cooperation proceeding under an MOU

- GIF MSR notable accomplishments
  - The participants conducted benchmark analyses on neutronics, mutiphysics, and safety
  - Studies are ongoing to measure the thermo physical properties of candidate salts
  - Identification of key research needed for viability assessment

Education and Training Task Force

- ❑ Formed to develop education and training materials related to Generation IV systems
- ❑ Created a webinar series (monthly) to provide presentations for the general public on the Gen IV systems and cross-cutting topics
- ❑ **See www.Gen-4.org**
- ❑ Connecting with other nuclear education organizations to share information on educational opportunities and Summer Schools

Over 20 Advanced Fission Reactor Designs in the United States

- **Sodium Fast Reactor**
  - TerraPower, General Electric, OKLO, etc
- **High Temperature Gas Reactor**
  - X-Energy, AREVA, TerraPower, Hybrid Energy, Ultra Safe, etc
- **Molten Salt Reactor**
  - TerraPower, Transatomic, Terrestrial, Elysium, FLIBE Energy, Kairos, etc
- **Lead Fast Reactor**
  - Westinghouse, Gen IV Energy, Lake-Chime, etc
- **Gas Fast Reactor**
  - General Atomics

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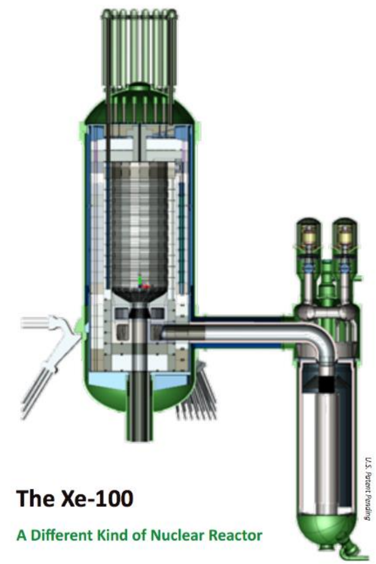
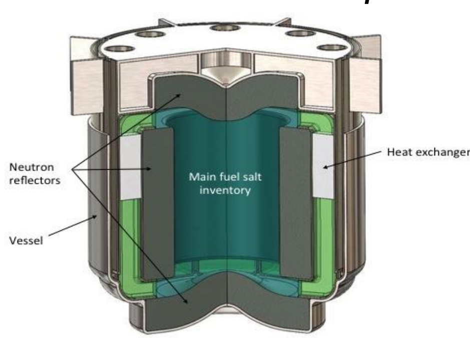
Addressing the Growing National Interest in Advanced Reactors

DOE is currently supporting innovative reactor technologies and improving their economic competitiveness through:

- Targeted laboratory R&D
- Industry projects to develop advanced reactor concepts
  - X-Energy (Pebble Bed High Temperature Gas Reactor)
  - Southern Company Services (Molten Chloride Fast Reactor)
- Facilitating industry access to DOE expertise through the Gateway for Accelerated Innovation in Nuclear (GAIN) initiative
  - Technology-centric working groups
  - Streamlining processes
  - Voucher program
  - Test bed
  - Regulatory advice



Pebble Bed Reactor Concept http://nextbigfuture.com/



Molten Chloride Salt Reactor Concept (https://hdiac.org/)

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DOE Advanced Reactor R&D

Fast Reactor Technologies

- For actinide management and electricity production
- Key work in advanced materials codification, knowledge recapture, validation of safety and performance models, component testing

Mechanisms Engineering Test Loop (METL) facility at ANL – multiple test vessels for component testing in prototypic sodium conditions

Gas Reactor Technologies

- For electricity and process heat production
- Key work in advanced materials codification and Scaled integral experiments to support design and licensing and fuel qualification

Molten Salt Reactor Technologies

- Fluoride High Temperature Reactor

Sandia National Lab Brayton Cycle Test Loop

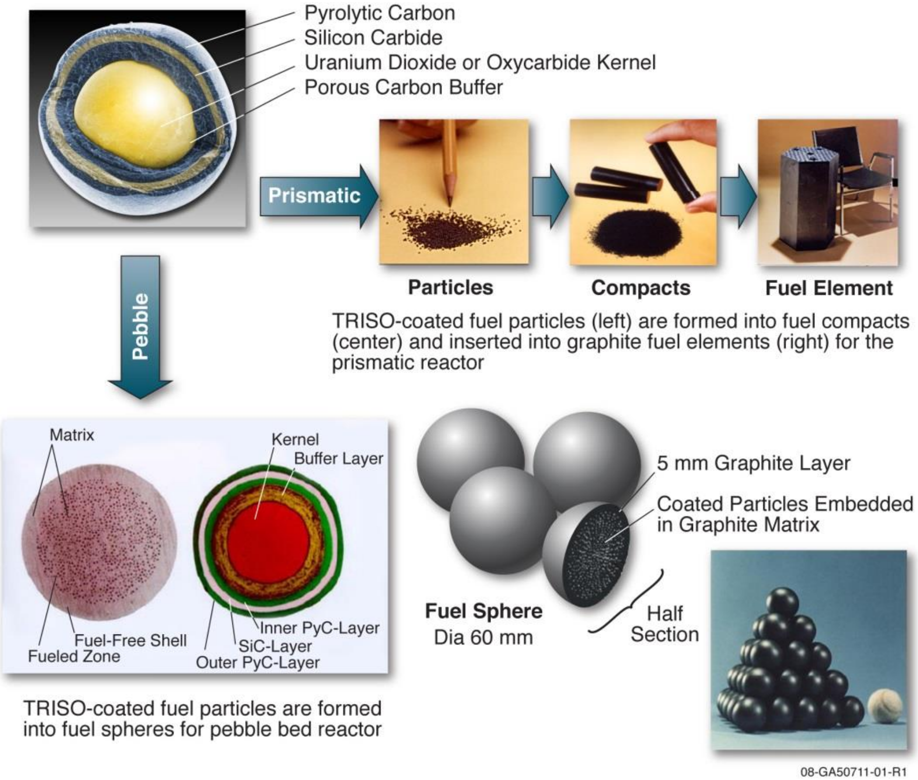
Advanced Energy Conversion and Special Purpose Applications

- Supercritical Carbon Dioxide (sCO2) Brayton Cycle
- Space and other remote applications

High Temperature Gas Reactor TRISO Fuel

Key aspects of TRISO Fuel:

- German industrial experience demonstrated TRISO-coated particle fuel can be fabricated to achieve high-quality levels with very low defects.
- Fuel is very robust with no failures anticipated during irradiation and under accident conditions.
- Fuel form retains fission products resulting in a high degree of safety.



TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor

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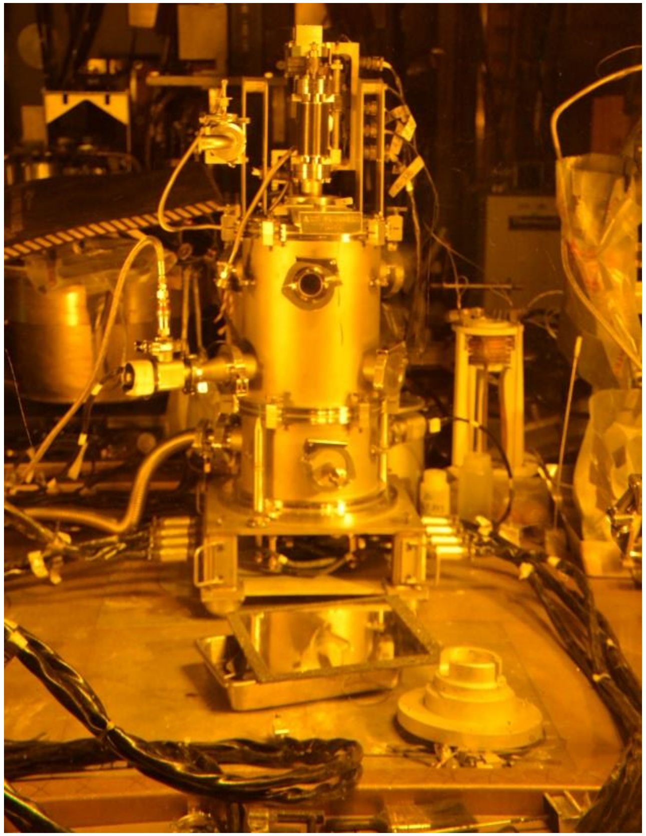
Fast Reactor Fuels

- **Advance the scientific understanding and engineering application of fuels for use in future fast-spectrum reactors, including:**
  - **fuels for enhanced resource utilization (including actinide transmutation),**
  - **support for driver/startup fuel concepts.**
- **Advanced fabrication methods including remote fabrication.**
- **Demonstrate acceptable performance of fast reactor fuels including**
  - **recycled metallic fuels**
  - **ultra high burnup**
- **Support development and validation of an advanced fuel performance code.**



Remote casting furnace in HFEF

Summary

- Nuclear power must be a major source of our energy production to meet global future energy needs
- Continue the safe and reliable operation of the current fleet
- Deploy SMRs in mid-2020’s
- Emerging interest in Micro Reactors
- Develop Generation IV reactor technologies for deployment in the 2030’s