Research Workshop :Future Opportunities in Nuclear Power,
October 16-17, 2014 Purdue University

Advances in Reactor Concepts: Generation IV Reactors – Research Opportunities

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Advanced Reactor Concepts

Advanced nuclear fission energy systems utilizing coolants such as liquid metal, fluoride salt, or gas

- Innovative design
- Economically competitive
- Improved conversion efficiency and reduced plant size
- Significant safety enhancement
- International collaboration

Generation IV International Forum (GIF) (2000) (13 members)

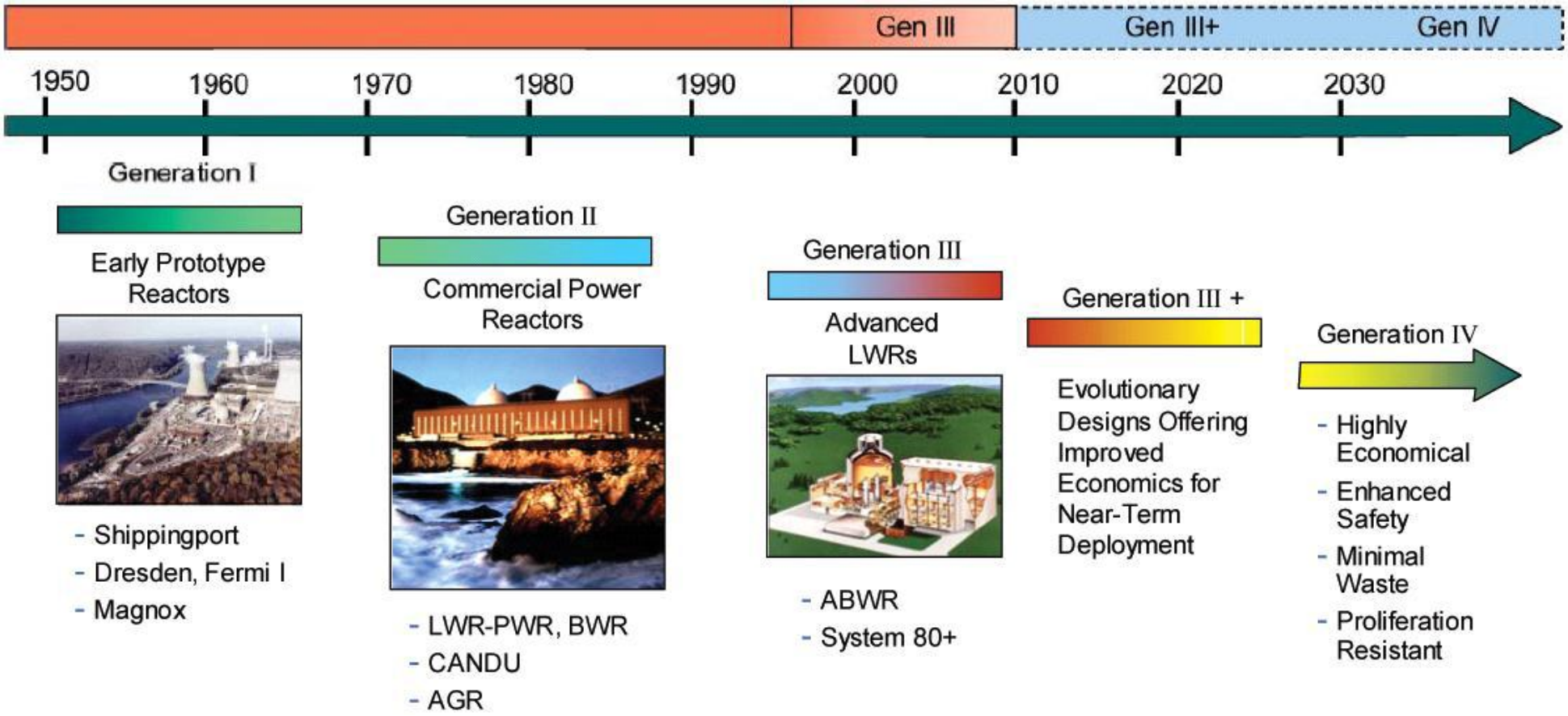
- Sustainability
- Safety and reliability
- Economics
- Proliferation resistance and physical protection.

Generation of Nuclear Energy Systems

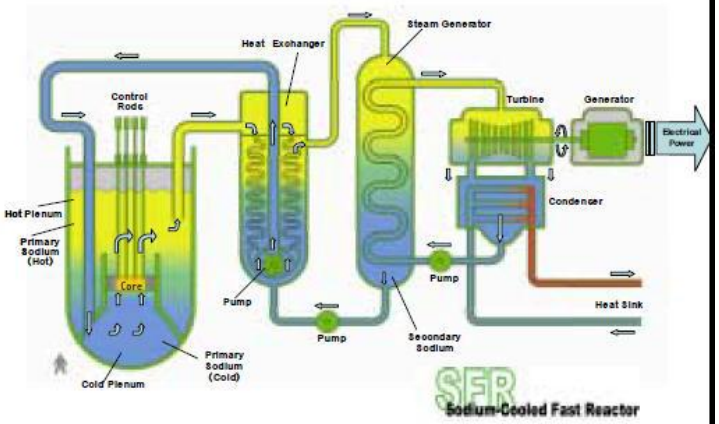
Current nuclear plants -Gen-II and Gen-III reactors.

Gen-III+ and Gen-IV reactors are expected as next nuclear power plants.

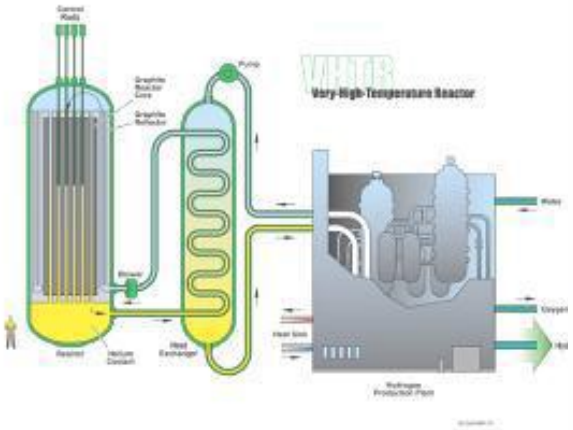
- **Gen-III reactors are featured by more safety measures.**
- **Gen-IV reactors promoted toward commercialization in around 2030s.**



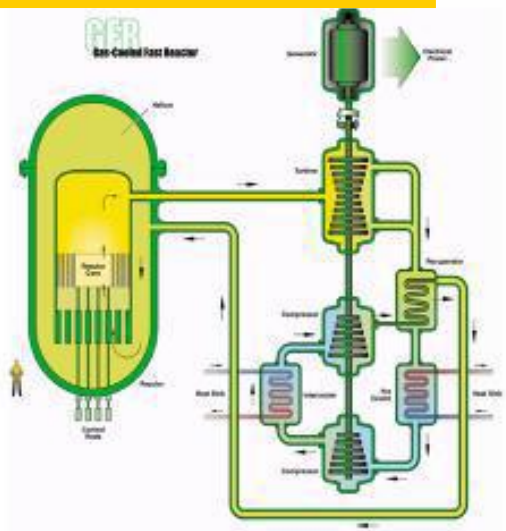
Six Gen IV Reactors



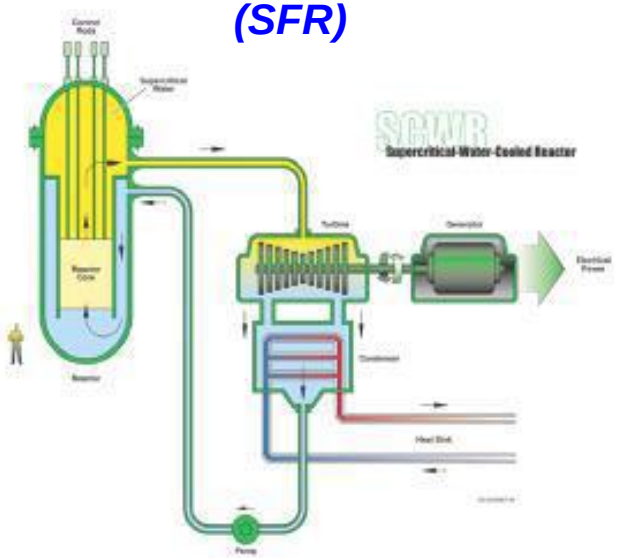
Sodium-cooled Fast Reactor (SFR)



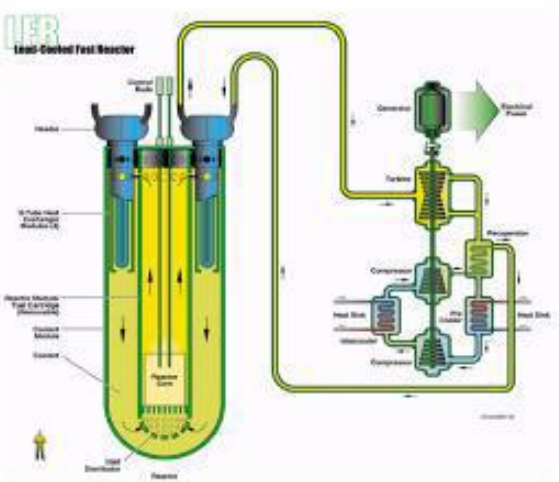
Very High Temperature Reactor (VHTR)



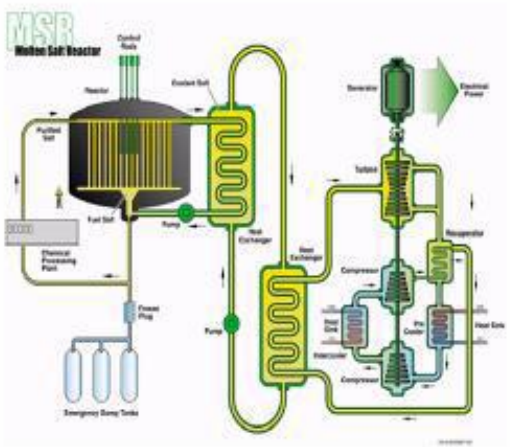
Gas-cooled Fast Reactor (GFR)



Supercritical Water-cooled Reactor (SCWR)



Lead-cooled Fast Reactor (LFR)



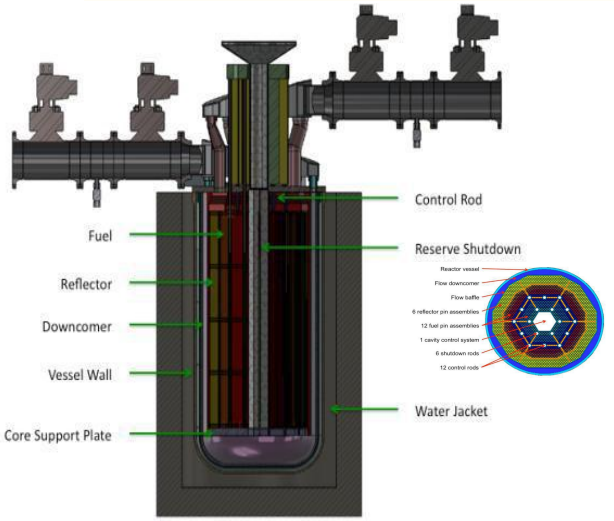
Molten Salt Reactor (MSR)

US-DOE Initiated Advanced Reactor Concepts

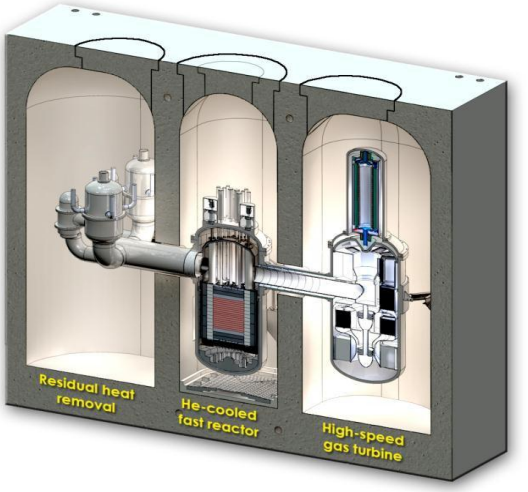
- **GE Hitachi Nuclear Energy –** GE PRISM and Advanced Recycling Center Sodium Fast Reactor (SFR)
- **Gen4 Energy** - Lead-Bismuth Fast Reactor (LFR)
- **Toshiba Corporation –** 4S Reactor Sodium Fast Reactor (SFR)
- **Westinghouse Electric Company –** Thorium-fueled Boiling Water Reactor (BWR)
- **Westinghouse Electric Company –** Thorium-fueled Advanced Recycling Fast Reactor (SFR)
- **General Atomics –** EM2, High Temperature Gas-Cooled Fast Reactor (GFR)
- **Flibe Energy –** Liquid Fluoride Thorium Reactor (LFTR)
- **Hybrid Power Technologies –** Hybrid-Nuclear Advanced Reactor (HTGR + natural gas plant)

--TerraPower Traveling Wave Reactor-(SFR)-Once through fuel- high burnup

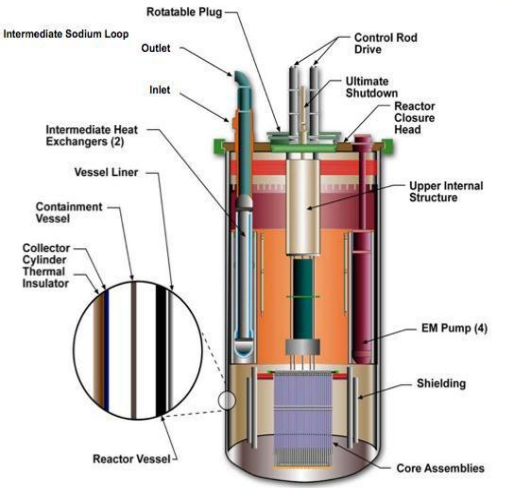
Nine Advance Reactor Concepts



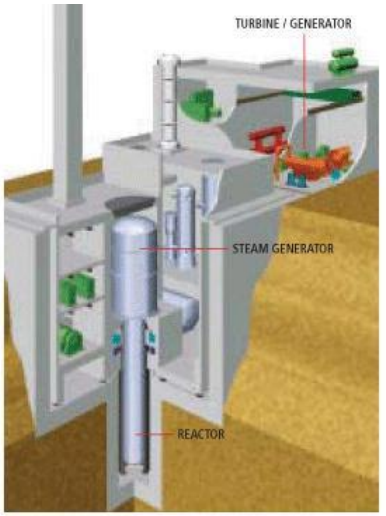
Gen4 Energy Concept **(LFR)** 25 MWe, LBE , UN



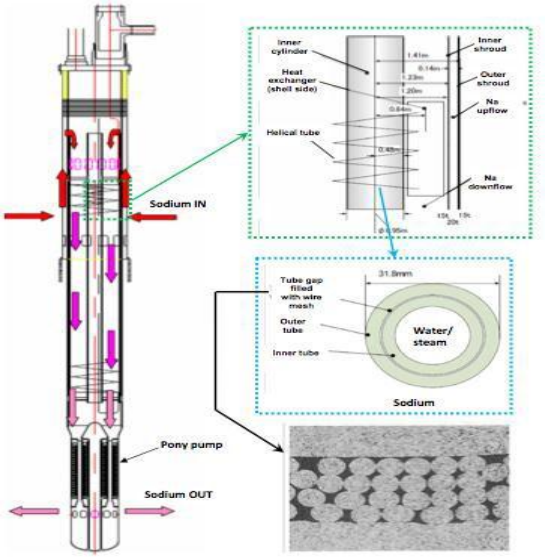
EM2 Concept **(GFR)** 245 MWe, He, UC



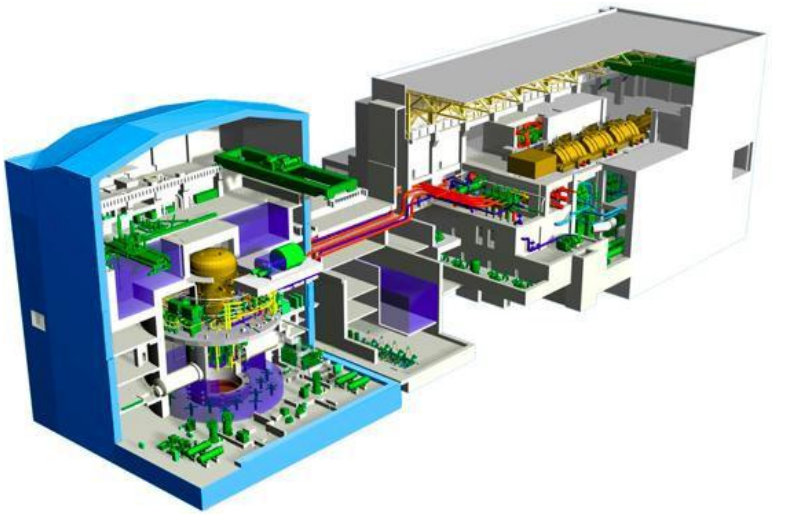
PRISM Concept **(SFR)** 300 MWe, Na, U-TRU metal alloy



4S Concept **(SFR)** 50 MWe, Na, U metal-alloy



Westinghouse Th Reactor **(SFR)** 410 MWe, Na, Th-TRU



Westinghouse Th **(BWR)** 1356 MWe, Water, Th-TRU fuel

Nine Advance Reactor Concepts

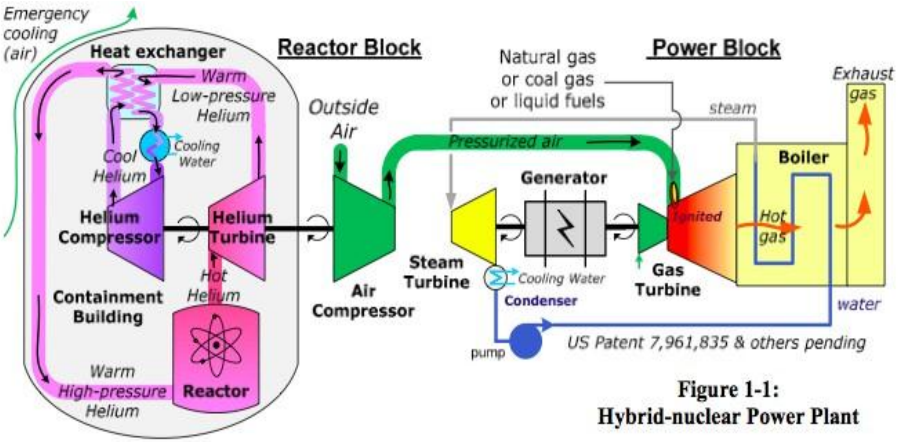
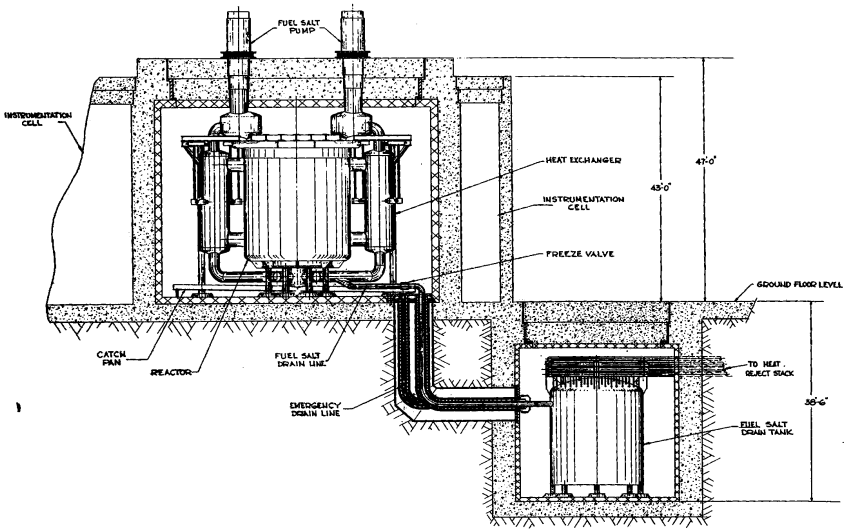
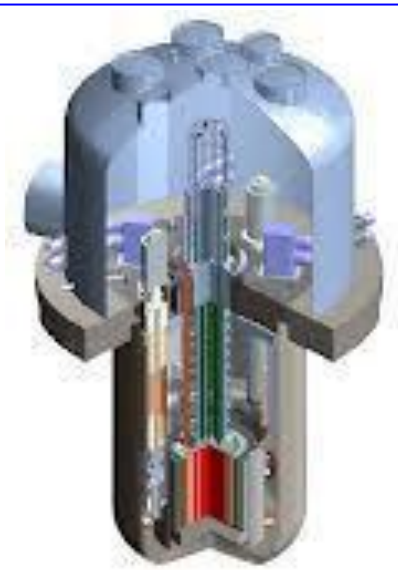


Figure 1-1:
Hybrid-nuclear Power Plant

Hybrid Power Technology **(HTGR)** 850 Mwe, He, UO2-TRISO



FIBLE Th-Fuel Thermal Reactor **(MSR)** 40 MWe, Li-F, Be Salt, Th-fuel, Nitrogen Brayton Cycle



Turns depleted uranium into electricity, using a simple fuel cycle without requiring separations.

SIZE	~550 MWe
TEMPERATURE	~510°C
PRESSURE	Low (Atmospheric)
PRIMARY FUEL	Depleted Uranium
COOLANT	Sodium
ENERGY CONVERSION	Steam (Rankine Cycle)
WASTE REPROCESSING	Not Required
COMMERCIAL OPERATION	Late 2020s

Travelling Wave Reactor **(SFR)** 550 MWe, Na, U-metal alloy, Once through high burnup -60 years

Research and Development Needs in ACRS

- Development of licensing approaches for advanced reactor concepts
  - Development of an advanced reactor regulatory strategy.
  - Development of **advanced safety analysis tools**.
- Accelerated demonstration and **development of Brayton cycle technologies**
  - Supercritical CO2 cycle offers compelling reductions in size and cost of the power conversion system.
- **Development of validated advanced reactor analysis methods**
  - Development of **advanced neutronics, thermal-hydraulics, and mechanical analysis tools to provide credible capabilities to design advanced concepts, and understand the design margins.**

R and D Needs in ACRS

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Priority R&D investments needed

- Sodium-cooled Reactors
- Gas-Cooled Fast Reactors
- Lead-Bismuth Eutectic-cooled Reactors

Specific R&D Needs

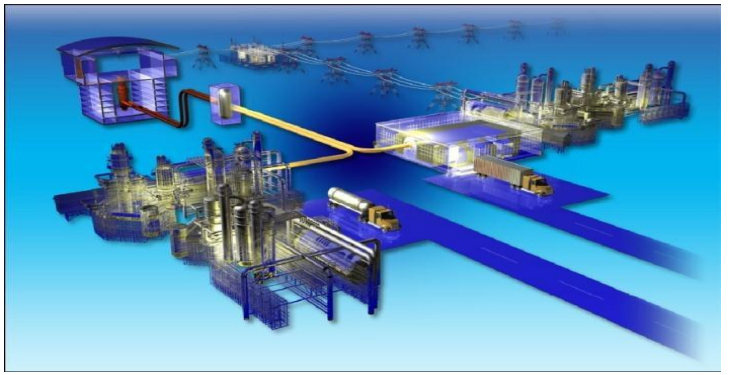
- **SFR thermal hydraulic analysis**
- **SFR steam generator operations under extreme modes.**
- **Technologies for under sodium viewing**
- **Advanced metal fuels for sodium cooled reactors**
- **Development/qualification of EM pumps**
- **LBE natural circulation fluid dynamics validation**
- **Advanced structural materials resistant to erosion/corrosion by LBE**
- **Trade study associated with oxide and nitride fuel for the LBE reactor**
- **Erosion/corrosion mechanisms and control approaches in LBE**
- **Ceramic reflector system for a gas fast reactor**
- **Silicon Carbide Composite material**
- **Fuel cladding system for high burnup, high temperature fuel**
- **Safety system for GFRs**
- **Safety studies for advanced designs**
- **Design and testing of reactor components**

Challenges for ACR Deployment

- **Licensing**
- **Solving Design Issues**
  - **Materials**
  - **Fuel Design and Qualification**
  - **I&C issues**
  - **Component design and testing**
  - **Erosion corrosion**
- **Lack of Cost information – both Overnight Construction Costs and Levelized Cost of Electricity**
- **Resistance to procurement of a First of a Kind design**
- **Risks associated with cost and licensing**
- **Proving that there are advantages to advanced reactors**

Potential benefits of Advanced Reactors

- **Inherent safety characteristics**
- **Improved economic competitiveness through efficiency improvements**
- **Process heat applications**
  - Expand use of nuclear energy beyond electricity generation
- **Modular construction**
  - Ability to build on gains made in constructing LWR SMRs
- **Resource management**
  - Potential uranium utilization savings
- **Waste management**
  - Use of fast spectrum neutrons for transmutation/actinide burning
- **Long-lived cores**
  - Higher burn-up fuel



Conclusions

- The advances reactor concepts include different designs of sizes 25- 1325 MWe, fast and thermal reactors, are modular in design, have various coolants: gas-He, liquid metals, Na, Pb-Bi, and molten
- Advance reactors have improved safety, fuel sustainability and security, economically competitive
- There are number technological and development challenges
- Number of research opportunities exit in realizing these design concepts.

Questions?

Discussion

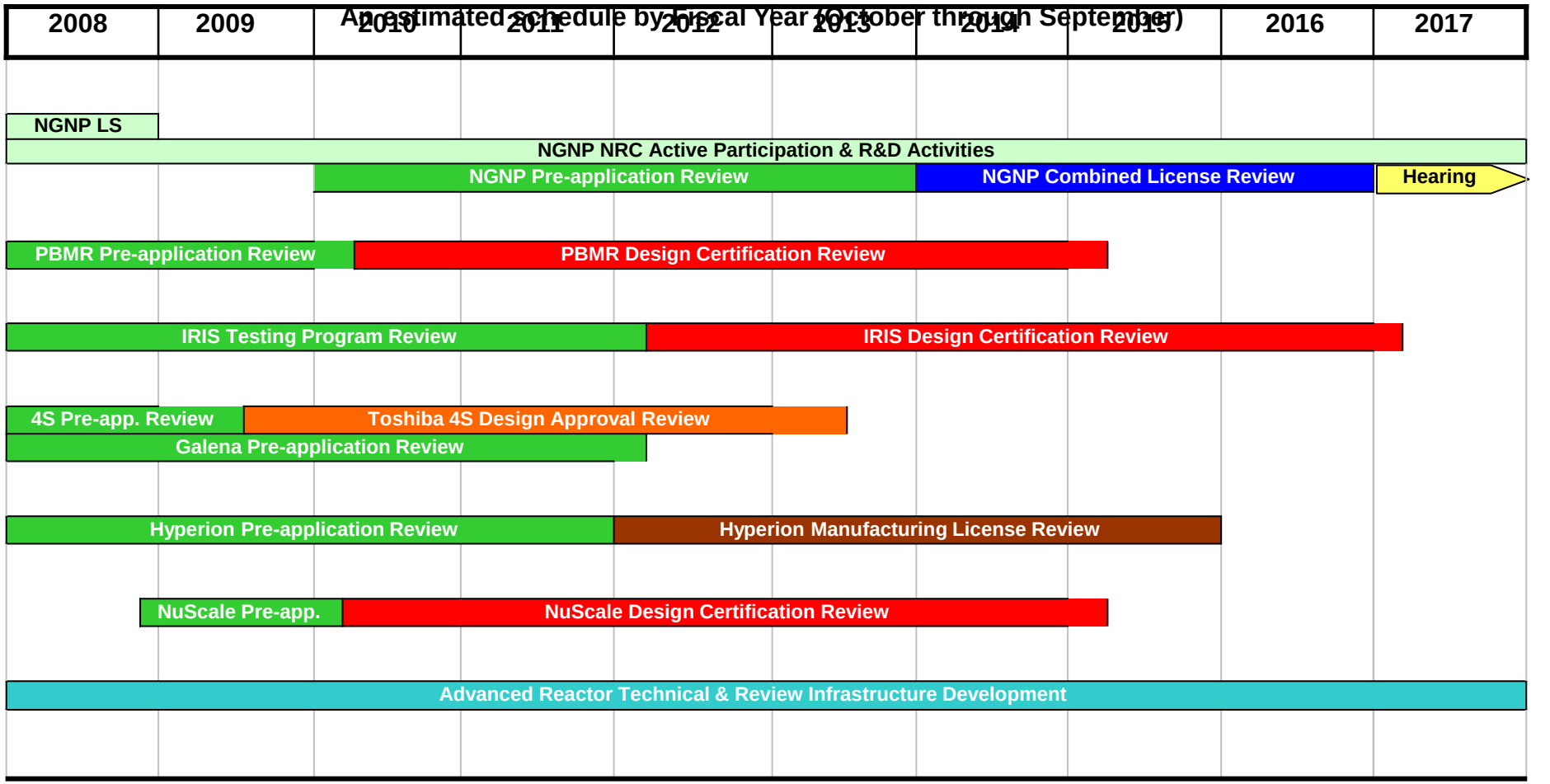
Generation IV system development in the period through 2013

Generation IV Systems	Canada	China	France	Japan	Korea	Russia	South Africa	Switzer-land	USA	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 or a Project Arrangement at some point during the period. This table does not necessarily reflect the status of participation as of 1 January 2014.

Potential Advanced Reactor Licensing Applications

An estimated schedule by Fiscal Year (October through September)



Legend:

NGNP Activities	Combined License Review	Design Approval	Hearing
Pre-application Review	Manufacturing License	Design Certification	R&D/Infrastructure Development

NOTE: Schedules depicted for future activities represent nominal assumed review durations based on submittal time frames in letters of intent from prospective applicants. Actual schedules will be determined when applications are docketed.

Requirements for Accident Tolerant Fuels (ATF)

Fuels with enhanced accident tolerance are those that, in comparison with the standard UO_2 – Zircaloy system, can tolerate loss of active cooling in the core for a considerably longer time period (depending on the LWR system and accident scenario) while maintaining or improving the fuel performance during normal operations.

To demonstrate the enhanced accident tolerance of candidate fuel designs, metrics must be developed and evaluated using a combination of design features for a given LWR design, potential improvements and the design of advanced fuel/cladding system.

High temperature during loss of active cooling

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

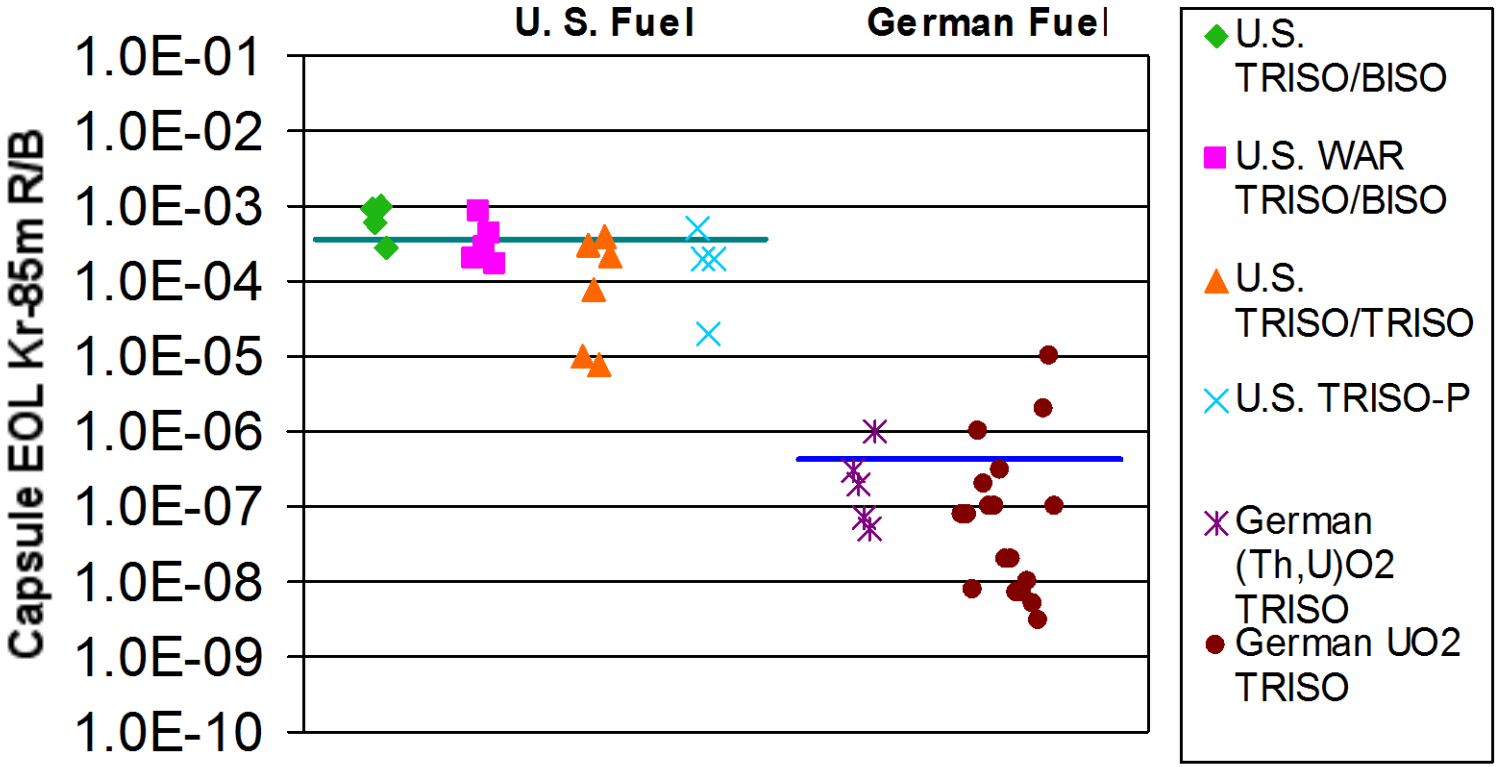
Slower Hydrogen Generation Rate
- Hydrogen bubble
- Hydrogen explosion
- Hydrogen embrittlement of the clad

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

Additional Fuel Work is Needed
Comparison of German and US EOL Gas Release Measurements from Numerous Irradiation Capsules

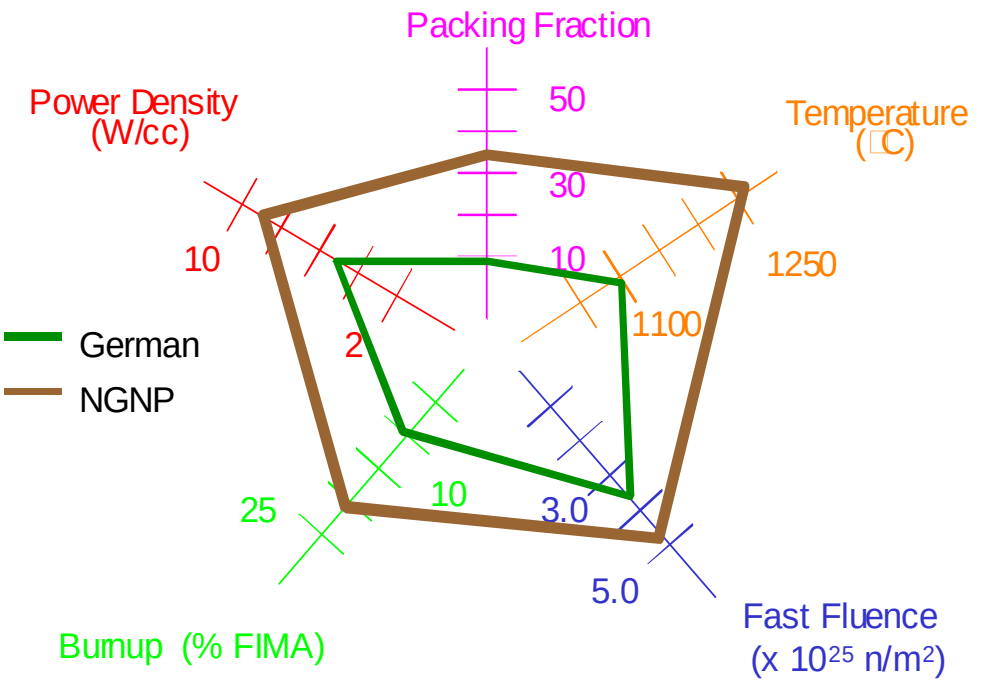


	U.S.	German
Irradiation temperature (C)	930 - 1350	800 - 1320
Burnup (%FIMA)	6.3 - 80	7.5 - 15.6
Fast fluence (10^{25} n/m^2)	2.0 - 10.2	0.1 - 8.5

Only German fuel had excellent EOL performance

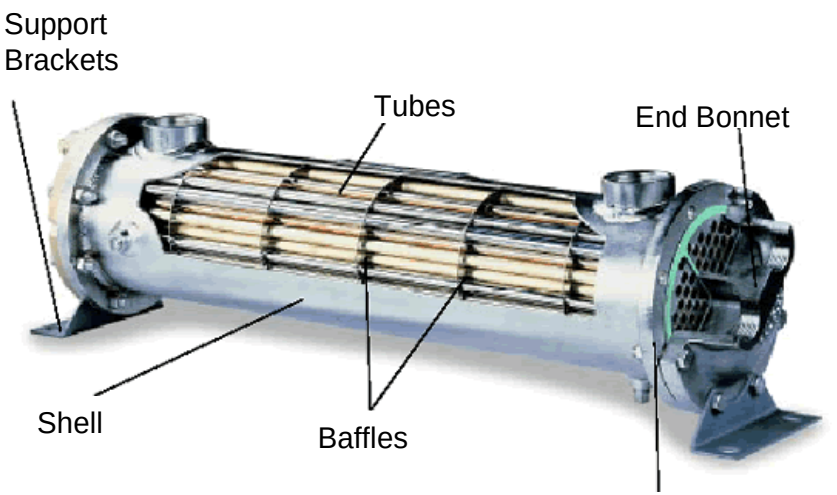
AGR Fuel Comparison of Fuel Service Conditions

- Germans qualified UO_2 TRISO fuel for pebble bed HTR-Module
  - Pebble; 1100°C, 8% FIMA, 3.5 x 10^{25} n/m^2, 3 W/cc, 10% packing fraction
- Japanese qualified UO_2 TRISO fuel for HTTR
  - Annual compact; 1200°C; 4% FIMA, 4x10^{25} n/m^2, 6 W/cc; 30% packing fraction
- Eskom RSA is qualifying pebbles to German conditions for PBMR
- Without an NGNP design, the AGR program is qualifying a design envelope for either a pebble bed or prismatic reactor
  - 1250°C, 15-20% FIMA, 4-5x10^{25} n/m^2, 6-12 W/cc, 35% packing fraction
  - UCO TRISO fuel in compact form



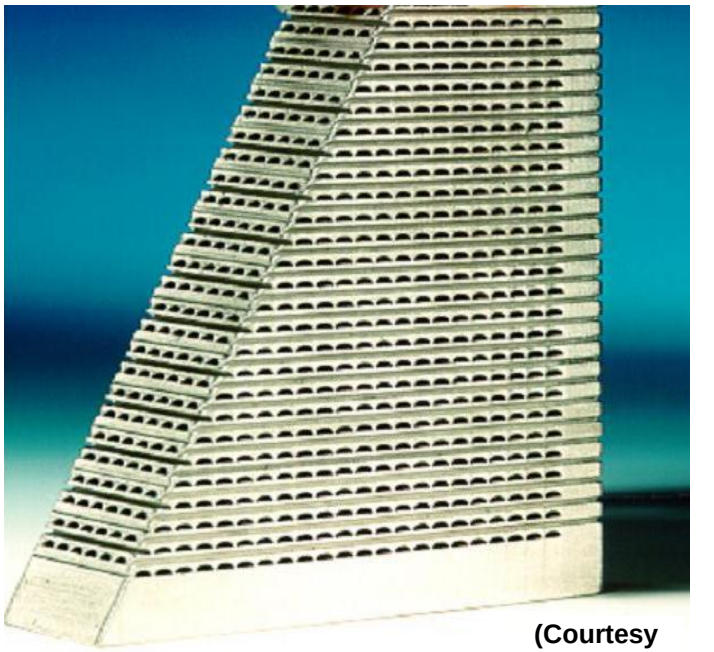
Heat Exchanger Concepts

- Might see temperature up to 950°C
- Creep fatigue is expected damage mechanism
- Only one alloy is Code qualified and only to 762°C



Straight-Tube HX

(Photo From API Heat Transfer)



(Courtesy Heatric)

High Temperature Alloys

Alloy	Ni	Fe	Cr	Co	Mo	Al	W	Ti	C	Si	Mn
Inconel 617	44.5	3	20-24	10-15	8-10	0.8-1.5		0.6	0.05-0.15	1	1
Alloy 230	Bal	3	20-24	5	1-3	0.2-0.5	13-15		0.05-0.15	.25-.75	0.3-1
Alloy 800H	30-35	39.5	19-23			0.15-0.6		0.15-0.6	0.05-0.1		
Alloy XR	Bal	20	23	1	10	0.1	1	0.03	0.15	0.5	1

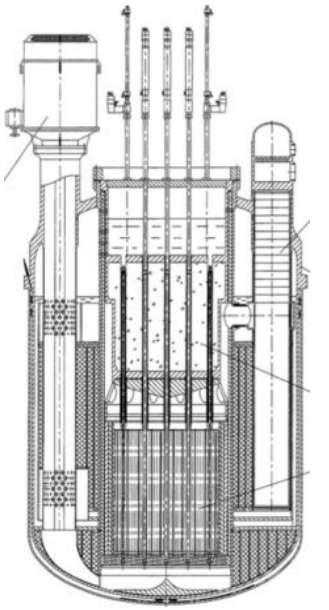
LBE as a Nuclear Coolant and Spallation Source Target

Opportunity

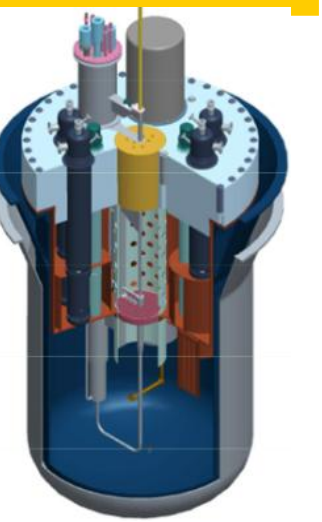
Excellent neutron yield
Low neutron reaction cross sections
Low melting point
Excellent thermal properties
Not susceptible to radiation damage

Challenge

Highly corrosive to steel
Liquid Metal Embrittlement
Liquid Metal Enhanced Creep



SVBR-75, Russia

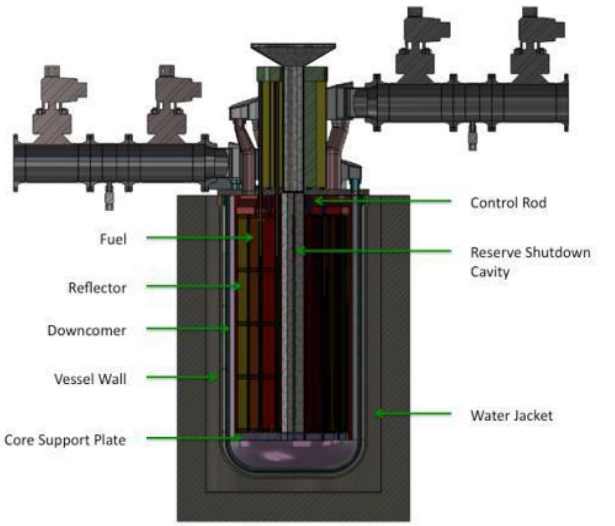


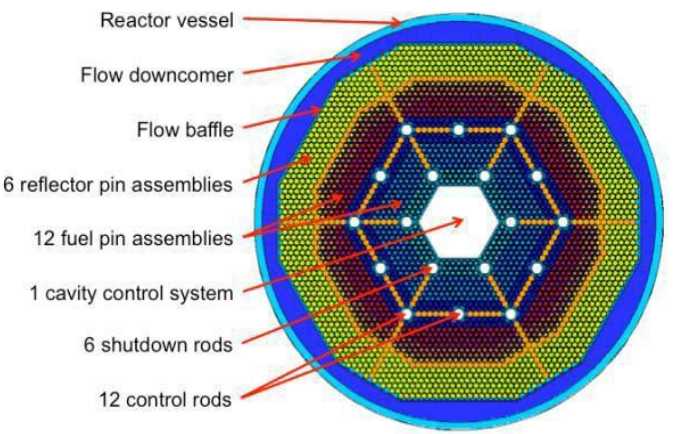
XT-ADS, EU
MYRRHA

Hyperion, US

Gen4Energy Concept

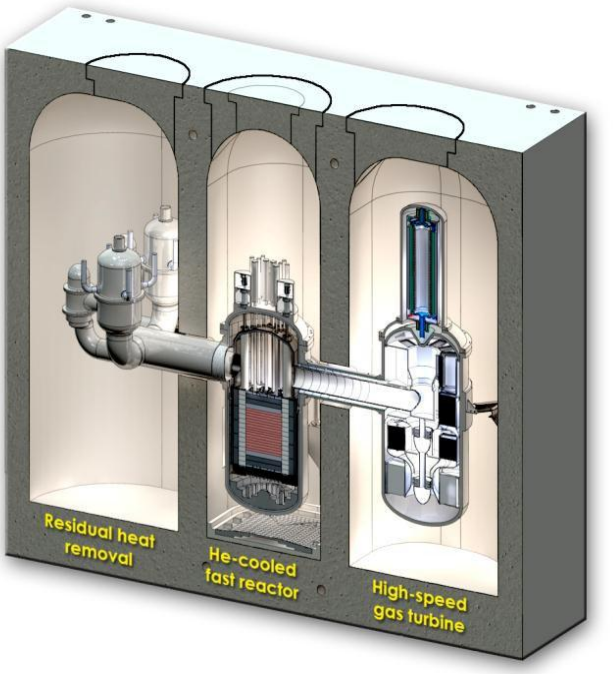
- **Small Fast Reactor**
  - 25 MWe
  - Lead-bismuth eutectic (LBE) coolant
  - Uranium nitride fuel
  - No onsite refueling
  - Focus on transportable, small size concept





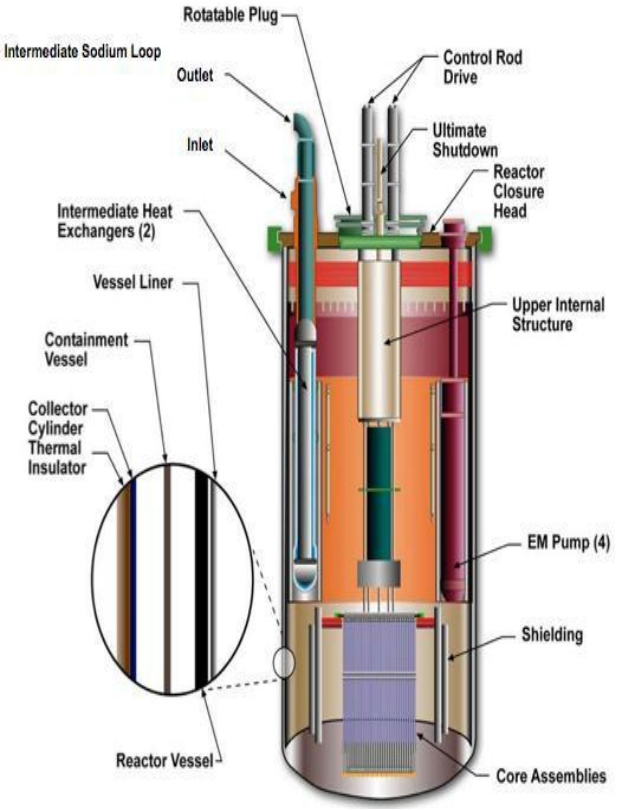
General Atomics EM2 Concept

- **Small Fast Reactor**
  - 245 MWe
  - Helium coolant
  - Uranium carbide fuel
  - Vented fuel for high burnup
  - 30 year refueling cycle
  - High temperature process heat
  - Brayton cycle with 49% efficiency
  - Focus on high temperature applications



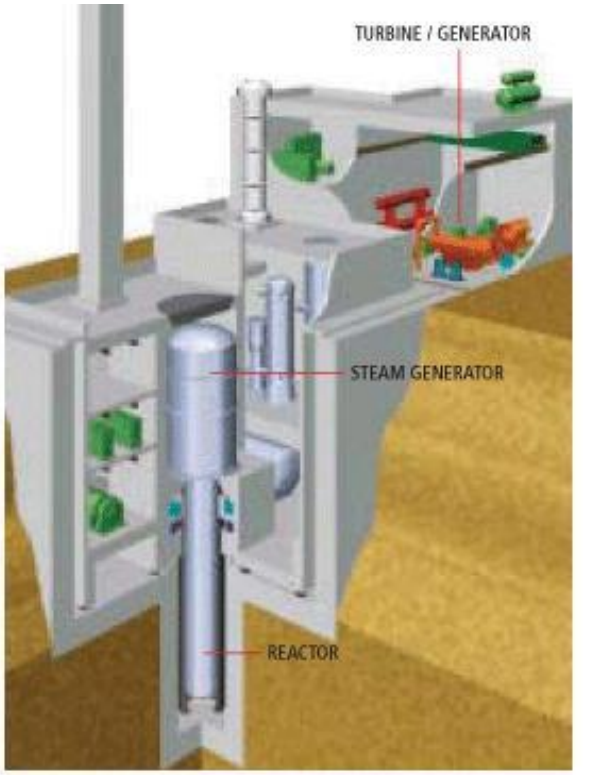
GE-Hitachi PRISM Concept

- **Small Fast Reactor**
  - 300 MWe
  - Sodium coolant
  - U-TRU metal alloy fuel
  - 1.5 year refueling cycle
  - Design life of 60 years
  - RVACS passive decay heat removal from vessel by air
  - Modular construction
  - Barge transportable
  - U.S. ALMR Program concept for closed fuel cycle
  - Recent proposal by GE-Hitachi for use by UK for plutonium disposition



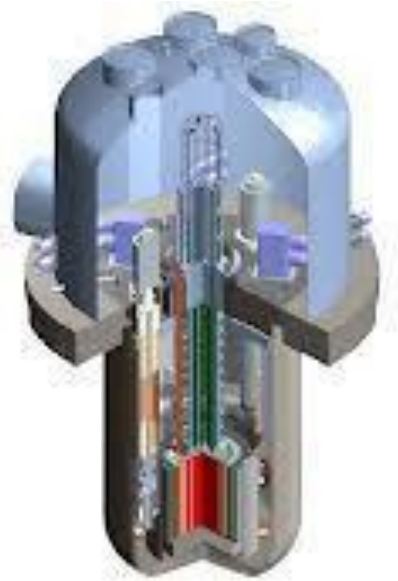
Toshiba 4S Concept

- **Small Fast Reactor**
  - 50 MWe
  - Sodium coolant
  - Uranium metal alloy fuel
  - Design life of 60 years
  - 10 year refueling cycle
  - Long, thin core with reflector control
  - Focus on distributed customers at remote sites



TerraPower Traveling Wave Reactor

- **Fast Reactor**
  - 550 MWe prototype
  - Sodium coolant
  - Uranium metal alloy fuel
  - Once-through high burnup targeted
  - Design life of 60 years
  - Focus on uranium utilization

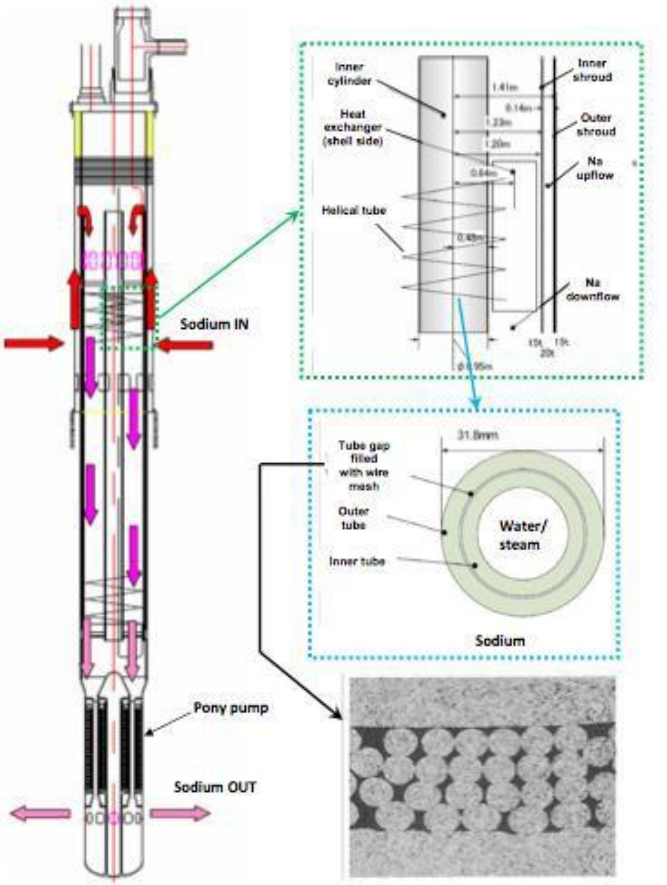


Turns depleted uranium into electricity, using a simple fuel cycle without requiring separations.

SIZE	~550 MWe
TEMPERATURE	~510°C
PRESSURE	Low (Atmospheric)
PRIMARY FUEL	Depleted Uranium
COOLANT	Sodium
ENERGY CONVERSION	Steam (Rankine Cycle)
WASTE REPROCESSING	Not Required
COMMERCIAL OPERATION	Late 2020s

Westinghouse Thorium-Fueled Fast Reactor Concept

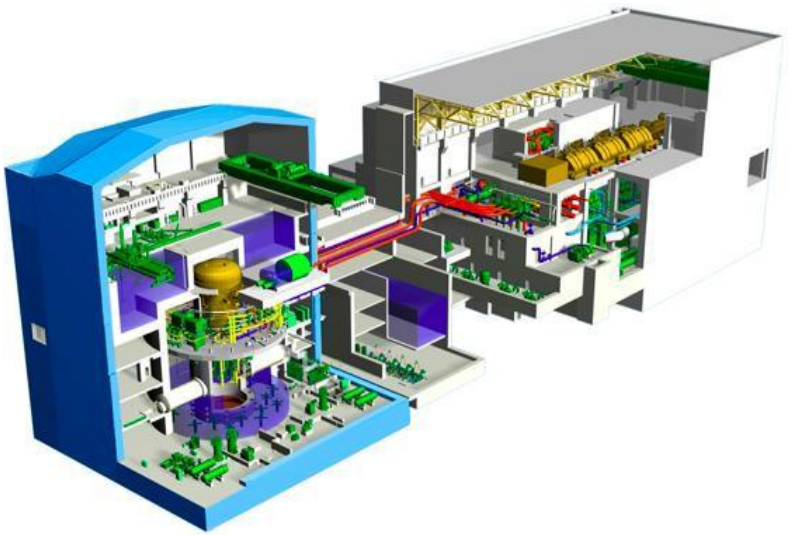
- **Fast Reactor**
  - 410 MWe
  - Sodium coolant
  - Thorium-TRU fuel
  - 1 year refueling cycle
  - 60 year design life
  - Pool design without intermediate loop
  - Double-walled steam generator
  - Focus on consumption of recycled TRU



Westinghouse Thorium-Fueled Boiling Water Reactor Concept

Boiling Water Reactor

- 1356 MWe
  - Water coolant
  - Thorium-TRU fuel
  - 1 year refueling cycle
  - 60 year design life
  - Ex-vessel features similar to the Advanced Boiling Water Reactor (ABWR) design



Hybrid Power Technologies' Nuclear Advanced Reactor Concept

- **High Temperature Gas Reactor**
  - 850 MWe
  - Helium coolant
  - UO2 TRISO fuel
  - 2 year refueling cycle
  - 40 year design life
  - Reactor powers the cc for

a natural gas combustion turbine

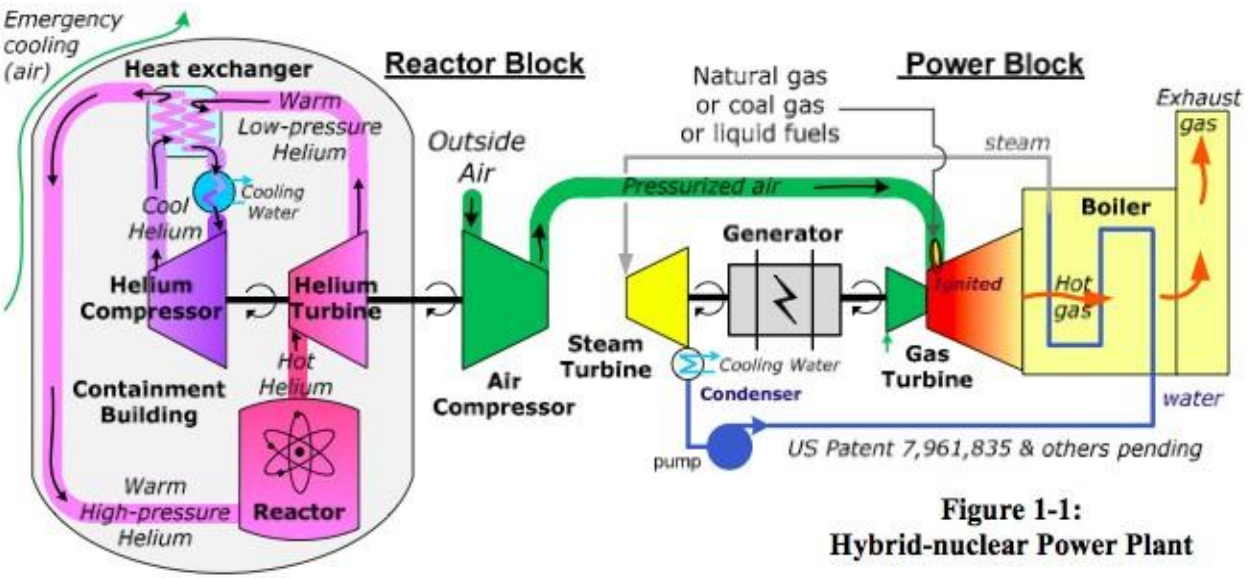


Figure 1-1:
Hybrid-nuclear Power Plant

FLIBE Thorium-Fueled Reactor Concept

- **Thermal Reactor**
  - 40 MWe
  - Lithium-Fluoride/Beryllium Salt coolant
  - Thorium-fuel in the coolant
  - 5-10 year design life
  - Nitrogen Brayton Cycle conversion system