Advances in Reactor Concepts: Generation IV Reactors – Research Opportunities

Shripad T. Revankar
School of Nuclear Engineering, Purdue University
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


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

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

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

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 numerous technological and development challenges.

• Number of research opportunities exist in realizing these design concepts.
Questions?
Discussion
### Generation IV system development in the period through 2013

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<th>Generation IV Systems</th>
<th>Canada</th>
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- 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

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**Legend:**
- **NGNP Activities**
- **Combined License Review**
- **Design Approval**
- **Manufacturing License**
- **Design Certification**
- **R&D/Infrastructure Development**
- **Hearing**

**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

Only German fuel had excellent EOL performance
• 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, 4 x $10^{25}$ 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, 4-5 x $10^{25}$ 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

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Support Brackets
Tubes
End Bonnet
Baffles
Shell
Tubesheet
Support Brackets
Tubes
Shell
Baffles
Tubesheet

Straight-Tube HX
(Photo From API Heat Transfer)

(Courtesy Heatric)
# High Temperature Alloys

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<th>Fe</th>
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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
**Small Fast Reactor**

- 25 MWe
- Lead-bismuth eutectic (LBE) coolant
- Uranium nitride fuel
- No onsite refueling
- Focus on transportable, small size 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
- **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
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 compressor for a natural gas combustion turbine

![Diagram of Hybrid-nuclear Power Plant](image)
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