U.S. DEPARTMENT OF ENERGY

Nuclear Energy

# Current U.S. & World Status of Fluoride Salt-Cooled High-Temperature Reactors

*NEAC Meeting*

*December 10th 2014*

*Crystal City, Virginia*

FHR

Fluoride Salt Cooled High Temperature Reactor



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***DOE National Technical Lead for Salt Reactors***

# FHRs Afford the Nuclear Industry a Successor Option for LWRs

- **Lower cost power remains the central development challenge**
  - Cost and reliability have been the Achilles Heels of advanced reactors
  - High thermal efficiency and low pressure form the foundation for lowering power cost
- **FHRs offer increased passive safety at any scale**
  - Inherent properties substantially reduce potential source term
  - Modular passive decay heat removal avoids core thermal size limit
  - Lack of cliff-like phenomena relaxes safety system performance requirements
- **High temperature broadens applicability of nuclear energy**
  - High temperature enables products not economically feasible with LWRs
    - *High exergy increases FHR heat delivery compatibility*
  - Lower cooling water requirements increases siting flexibility
- **Deployment time frame matches period when large number of LWRs may retire**

# FHR Reactor Class Shows Substantial Promise

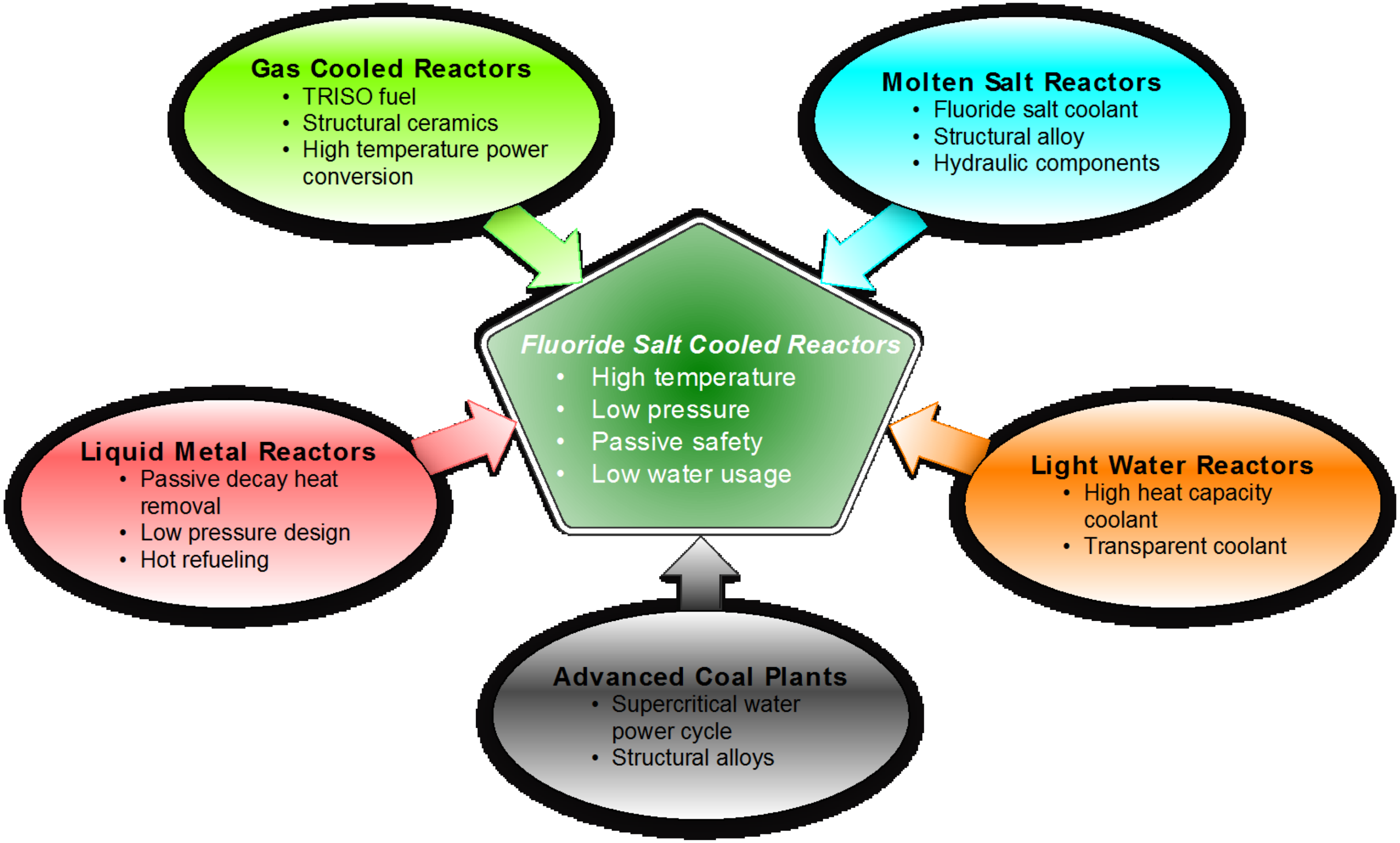
## *Still Requires Significant Research, Development, and Demonstration*

- **Tritium release prevention is the most significant technical issue**
  - Tritium stripping membranes are promising new technology
  - Double walled heat exchangers acceptable
- **Replacement industrial scale lithium enrichment**
  - Recent innovation shows potential to make substantial improvement
- **Salt chemistry control system requires design for large scale**
- **Qualified fuel must be developed**
- **Structural ceramics must become safety grade nuclear engineering materials**
- **Fully qualified primary coolant boundary alloy required**
- **Safety and licensing approach must be developed and demonstrated**
- **Instrumentation has substantial technical differences from LWR technology**
- **More complete reactor conceptual design required**

# FHRs Benefit From Multiple DOE Initiatives

| | |
|---|---|
| $^{7}Li$ Cost | • Innovative separation technique – ongoing ORNL LDRD<br>• Higher separation coefficient materials |
| Tritium Management | • Turbulent flow tritium stripper<br>• Double walled heat exchangers |
| Structural Ceramics | • SiC channel boxes for BWRs<br>• SiC leaf springs for LWR fuel assemblies<br>• ASTM and ASME standards |
| Safety & Licensing | • DOE-NRC joint initiative on advanced reactor design criteria<br>• ANS standard on FHR design safety |
| Fuel Cost and Qualification | • SiC accident tolerant cladding for LWRs<br>• AGR TRISO testing |

# FHRs Inherit Desirable Attributes From Other Reactor Classes




Prior reactor development efforts provide a substantial foundation for FHRs

# FHR Issues and Challenges Evolve From Those of Other Reactors

- **Liquid metal reactors and dissolved fuel MSRs both require heat transfer across a high differential pressure**
- **Dissolved fuel MSRs have both material commonalities and differences**
  - Oxide layers are readily fluxed away by molten fluoride salts necessitating thermodynamically compatible salt wetted materials
  - Tritium control materials

  Common

  - Little neutron embrittlement of primary coolant boundary
  - Less complex chemical environment
  - No circulating redox control buffer ($U^{3+}/U^{4+}$)

  Different

- **HTGRs have similar fuel but different containment and source term issues**
  - Liquid salt chemically binds radionuclides
  - Multiple containment layers
  - No pressure driven radionuclide dispersal

# FHR Safety Derives from Inherent Material Properties and Sound Design

**Inherent**

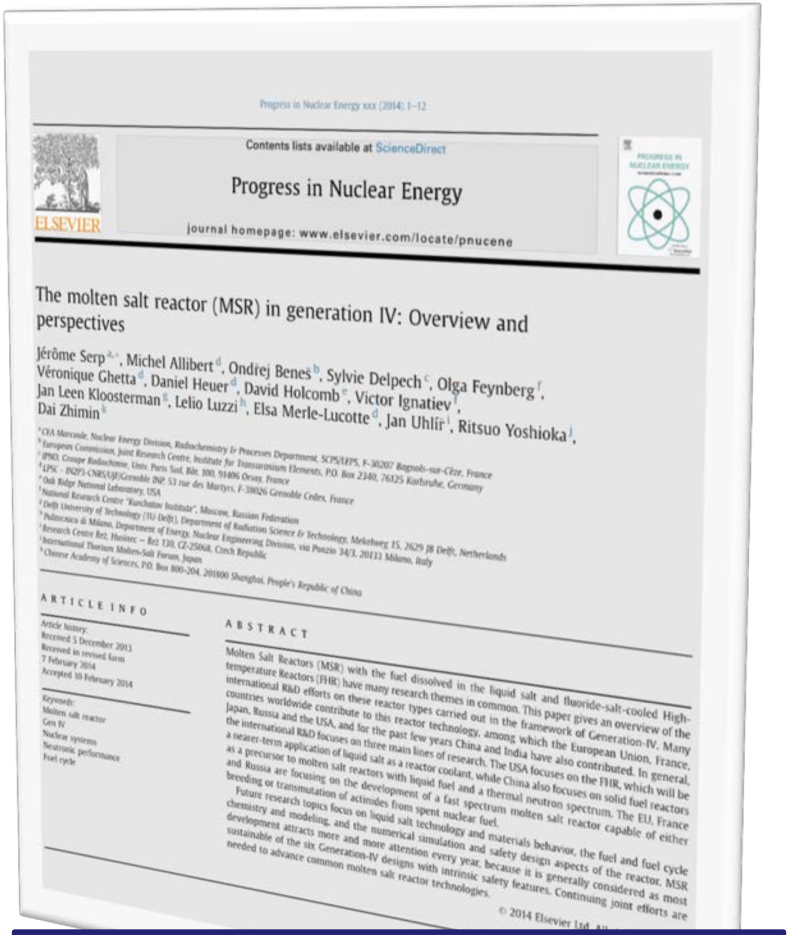
- Large temperature margin to fuel failure
- Good natural circulation cooling
- Large negative temperature reactivity feedback
- High radionuclide solubility in salt
- Low pressure

**Engineered**

- High quality fuel fabrication
- Effective decay heat sinking to environment
- Passive, thermally driven negative reactivity insertion
- Multi-layer containment

# Several Countries are Cooperating on Liquid and Solid Fueled MSRs Through the GIF Process

- **Molten salt reactors have two primary subclasses – dissolved and solid fuel**
  - FHRs are solid fuel MSRs
- **France, EU members, Russia, China, Japan, Korea, and the US participate through the MSR system steering committee**
  - Pre-commercial nature of the reactor class promotes open sharing of research results
  - Safety, economics, and proliferation resistance have separate collaborative efforts
- **Other countries have supportive technology development efforts**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The molten salt reactor (MSR) in generation IV: Overview and perspectives

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ABSTRACT
Molten Salt Reactors (MSR) with the fuel dissolved in the liquid salt and fluoride-salt-cooled High-temperature Reactors (FHR) have many research themes in common. This paper gives an overview of the international R&D efforts on these reactor types carried out in the framework of Generation-IV. Many countries worldwide contribute to this reactor technology, among which the European Union, France, Japan, Russia and the USA, and for the past few years China and India have also contributed. In general, the international R&D focuses on three main lines of research. The USA focuses on the FHR, which will be a nearer-term application of liquid salt as a reactor coolant, while China also focuses on solid fuel reactors as a precursor to molten salt reactors with liquid fuel and a thermal neutron spectrum. The EU, France and Russia are focusing on the development of a fast spectrum molten salt reactor capable of either breeding or transmutation of actinides from spent nuclear fuel.
Future research topics focus on liquid salt technology and materials behavior, the fuel and fuel cycle chemistry and modeling, and the numerical simulation and safety design aspects of the reactor. MSR development attracts more and more attention every year, because it is generally considered as most sustainable of the six Generation-IV designs with intrinsic safety features. Continuing joint efforts are needed to advance common molten salt reactor technologies.


2014 Overview of MSR & FHR Technology and Cooperation

# US and China Are Initiating a Cooperative Research and Development Agreement (CRADA) on FHRs

- **Collaboration supports the US-China memorandum of understanding on cooperation in civilian nuclear energy science and technology**
- **ORNL and the Shanghai Institute of Applied Physics (SINAP) are the lead organizations**
- **Project is intended to benefit both countries through more efficiently and rapidly advancing a reactor class of common interest**
- **FHR remain at a pre-commercial level of maturity**
  - All of the results are intended to be openly available
  - Project is scheduled to end after SINAP's higher-power test reactor has completed its operational testing program
- **Collaboration includes research and development to support the evaluation, design, and licensing of a new reactor class**
  - Does not include fissile material separation technology

SINAP

# Chinese Salt Reactor Is Supported As A Long-Term Development Effort By Multiple Government Agencies

- **January 2011; Chinese Academy of Sciences (CAS) initiated the "Thorium Molten Salt Reactor Nuclear Energy System"(TMSR) Strategic Pioneer Science & Technology Project**
  - 20-30 year time frame
- **August 2013; the TMSR Project was chosen as one of the National-Energy Major R&D projects of the China National Energy Administration (CNEA)**

| Anticipated Funding | Billion (Chinese RMB) |
|---|---|
| CAS | 2.172 |
| CNEA* | 1 |
| Shanghai* | 2 |

* Not all funding committed

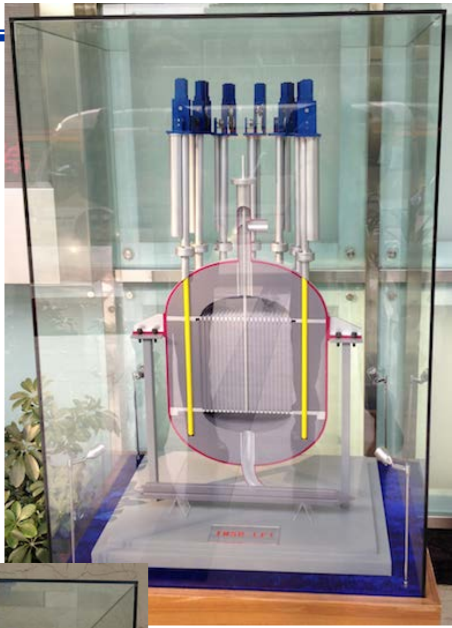
Labor ~ 1/8 budget

- **September 2014; Shanghai local government agrees to initiate a TMSR major innovation project, supporting the infrastructure for the TMSR-Simulator, TMSR test reactors, engineering design of TMSR demonstration reactor, and industrial development required manufacturing capabilities**

# Chinese Program Includes Both Solid and Liquid Fueled MSR Variants

CRADA is limited to solid fuel MSRs

- **Both solid and liquid fuel Chinese test reactors are LEU fueled**
  - Liquid fuel test reactor includes sufficient thorium to demonstrate separation technology
- **Solid fuel core employs a static pebble bed composed of fuel from HTR-PM program**
  - Fuel can be added on-line to compensate for burn-up
  - Thorium based fuel can be added in later cores
  - Electrically heated simulator is on near-term development path
- **Liquid fuel system is being pursued as a longer-term science focused program**
- **Current liquid fuel reactor conceptual design employs an innovative dual cycle processing scheme to enable thorium utilization while minimizing potential spread of fissile material processing technology**



Mock-ups of solid and liquid reactor vessels in SINAP's lobby

# Initial CRADA Tasks Include Experimental, Computational, and Analytical Efforts

- **Task 1: Fluoride Salt Loop Startup and Pebble Bed Heat Transfer Testing**
  - SINAP staff would participate in the experimental program
- **Task 2: Component & Instrumentation Development**
  - 2.1 Ultrasonic flowmeter demonstration & validation
  - 2.2 High-Temperature Fission Chamber Evaluation
  - 2.3 Fluoride Salt Pump Development and Demonstration
- **Task 3: Analysis Software Support**
  - Identify international codes that meet SINAP needs
  - Identify and support open-source benchmark problems for FHR systems
  - Modify SCALE (ORNL's reactor physics code suite) for FHRs
  - Investigate process to provide secure server for access to export controlled codes
- **Task 4: Training and Education**
  - Summer school near Shanghai
  - Student and staff exchanges
  - Training on SCALE code system for licensed SINAP users

# Initial CRADA Tasks Include Experimental, Computational, and Analytical Efforts

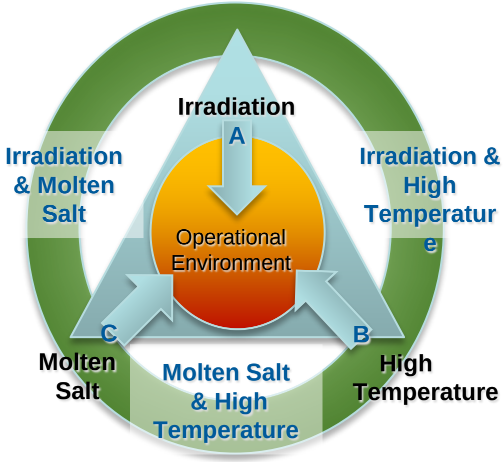
- **Task 5: Information Exchange and Program Coordination**
  - Potential approaches and technologies for sequestering, mitigating, or managing tritium production in FHRs
  - Processes and procedures for high-temperature materials testing and qualification that conforms to ASTM and ASME quality requirements
  - Instrumentation and controls for high-temperature, liquid salt systems
  - Adequacy and testing of components for performance and safety
  - Licensing approaches and safety analysis for FHR systems
  - Reactor physics issues for FHR operations and safety
  - National and international standards and requirements for testing and qualification of nuclear fuel
  - Hydraulic and heat transfer technical issues
  - Fluoride salt chemistry and control technologies
  - Quality assurance standards and practices for nuclear facilities

# U.S. Has Provided 75 kg of MSRE Intermediate Loop Salt to Czech Republic to Use for Criticality Testing

- **UJV-Rez has unique critical facility (LR-0) designed for use with salt**
  - Limited fluoride salt data is available for reactor physics code validation
  - Determination of biases and uncertainties are needed to support design and eventual licensing of FHRs
- **Currently no Czech government funded MSR development work underway**
  - UJV funding equipment purchases to be ready for testing
- **Czech government responsibilities have been realigned**
  - Proposal was made to Ministry of Industry and Trade in 2013
    - *Not selected as not within mission*
  - Proposal resubmitted to Czech Technological Agency
    - *Decision expected by end of 2014*

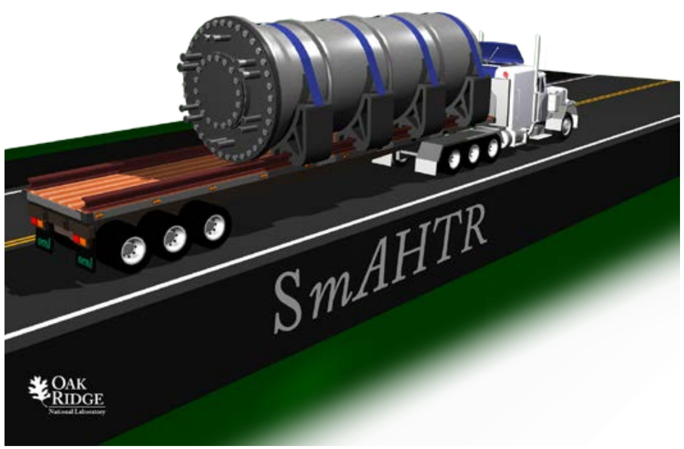
# Australia Has Begun FHR Materials Development and Evaluation Project

- **Materials assessment in cooperation with SINAP**
  - MOU signed and successful grant application announced in December 2012
- **Australian Nuclear Science and Technology Organization deliverables relate to the proposed MSR materials (Ni based alloys, graphite, etc.), the main tasks are:**
  - Corrosion in molten salt - fluorides
  - Radiation effects (ions/neutrons)
  - High temperature behavior
  - Synergistic effects

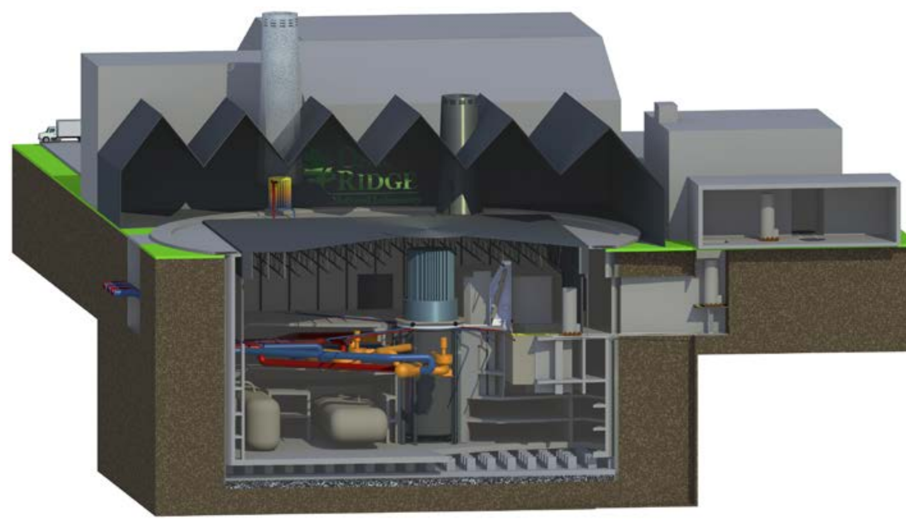


# Prior National Laboratory FHR Concept Development Efforts Have Resulted in SmAHTR and AHTR

- **No DOE funded FHR focused technology development work is currently underway in the national laboratory system**
  - FHR concept and technology development work has been sponsored by the Advanced Reactor Technology program
  - Currently funded to oversee/coordinate university work, GIF MSR activities, CRADA, and international activities
- **Both concepts remain at a preconceptual level of maturity**

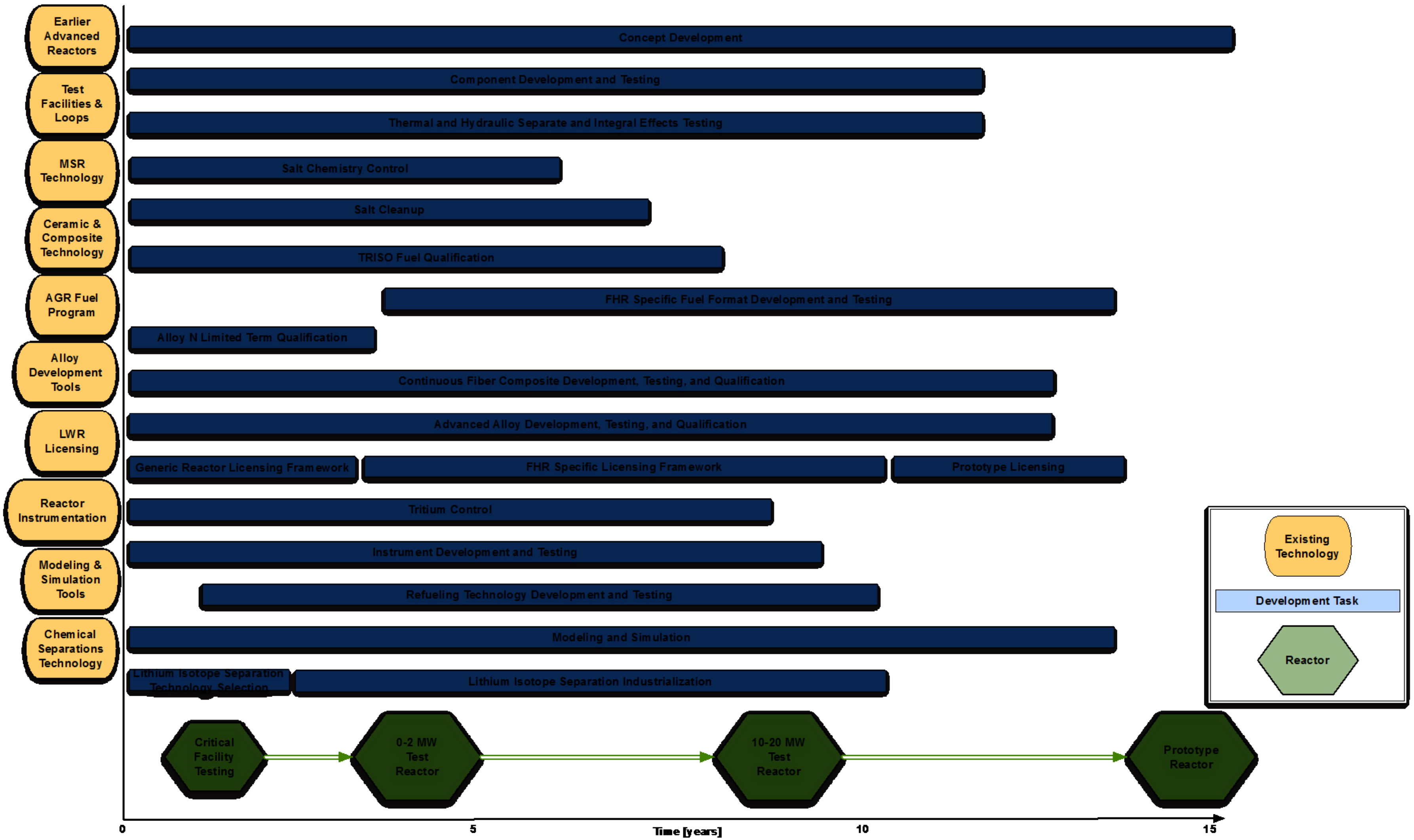



SmAHTR–125 MW(t)



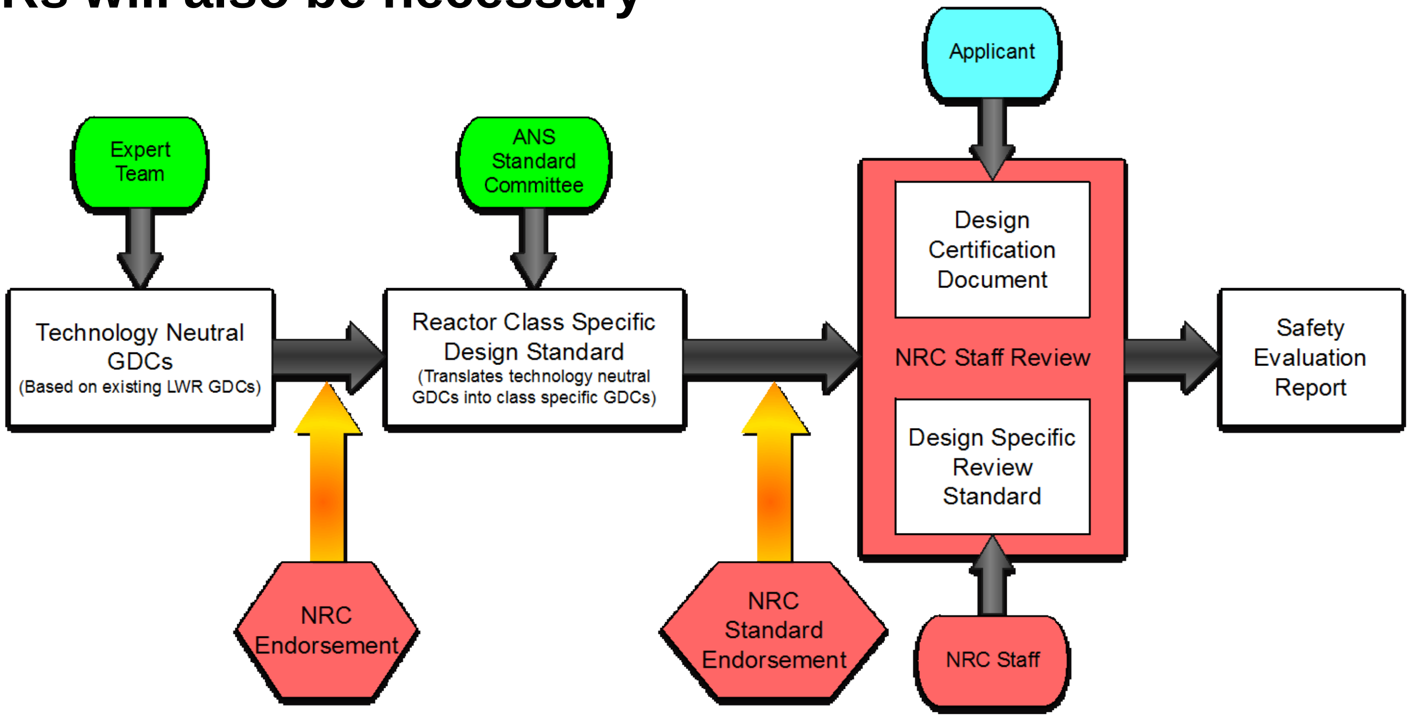
AHTR–3400MW(t)

# FHR Technology Development Roadmap Including an Overall Development Timeline Was Created in 2013



# DOE & NRC have Initiated a Collaborative Effort on Technology Neutral Licensing of Advanced Reactors

- **Developing modified set of GDCs for advanced (non LWR) reactor classes – (INL/EXT-14-31179)**
- **FHR Design/Safety Standard (ANS 20.1) will provide class specific criteria**
- **Design specific review standard analogous to NUREG-0800 for LWRs will also be necessary**



# DOE's Focused Investment in FHRs is Through University Research

- **In 2011 DOE funded a multi-university (Massachusetts Institute of Technology, University of California at Berkeley, and University of Wisconsin) integrated research project on FHR concept and technology development**
  - Thermal hydraulics and safety tests at UC-B
  - Material and component selection and performance (UW)
  - Coolant/material tests in MIT research reactor
  - FHR test reactor functional requirements and pre-conceptual design (MIT)
  - Commercial reactor conceptual design (UC-B)
  - Developing potential commercialization strategies linked to specific strengths of molten salt systems (MIT)
- **In 2014 DOE funded two additional integrated research projects on FHRs one lead by Georgia Tech and the other by MIT**
  - Projects are focused on resolving FHR technology issues
  - Joint planning has occurred to minimize overlap and emphasize synergy

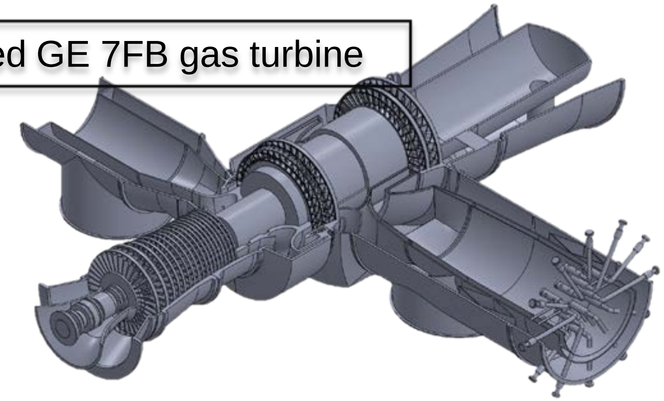
# Multiple Single Topic NEUP Projects Also Benefit FHRs

- High Temperature Inspection Capabilities (Iowa State) - 2013
- Compact Heat Exchanger Design and Testing (Ohio State) - 2013
- Tritium Migration/Control for Advanced Reactors (Ohio State) - 2013
- Optical materials for in-vessel sensing (Clemson) - 2013
- FHR Fuel and Core Design (Ga Tech) - 2012
- Pebble Fuel Handling (UCB) - 2011
- Material and component selection and performance (Wisconsin)
- Carbide coatings for salt valves (Johns Hopkins) - 2010
- DRACS loop design and testing (Ohio State) – 2010
- Thermal Transient Flow Rate Sensors for High Temperature, Irradiation, Corrosive Environment (UNLV) - 2010
- Heat transfer salts for nuclear reactor systems (Wisconsin) - 2010

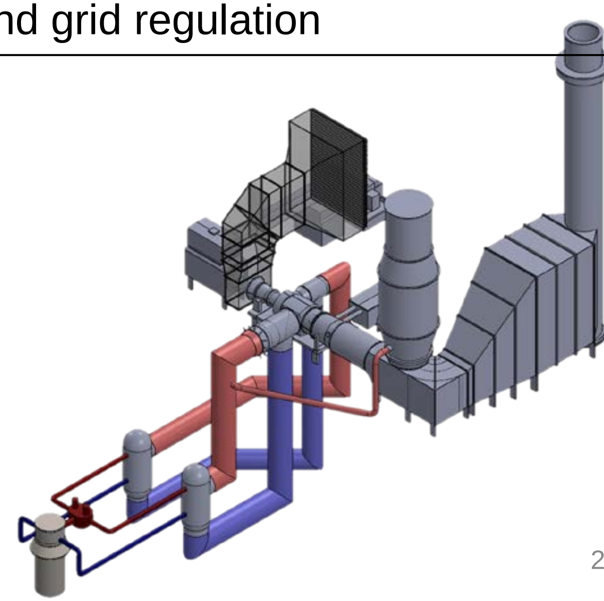
# IRP Project Investigating Potential to Open New Markets via Use of Open Air Brayton Cycle

- **Air Brayton cycle rejects heat to air**
  - Avoids need for significant cooling water
  - Baseline for Chinese program
- **Higher core outlet temperature required to make air-Brayton cycle preferable**
  - Increases importance of improved structural alloys

Modified GE 7FB gas turbine



Open-air Brayton Combined Cycle could enable use of natural gas to support peak power and grid regulation

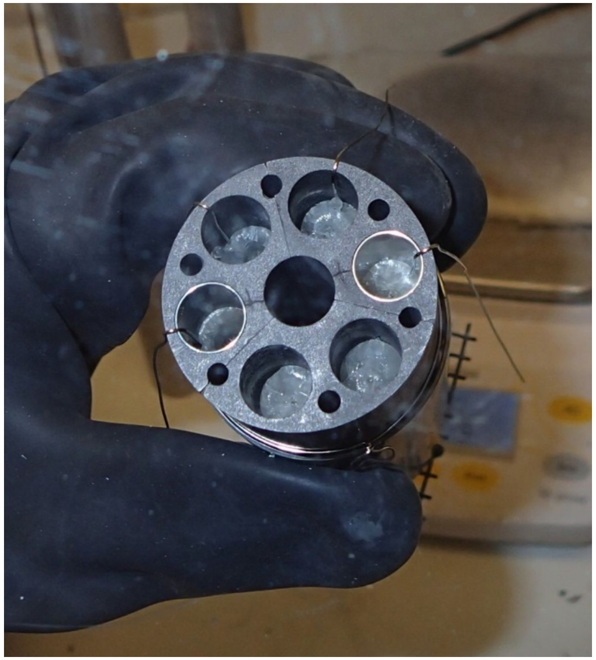


2011 IRP

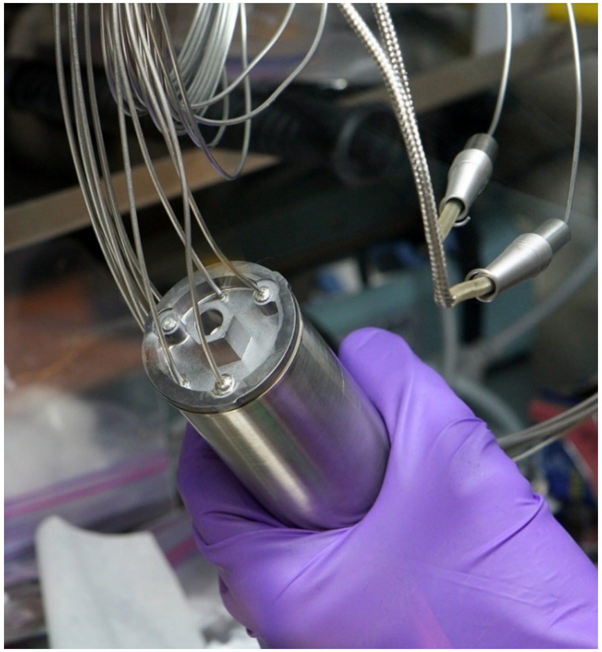
# MIT Completed First Irradiation of Samples in FLiBe at 700°C

## Irradiated samples extracted, PIE ongoing

Graphite sample holder filled with samples and FLiBe



Capsule sealed with TCs and gas sampling lines



FS-1 capsule being inserted into the top of the ICSA thimble

**Samples in FS-1 are all identical to UW corrosion tests: 316SS, Hastelloy, SiC (multiple types) and Surrogate Coated-Particle Fuel ($ZrO_2$).**

# UCB Has Recently Completed a Compact Integral Effects Test (CIET) Facility


- **FHRs can benefit extensively from surrogate material testing due to the close match of salt properties with simulant fluids**
- **CIET will provide integral effects test data to validate thermal hydraulics safety codes for application to FHRs**

# Silicon Carbide Compatibility With Fluoride Salts Largely Depends on Purity and Stoichiometry

- **Free silicon readily forms $SiF_4$**
  - Radiolysis can enhance corrosion
- **Binder phase oxides readily dissolve in fluoride salts**

Cast & fired

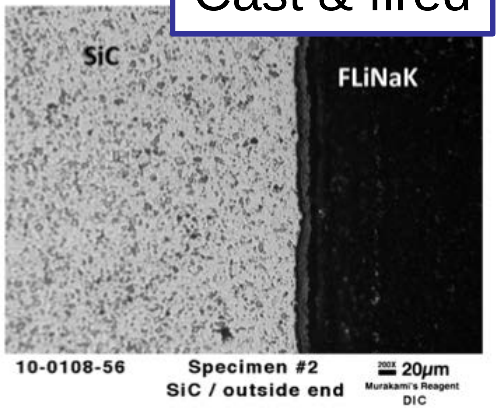
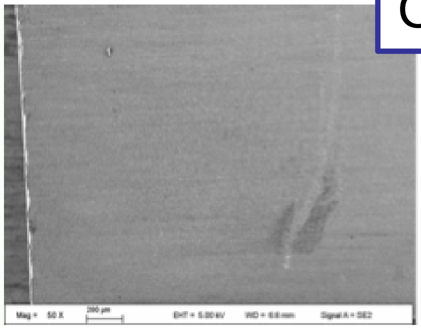
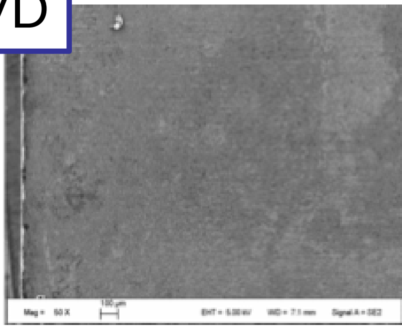


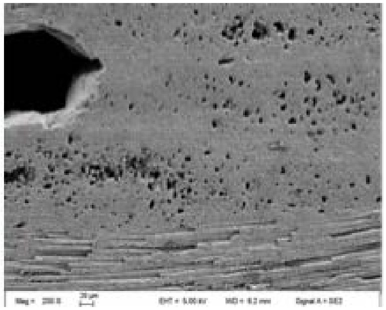

**Fig. 6.** SiC specimen after 90 day exposure to 700 °C FLiNaK salt.

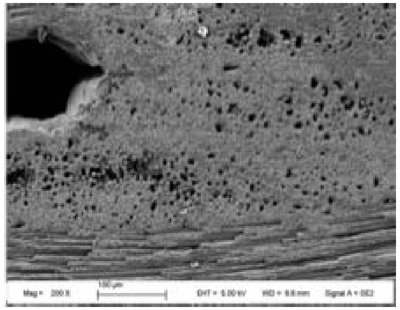
High purity SiC exhibits little corrosion

CVD

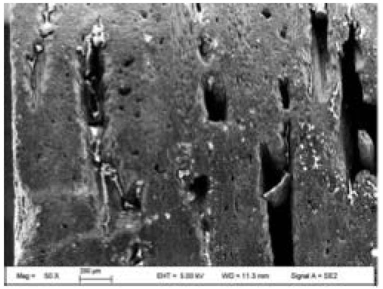


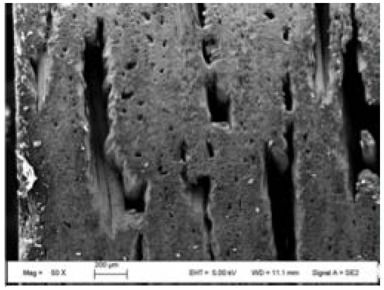






CVI SiC composites exhibit small weight loss

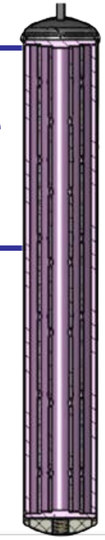




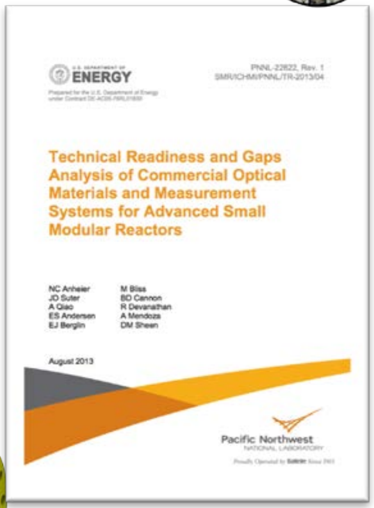
2011 IRP

# Diverse Additional Efforts Over the Past Decade Have Begun to Address Key FHR Technical Issues

- **Structural and Functional Materials**
  - Reevaluation of Alloy N with regard to the modern ASME BPVC
  - Evaluation of weld on liners for salt environments
  - Design and testing of improved performance, salt-compatible structural alloys
- **Instrumentation & Controls**
  - High temperature tolerant, salt-compatible fission chambers – NEET
  - Activation based salt flowmeter – university student design projects
  - Control system modeling tool development – AdvSMR
  - Technology for optical access within primary coolant boundary – AdvSMR
- **Components**
  - Issues and technologies for a salt-compatible, canned rotor, magnetic bearing pump – NEET



High Temperature Fission Chamber



ENERGY

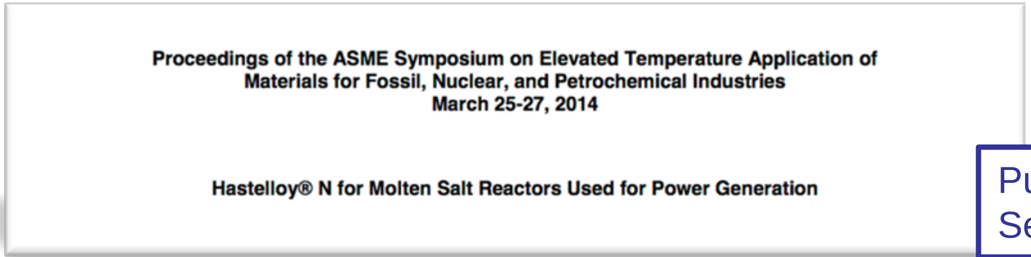
PNNL-22822, Rev. 1
SMR/ICHMI/PNNL/TR-2013/04

Technical Readiness and Gaps Analysis of Commercial Optical Materials and Measurement Systems for Advanced Small Modular Reactors

NC Anheier, JD Suter, A Qiao, ES Andersen, EJ Berglin, M Bliss, BD Cannon, R Devanathan, A Mendoza, DM Sheen

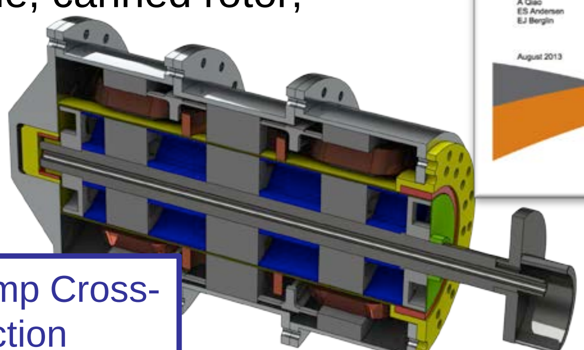
August 2013

Pacific Northwest



Proceedings of the ASME Symposium on Elevated Temperature Application of Materials for Fossil, Nuclear, and Petrochemical Industries
March 25-27, 2014

Hastelloy® N for Molten Salt Reactors Used for Power Generation



Pump Cross-Section

# FHRs are Emerging from Concept Viability Assessment and Entering into Engineering Development

- **None of the identified technology gaps are anticipated to take more that a decade to overcome**
  - Required technologies appear to be reasonable advancements over the current state-of-the-art
  - No technology breakthroughs required
  - Significant technology development and demonstration remains
  - Requires an adequately resourced program
- **Development tasks can largely be performed in parallel**
  - Schedule is resource constrained not time constrained
- **Widespread commercial deployment remains 20+ years in the future**
  - Key development challenge is the financial lift necessary to mature long-payoff technologies

# Combination of Multiple Initiatives Worldwide Are Advancing FHR Technical Maturity

# Questions

http://www.ornl.gov/science-discovery/nuclear-science/research-areas/reactor-technology/advanced-reactor-concepts/fluoride-salt-cooled-high-temperature-reactors

*There is no heavier burden than a great potential*
– Linus van Pelt