U.S. DEPARTMENT OF ENERGY

Nuclear Energy

U.S. MSR Development Program & Supportive Tasks

FHR Integrated Research Project 2 Workshop 2

At the University of California at Berkeley

Clark Kerr Campus

14-15 April 2016

Presented by:

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Molten Salts Enable a Broad Spectrum of Reactors

Any reactor that employs a molten salt to perform a significant function is a molten salt reactor.

- MSRs have two primary subclasses – salt-fueled and salt-cooled
  - Both subclasses have fast and thermal spectrum variants (epithermal and flux trap systems also possible)
  - Salt-fueled systems (e.g. molten salt in fuel rods) can be cooled by non-fuel salt
  - Salt-fueled systems can employ non-salt coolants
- Fuel cycle of salt-fueled reactors is intimately connected with the reactor
  - U/Pu, Th/U, and TRU based fuel systems are all possible
  - Breeding, burning, converter fuel cycles are all possible
  - Open, closed, and modified-open fuel cycles are all possible
  - Single and dual fluid systems are possible
- Fuel cycle of salt-cooled reactors resembles that of other solid-fuel reactors
  - Fluoride salt-cooled high-temperature reactors (FHRs) are a near term option
  - Fast spectrum fuel cycle resembles SFRs
  - Thermal spectrum fuel cycle resembles LWRs
    - Tritium production is significantly larger in fluoride salt systems

FHR Development is Supported Through NE's Office of Advanced Reactor Technologies

- **Mission of DOE-NE Office of Advanced Reactor Technologies (ART) is to develop future nuclear energy concepts that have the potential to provide significant safety and economic improvements over existing reactor concepts**
  - ART provides funding to the Nuclear Energy University Program
- **ART supports**
  - Reactor concept and technology development
  - Advanced reactor licensing framework development
    - *In collaboration with the NRC*
- **ART employs international collaboration to leverage and expand R&D investments**

FHRs have the long-term potential to economically and reliably produce large quantities of energy while maintaining full passive safety

US MSR Development Efforts Have Both Government and Industry Elements

- **US government effort is managed through the Department of Energy's (DOE) Office of Advanced Reactor Technologies**
  - Government effort includes partnering with commercial entities, university research grants, student support, and national laboratory led R&D
- **DOE program now includes both solid and liquid fuel MSRs**
  - FHR technology development effort is concentrated at university projects
- **Nuclear industry has recently become more active in broadly supporting advanced reactor development and MSR evaluation**
  - Nuclear Energy Institute has initiated an advanced reactor working group with strong utility leadership
  - Electric Power Research Institute recently sponsored a liquid fuel MSR evaluation project and have announced a $4M R&D program on advanced reactors
    - *http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002005460*
- **Close ties exist between government and private Canadian and US MSR efforts**
  - Evaluation of common safety evaluation approaches under consideration

DOE-NE is Investing in the Molten Chloride Fast Reactor Through a Public-Private Partnership

- **First U.S. Government liquid fueled MSR funding in 40 years!**
- **Award made following a competitive process**
- **$40M of government funding over 5 years with a substantial private match (>20%)**
- **Southern Company Services is the lead for the program**
  - TerraPower, ORNL, EPRI, and Vanderbilt University are the supporting institutions

The FY15 Omnibus Spending Bill included the following:
$12,500,000 is for the further development of two performance based advanced reactor concepts, of which $7,500,000 is for industry-only competition of two performance-based advanced reactor concepts and $5,000,000 is for the national laboratories selected to work with the awardees to perform the work required by the awardees to meet the goals of the awards

MCFR Commercial Development Roadmap Has Three Phases

Early validation

- Completed by 2019
  - Supported jointly by U.S. Government and Southern Nuclear Services led consortium

Critical test reactor

- Mid 2020s

Commercial prototype

- By 2035

Contract is still under negotiation.

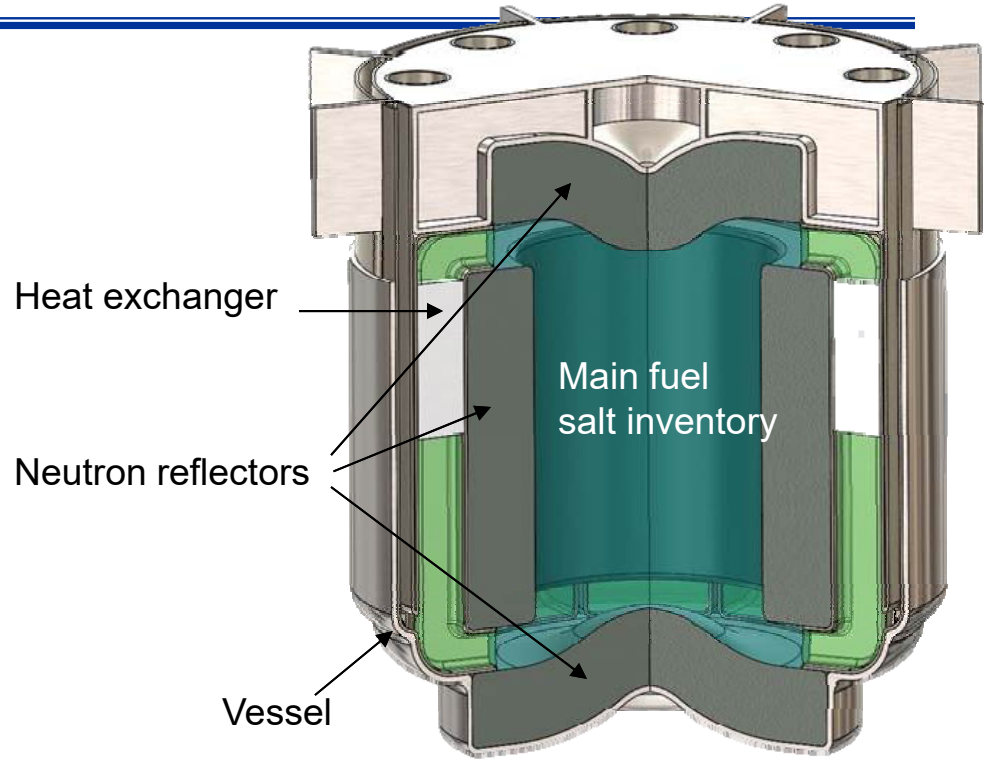


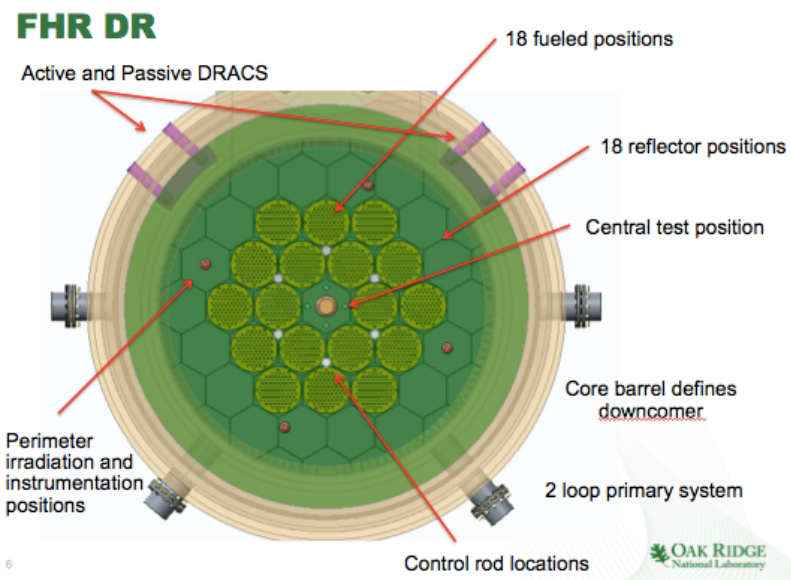
Image courtesy of TerraPower

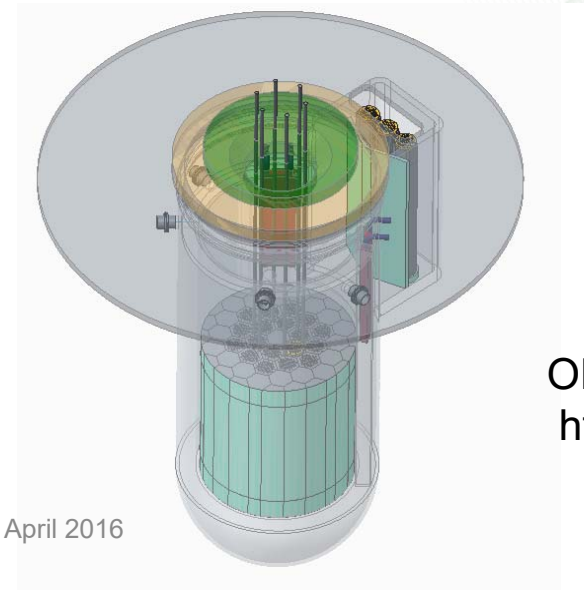
The MCFR core is composed of the reactor vessel, fuel salt, neutron reflectors, and primary heat exchangers.

Advanced Test/Demo Reactor Planning Study is Currently Underway

- **FY15 Omnibus Spending Bill**
  - *$7,000,000 is for an advanced test/demonstration reactor planning study by the national laboratories, industry, and other relevant stakeholders of such a reactor in the U.S. The study will evaluate advanced reactor technology options, capabilities, and requirements within the context of national needs and public policy to support innovation in nuclear energy.*
- **Nuclear Energy Advisory Council (NEAC) providing study advice.**
  - The objective of the study is to provide transparent, and defensible options to address need for, and technology of, a test and or demonstration reactor(s) to be built to support innovation and long term commercialization.
- **Draft report provided to DOE March 31st 2016.**

Candidate FHR Demonstration Reactor Point Design Recently Completed





Problem statement	The Fluoride Salt Cooled High Temperature Reactor (FHR) is a reactor concept that leverages proven fuel forms and high temperature, low pressure salt coolant. The FHR demonstration reactor design is intended to advance technological maturity of FHR systems as a whole.
Technical approach	The foundation of the approach consists of assessment and down selection of technology options. Corresponding design efforts are underway for the reactor core, balance of plant, and operational systems. The effort uses state-of-the-art computational tools and leverages the lessons learned from HFIR and MSRE operation.
Benefit	Specific benefits include demonstration of operational performance of key FHR technologies and processes. The FHR demonstration reactor will enable rapid deployment of an inherently safe, high efficiency, and high temperature energy source.

ORNL/TM-2016/85 describes reactor concept
http://info.ornl.gov/sites/publications/Files/Pub61577.pdf

DOE's Focused Investment in FHRs Remains Primarily 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 led 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
- **UK has created a parallel university collaboration program**
  - http://www.epsrc.ac.uk/funding/calls/neupcollaborativefundingopportunity/

Multiple Single Topic NEUP Projects Also Benefit FHRs

2011-2015 FHR NEUP Project Awards

- Experimental Validation of a Compact Double-Walled Twisted-Tube Heat Exchanger Concept (New Mexico) – 2015
- Development and Demonstration of an In-Situ Tritium Scavenger (Wisconsin) – 2015
- Coiled Tube Gas Heaters for Nuclear Gas-Brayton Power Conversion (UC Berkeley) - 2014
- 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 (GaTech) - 2012
- Pebble Fuel Handling (UCB) – 2011

DOE-NE Has Recently Initiated Two FHR Technical Tasks at its National Laboratories

- **Development and demonstration of tritium management technology for FHRs**
  - Using prototypical materials and conditions (temperatures, flow velocities, redox, etc.)
  - Follow-on engineering scale technology demonstration included in DOE-NE planning process
  - Significant synergies with ORNL-SINAP CRADA anticipated
  - Multiple approaches/technologies are planned for evaluation
- **Reactor physics criticality modeling and molten salt cross section sensitivity/uncertainty computation in collaboration with the Czech Republic**
  - Using LR-0 critical facility
  - U.S. origin isotopically selected FLiBe salt
  - Data will be openly available
  - Criticality benchmark will support validation of FHR physics codes

DOE's National Nuclear Security Administration Has Begun to Evaluate MSR Safeguards Issues

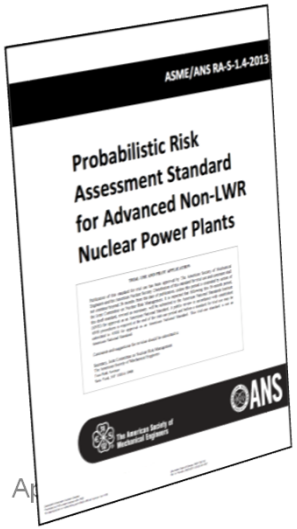
- **Develop path forward on how to approach the safeguards issues surrounding MSRs**
- **Effort leverages expertise in safeguards, proliferation resistance, and molten salt reactor technology**
- **Currently a scoping level study just getting underway**
- **Assessing and developing approaches and technologies to support IAEA will be primary focus**
  - Material control and accountability
  - Safeguards technology
  - Inspection regimes

NRC Has Begun To Integrate Advanced Reactors Into Its Licensing Structures

- **Advanced Reactor Policy Statement was published in 2008 (73 FR 60612)**
- **NRC augmented it test reactor licensing framework in 2012 (NUREG 1537) to accommodate aqueous homogeneous reactors**
- **NRC provided a report to Congress on advanced reactors licensing in 2012 noting the need for regulatory guidance for non-light water reactor designs**
- **DOE-NRC undertook a joint initiative on advanced reactor licensing in 2013**
  - DOE-NE has proposed a set of advanced reactor design criteria (ARDC) that are intended to preserve the safety intent of the general design criteria (GDC) of 10CFR50 Appendix A (INL/EXT-14-31179)
  - NRC has recently issued draft ARDCs for public comment (ML16096A420) in preparation for issuing a draft and then final Regulatory Guide
- **Next step in the joint initiative is to identify the LWR specific aspects of NRCs supporting regulatory framework documents (e.g. NUREG-0800) in preparation for developing technology neutral, performance-based regulation**

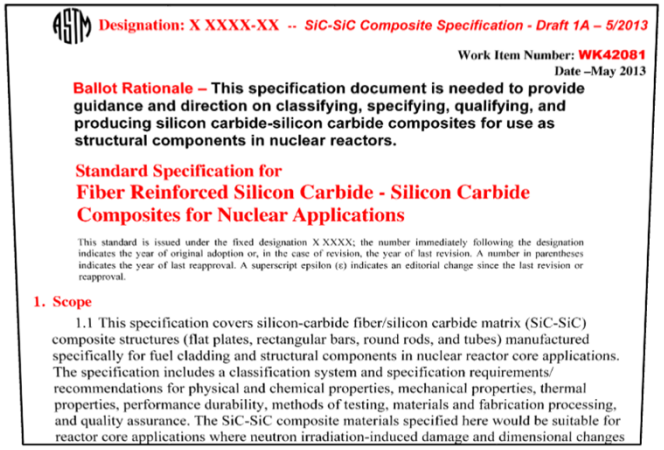
Multiple Recent Industry Consensus Standards Activities Support MSRs

- **ASME-ANS joint standard on non-LWR PRA adopted for trial use in 2013**
- **ANS working group 20.1 that is developing an FHR design safety standard is nearing an initial draft**
- **ANS working group 20.2 focused on developing a liquid fuel MSR design safety standard recently approved**
- **ASTM & ASME BPVC standards on advanced ceramic composites and graphite are under development**


ASME/ANS RA-S-1.4-2013

Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants

ANS


Designation: X XXXX-XX -- SiC-SiC Composite Specification - Draft 1A – 5/2013

Work Item Number: WK42081
Date –May 2013

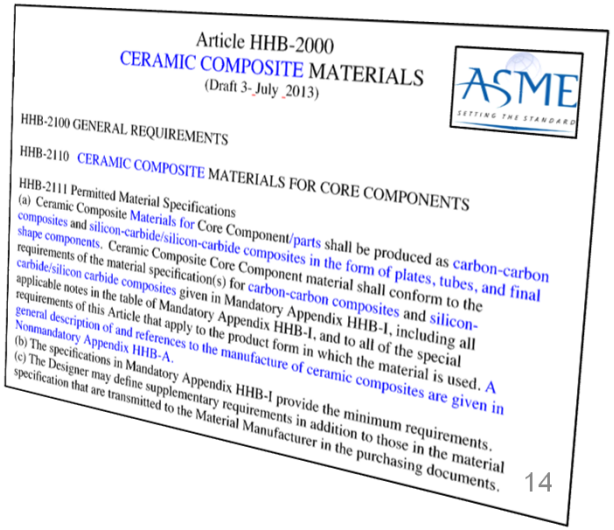
Ballot Rationale – This specification document is needed to provide guidance and direction on classifying, specifying, qualifying, and producing silicon carbide-silicon carbide composites for use as structural components in nuclear reactors.

Standard Specification for
Fiber Reinforced Silicon Carbide - Silicon Carbide Composites for Nuclear Applications

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers silicon-carbide fiber/silicon carbide matrix (SiC-SiC) composite structures (flat plates, rectangular bars, round rods, and tubes) manufactured specifically for fuel cladding and structural components in nuclear reactor core applications. The specification includes a classification system and specification requirements/ recommendations for physical and chemical properties, mechanical properties, thermal properties, performance durability, methods of testing, materials and fabrication processing, and quality assurance. The SiC-SiC composite materials specified here would be suitable for reactor core applications where neutron irradiation-induced damage and dimensional changes


Article HHB-2000
CERAMIC COMPOSITE MATERIALS
(Draft 3- July 2013)

ASME SETTING THE STANDARD

HHB-2100 GENERAL REQUIREMENTS

HHB-2110 CERAMIC COMPOSITE MATERIALS FOR CORE COMPONENTS

HHB-2111 Permitted Material Specifications
(a) Ceramic Composite Materials for Core Component/parts shall be produced as carbon-carbon composites and silicon-carbide/silicon-carbide composites in the form of plates, tubes, and final shape components. Ceramic Composite Core Component material shall conform to the requirements of the material specification(s) for carbon-carbon composites and silicon-carbide/silicon carbide composites given in Mandatory Appendix HHB-I, and to all of the special applicable notes in the table of Mandatory Appendix HHB-I, including all requirements of this Article that apply to the product form in which the material is used. A general description of and references to the manufacture of ceramic composites are given in Nonmandatory Appendix HHB-A.
(b) The specifications in Mandatory Appendix HHB-I provide the minimum requirements.
(c) The Designer may define supplementary requirements in addition to those in the material specification that are transmitted to the Material Manufacturer in the purchasing documents.

US and China Are Continuing Cooperation on FHR Research and Development

- **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) of the Chinese Academy of Sciences (CAS) are the lead organizations**
  - ORNL will call on expertise throughout the US to support CRADA tasks
- **Project is intended to benefit both countries through more efficiently and rapidly advancing a reactor class of common interest**
- **FHRs 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 fuel development or fissile material separation technology

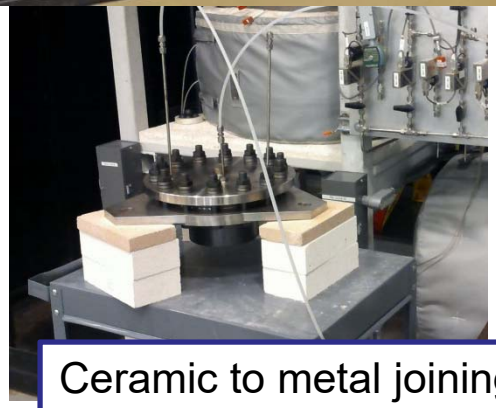
Initial CRADA Tasks Include Experimental, Computational, and Analytical Efforts

Phase I is nearing completion

- **Task 1: Fluoride Salt Loop Startup and Pebble Bed Heat Transfer Testing**
  - SINAP staff are participating in the experimental program
- **Task 2: Component & Instrumentation Development**
  - Ultrasonic flowmeter demonstration & validation
  - Fluoride Salt Pump Development and Demonstration
- **Task 3: Analysis Software Support**
  - 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**
  - Subcontract with University of California at Berkeley
- **Task 5: Information Exchange and Program Coordination**
  - Licensing approaches and safety analysis for FHR systems
  - FHR technical issues (materials, information management, seismic design)

ORNL FLiNaK Salt Test Loop Commissioned

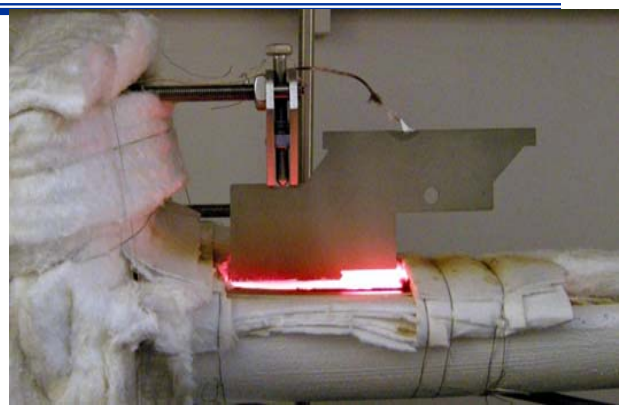
- **Versatile liquid salt test loop embodies multiple innovative technologies providing a technology demonstration platform**
  - Integration of ceramic and metal components
  - Molten salt compatible gaskets (all prior loops have relied on welded joints)
  - Liquid salt instrumentation
    - *Ultrasonic flow meter*
    - *Radar level gauge*
  - Integration of salt cleaning with loop
- **Molten salt thermal and hydraulic performance testing underway**
  - Pebble bed pressure drop and heat transfer
  - Pump performance
- **SINAP staff are at ORNL and participating in the measurements**

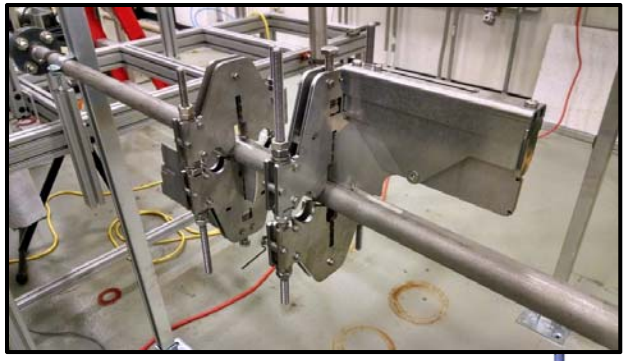


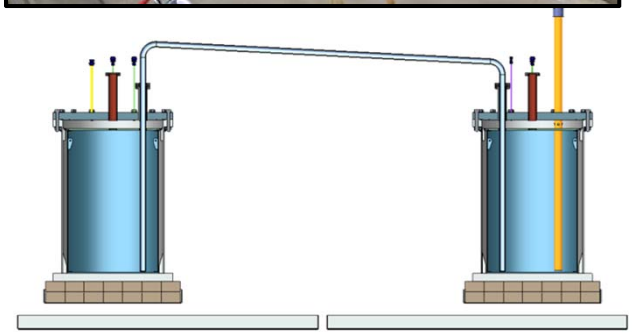
Ceramic to metal joining test fixture

High-temperature Liquid Salt Flow Meter Calibration

- **Calibrated salt mass flow measurement is needed to operate high-temperature salt reactors**
  - SINAP and ORNL fluoride salt loops are currently using FLEXIM ultrasonic flow meters that are not calibrated
  - Calibration methods for high temperature (700ºC) are currently unavailable
- **Current status and next steps**
  - System assembly just getting underway
  - Performed water flow calibration and setting up instruments for salt flow calibration
  - Perform initial flow calibration measurements in June 2016
  - SINAP staff working on the experiments







ORNL Provided Training for Chinese Regulators on FHRs

- **Conducted at Shanghai Institute of Applied Physics from Dec 7-9**
  - In support of SINAP/ORNL CRADA
  - Focus of training for China's National Nuclear Safety Administration (NNSA)
- **Attendance from NNSA and SINAP staffs and support organizations: 270**
  - 50: NNSA staff and 20 support organizations
  - 200: staff from SINAP and other institutes from Chinese Academy of Sciences
  - 10 modules: FHR reactor technology, systems, and safety

FHR Training for Shanghai Institute of Applied Physics and the National Nuclear Safety Administration of China
Oak Ridge National Laboratory
December 7-9, 2015

MODULE 1: History and Background	**MODULE 6:** Instrumentation and Control
MODULE 2: General Descriptions of Concepts	**MODULE 7:** Fuels and Materials
MODULE 3: Coolant and T/H Parameters	**MODULE 8:** Safety & Analysis / Design Requirements
MODULE 4: Neutronics and Core Design	**MODULE 9:** Regulatory Issues and Challenges
MODULE 5: Systems and Components	**MODULE 10:** Technology Development Issues

MSR Potential Remains Substantial and Untapped

- **Optimum MSR and fuel cycle depends upon the mission**
  - Solid fuel systems minimize deviations from precedent
  - DMSRs build upon prior MSR heritage
  - FS-MSRs avoid requirement for future uranium enrichment
  - TRU fuel reduces amount of existing HLW
- **Liquid fuel inherently intimately interconnects the fuel cycle with the reactor**
- **MSR fuel cycles can be highly proliferation resistant or have substantial proliferation vulnerabilities**
- **Basic elements of MSR fuel cycles have been identified and demonstrated with varying degrees of sophistication**
- **Significant research, development, and demonstration remains to enable any MSR**

It Appears We Have Come Full Circle from the Late 1960s on MSRs

From the Preface of a Series of Papers Published in *Nuclear Applications & Technology* on MSRs from 1969 by Alvin M. Weinberg:

The tone of optimism that pervades these papers is hard to suppress. And indeed, the enthusiasm displayed here is no longer confined to Oak Ridge. There are now several groups working vigorously on molten salts outside Oak Ridge.