U.S. DEPARTMENT OF ENERGY

Nuclear Energy

U.S. MSR Development Programs & Supportive Efforts

GIF Molten Salt Reactor pSSC

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January 23-25th 2017

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
- **Gateway for Accelerated Innovation in Nuclear (GAIN) initiative includes MSRs**
  - Active MSR technical working group with both vendor and utility representatives
- **Nuclear industry has recently become more active in broadly supporting advanced reactor development and MSR evaluation**
- **NRC's Non-Light Water Reactor vision and strategy document includes significant emphasis on MSRs**
  - https://www.nrc.gov/docs/ML1633/ML16334A495.pdf
- **NRC has contracted ORNL to provide MSR training for its staff**
- **Legislation to develop a technology-neutral, performance-based advanced reactor regulatory process being reintroduced in new Congress**

Key Recent Developments

- **U.S. signed GIF MSR MOU**
- **GAIN MSR industry working group recently requested DOE initiate a significant base MSR R&D program**
  - Letter signed by six MSR reactor vendors
- **Terrestrial Energy USA has notified the NRC that it intends to submit either a design certification or construction permit application no later than October 2019 (ML16336A508)**
- **Terrestrial Energy USA's has been invited (based upon evaluation of its part 1 application) by US DOE to submit part II of is application of a loan guarantee**
  - $800M - $1.2B loan guarantee sought

Pursuant to Section 7 of the Generation IV International Forum Memorandum of Understanding for Collaboration on The Molten Salt Reactor System Nuclear Energy System under which cooperation began on 6 October 2010 between the COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES and the EUROPEAN COMMISSION JOINT RESEARCH CENTRE, and to which ROSATOM and the PAUL SCHERRER INSTITUTE subsequently became Participants on 12 November 2013 and 20 November 2015 respectively, the UNITED STATES DEPARTMENT OF ENERGY is a new Participant from the date of signature hereunder:

FOR THE UNITED STATES DEPARTMENT OF ENERGY:

Ray Furstenau

Ray Furstenau

Associate Principal Deputy Assistant Secretary
for the Office of Nuclear Energy

Date: 5 January 2017

Place: Washington, DC

MSR

600 18th Street North
Birmingham, AL 35203

December 15, 2016

Dr. Rita Baranwal
Director, DOE Gateway for Accelerated Innovation in Nuclear
Idaho National Laboratory
P.O. Box 1625, MS 3855
Idaho Falls, ID 83415

Subject: Separate Effects Test Program for MSR Development

Dear Dr. Baranwal:

As the member companies of the Molten Salt Reactor (MSR) Technology Working Group (TWG), we are collaborating to accelerate the development and market deployment of MSR technologies. The MSR TWG, an independent sub-committee of the Nuclear Energy Institute's (NEI) Advanced Reactor Working Group (ARWG) Technology Task Force, has been extremely impressed with and encouraged by the engagement and sense of urgency DOE has shown in implementing the GAIN initiative, and we sincerely believe that working together will lead to beneficial results for all stakeholders. The MSR TWG also appreciates DOE's interest in performing a feasibility study for a MSR Engineering Facility. The MSR TWG has discussed this topic and has concluded that DOE should establish a Separate Effects Test (SET) program for the development of MSRs while also supporting the early development of supply chain infrastructure. The unique combination of energy density, economics, and safety found in MSRs merits a broad investment

GAIN MSR Technical Working Group Includes Developers, Utilities, and Industry Groups

ONE

TerraPower

Fast
Breeder
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

TWO

Thorcon

Thermal
Burner
Liquid Fuel
Salt Cooled
Thorium

THREE

Terrestrial Energy

Thermal
Burner
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

FOUR

Flibe Energy

Thermal
Breeder
Liquid Fuel
Salt Cooled
Thorium

FIVE

Transatomic Power

Hybrid
Burner
Liquid Fuel
Salt Cooled
Uranium

SIX

Elysium Industries

Liquid Fuel
Salt Cooled

SEVEN

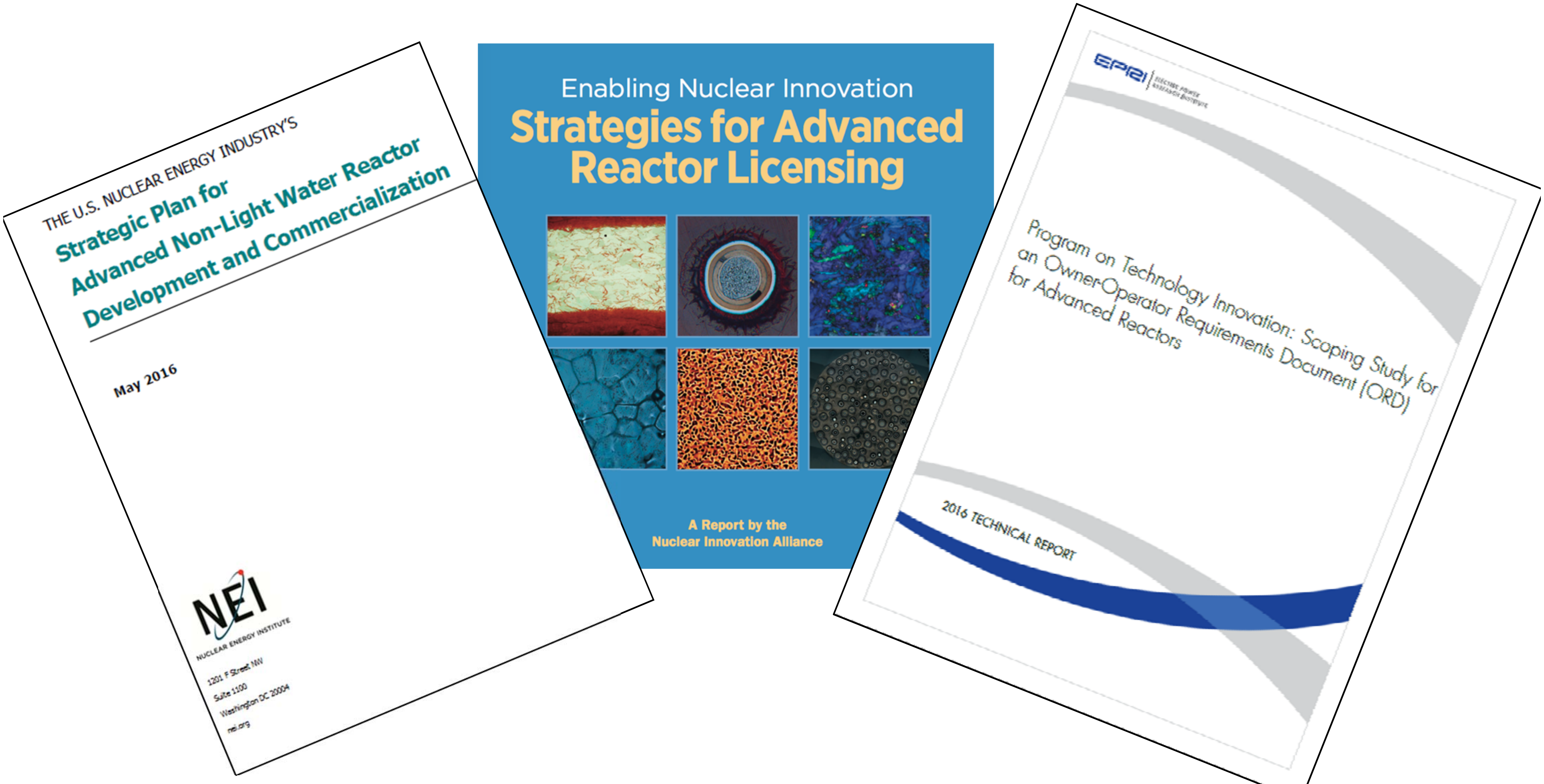
Alpha Tech Research Corp

Liquid Fuel
Thorium
Fluoride Salt

Southern Company
Exelon.
EPRI
DUKE ENERGY.
NEI
NUCLEAR ENERGY INSTITUTE

U.S. government is not pursuing reactor concepts that include creating separated fissile material

Nuclear Industry Has Begun to Develop Advanced Reactor Planning Documents



Molten salt reactors are prominently considered

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

- **First US 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

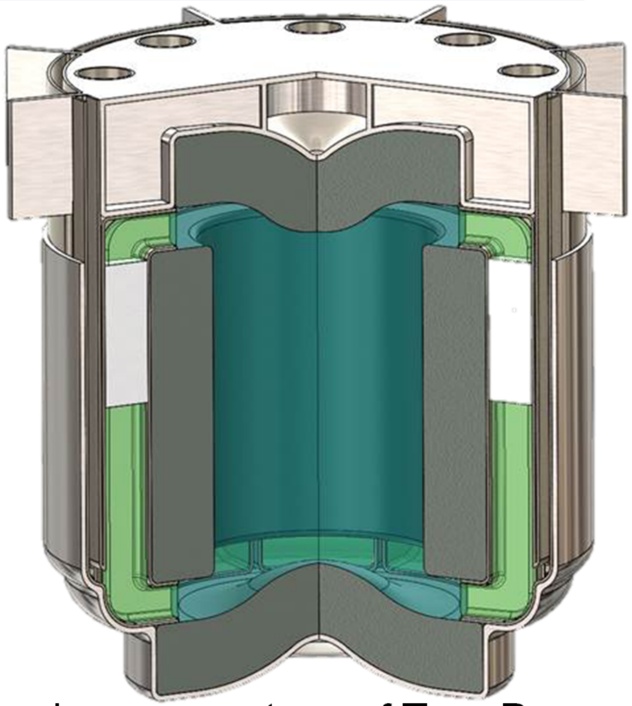


Image courtesy of TerraPower

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

DOE Has Recently Announced Additional Molten Salt Technology Investments

- **GAIN**
  - Terrestrial Energy – Molten salt physical property verification – with Argonne National Lab
  - TransAtomic Energy – Optimization and assessment of their reactor neutronics and fuel cycle – with ORNL
- **Office of Technology Transitions** (all with ORNL)
  - Liquid salt environment creep testing system development and commercialization
    - *Based on US Patent 9,291,537 B2*
  - MSR neutronics tools
  - New high-strength Ni-based alloys for high temperature service in liquid fluoride salt environments
    - *Multiple alloy patent applications remain in process*
    - *US Patent 9,277,245 B2 on heat exchanger life extension recently issued*

DOE's Focused Investment in FHRs Remains Primarily Through University Research

- **In 2011, DOE funded a multi-university (Massachusetts Institute of Technology [MIT], University of California, Berkeley [UC-B], and University of Wisconsin [UW]) integrated research project on FHR concept and technology development**
  - Thermal hydraulics and safety tests (UC-B)
  - Material and component selection and performance (UW)
  - Coolant/material tests in MIT research reactor (MIT)
  - 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 were focused on resolving FHR technology issues
  - Joint planning has occurred to minimize overlap and emphasize synergy

DOE-NE Has Recently Supported Two MSR 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.)
  - Multiple approaches/technologies are planned for evaluation
    - *Blocking, trapping, and stripping*
- **Reactor physics criticality modeling and molten salt cross section sensitivity/uncertainty computation in collaboration with the Czech Republic**
  - Using LR-0 critical facility
  - US origin isotopically selected FLiBe salt
  - Final project report available at - http://info.ornl.gov/sites/publications/Files/Pub72095.pdf

5.6.12 Task 4.3.8 Tritium adsorption on carbon in contact with the coolant

Some of the tritium generated by the MSRE was found within the graphite moderator.[38] Although a similar situation in an MSBR will be helpful, it is not likely to prevent excessive amounts of tritium from diffusing into the coolant. However, it is possible that graphite (or carbon) in contact with the coolant could adsorb a large fraction of the tritium. Initial studies have shown that the capacity of carbon for tritium might be adequate (~10 Ci of T_2 per kg of carbon), but that kinetics may be inadequate to permit high removal efficiency. A catalytic effect of very thin nickel coatings in enhancing the kinetics would be expected by analogy with many industrial catalytic processes. This subtask would be directed toward the preparation and testing of nickel coatings, and determining the feasibility of this approach for removing tritium from the coolant.

From ORNL-5018 *Program Plan for the Development of Molten Salt Breeder Reactors*, 1972

Proliferation Resistance Has Become A Dominant Concern For All Fuel Cycles

- **MSRs can be highly proliferation resistant or vulnerable depending on the plant design**
  - MSR designs until the mid-1970s did not consider proliferation issues
  - Several current MSR design variants do not include separation of actinide materials
- **Liquid fuel changes the barriers to materials diversion**
  - Lack of discrete fuel elements combined with continuous transmutation prevents simple accounting
  - Solid LEU fresh fuel salt in transport and storage accountancy resembles LWR fuel
  - Homogenized fuel results in an undesirable isotopic ratio a few months following initial startup (no short cycling)
  - Extreme radiation environment near fuel makes changes to plant configuration necessary for fuel diversion very difficult
  - High salt melting temperature makes ad hoc salt removal technically difficult
  - Low excess reactivity prevents covert fuel diversion

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 MSR technologies**
- **Initial scoping study recently completed by a national laboratory team**
- **Follow on project getting underway**
  - Detailed work products will have restricted access as they may reveal limitations/vulnerabilities
- **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 its 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**

U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

ML16356A670

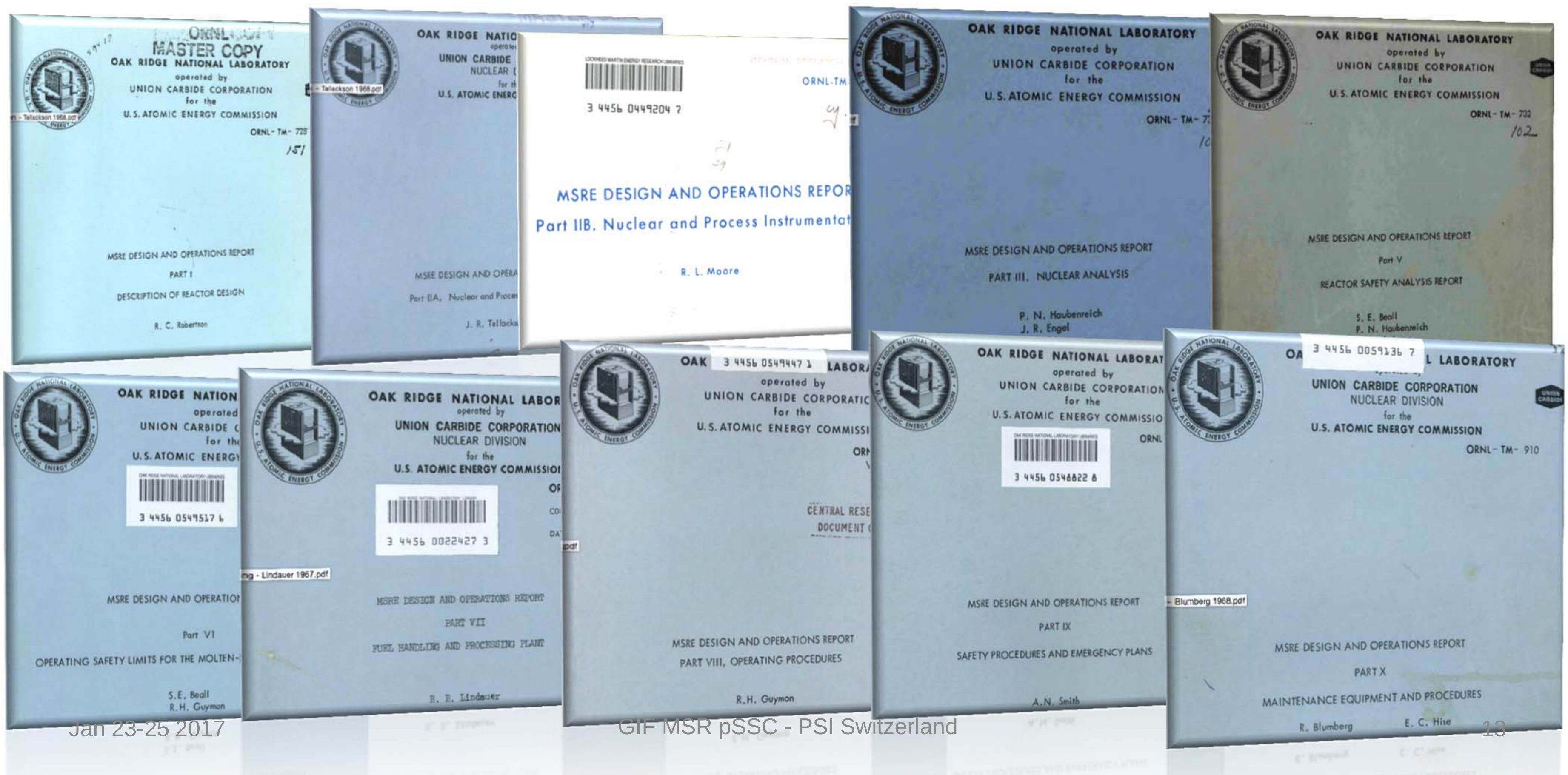
NRC Vision and Strategy:
Safely Achieving Effective and Efficient
Non-Light Water Reactor
Mission Readiness

December 2016

- **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 released proposed ARDCs (ML16096A420) in preparation for developing a Regulatory Guide
- **NRC has recently published its "Vision and Strategy" developing non-LWR regulation (ML16356A670)**

NRC is Sponsoring Staff Training on MSRs

- **Content is under development at ORNL (Spring 2017 completion)**
  - Two-day introductory level course
- **Canadian Nuclear Safety Commission has requested development of MSR experiment operational experience training**



US and China Have Been Cooperating on FHR R&D

- **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**
- **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

ORNL FLiNaK Test Loop Has Started-Up

- **Loop originated in ORNL LDRD, was expanded through DOE-NE, and brought into operation under SINAP**
- **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
- **First hot functional testing performed in June 2016**
- **SINAP staff have been participating in the measurements**

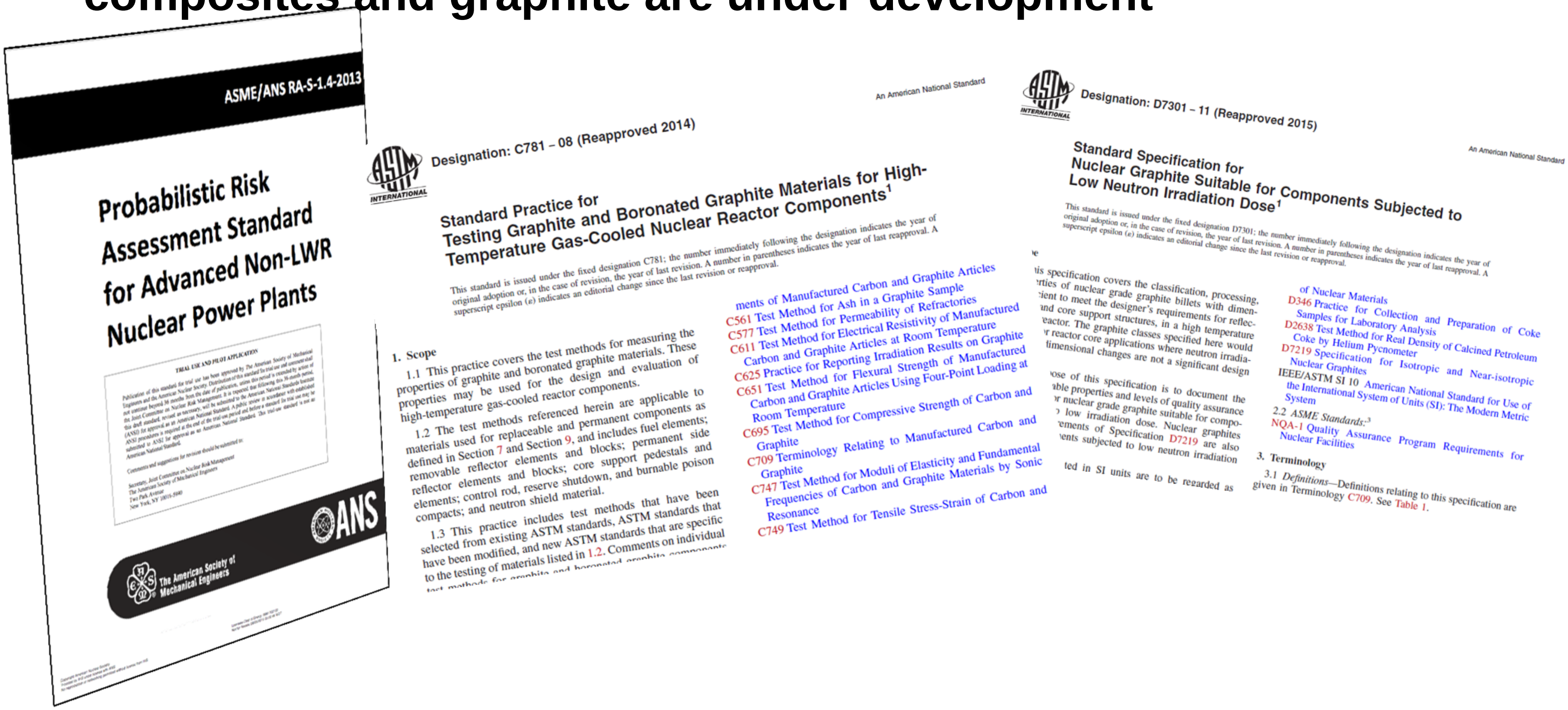
Thermal images of loop containing hot salt

American Nuclear Society Has Four Standards Under Development Directly Supporting MSRs

- **ANS-20.1, “Nuclear Safety Design Criteria for Fluoride Salt-Cooled High-Temperature Reactor Nuclear Power Plants” (in development)**
- **ANS-20.2, “Nuclear Safety Design Criteria and Functional Performance Requirements for Liquid-Fuel Molten Salt Reactor Nuclear Power Plants” (in development)**
- **ANS-30.1, “Integrating Risk and Performance Objectives into New Reactor Nuclear Safety Designs” (in development-first draft)**
- **ANS-30.2, “Categorization and Classification of Structures, Systems, and Components for New Nuclear Power Plants” (in development)**
  - **Membership solicited from IEEE and ASME**

Multiple Recent Industry Consensus Standards Activities Support MSRs

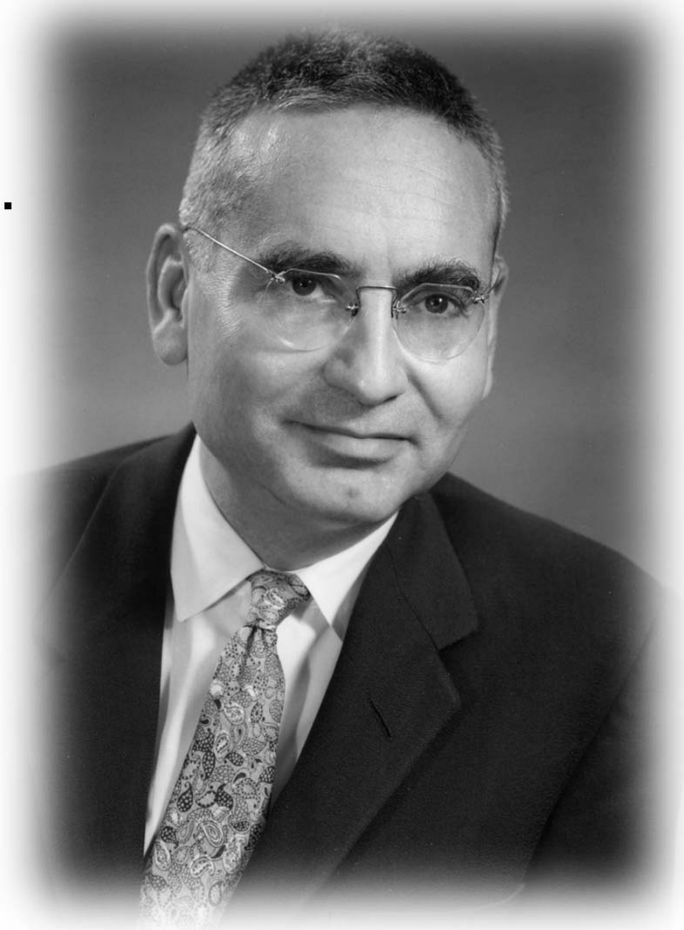
- **ASME-ANS joint standard on non-LWR PRA adopted for trial use in 2013**
- **ASTM & ASME BPVC standards on advanced ceramic composites and graphite are under development**



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.



MSRE showed that MSRs are possible today's efforts are to prove they are practical