U.S. DEPARTMENT OF ENERGY | Office of Nuclear Energy

Molten Salt Reactor PROGRAM

Revival of MSRs in the U.S. – *Third Millenium Activities*

David Holcomb

Idaho National Laboratory

MSR Workshop

Knoxville, TN; November 2024

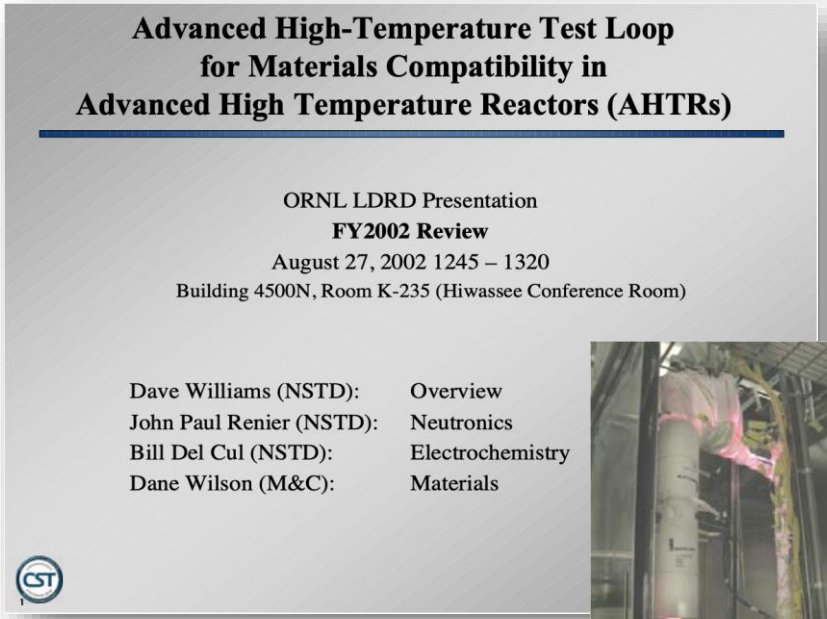
Status in 2001

- Original Molten Salt Breeder Reactor (MSBR) program staff mostly unavailable
- Program documents largely confined to repositories
- Perception that MSRs were inherently, highly proliferation vulnerable
- Fracking bringing natural gas prices to historic lows
- Climate change concerns had not yet entered widespread consciousness
  - A. M. Weinberg, *Global Effects of Man's Production of Energy*, *Science*, 1974, DOI: 10.1126/science.186.4160.205
- Existing nuclear fleet capacity factor was approaching 90%
  - Ample reserve capacity
  - Ample fuel supplies
  - Watts Bar Unit 2 remained uncompleted in mothball status
  - Yucca Mountain approved in 2002

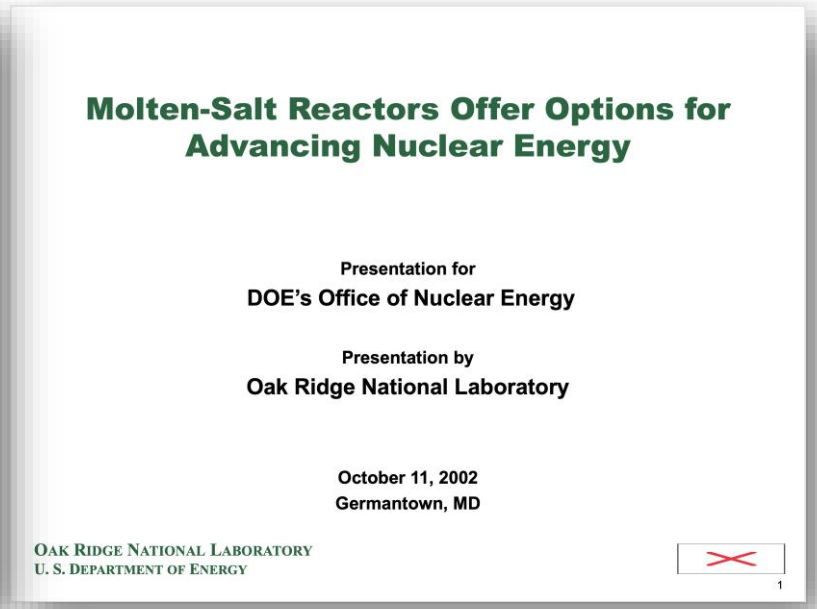
Multiple Efforts in Early 2000s to Trigger DOE Interest In MSR Development Revival

- DOE-NE strategy 2001 – Systems to be ready by 2025
  - "Molten salt reactors are too much of a technology stretch"
  - "Utilities are too uncomfortable with operations"

Line item for a quasi-poloidal stellarator in FY 2003 budget



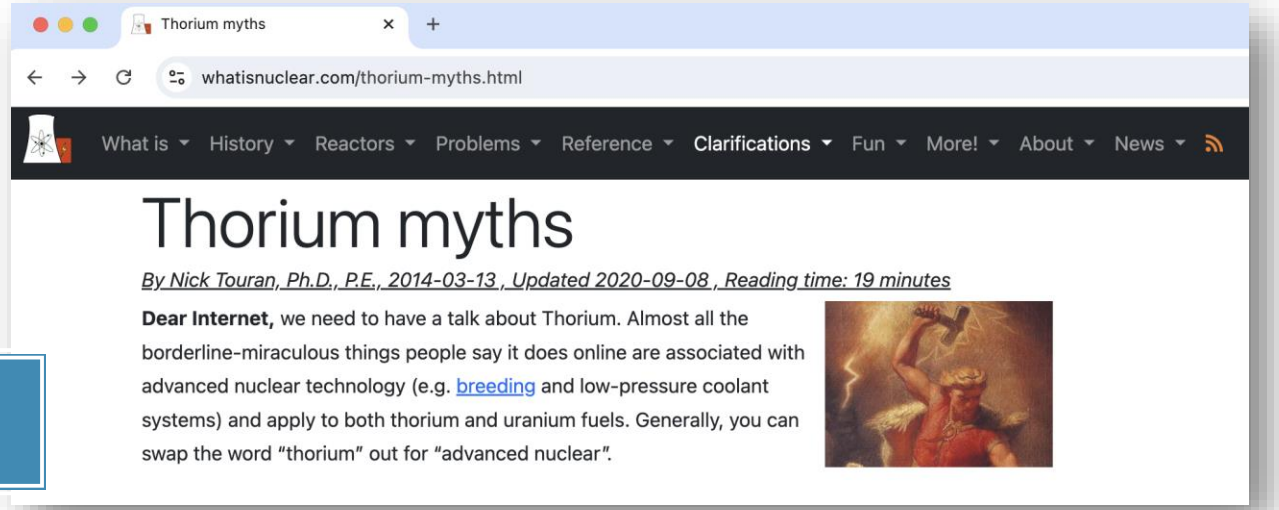
Molten Salt Test Loop for 2001 LDRD



Key Events in Re-Initiating MSRs in the U.S.

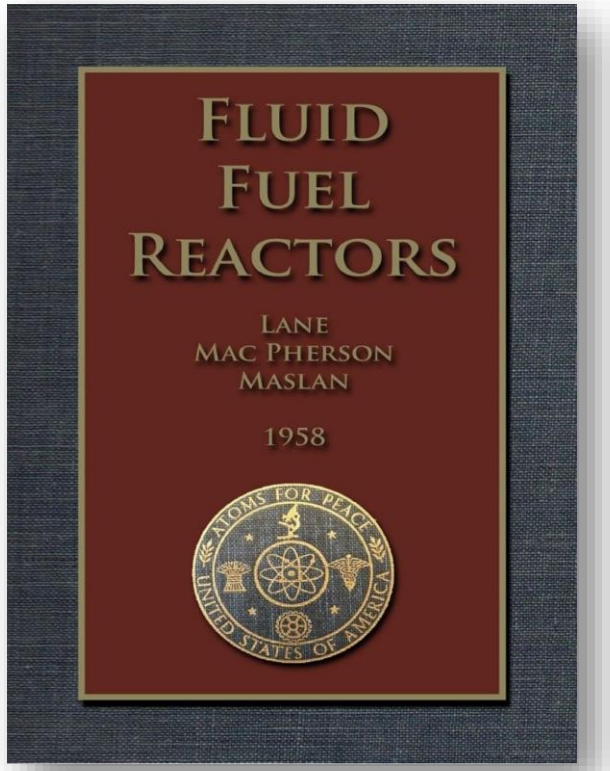
- Generation IV international forum created
  - MSRs were one of the six reactor types selected
  - U.S. only elected observer status (no program to contribute)
- MSRs considered for space power (propulsion and surface power)
- FHR (re)invented
  - DOE provided funding to evaluate a liquid salt-cooled version of the Next Generation Nuclear Plant to ORNL, Sandia, and UC-Berkeley
  - Series of university-integrated research projects
  - Series of capstone design courses at UC-Berkeley
- Social media provided a platform for external voices
- Internet enabled widespread distribution of historic MSBR program documents

Social media both includes information, misinformation, and corrections



On-line Availability of the Historic MBSR Program Documents Significantly Broadened Availability

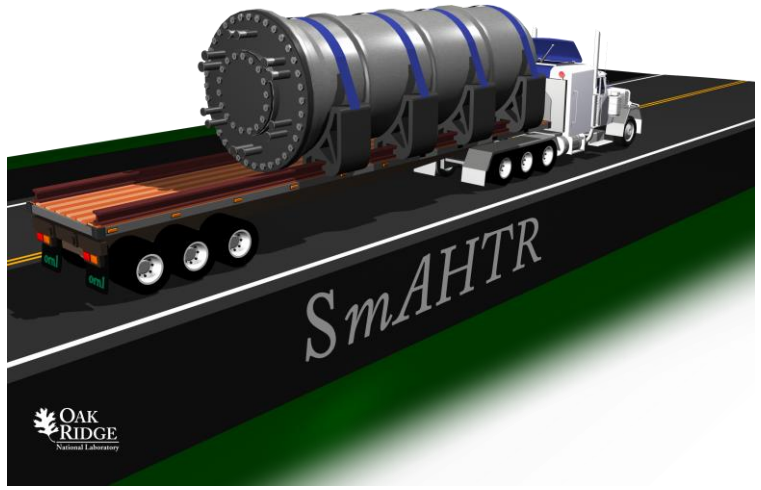
- Documents were largely in the public domain due to age
  - Documents confined to ORNL library, repository libraries, and laboratory records vault
- Fluid fuel reactors published as part of *Atoms for Peace* program in 1958
  - Gordon McDowell prepared kindle edition in 2018 ($3)
- NASA provided first funding to digitize a significant fraction of the historic archive - 2002 (Kirk Sorensen was a NASA engineer at the time)
- ORNL's library began to digitize its collection of historic documents
  - Staff requests to prioritize MSR information
- DOE's Office of Scientific and Technical Information transitioned from primarily physical to electronic distribution
  - Mission to digitize entire historic archive
  - GAIN initiative provided funding to digitize MSR documents (2015)



GAIN = Gateway for Accelerated Innovation in Nuclear

DOE Focused On Nearer Term, Salt-Cooled Reactor Technology

- 2004–2006: Advanced High Temperature Reactor option to salt cool Next Generation Nuclear Plant – ORNL/TM-2004/104
  - Joint effort of ORNL, UC-Berkeley, and Sandia National Laboratories (SNL)
- 2009–10 ORNL developed preconceptual design for the Small-modular Advanced High-Temperature Reactor (SmAHTR) – ORNL/TM-2010/199
  - Sherrell Greene led development team



First DOE-NE Fluoride Salt-Cooled High-Temperature Reactor Workshop

September 20–21, 2010
ORNL Conference Center

Workshop Summary Report

On September 20–21, 2010, Oak Ridge National Laboratory (ORNL) hosted the first U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) sponsored workshop on fluoride salt-cooled high-temperature reactors (FHRs). The purposes of the workshop were to (1) facilitate information exchange on FHRs, (2) assess the current status of FHR reactor concepts and their technology, and (3) inform the FHR research, development, and demonstration (RD&D) plan. As an initial workshop that included participants that have not been deeply involved in FHR development, a significant part of the workshop purpose was to educate the participants as to the current FHR program and technology status.

The workshop had 84 participants. The workshop attendees list is available at https://www.ornl.gov/fhr/documents/FHRWorkshopAttendees.pdf. Attendees represented five national laboratories, four countries, and a broad spectrum of both the nuclear industry and university researchers. Participation by multiple reactor vendors and technology suppliers was especially noteworthy given the long lead-time remaining and unproven economics for FHRs.

By 2011 Cracks Were Beginning to Appear in the No Liquid Fuel Salt Policy

- Separate projects sponsored by DOE-NE Advanced Reactor Concepts and Fuel Cycle Technology programs
  - Rationale for evaluation was to develop comparative metrics for different fuel cycle and energy generation technology options

DOE is not currently pursing the development of MSRs. However, the U.S. had a large, active MSR development program from the 1940s–70s that included the operation of two test reactors, and DOE realizes that MSRs can have desirable characteristics and thus has not foreclosed pursuing the technology in the future.


OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2011/105

Fast Spectrum Molten Salt Reactor Options

July 2011

Prepared by
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UT-BATTELLE

DOE Supported a Series of MSR-Integrated Research Projects – Multi-University, Few Million-Dollar Efforts

- 2011 – FHR concept and technology development
- 2014 – Two projects on resolving FHR technology issues
- 2017 – NuSTEM advancing MSR science and technology and developing experts for the future
- 2020 – Molten Salt Reactor Test Bed with Neutron Irradiation
- 2022 – Understanding role of fission products and impurities

Gradual MSR Stature Increase within DOE Activities

- GIF participation support 2002–present
- 2003–05 Advanced High Temperature Reactor
- 2011 Blue Sky Evaluation – molten salt fast reactors
- 2014 FHR development roadmap
- 2016 GAIN program
  - https://gain.inl.gov/resources/nuclear-technologies/molten-salt-reactors/
- 2016–17 U.S. became a member of Generation IV International Forum Molten Salt Reactor Provisional System Steering Committee
- 2017 DOE advanced reactor support organized into campaigns
  - MSRs included as a peer reactor class

Diverse Set of Companies Founded (2010–15) Each with Different Approach

Kairos Power

TERRESTRIAL ENERGY

Flibe ENERGY

TerraPower

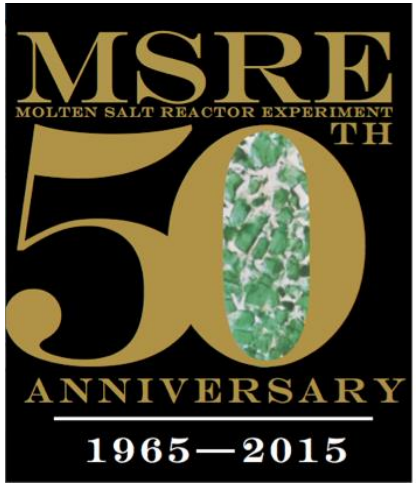
Thorcon

TRANSATOMIC

E I

EXODYS ENERGY

Common Element is the Mission Focus



2015 - Liquid Fueled MSRs Return

- DOE-NRC workshop on advanced fuel cycles included MSRs
- ANS 20.2 – Liquid-fueled MSR design safety working group formed
- MIT completed first irradiation of samples in FLiBe at 700°C
- UCB completed compact integral effects test facility

2015–16 DOE-NE Began Investment in the Molten Chloride Fast Reactor through a Public-Private Partnership with Southern Company Services

- First U.S. Government liquid-fueled MSR funding in 40 years!
  - Integral effects test facility
- 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

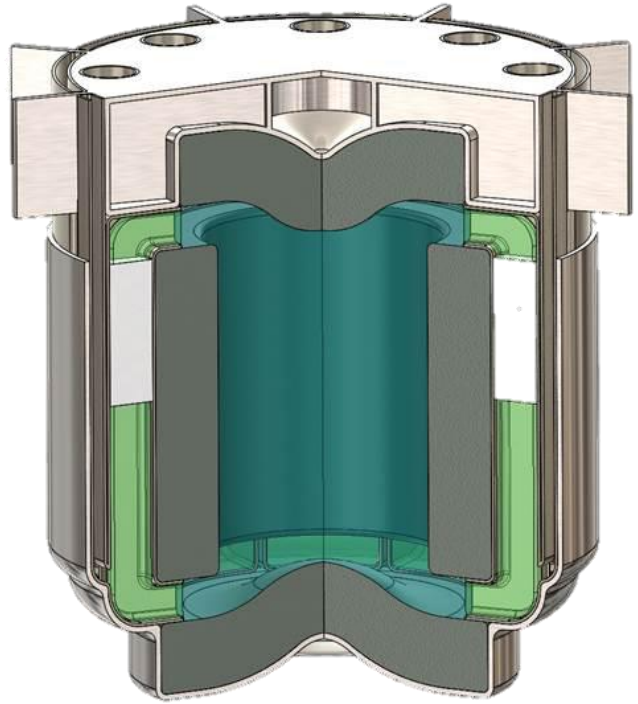


Image courtesy of TerraPower

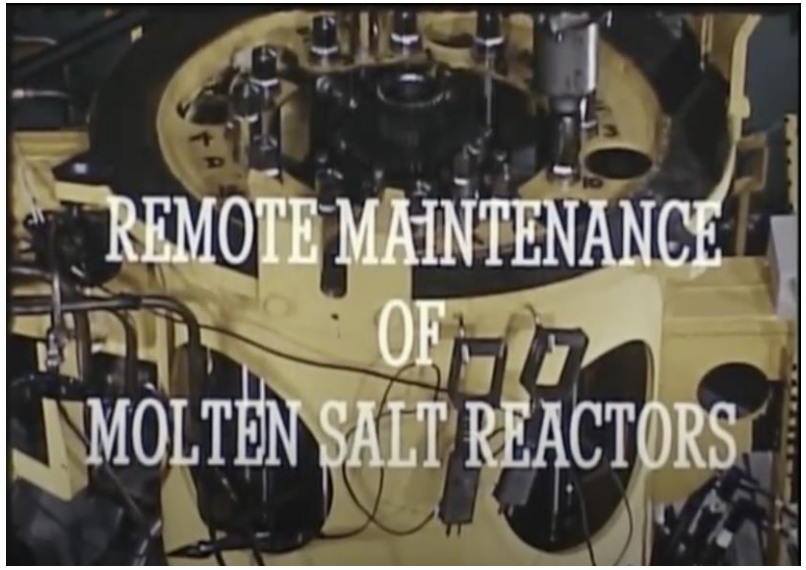
The FY-15 Omnibus Spending Bill included the following:
$12,500,000 is for the further development of two performance based advanced reactor concepts, of which $7,500,000 is for industry-only competition of two performance-based advanced reactor concepts and $5,000,000 is for the national laboratories selected to work with the awardees to perform the work required by the awardees to meet the goals of the awards.

MSBR Program Videos Found, Digitized, and Released

- Film (old 16 mm reels) located in Y-12 vaults

Produced in 1969

https://www.youtube.com/watch?v=tyDbq5HRs0o



Mock-up Maintenance Facility Constructed in 1959

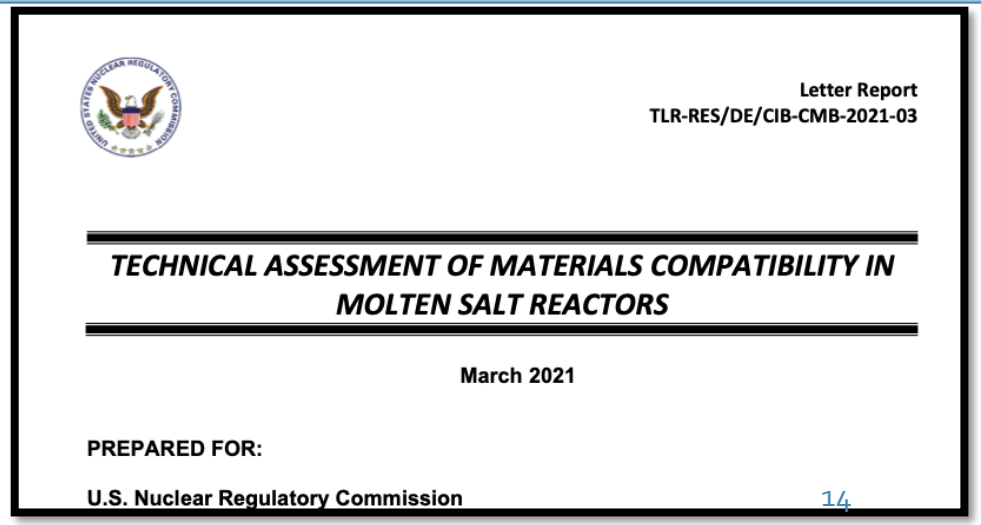
https://www.youtube.com/watch?v=uHT-w2x6dDg

NRC Has Been Preparing to Efficiently and Effectively License MSRs

- Developing guidance for preparing and reviewing nonpower MSR license applications (NUREG-1537) via ORNL/TM-2018/834
- Staff training 2017 (updated in 2022)
- Developing advanced reactor generic environmental impact statement
- Approving fuel salt qualification qualification guidance NUREG/CR-7299
- Adding molten salt capabilities to MELCOR (SAND2023-01803)
- Evaluating materials requirements

Licensing Activities Underway

1. Hermes Test Reactor Construction Permit Issued to Kairos Power – 12/2023
2. Safety evaluation issued for Hermes-2 to Kairos Power – 7/2024
3. ACU MSRR Safety Evaluation target issuance – 9/2024
4. Terrestrial Energy issuance of draft safety evaluation – 2/2025



Letter Report
TLR-RES/DE/CIB-CMB-2021-03

TECHNICAL ASSESSMENT OF MATERIALS COMPATIBILITY IN MOLTEN SALT REACTORS

March 2021

PREPARED FOR:

U.S. Nuclear Regulatory Commission

Advanced Reactor Demonstration Program - 2020

- MSRs included in **risk reduction for future demonstrations**
  - Considered too immature to result in deployed reactor within 7 years
- Goal of the risk reduction program is to design and develop safe and affordable reactor technologies that can be licensed and deployed over the next 10 to 14 years.

Hermes Reduced-Scale Test Reactor - Kairos Power, LLC (Alameda, CA) will design, construct, and operate its Hermes reduced-scale test reactor. Hermes is intended to lead to the development of Kairos Power's commercial-scale KP-FHR (Kairos Power Fluoride Salt-Cooled High Temperature Reactor), a novel advanced nuclear reactor technology that leverages TRI-structural ISOtropic particle fuel (TRISO) fuel in pebble form combined with a low-pressure fluoride salt coolant. **Total award value over 7 years:** $629 million (DOE share is $303 million)

Molten Chloride Reactor Experiment – Southern Company Services Inc. (Birmingham, AL) will lead a project to design, construct, and operate the Molten Chloride Reactor Experiment (MCRE) –the world's first critical fast-spectrum salt reactor relevant to TerraPower's Molten Chloride Fast Reactor. Total award value over 7 years: $113 million (DOE share is $90.4 million)

Government Funding Continues to Emphasize Reactor Technology Readiness Over Potential Value

- Technology readiness features prominently in current recommendations
  - ARDP investment groupings are readiness based
  - *Laying the Foundation New and Advanced Nuclear Reactors in the United States* from the National Academies (2023) prominently features technology readiness
- Potential value of different reactors are not identical
  - MSRs have very high potential value but require sustained investment
- Technologies are at higher maturities because they have had more investment
  - Original investment decisions made circa 1950
- Historic investment choices have largely not been re-examined with today's needs and technologies
- Nuclear energy not considered holistically
  - Fuel cycle technologies remain distinct from reactor development

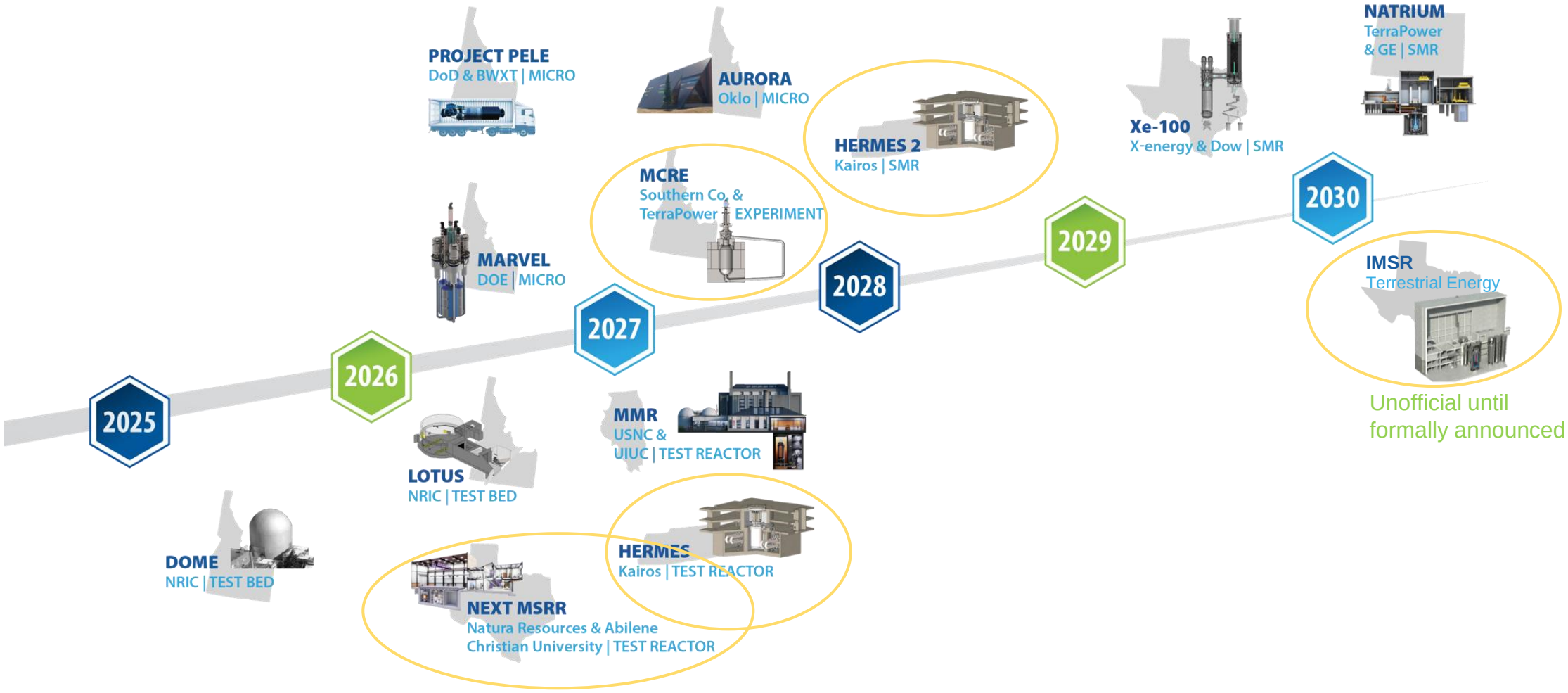
Rather than throw such huge resources into a massive LMFBR program with short-term deadlines, the AEC might have done better to initiate a slower and broader program that would have afforded the opportunity to change course as difficulties arose – Glenn Seaborg

LMFBR = liquid-metal fast breeder reactor

2020 Natura Resources Founded

- Initial phase research through the Nuclear Energy eXperimental Testing Research Alliance (NEXTRA)
  - Abilene Christian University (ACU), The Georgia Institute of Technology, Texas A&M University, and the University of Texas at Austin
- 2015 – Nuclear Energy eXperimental Testing (NEXT) Lab is founded at ACU
- 2019 – NEXT presents plans to build research and test an MSR at ACU
  - First university-based molten-salt research reactor
- Mission focused
  - Reliable energy, medical isotopes, and clean water

Molten Salt Reactors Feature Prominently in U.S. Advanced Reactor Timeline



MSR Research, Development, and Demonstration is Expanding and Diversifying in the United States

- Multiple companies are pursuing deployment in the 2020s and early 2030s
- Regulator is preparing capabilities to efficiently evaluate reactor safety adequacy
- Advancement of multiple MSR supportive technologies from modeling and simulation to electrochemistry to materials science has substantially decreased the technical difficulty of implementing MSRs
- Pressing need for safe, reliable, efficient energy production driving MSR development faster than at any time in the past half century
- No MSR has yet reached the market, no developer has openly committed the funds necessary to complete MSR development and deployment

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