Module 1: Overview, History, Background, and Current MSR Developments

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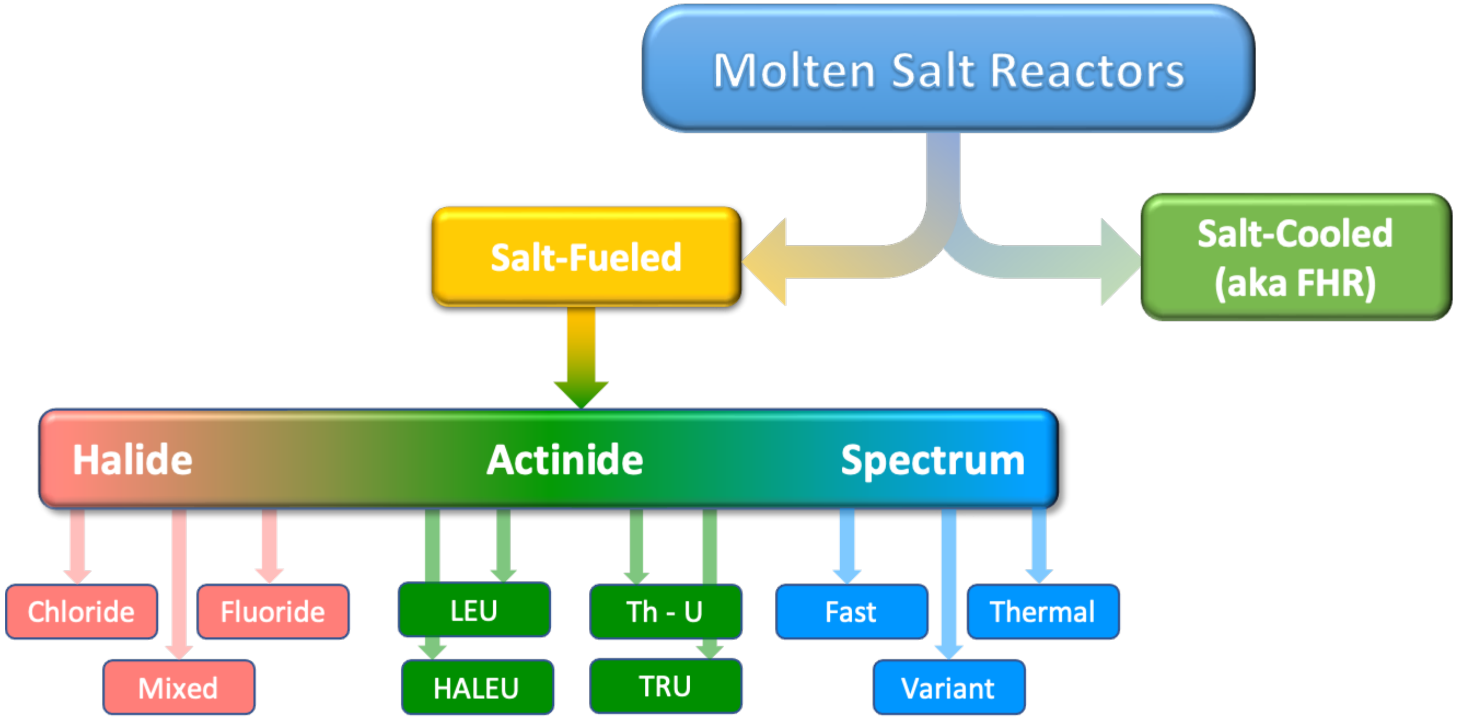
MSR Training Modules

1. History, Background, and Current MSR Developments
2. Overview of Technology and Concepts
3. Fuel and Coolant Salt Properties
4. Heat Transfer and Fuel Salt Processing
5. Reactor Physics
6. Materials
7. Safety Concepts and Fuel Qualification
8. Instrumentation
9. Fuel Cycle and Safeguards
10. Operating Experience
11. Safety Analysis
12. Waste Streams
13. Regulatory Issues and Challenges

Molten Salt Reactors Are a Class of Reactors in Which a Molten Salt Performs a Significant Function in Core

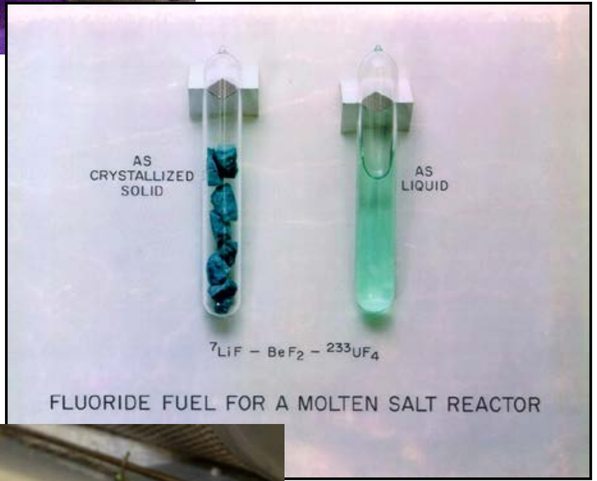


- Liquid- and solid-fueled variants
- Chloride-, fluoride-, and mixed halide-based fuel salts
- Salt and liquid-metal coolants
- Thermal, fast, time-variant, and spatially-variant neutron spectra
- Wide range of power scales
- Intensive, minimal, or inherent fuel processing
- Multiple different primary system configurations
- Nearly all fuel cycles

What is So Special About Salts (versus water, liquid metals, gas)?

- High solubility for uranium, plutonium, and thorium
- Stable thermodynamically
  - No radiolytic decomposition at elevated temperature
- Low chemical potential energy (no vigorous reactions with air or water)
- Excellent heat transfer
  - Forced and natural circulation
  - Large heat capacity
- Very high boiling points
  - Low vapor pressure at operating temperatures
- Adequately compatible with nickel-based structural alloys and graphite
- Compatible with chemical processing
- May be transparent without fission products

FLiBe Salt



Plutonium Chloride

There were two people at the [Manhattan Project] metallurgical laboratory, Harold Urey, the isotope chemist, and Eugene Wigner, the designer of Hanford, both Nobel Prize winners who always argued that we ought to investigate whether chain reactors, engineering devices that produced energy from the chain reaction, ought to be basically mechanical engineering devices or chemical engineering devices. <u>And Wigner and Urey insisted that we ought to be looking at chemical devices—that means devices in which the fuel elements were replaced by liquids.</u>

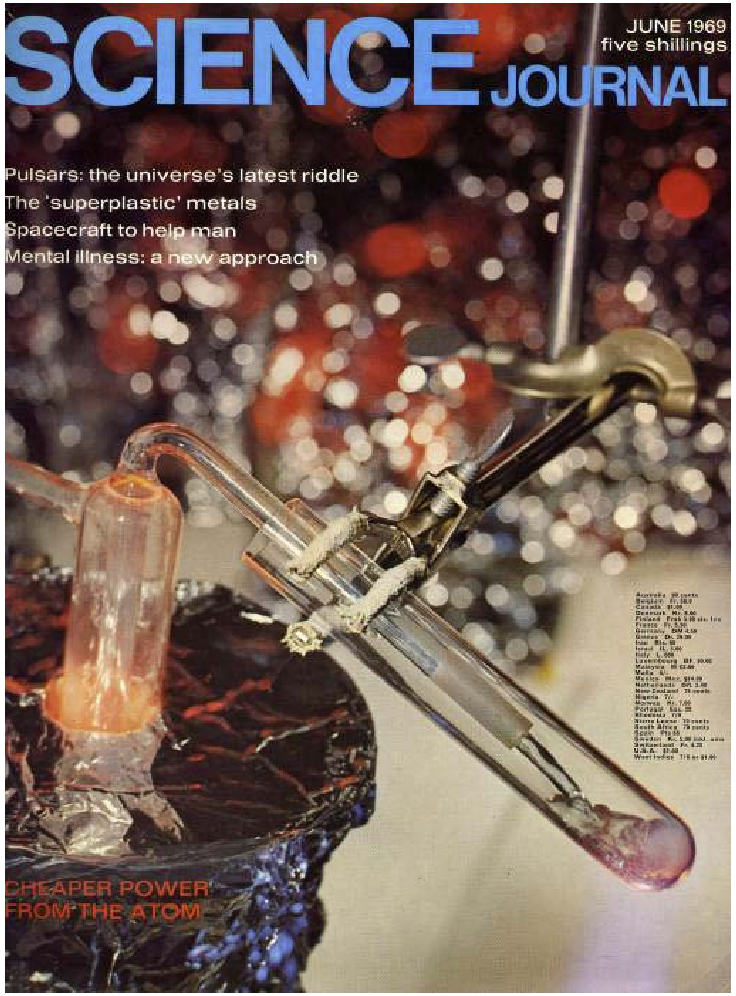
The Proto-History of the Molten Salt System
Alvin M. Weinberg, *Former Director, Oak Ridge National Laboratory*
February 28, 1997

Eugene Wigner

Harold Urey

Molten Salt Reactors Grew With the First Nuclear Era

- Molten-salt-fueled reactors
  - Extensive development program from 1940s to 1970s including MSRE
  - Were presented by the US to the world at the second Atoms for Peace conference in 1958
  - Were the variant of *Fluid Fueled Reactors* selected as having the "highest potential for achieving technical feasibility"
    - Th-U breeding fuel cycle in a homogeneous reactor first described in 1944
- Salt-cooled reactors (generally referred to as fluoride salt-cooled high-temperature reactors - FHRs)
  - Originally proposed along with the development of pebble-bed TRISO fuel
  - Reinvigorated 20 years ago as an alternative to high-temperature gas-cooled reactors taking advantage of the improved heat transfer properties of liquid salts



ORNL photograph of molten salt, featured on the cover of the British *Science Journal* in June 1969. (Used by permission)

Molten Salt Reactor Technology Early Timeline

- Originally proposed by Ed Bettis and Ray Briant of ORNL in late 1940s
- Aircraft Nuclear Propulsion Program (1946–1961)
  - Large investment ($1B)
  - Aircraft Reactor Experiment (ARE) (1953–1954)*
  - Aircraft Reactor Test (1954–1957)
- Civilian Molten Salt Reactor Program (1958–1960)
- Molten Salt Reactor Experiment (MSRE) (1960–1969)*
- Molten Salt Demonstration Reactor
- Molten Salt Breeder Experiment (1970–1976)
- Molten Salt Breeder Reactor (1970–1976)
- Denatured Molten Salt Reactor (1978–1980)

*** ORNL designed, constructed, and operated the only two MSRs - ARE and MSRE**

*** ANP 1946–1961: $1B**

*** ANP ended with advent of ICBMs in early 1960s**

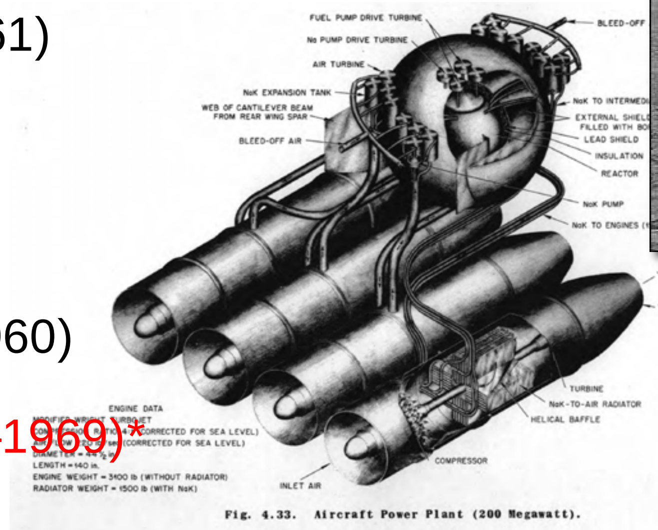
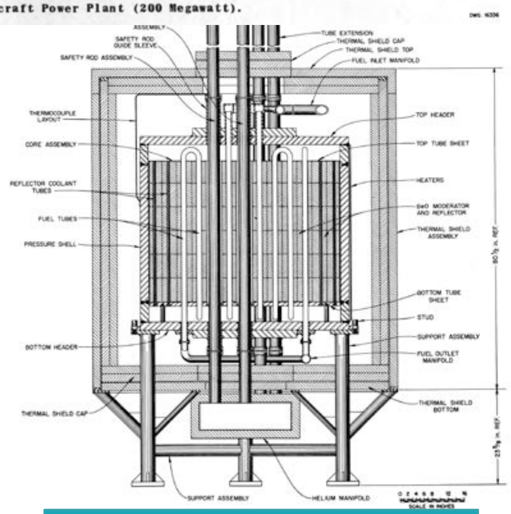


Fig. 4.33. Aircraft Power Plant (200 Megawatt).



ARE Elevation Section

MSRE Core Assembly

OAK RIDGE National Laboratory

Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept in 1954

- Demonstrated ability to build and operate a high temperature (860°C), low power circulating fuel reactor
  - Operated from 11/03/54 to 11/12/54
- Liquid fluoride salt circulated through beryllium oxide reflector in Inconel tubes
- $^{235}UF_4$ dissolved in $NaF\text{-}ZrF_4$
- Nuclear operation over 221 h period
  - Last 74 hours were in MW range
  - Up to 2.5 MW_t
- Produced 96 MW-h of nuclear energy

ARE Core During Assembly

- Gaseous fission products were removed naturally through pumping action
- Very stable operation due to high negative reactivity coefficient
- Demonstrated load-following operation without control rods
- Low power experiments
  - Reactor power calibration
  - Rod calibration
  - Preliminary measurement of the temperature coefficient
- High power experiments
  - Power levels: 10 kw, 100 kw, 500 kw, and 1 MW
  - Temperature coefficient of reactivity
  - Reactor power calibration from process instrumentation
  - 25 h Xe buildup experiment – no build up in salt
  - Reactor temperature cycling - 21 times high->low power
  - Time lags - temperature measurement responses - long transit time of fuel

Concepts Underlying Many of Today's Innovative Designs Were Explored in the First Reactor Era

- Hydroxide moderators, coolants, and fuel carriers
  - No practical solution to high-temperature corrosion with thermal gradient proven
  - Redox control provides partial solution
- Fuel salt in tubes
  - Original design for ARE
  - MOSEL reactor (also considered sodium cooling)
- Liquid metal cooled and reflected tube fuel for fast spectrum chloride reactors
  - Sodium, lead, and bismuth investigated
- Mixed halide fuel – blanket salts
  - Mixing halides lowers melting point and minimizes carrier salt

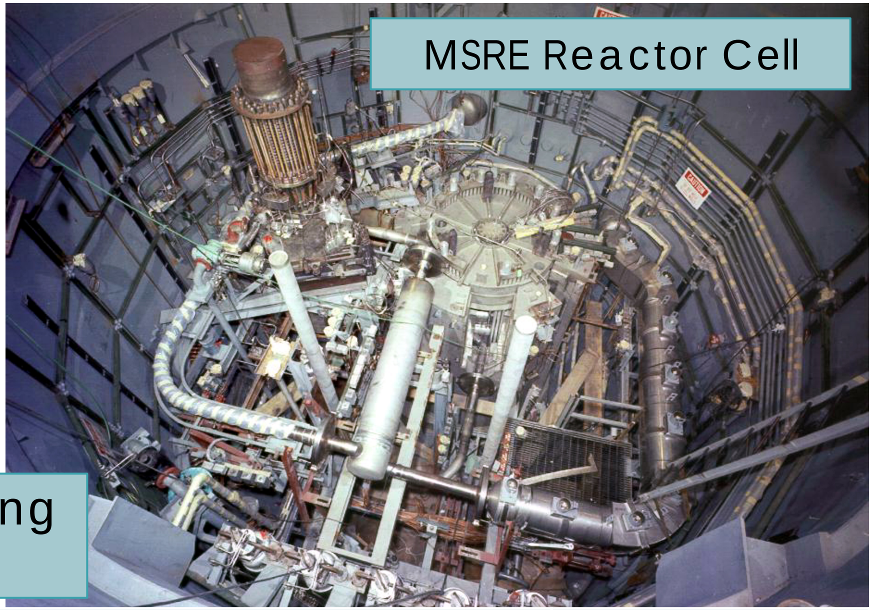
ORNL Successfully Demonstrated Key MSR Technology At the MSRE

- Design of MSRE commences–**1960**
- ORNL receives directive to construct and operate MSRE–**April 28, 1961**
- Construction begins–**1962**
- Salt loaded into tanks–**Oct. 24, 1964**
- Salt first circulated through core–**Jan. 12, 1965**
- First criticality (U^{235})–**June 1, 1965**
- First operation in megawatt range–**Jan. 24, 1966**
- Full power reached–**May 23, 1966**
- Nuclear operation with U^{235} concluded–**March 26, 1968**
- Strip uranium from fuel salt –**Aug. 23-29, 1968**
- First criticality with U^{233}–**Oct. 2, 1968**
- Full power reached with U^{233}–**Jan. 28, 1969**
- Nuclear operation concluded –**Dec. 12, 1969**

MSRE stands for not only molten salt reactor experiment but also for mighty smooth running experiment–Alvin Weinberg

So far the Molten Salt Reactor Experiment has operated successfully and has earned a reputation for reliability. USAEC Chairman–Glenn T. Seaborg

MSRE Reactor Cell



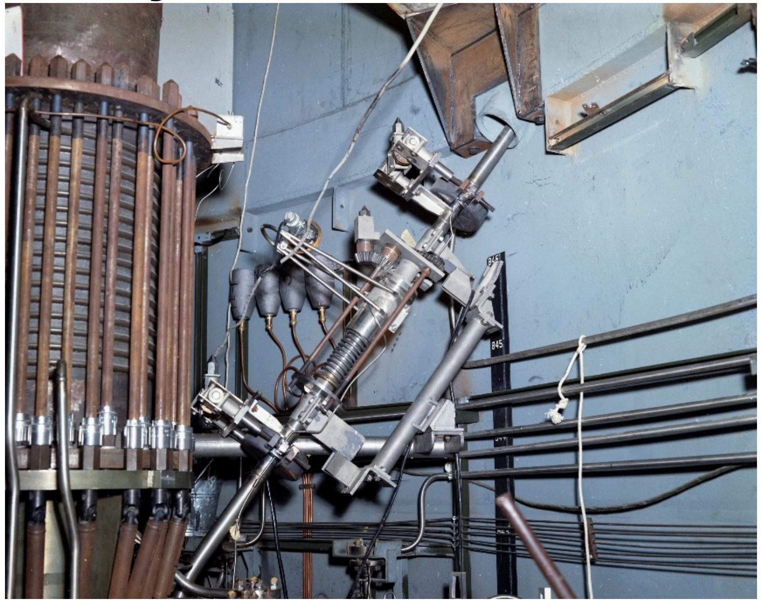
MSRE Operating Statistics

Full power	13,172 h ^{235}U 9,005 h ^{233}U 4,167 h
Fuel salt circulation time	21,788 h
Coolant salt circulation time	26,076 h
Availability during planned reliability testing period (final 15 months with ^{235}U)	86%
Availability during final runs with ^{235}U	98.6%
Availability during final runs with ^{233}U	99.9%

OAK RIDGE National Laboratory

MSRE Successfully Demonstrated Key MSR Technologies

- Salt chemistry was well-behaved
  - Almost no corrosion
  - UF_4 to UF_3 ratio maintained
  - Molten salts are stable under reactor conditions
- Alloy N performed adequately
  - Little change: ultimate strength, yield strength, creep rate
  - Rupture ductility and creep rupture life in specimens reduced
- Nuclear performance closely paralleled predictions
- Fission products behaved as anticipated
  - Noble gases Xe and Kr efficiently stripped out in offgas system
  - Most other FPs remained in fuel salt
- On-line and chemistry adjustment performed well

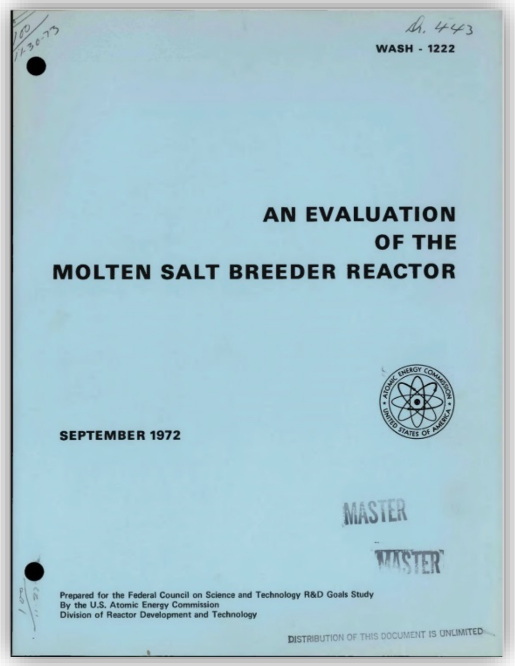


MSRE Sampler-Enricher Mechanism

MSRE Sample & Enricher Capsules

Substantial Technical Progress Continued into the 1970s

- Adequate solutions identified for major technical issues identified during program evaluation (WASH-1222)
  - Limited graphite lifetime lowers power density
  - Remote operations and maintenance requires development and demonstration
- Proliferation vulnerability issues arose in mid 1970s
  - Designs that do not include on-site fissile materials separations developed in late 1970s
- US program planned to transition to larger scale demonstration following MSRE success
  - Effort discontinued to devote resources to "*higher priority energy development efforts*"
  - MSRs not included in 1977 budget


WASH - 1222

AN EVALUATION OF THE MOLTEN SALT BREEDER REACTOR

SEPTEMBER 1972

MASTER

Prepared for the Federal Council on Science and Technology R&D Goals Study
By the U.S. Atomic Energy Commission
Division of Reactor Development and Technology

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

AEC Technology Assessment of MSBR for Federal Council on S&T R&D Goals

When MSBR program progressed to need for substantial increase in funds, AEC could not justify the diversion of funding from the LMFBR program -- Herbert. G. MacPherson (1985)

Proliferation Concerns Arose Just As the US MSR Program Was Discontinued

- ORNL laboratory director's letter describes safeguards characteristics of MSRs as topic one in letter requesting program continuation – Jan 1976
- MSBR Program was not included in 1977 Presidential budget request – Spring 1976
- President Ford calls for changing U.S. domestic nuclear programs to support non-proliferation goals – Oct 1976

In addition to having a technology base which is different from fast reactors, molten-salt reactors appear to have favorable characteristics relative to many of the issues being raised concerning nuclear energy including the following:

(1) Questions of a safeguards nature appear to be somewhat more straightforward for molten-salt reactors than for solid-fuel reactors since an MSR is essentially self-contained with respect to the fuel recycle operations of chemical processing. Fuel refabrication and transportation of spent and refabricated fuel are not required.

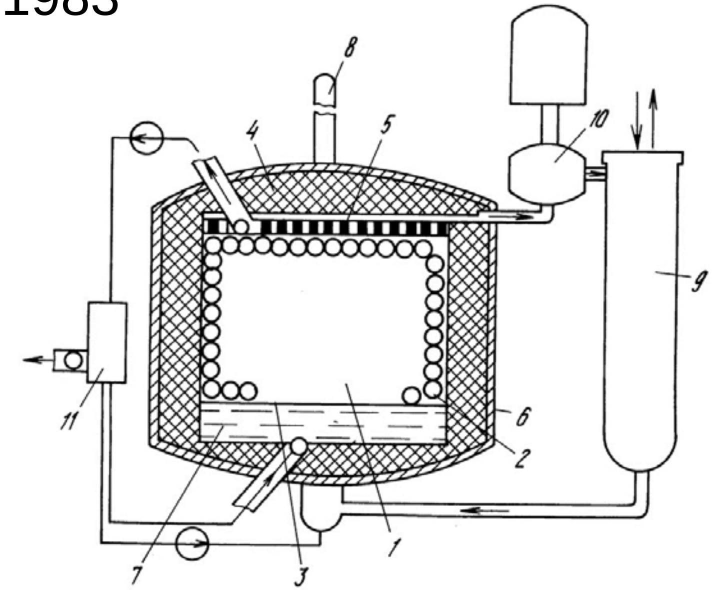
ORNL Director's letter to ERDA January 1976

Statement by the President on Nuclear Policy
Gerald R. Ford – October 28, 1976

...the previous emphasis has been on breeding performance and low fissile inventory to help limit the demand on nonrenewable natural resources (uranium) in an expanding nuclear economy; little or no thought has been given to alternative uses of nuclear fuels such as proliferation of nuclear explosives. - ORNL/TM-6413 J.R. Engel et al.

FHRs Have Also Been Considered for Decades

- Concept of using fluoride salt as coolant along with a graphite moderator and tristructural-isotropic (TRISO) fuel is approaching 40 years old
  - No FHR has ever been operated
- Concept first suggested in Soviet paper in 1983



Belousov et. al., Voprosy atomnoi nauki i tekhniki

- FHR concept gained momentum when reintroduced in the US twenty years later
- FHR concept established new family of high-temperature reactors defined by two characteristics
  - High-temperature fuel
  - Low-pressure liquid coolant
- Technology being commercialized by Kairos Power LLC.
  - Substantial topical reports submitted to NRC for review
  - Pre-application licensing engagement underway for several years

Our schedule is driven by the goal of a U.S. demonstration plant before 2030 and a rapid deployment thereafter. – Kairospower.com

Liquid-Fueled MSRs Have Substantial Conceptual Differences from Solid-Fuel Reactors

- Low intrinsic fuel-salt pressure decreases radionuclide release probability and magnitude
  - Higher primary coolant salt pressure vs. fuel salt pressure means that primary heat exchanger leaks would be into the fuel salt
- Delayed neutron precursors are mobile
  - Mobile fission gas bubbles also impact reactivity
- Fission products are not all in fuel salt
  - May require decay cooling of additional locations (e.g., fission gas decay tanks)
  - Fewer radionuclides remain to be released in fuel/core accidents
  - Potential for fissile material to be transported with fission products
- Some fission products form stable, low volatility salts (e.g., cesium and strontium) decreasing their availability for release
- High temperature and large salt coefficient of thermal expansion (i.e., density changes) facilitate passive decay heat removal options
  - Higher radiative heat transfer improves RVACS performance
  - Strong natural circulation facilitates DRACS performance
  - Potential for overcooling accidents
- Online refueling minimizes excess reactivity available

Conceptual Differences Arising from MSRs with Liquid Salt Fuel (cont.)

- Fuel composition and chemistry can be continuously adjusted
  - Qualified fuel is likely to be a composition specification based on physical and chemical properties of fuel salt (no time dependence in fuel condition)
  - Enables maintaining chemical compatibility with container alloy
- Area surrounding fuel salt will have very high radiation flux
  - Draining and flushing fuel salt required for significant maintenance
  - Solid state electronics would only be possible with substantial shielding
- Core first wall will be subjected to significantly increased neutron fluence
  - Radiation embrittlement and swelling will likely be the first wall limiting phenomena
  - Creep and creep-fatigue will likely remain dominant issues for non-first wall materials
  - Interior vessel shielding (neutron reflectors and/or absorbers) commonly employed
  - All major components (including vessel) are intended for replacement
- No cliff-edge or cascading failure phenomena
  - Failure of individual containment layers does not substantially increase failure probability of other layers
  - Functional containment will have substantial impact on design requirements
- Fissile material accountability goes well beyond “item counting”

Brief Profiles of Current MSR Developments

MSRs Have a Diverse Set of Stakeholders Due to Their Potentially Advantageous Characteristics

- MSR companies and technologies are developing rapidly
  - Information will be overtaken by events
- Discussion is limited to publicly disclosed information – primarily from private stakeholders
- MSRs have a higher fraction of non-governmental activities than other reactors due to combination of persistently low government support and government tendency to support technologies for other than market-based reasons
  - Some stakeholders have not disclosed their technologies and strategies
  - None have publicly provided detailed information

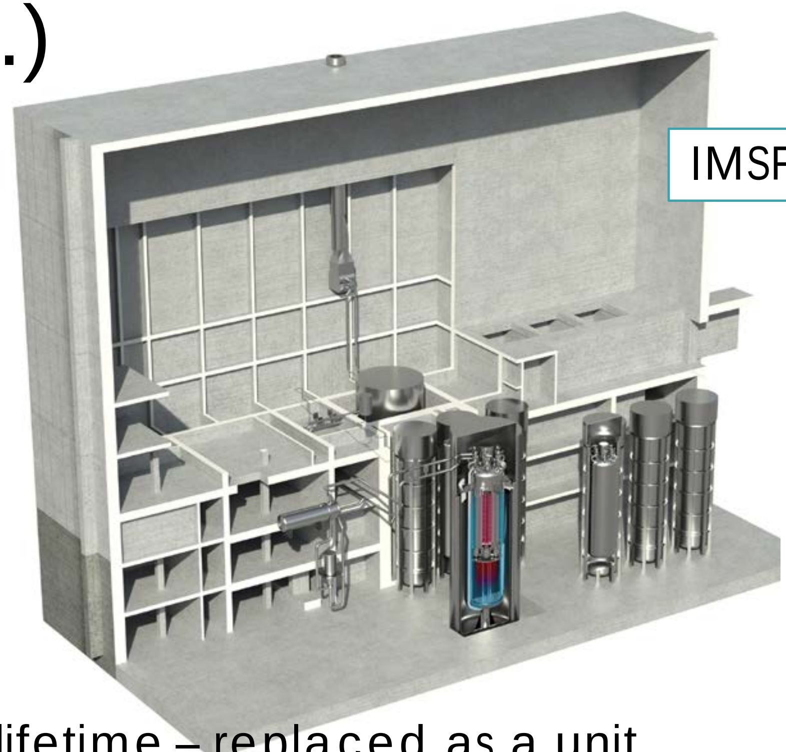
> When significant evidence is available that demonstrates realistic solutions are practical, a further assessment could then be made as to the advisability of advancing into the detailed design and engineering phase of the development process including that of industrial involvement. Proceeding with this next step would also be contingent upon obtaining a firm demonstration of interest and commitment to the concept by the power industry and the utilities and reasonable assurances that large scale government and Industrial resources can be made available on a continuing basis to this program in light of other commitments to the commercial nuclear power program and higher priority energy development efforts. - WASH 1222

Focus of Discussion is on Potential Future License Applicants

- Commercial reactor developers with potential for US deployment
  - Commercial reactors less likely for US deployment summarized
- Research and test reactors
  - May serve as precursors to commercial reactors
- International government-supported development
- Other related, regulated entities and processes
  - Curio Solutions, Core Power Ltd., Molten Salt Solutions
  - Uranium carbonate thermochemical cycle for hydrogen production

Terrestrial Energy (Inc, USA, Ltd.)

- Canadian company with US and UK affiliates
- Design referred to as IMSR® (Integral Molten Salt Reactor)
  - Denatured U/Pu fuel cycle – LEU fuel
  - Graphite moderator
  - Sealed unit with integrated pumps, heat exchangers, and shutdown rods
- Seven-year reactor vessel, moderator, and fuel salt lifetime – replaced as a unit
  - Feed, seed, and breed fuel cycle
  - Started on slightly enriched uranium, 5% enriched fuel added
  - Fuel volume increases by 1/3 over seven years
  - 2/3 of fuel used to start daughter reactor – 1/3 to start additional reactors
  - No fuel waste while reactor class continues
- Twin reactor configuration
  - Reactor swapped every seven years



IMSR® Plant Layout

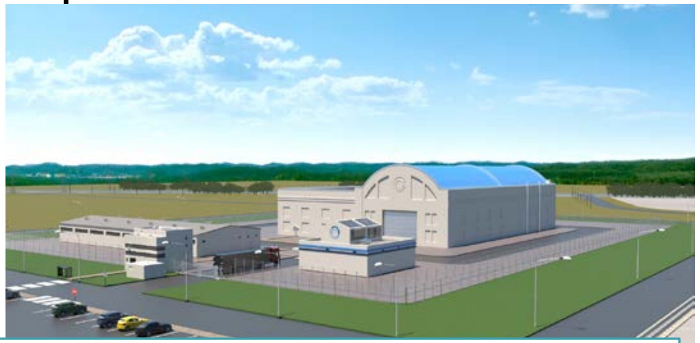
IMSR® Replaceable Core Unit

Images courtesy of Terrestrial Energy Inc.

Kairos Power

Kairos Power

- Only solid-fuel commercial MSR concept in the United States
  - Aimed at demonstration by 2030
  - 320 MWth – 140 MWe (per unit)
  - 650 °C core outlet temperature
  - 19.75 wt % uranium enrichment
  - 316 SS reactor structural material
  - FLiBe coolant salt – with ^{7}Li enriched lithium



Hermes Facility (artist rendering) Oak Ridge, Tennessee

Kairos Power Headquarters and Lab Facilities in Alameda, California

- Relies on the advanced gas reactor TRISO qualification effort to provide salt-compatible qualified fuel
  - Pebble bed – on-line refueling

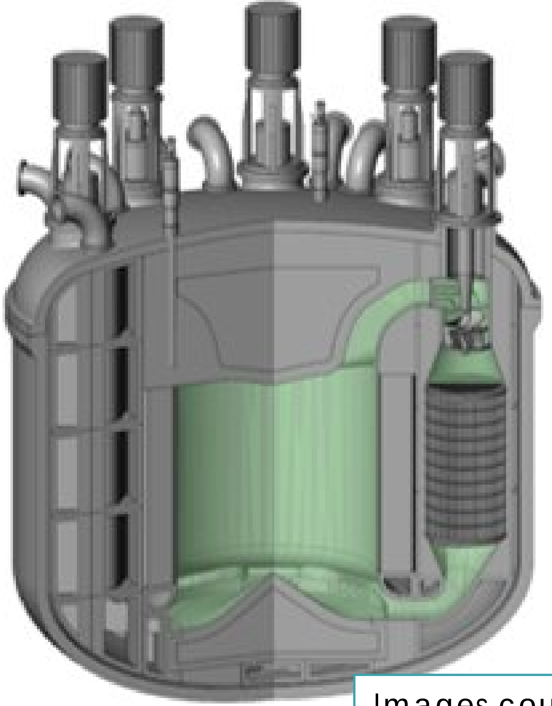
Images courtesy of Kairos Power

- Extensive use of simulant fluids for thermal and hydraulic design validation
- Coupled to a steam cycle via nitrate salt loop
  - Provides tritium trap
- *Hermes* low-power demonstration reactor license application under review

TerraPower

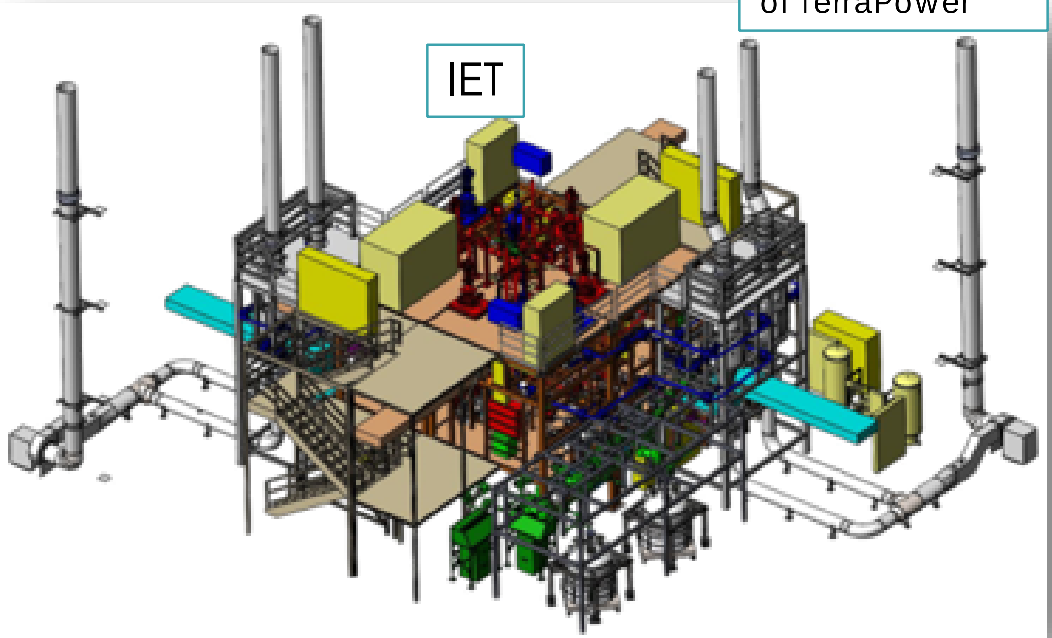
- US company working on fast-spectrum, chloride-salt MSR (MCFR)
- Integrated effects test (IET) facility currently being deployed
  - Supported by DOE cost sharing award in 2016
  - Investigating non-nuclear components and operational requirements
- Molten chloride reactor experiment being supported by DOE-NE advanced reactor demonstration program
  - Southern Company prime recipient
  - First fast-spectrum MSR
  - Scheduled for first criticality in 2026 at INL
- Fast spectrum molten chloride fuel salt – MCFR
  - Breed-and-burn fuel cycle objective – avoid need for on-going enrichment or fissile material separation following startup

MCFR



Images courtesy of TerraPower

IET

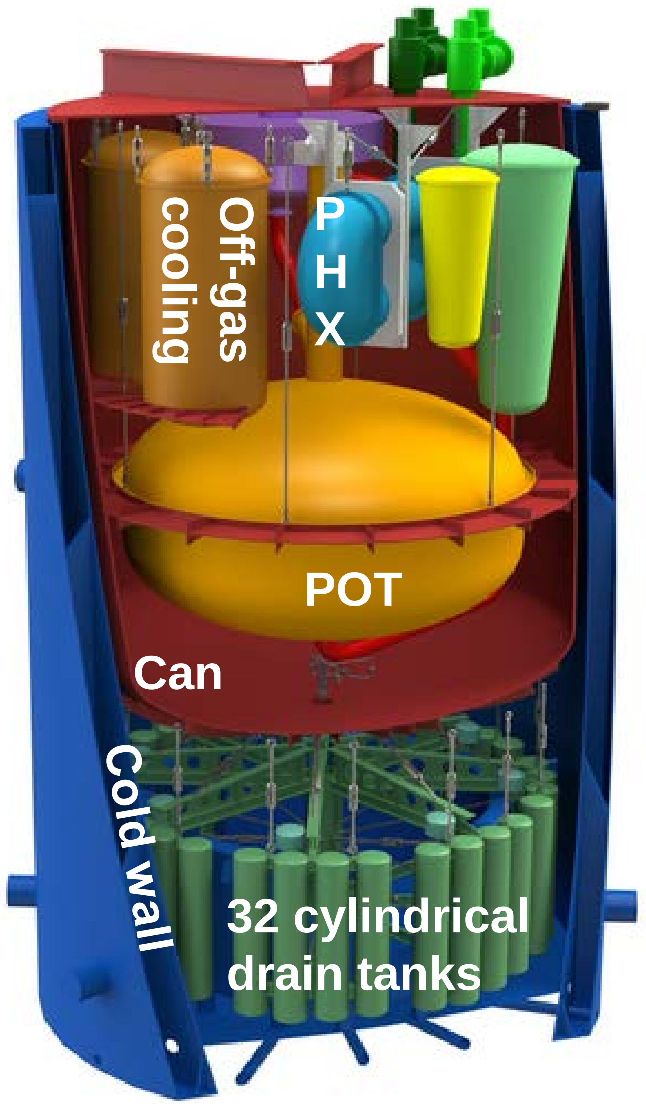


ThorCon Power

- Thermal spectrum fluoride salt MSR
- Designed for shipyard fabrication and barge deployment
- $NaF\text{-}BeF_2\text{-}UF_4$ (72-16-12 mol %)
- Fuel salt and moderator graphite replaced every four years
  - Twin reactor configuration
- Vessel life extended by interior neutron shielding
- Fuel salt drain tanks for criticality safety
- Wet cooling wall for decay heat rejection
- Thorconpower.com provides most detailed information on reactor design

Fission Datasheet

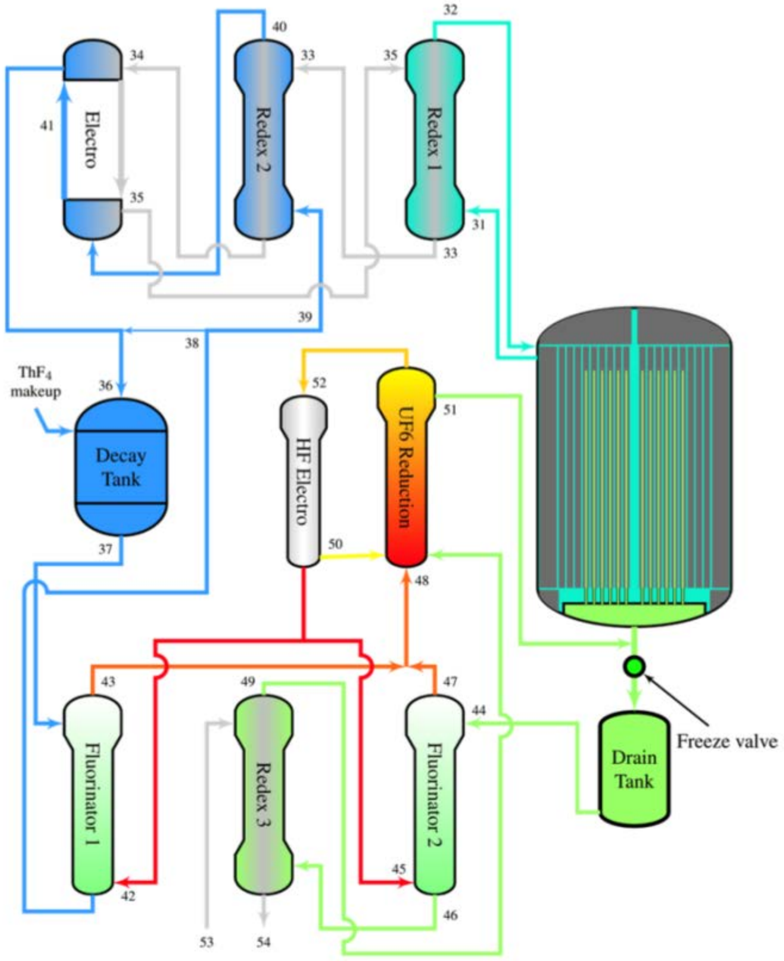
- 515 MWe (2 modules)
- 46% efficiency @ 30 °C
- 3305 kg/s fuel salt flow
- 704 °C core outlet
- 564 °C core inlet
- 11.6 s loop transit time
- 7.8 m can diameter
- 10.3 m can height
- 316 SS pot (vessel)



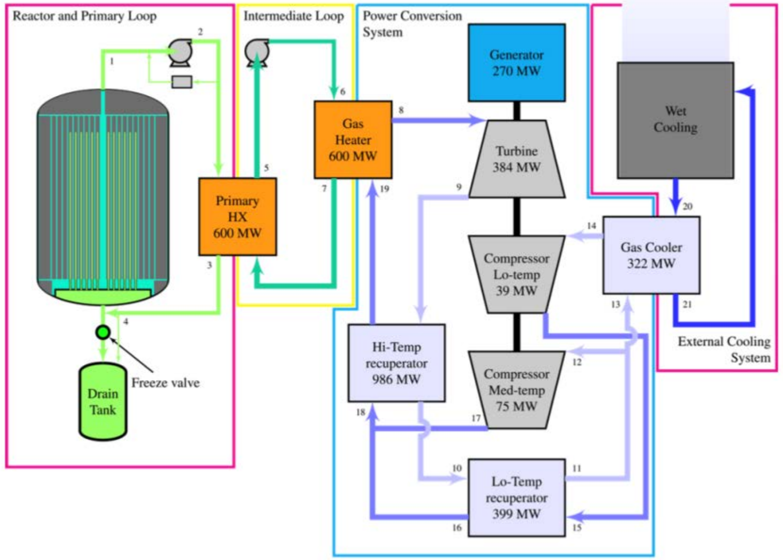
Images courtesy of ThorCon

Flibe Energy

- US Company
- Liquid Fluoride Thorium Reactor (LFTR) - thorium breeder fuel cycle
- Graphite moderated, thermal spectrum, $LiF\text{-}BeF_2\text{-}UF_4$ fuel
- Freeze valve and drain tank based decay heat rejection
- Most detailed technical information available from EPRI technical report – 3002005460, October 2015
  - http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002005460



Reprocessing Flows



Power System

Images courtesy of Flibe Energy

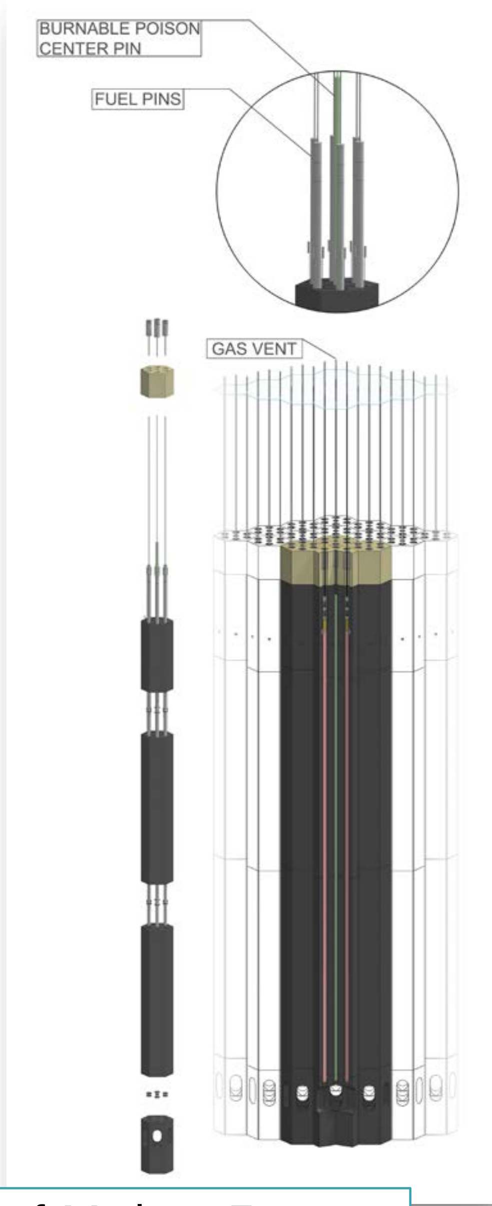
Alpha Tech Research

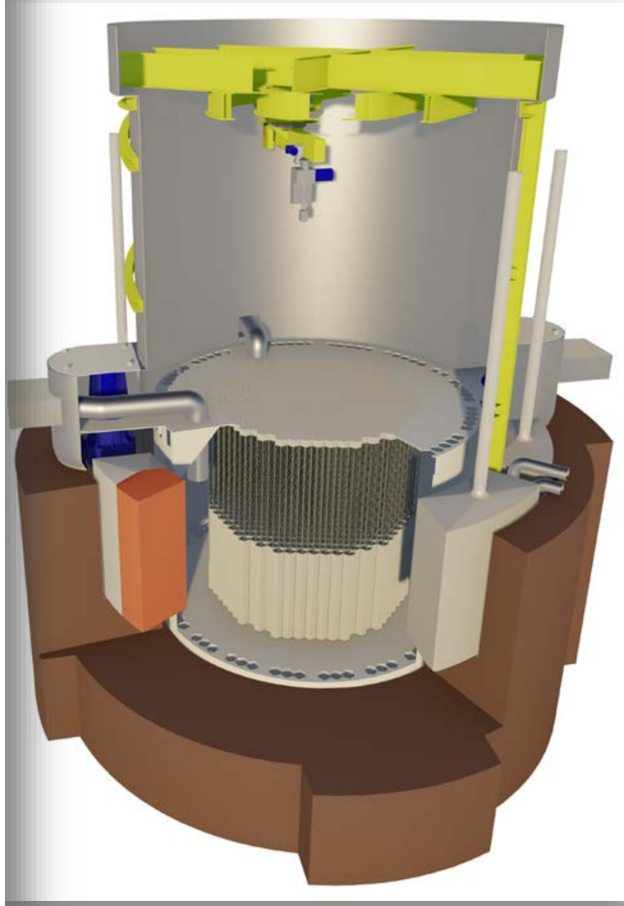
- US Company – founded 2016
- Micro Molten Salt Reactor design (a.k.a. ARC Generator)
- 12 MWe
- Fluoride fuel salt – thermal spectrum - LEU
- Liquid lead coolant
- Continuous Electrochemical Extraction (CELEX)
  - Additional products – isotopes and rare earth metals

Image courtesy of Alpha Tech

Moltex Energy – Stable Salt Reactor

- UK origin with Canadian and US presence
- Vented pin fuel – fixed position
- Two reactor concepts
  - Thermal spectrum LEU fueled (6%)
    - Fuel pins in graphite matrix cooled by unfueled fluoride salt
  - Fast spectrum waste burner intended to consume actinides from used water reactor fuel
    - Chloride salt fueled and cooled





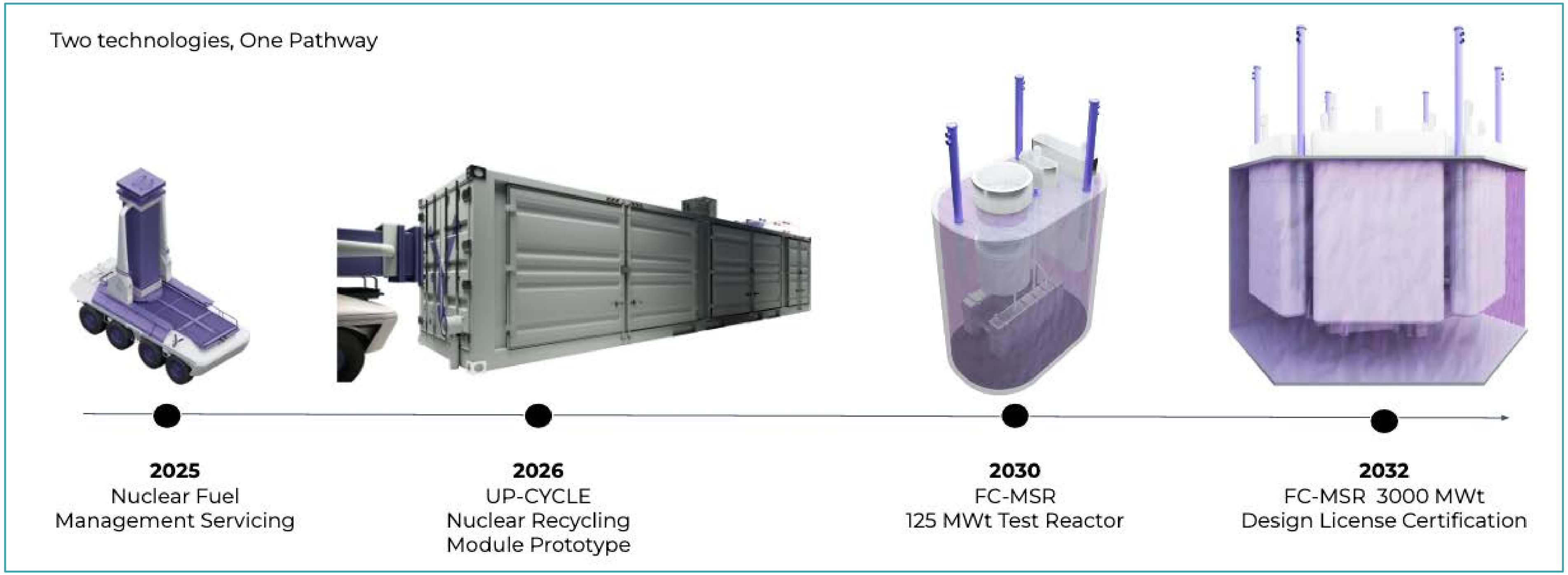
Images courtesy of Moltex Energy

Exodys Energy Combining Used LWR Fuel Actinide Reuse and Fast Spectrum MSRs

EXODYS ENERGY

- Focused on reusing actinides from spent LWR fuel
- Chloride fuel fast spectrum MSR
- Technology derives from Elysium Industries design
- Core outlet temperature of > 600ºC

Image courtesy Exodys Energy



OAK RIDGE National Laboratory

Dual Fluid Energy

- Canadian company with German origin
- Chloride salt fuel in tubes
  - Lead cooled
- Company also indicates consideration of a liquid metal fueled and cooled variant
- Configuration similar to historic liquid-metal cooled, tube-fueled MSRs
  - ORNL's lead-cooled fireball design
  - ANL's sodium cooled fast spectrum chloride
  - Multiple historic designs (e.g., MOSEL and the pre-1967 MSBR) had fuel salt in tubes in core surrounded by blanket/cooling salt
- Two different fluid systems at high temperature, with a temperature gradient, results in challenging corrosion issues

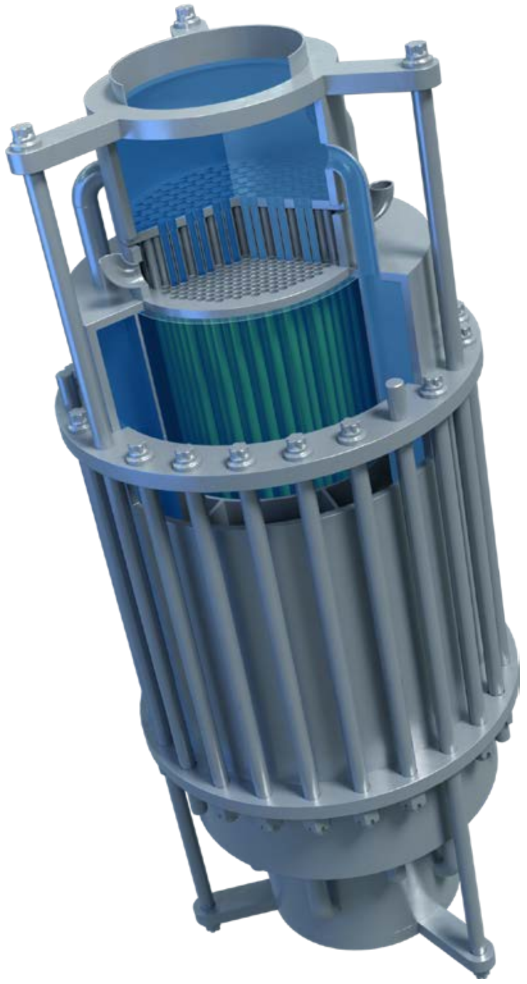
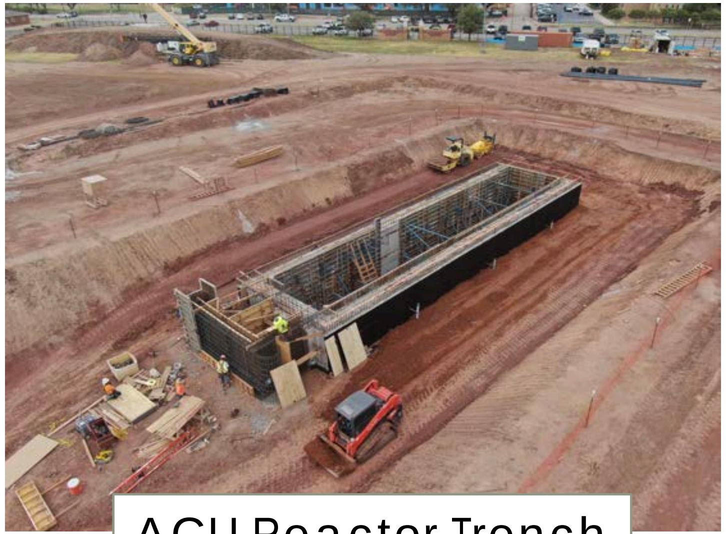


Figure courtesy of Dual Fluid Energy

Natura Resources – Abeline Christian University

- Research reactor to be built at ACU
  - Fluoride salt fueled, HALEU fuel, graphite moderated
  - Construction permit application filed August 15, 2022
  - Planned criticality in 2025
  - Requested fuel from DOE-NE under university reactor fuel support program
  - Close analog to MSRE
- Nuclear Energy eXperimental and Testing Research Alliance (NEXTRA) consisting of
  - Abilene Christian University, The Georgia Institute of Technology, Texas A&M University and the University of Texas at Austin
- Intended to provide data necessary to design and license subsequent commercial power plant

Natura Resources SUSTAINABLE ENERGY



ACU Reactor Trench

Image courtesy ACU

Multiple Non-US Companies Are Developing MSRs

Unlikely to Seek NRC Licensing

- Copenhagen Atomics – thermal spectrum, Th/U fuel cycle, fuel salt in tubes, heavy water moderated, vacuum isolated - https://www.copenhagenatomics.com/
- Seaborg – thermal spectrum, fuel salt in tubes, hydroxide moderated - https://www.seaborg.com/
- NAAREA – new small French company – have not released design information - https://www.naarea.fr/
- Thorium Tech Solution Inc. (TTS) - http://ttsinc.jp/indexenglish.html
  - "Fuji" reactors
  - Thermal spectrum thorium
- Thorizon – Dutch company seeking to combine used actinide consumption with thorium
  - Associated with Orano and Dutch nuclear operator
- Samsung partnering with Korean Atomic Energy Research Agency to investigate MSRs for maritime propulsion
  - Licensing requirements for entering US waters need to be established

Other US Companies Also Developing MSR Technologies (all at very early development stages)

- Curio Solutions is evaluating alternate fuel cycles including Th/U fuel cycle at MSRs and LWR fuel recycling using MSRs
- Core Power is evaluating MSRs as a means to produce fuels for maritime propulsion (green ammonia)
- Molten Salt Solutions
  - Commercializing isotope enrichment (lithium and chlorine) based upon liquid-liquid or liquid-solid (chromatographic methods) extraction
  - Commercializing fuel salt synthesis methods based on low-temperature, non-aqueous organic technology
- Uranium carbonate thermochemical cycle hydrogen production
  - Uranium used for chemical purposes (US Patent 7,666,387 B2 Feb. 23, 2010)
  - Required temperatures couple well to MSRs

Shanghai Institute of Applied Physics – TMSR-LF1 Reactor Approved for Startup in 2022!

SINAP | TMSR

- Program initiated by the Chinese Academy of Sciences (CAS) in 2011
- Thorium Molten Salt Reactor – Liquid Fuel 1 (TMSR-LF1)
  - 2 MWth
- Thermal spectrum LEU fuel
  - Small thorium contribution
  - Planned for gradual thorium increase
- 20-30 years development timeline

Chinese Proposed TMSR Roadmap

➢Small modular TMSR research facility (including research reactor TMSR-LF50) by 2025

➢Small modular industry-demo reactor TMSR-LF150 by 2030.

➢TMSR fuel salt batch pyro-process industry-demo facility, and realize Th-U Fuel Cycle utilization by 2040s.

Academic National Efforts

- India – Conceptual design activities for thorium molten salt breeder reactor
- EU – Extended academic effort on fast spectrum thorium molten salt reactors participating in multiple EU initiatives
  - http://lpsc.in2p3.fr/index.php/en/groupes-de-physique/enjeux-societaux/msfr
  - http://samofar.eu/
- Kurchatov Institute MOSART - MOlten Salt Actinide Recycler & Transmuter
  - IAEA TecDoc 1626; Chapter 9 – overview