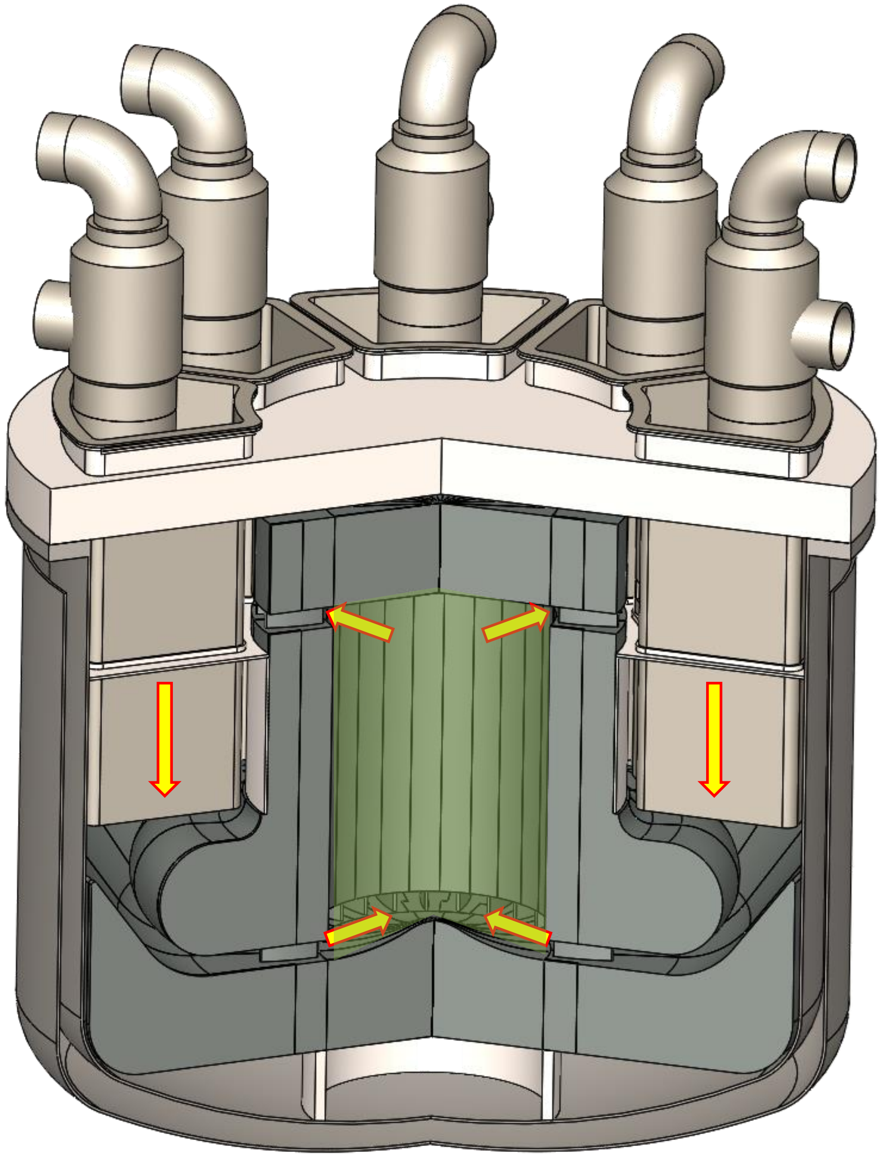
TerraPower's Molten Chloride Fast Reactor (MCFR)

Jeff Latkowski

February 22, 2021

Key Molten Salt Reactor (MSR) distinguishing features

- MSRs use liquid salt fuel.
- The liquid fuel flows through the core.
- Heated salt rises.
- Heated salt expands.



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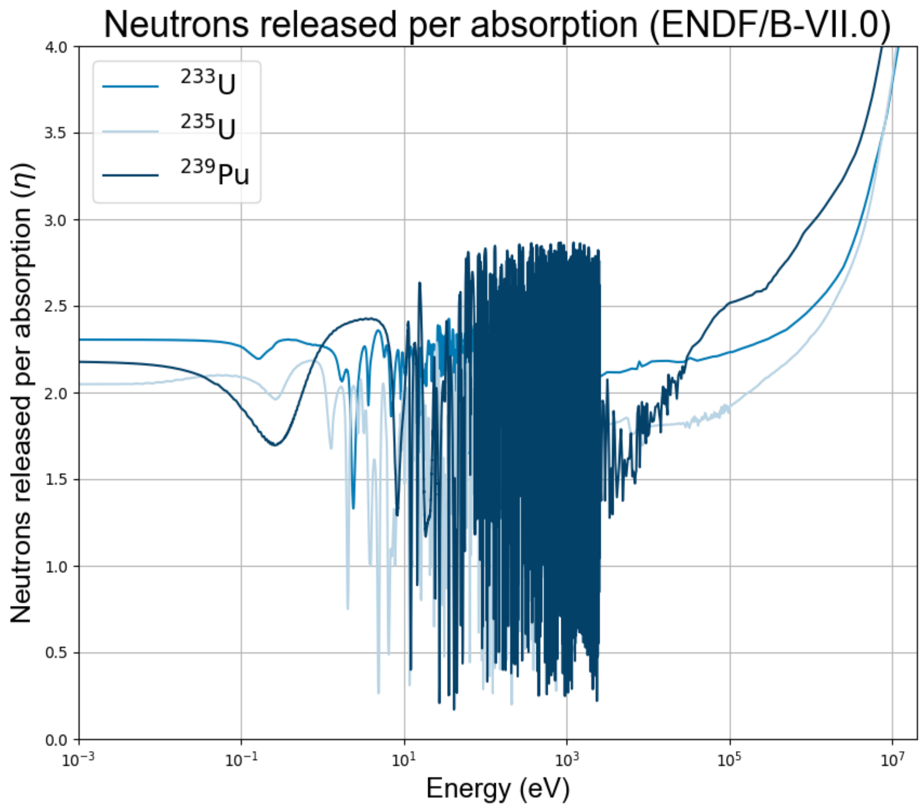
The Molten Chloride Fast Reactor (MCFR) has important features not shared by all MSRs

- The MCFR is a fast spectrum chloride rather than a thermal spectrum fluoride.
- The MCFR operates on the U-Pu cycle (not Th).
- The baseline MCFR is a net breed & burn machine. The make-up feed is DU or NatU.
- The fast spectrum improves the neutron economy & largely mitigates fission product poisoning. The MCFR is not an online reprocessing plant.



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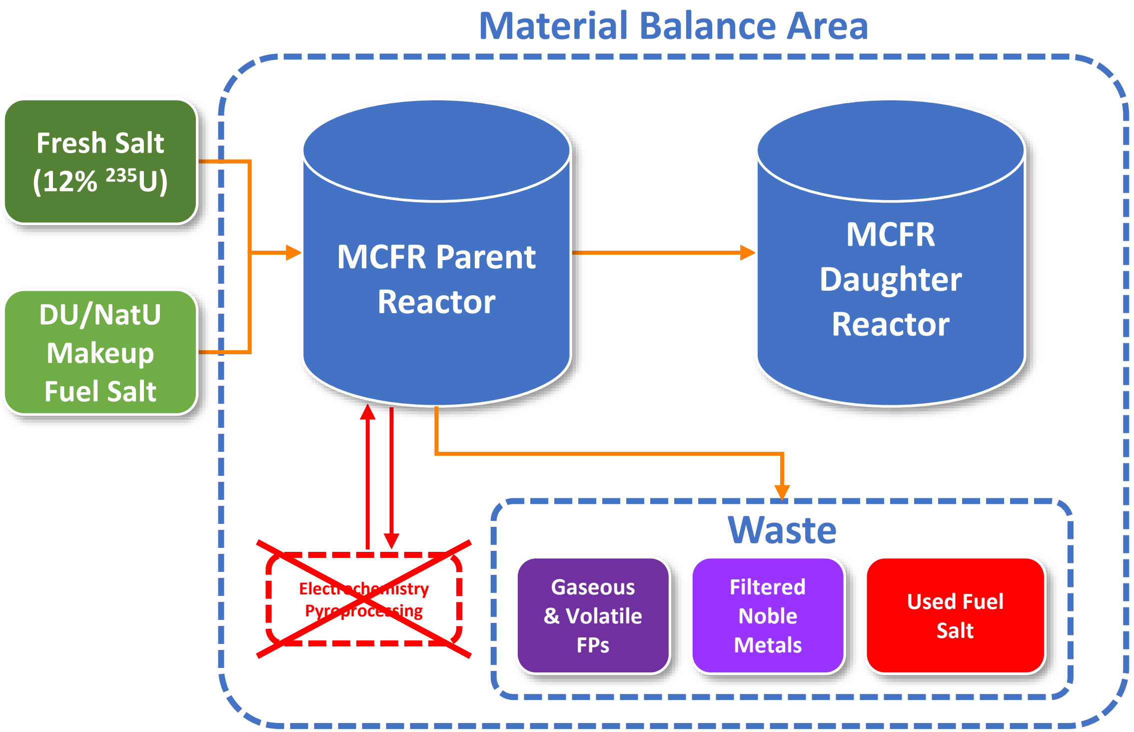
Multiple MCFR products are possible

- Near-term option is HALEU-fueled & fed machine, at 10s-100s of MW_e
  - Earliest commercial product, smaller physical scale, direct descendant of the Demo
- Longer-term HALEU-fueled machine is larger, grid-scale machine at high 100s of MW_e or GW_e
  - Physically large enough for low leakage and net breed & burn with DU/NatU feed
  - Pu fission becomes larger fraction over time
  - Most of our results and costing estimates are for this machine

Information shared today focused on this option.

- Alternate/advanced option is a Pu/waste-burning machine
  - Fueled with materials separated by others
  - Options to consider LWR fuel reuse, following chlorination and volatility-based separations

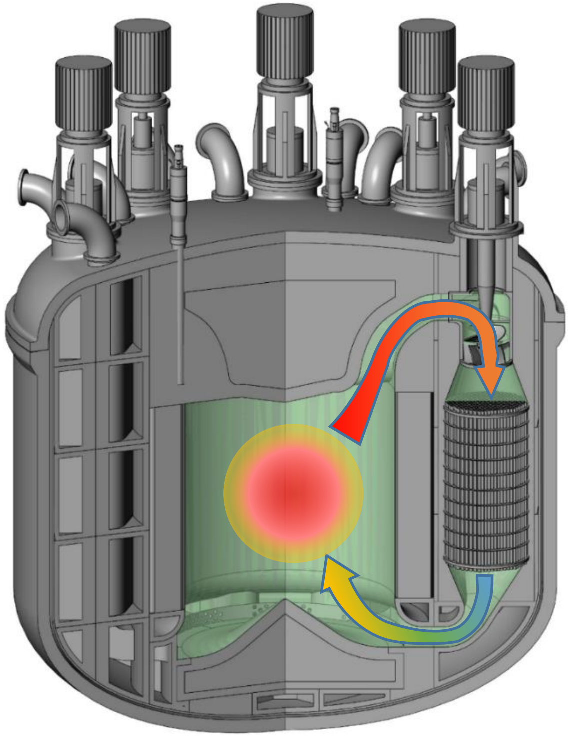
MCFR fuel cycle does not require enrichment after initial startup

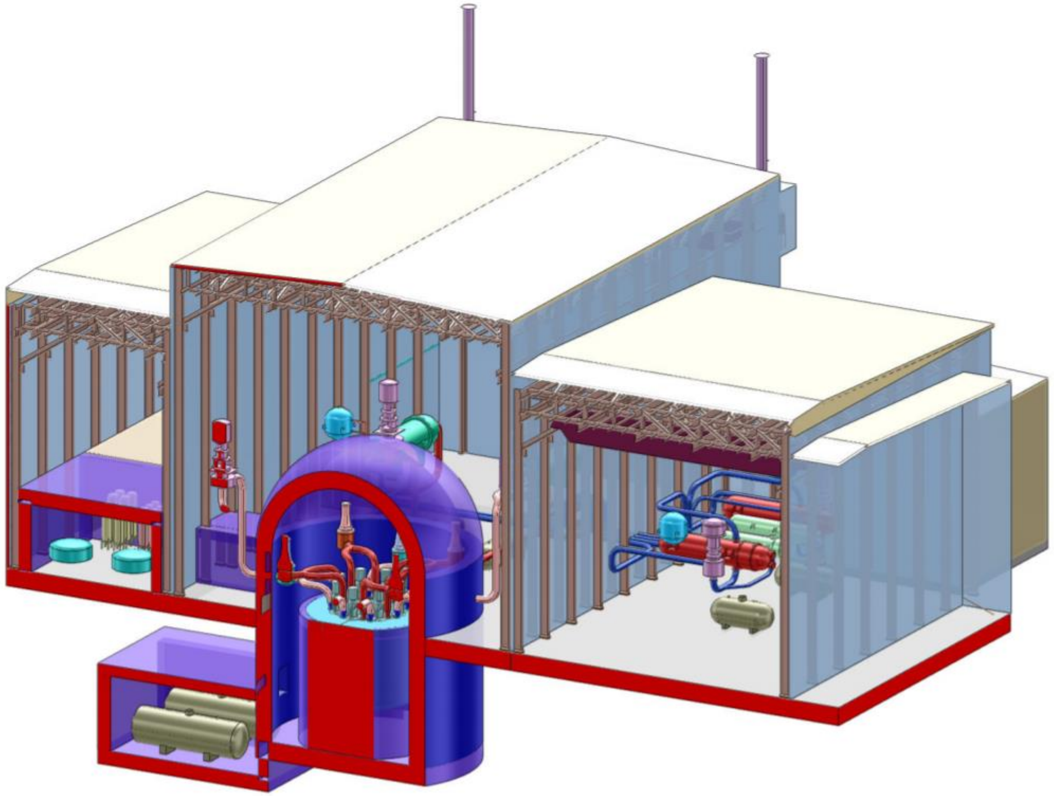


- First plants start with 12% enrichment
- Noble gases/volatile fission products removed via limited gas sparging
- Noble metals & insoluble fission products mechanically filtered
- Lanthanides not removed/stay in salt
- No pyroprocessing or electrochemistry is utilized
- DU/NatU is fed to replace used fuel
- Once-through burnup = 183,000 MWd/MT (19%)
- Twice-through burnup = 334,000 MWd/MT (36%)

MCFR technology has many features with the potential to improve economics

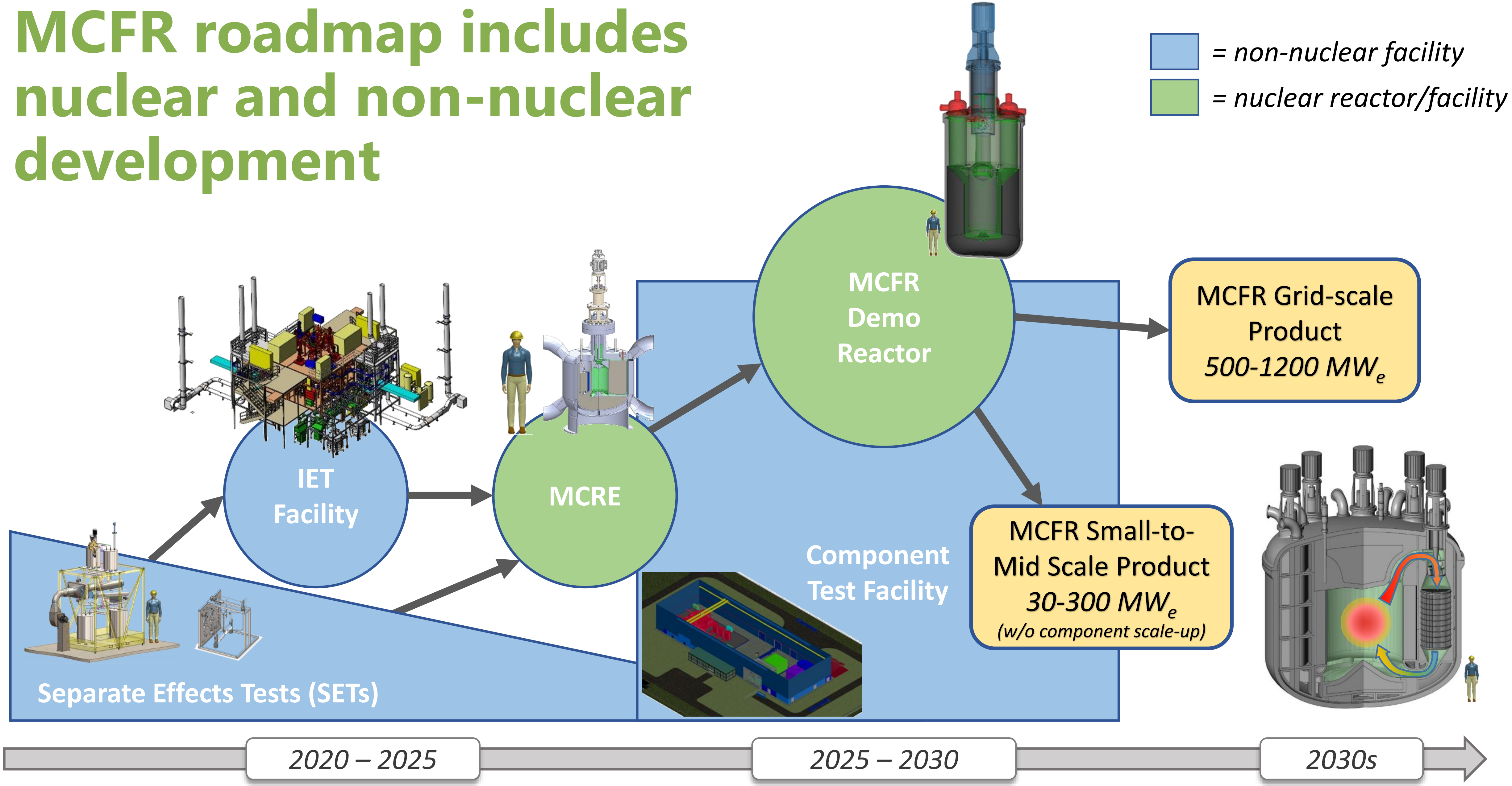
- Low pressure — Cost ↓
- Salt synthesis vs. solid fuel fabrication — Cost ↓
- Online refueling — Avail. ↑
- High grade heat — Revenue ↑





The updated system design & costing study (2019 vs. 2016) result is $2.2B base construction cost, $2800/kWe and $60/MWh for NOAK 800 MWe plant. We also see opportunities to drive to < $2B, < $2500/kWe and < $50/MWh.

MCFR roadmap includes nuclear and non-nuclear development



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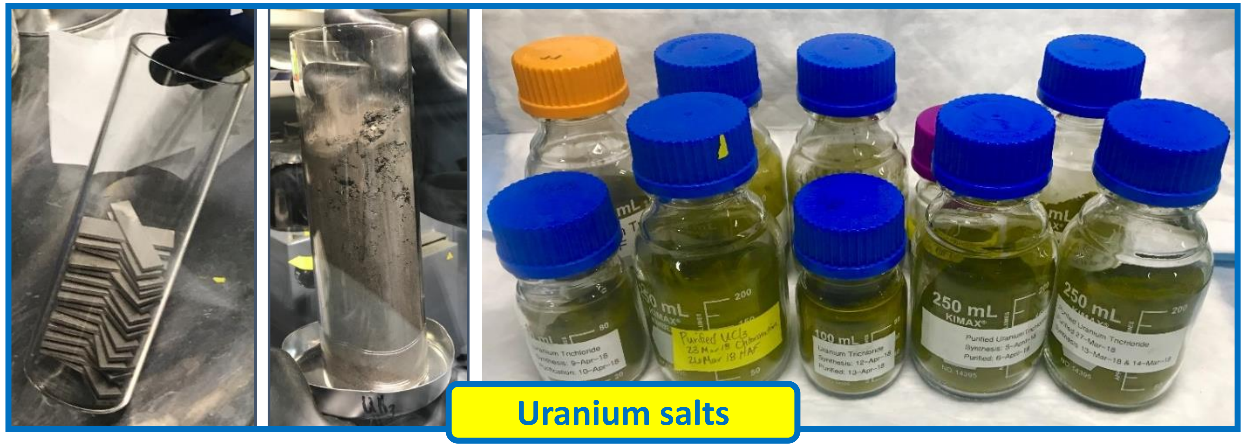
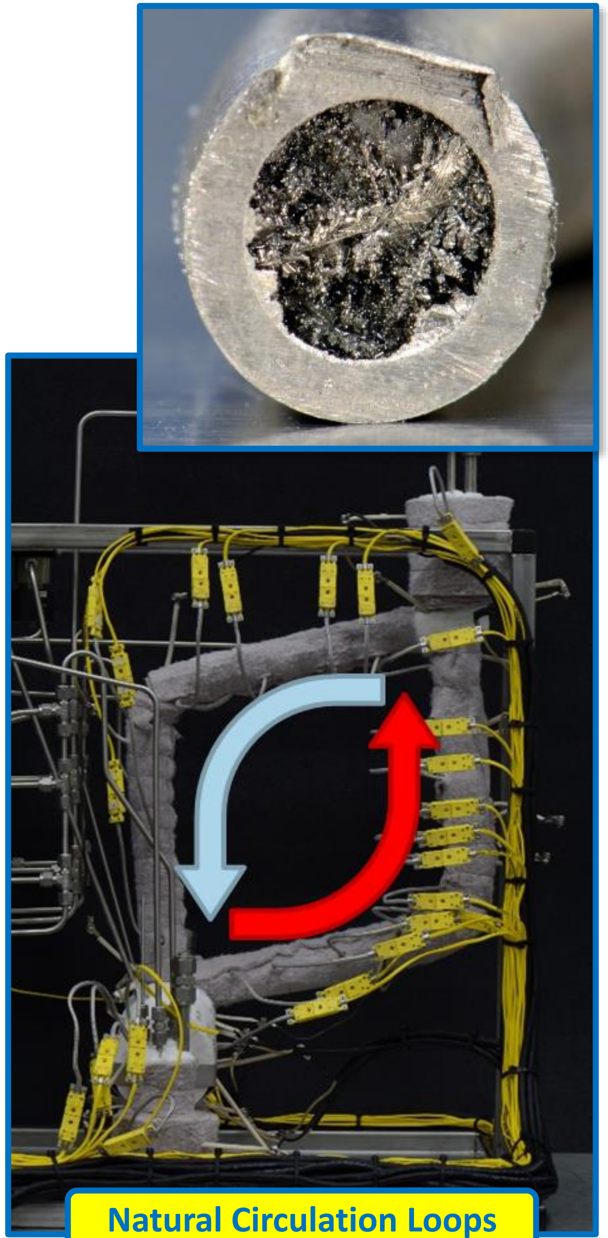
The MCFR team is advancing the technology



Uranium salts

Plutonium salts

Coolant salts



Natural Circulation Loops

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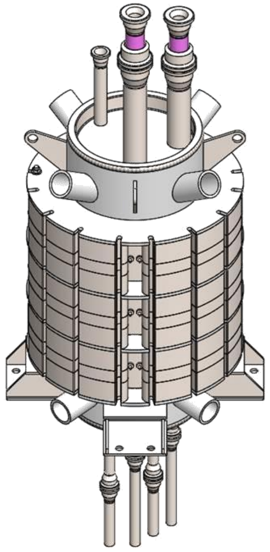
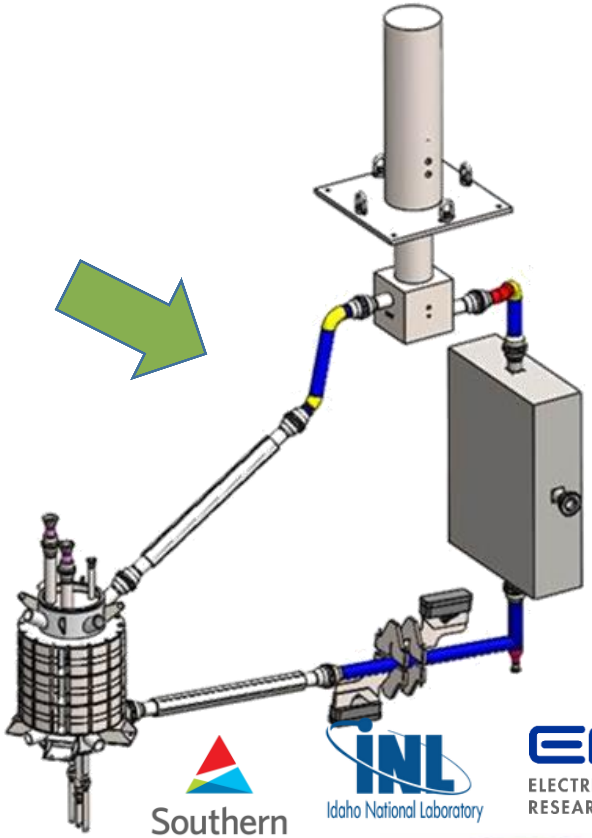
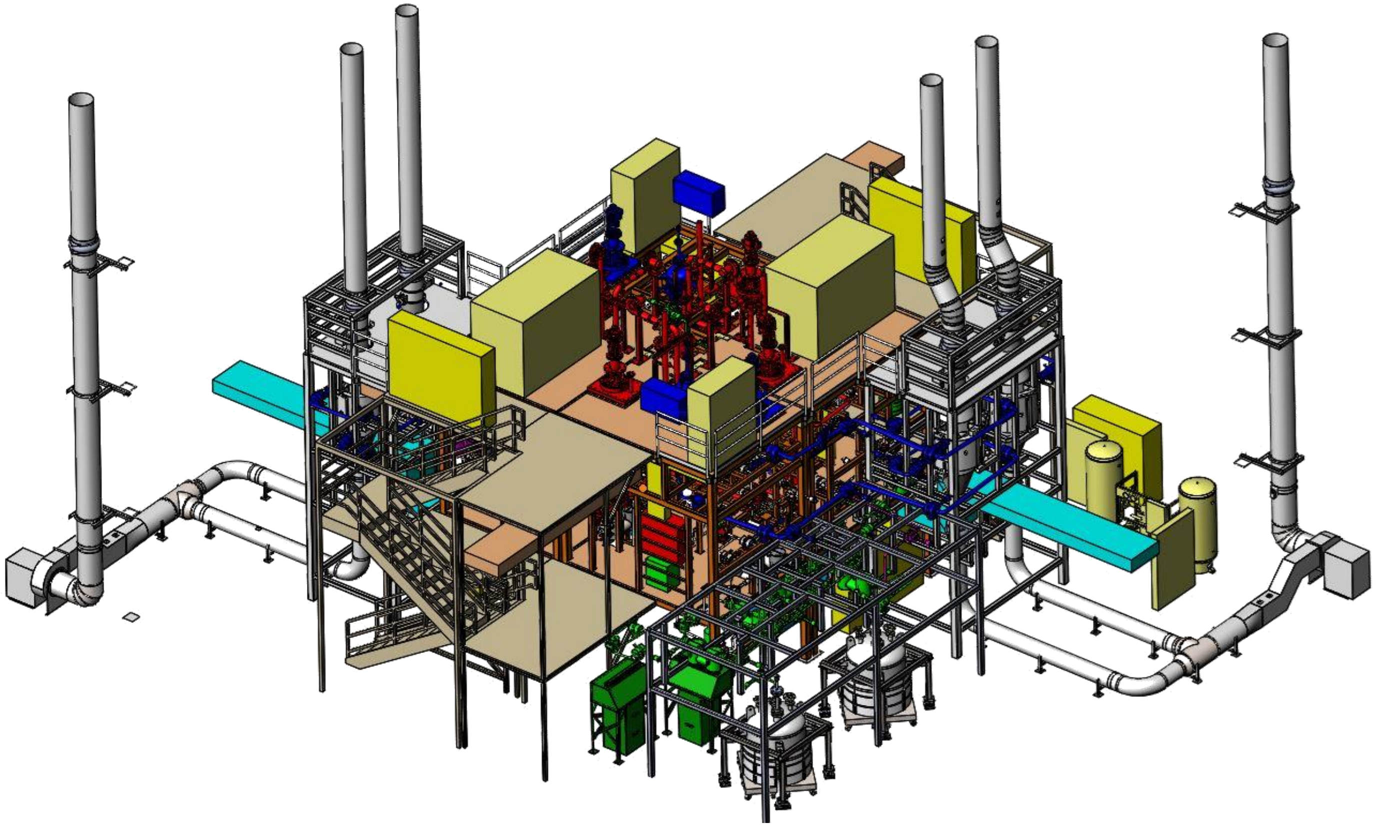
100% design of the Integrated Effects Test is complete; modules to be constructed this summer

IET operations are planned for early 2022.
All major procurements already completed.







Southern Company

INL Idaho National Laboratory

EPRI ELECTRIC POWER RESEARCH INSTITUTE

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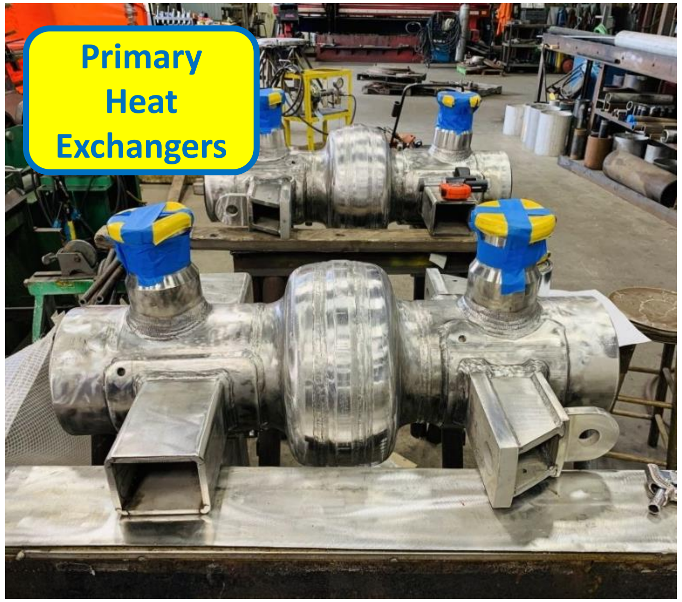
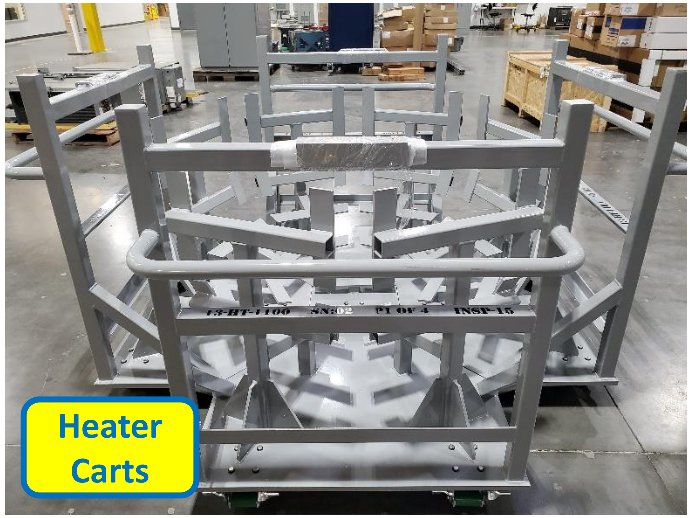
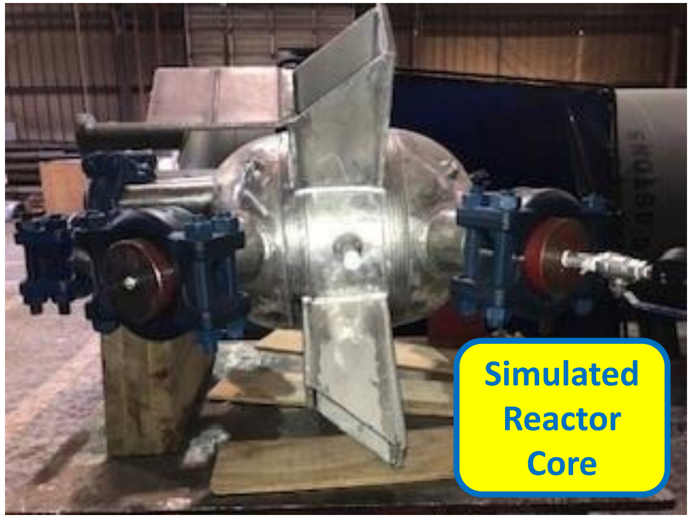
The Integrated Effects Test is becoming a real machine that will provide invaluable molten salt experience







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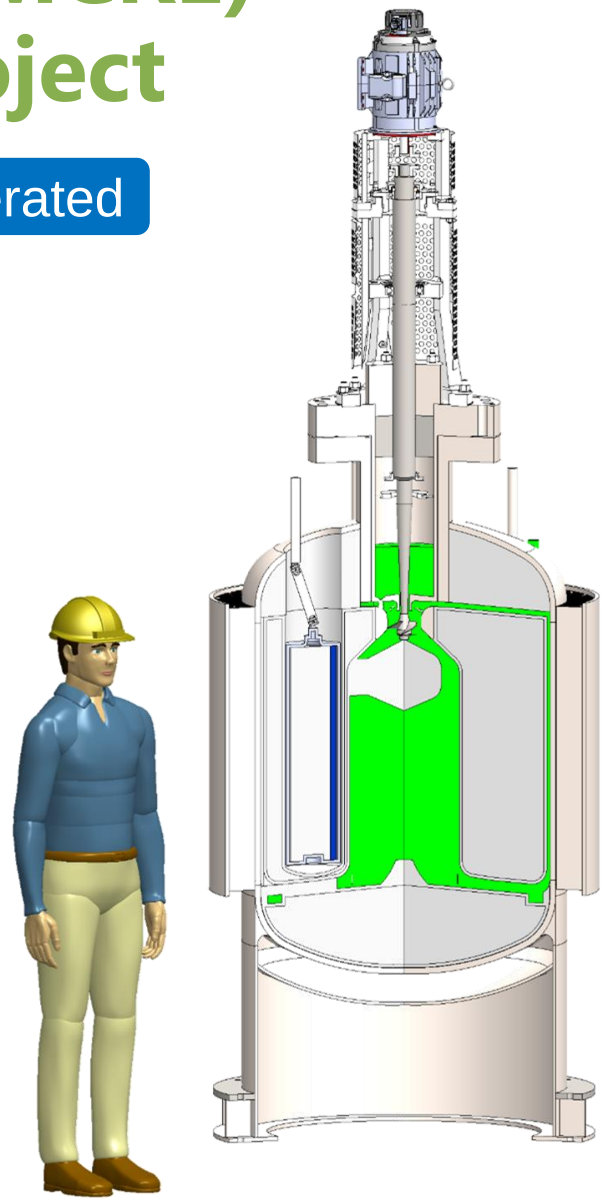
The Molten Chloride Reactor Experiment (MCRE) proposal has been selected as an ARDP project

1st fast spectrum MSR, 1st chloride MSR, 4th MSR ever operated

- Focus is transients in a low-β, fast- spectrum, flowing fuel.
- Most likely sited at INL/Lotus (formerly the ZPPR cell).
- Still evaluating HEU vs. Pu fuel (sizing, synthesis, power, etc.).
- Expect first critical late 2025.

Southern Company, 3M, orano, INL Idaho National Laboratory, EPRI ELECTRIC POWER RESEARCH INSTITUTE, CORE-POWER, NRIC, TerraPower

Parameter	MCRE
Thermal Power	300 kW
Power Density in Core	3.9 MW/m^3
Mass Flow Rate	100 kg/s
Temperature Rise	5°C
Heat Removal	Gas-Cooled Vessel
Fuel Salt Composition	36%$PuCl_3$ – 64%NaCl
Chlorine Enrichment	Natural
Active Core Diameter	0.38 m
Fuel Salt Volume & Mass	135 liters, 450 kg
$PuCl_3$ Mass	350 kg
Active Core Volume Fraction	0.70

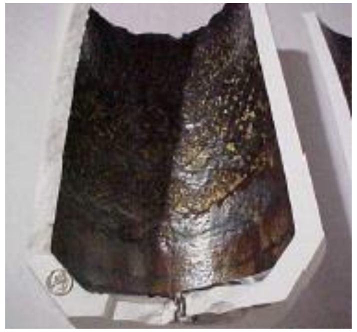


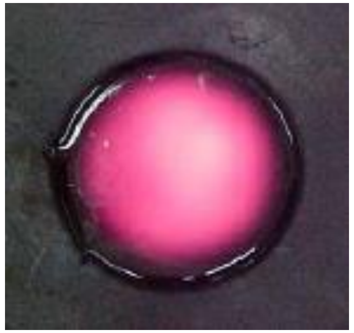
MCFR wastes could utilize a variety of potential disposal options – much further work is needed

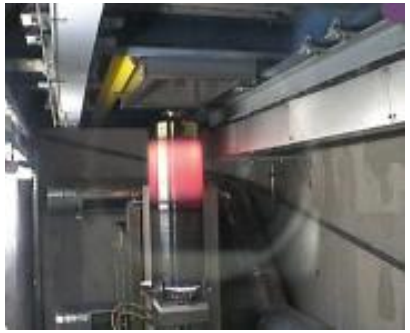
Direct disposal in salt repository: No ^{37}Cl recovery, no chemical durability, migration with water.

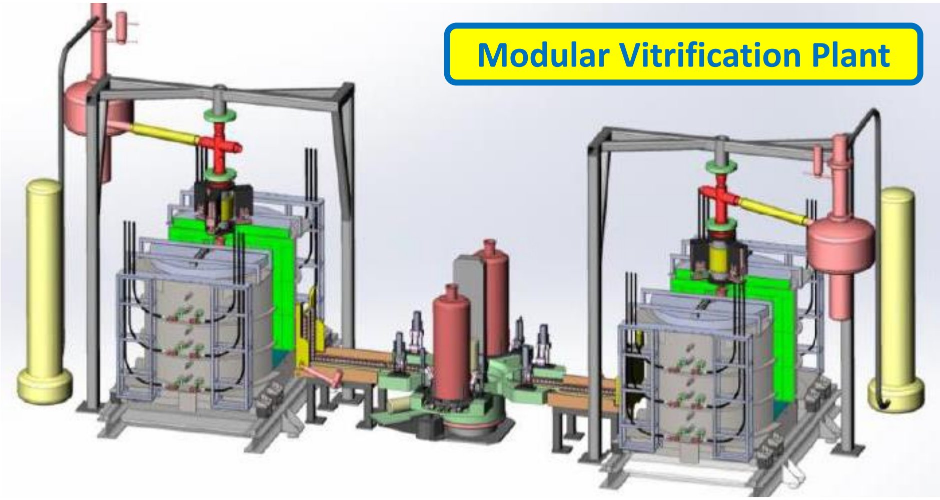
SynRoc could be a viable option: reaction with O_2 to form oxychlorides or oxide compounds with ^{37}Cl recovery. Metal oxides incorporated into SynRoc.

Recovery of enriched chlorine and conversion to accepted waste forms: Fe-phosphate glass may be a good option.









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MCFR waste disposal & decommissioning estimates

- Fuel disposal assumes either MA+FP separation followed by vitrification or, alternatively, vitrification of everything (viability of this is TBD, downside is loss of fuel reuse option).
- Cost of modular vitrification plant (CapEx and O&M) included in LCOE.
- Ultimate disposal of the fuel in a repository at cost of 1 mill/kWh (note that this significantly penalizes advanced reactors, which get higher burnup).
- Plant decommissioning assumed to be $540M – points to current estimate for Crystal River D&D. (Gen IV International Forum Cost Estimating Guidance would suggest a lower cost of $211M.)
- Impact on LCOE calculated per aforementioned Gen IV document.

Net impact to LCOE, as estimated, is approximately $1.60/MWh for 780 MW_e plant's 60-year lifetime. Considerable work needed to prove out these pathways.

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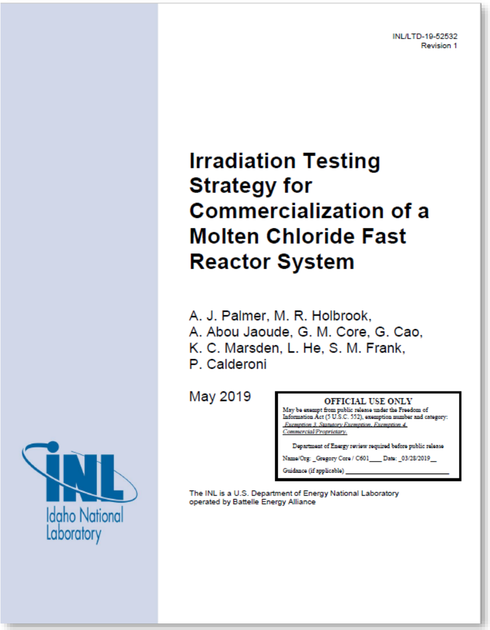
We are working with multiple national labs and government agencies to support MCFR development


INL/LTD-19-52532
Revision 1

Irradiation Testing Strategy for Commercialization of a Molten Chloride Fast Reactor System

A. J. Palmer, M. R. Holbrook, A. Abou Jaoude, G. M. Core, G. Cao, K. C. Marsden, L. He, S. M. Frank, P. Calderoni

May 2019

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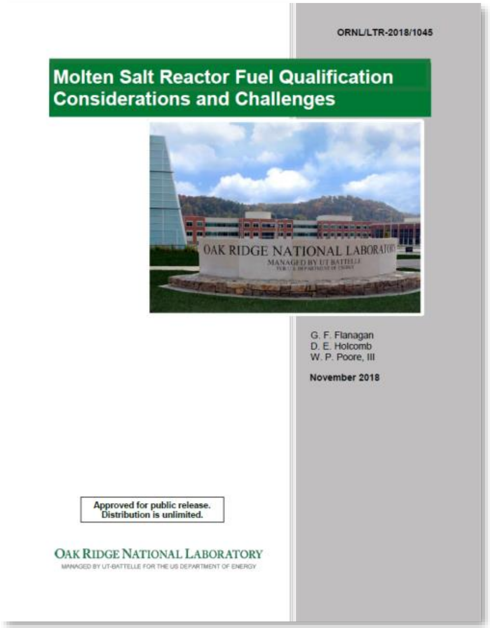
Irradiation testing roadmap


ORNL/LTR-2018/1045

Molten Salt Reactor Fuel Qualification Considerations and Challenges

G. F. Flanagan
D. E. Holcomb
W. P. Poore, III

November 2018

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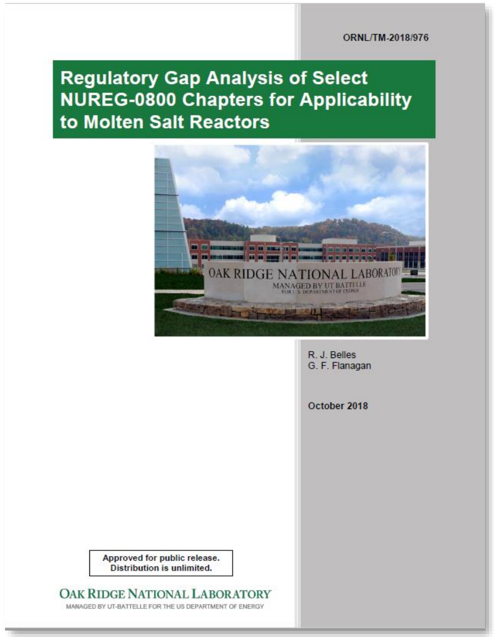
Fuel Qualification (utilizes fundamentally different approach)


ORNL/TM-2018/976

Regulatory Gap Analysis of Select NUREG-0800 Chapters for Applicability to Molten Salt Reactors

R. J. Belles
G. F. Flanagan

October 2018

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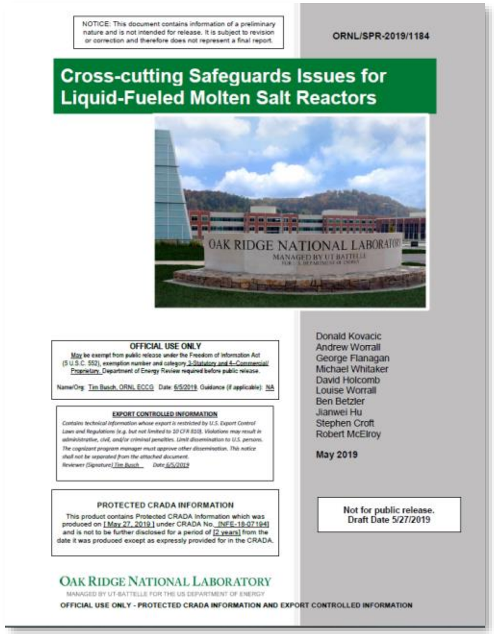
Licensing pathways and development


NOTICE: This document contains information of a preliminary nature and is not intended for release. It is subject to revision or correction and therefore does not represent a final report.

ORNL/SPR-2019/1184

Cross-cutting Safeguards Issues for Liquid-Fueled Molten Salt Reactors

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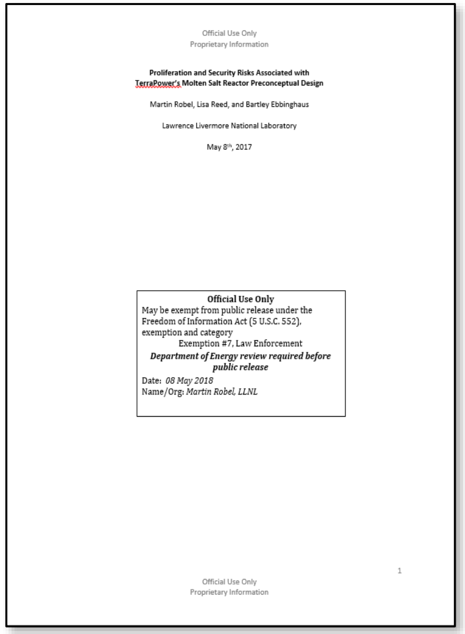
Safeguards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Proliferation and Security Risks Associated with TerraPower's Molten Salt Reactor Preconceptual Design

Martin Robel, Lisa Reed, and Bartley Ebbinghaus

Lawrence Livermore National Laboratory

May 8th, 2017

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Date: *08 May 2018*
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Summary

- The MCFR has a high potential to provide a low-cost, attractive solution for advanced nuclear.
- A robust testing program, including Separate Effects Tests (SETs), the Integrated Effects Test (IET), and the Molten Chloride Reactor Experiment (MCRE), strengthen the MCFR development program.
- MCFR offers a high burn-up option in a once-through (or twice-through) fuel cycle. Disposition of MCFR wastes is still TBD, but interesting and affordable options exist.

- ✓ Simple Design
- ✓ Extensive Testing Campaigns
- ✓ Passive Safety
- ✓ Safety & Safeguards by Design
- ✓ Simple Fuel Synthesis and Qualification
- ✓ Fuel Flexibility
- ✓ Proliferation-Resistant Fuel Cycle
- ✓ High Fuel Utilization, Low Lifetime Quantities
- ✓ High Thermal Efficiency
- ✓ Low System Pressures
- ✓ High Availability
- ✓ Load Following
- ✓ Broad Applications, including Process Heat

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Thank You