TerraPower’s Molten Chloride Fast Reactor (MCFR)

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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**.
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.
Multiple MCFR products are possible

• Near-term option is HALEU-fueled & fed machine, at 10s-100s of MWₐ
  – 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 MWₑ or GWₑ
  – 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

• 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%)

Material Balance Area

Fresh Salt (12% 235U)

DU/NatU Makeup Fuel Salt

MCFR Parent Reactor

MCFR Daughter Reactor

Waste

Gaseous & Volatile FPs

Filtered Noble Metals

Used Fuel Salt

Electrochemistry

Pyroprocessing

Gaseous & Volatile FPs

Filtered Noble Metals

Used Fuel Salt

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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

Separate Effects Tests (SETs)

IET Facility

MCRE

Component Test Facility

MCFR Demo Reactor

MCFR Grid-scale Product 500-1200 MW_e

MCFR Small-to-Mid Scale Product 30-300 MW_e (w/o component scale-up)

2020 – 2025

2025 – 2030

2030s

= non-nuclear facility

= nuclear reactor/facility
The MCFR team is advancing the technology.
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.
The Integrated Effects Test is becoming a real machine that will provide invaluable molten salt experience.
The Molten Chloride Reactor Experiment (MCRE) proposal has been selected as an ARDP project.

- 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.

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MCRE</th>
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<tbody>
<tr>
<td>Thermal Power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Power Density in Core</td>
<td>3.9 MW/m³</td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td>100 kg/s</td>
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<tr>
<td>Temperature Rise</td>
<td>5°C</td>
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<tr>
<td>Heat Removal</td>
<td>Gas-Cooled Vessel</td>
</tr>
<tr>
<td>Fuel Salt Composition</td>
<td>36%PuCl₃ – 64%NaCl</td>
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<tr>
<td>Chlorine Enrichment</td>
<td>Natural</td>
</tr>
<tr>
<td>Active Core Diameter</td>
<td>0.38 m</td>
</tr>
<tr>
<td>Fuel Salt Volume &amp; Mass</td>
<td>135 liters, 450 kg</td>
</tr>
<tr>
<td>PuCl₃ Mass</td>
<td>350 kg</td>
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<tr>
<td>Active Core Volume Fraction</td>
<td>0.70</td>
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MCFR wastes could utilize a variety of potential disposal options – much further work is needed

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

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

SynRoc could be a viable option: reaction with $\text{O}_2$ to form oxychlorides or oxide compounds with $^{37}\text{Cl}$ recovery. Metal oxides incorporated into SynRoc.
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<sub>e</sub> plant’s 60-year lifetime. Considerable work needed to prove out these pathways.
We are working with multiple national labs and government agencies to support MCFR development.
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.
Thank You