Seminar overview

- Historical and international context of the work.
- Contemporary R&D issues, i.e. funding sources.
- FHR relevance.
- MSR salt & lattice choices.
- LEU fueled MSRs as a transition technology to TRU and Th cycle
Introductory remarks

- All my research is fundamental science, the results of which are being posted on the website below, while the publications are being drafted out for submission to conferences and journals.

- [http://web.utk.edu/~ochvala/MSR/](http://web.utk.edu/~ochvala/MSR/)

- This talk will largely focus on upcoming ICAPP 2014 paper, and some expansion of that.

- Check this website for updates and new results.
Little bit of history

- 1954 Aircraft reactor experiment
1965-1969 Molten Salt Reactor Experiment
Current predicament

- ORNL's program in the 1960s was predicated on many historical circumstances, which are not valid any more.

- Current political priorities: inherent “walkaway” safety, proliferation resistance, TRU actinide minimization and spent nuclear fuel inventory management, among others.

- Economic reality: minimization of upfront (fixed) costs, maximization of resource utilization (see later), and exploring new markets.

- Any futuristic R&D program needs to get actually funded.

- Any new reactor R&D and deployment (R&D&D) needs:
  - to get regulated using the standard rules tailored to LWR → significant but not insurmountable challenge,
  - necessitates new generation of experts in related areas.
Partial solutions

- Move beyond ORNL's thinking and specific limitations.
- Acknowledge differences between near-term and ultimate solutions, and realize the consequences to plant engineering.
- Use LEU as fuel – no Thorium means lower enrichment and less challenges from the regulatory authority.
- Simplify on-site reprocessing to basic fuel reconditioning
  - Gaseous FP sparging with He or other noble gas.
  - Extraction of refractory metals by Ni sponge in the primary circuit cold leg.
  - Move actual fuel reprocessing to a central location (i.e. later).
- Carrier salt selection is crucial to system performance.
Salt selection – considering fluorides

- Alkali-halide carrier salts: fluoride has the least corrosion issues of all halides due to its extreme electro-negativity.
- $^{19}\text{F}$ is rather light, no truly fast-only reactors feasible with $\text{UF}_4$ as a fuel.
- French salt-only configuration is close to hard, though.
- Thermal reactors have many advantages:
  - Much less fissile feed need for criticality (fixed costs).
  - Maximum reactionary configuration feasible (safety).
- Several fluoride salts are commonly considered.
- Issues: salt up-front cost ($^7\text{Li}$), small scale lab work impediments (Be), tritium production (Li, Be), and industry start-up expenses (Rb).
Salt selection – parameter space exploration

- Lets see what the parameter space looks like for a basic lattice configuration with graphite moderator and several carrier fuel salt choices at BoC.

- Low fuel enrichment and decent conversion ratios (CR) are attractive, while maintaining MS fluid fuel advantages such as **high temperature & low pressure** operation, and **passive safety** inherent to fluid core design.

- FHRs are 80% of work for 20% of benefits [Kirk Sorensen]
  - Medical isotopes nuances - i.e. $^{99}$Mo production.

- Need for industrial heat is real and pressing. Frackgas will not last for centuries.

- Finding industrial application to fund the R&D is a matter of skill and opportunity.
Other ignored engineering design issues

- Salt THD performance, but all are good enough.
- Vessel material – SS316, HastN, Inconnel, ...
  - Temperature dependent
  - Important fixed expense
- HX configuration and design
  - SmAHTR shows possible avenues of exploration, but is wrong.
  - DR(A)CS outside of scope of this presentation.
- New and innovative ideas of trading fixed costs for variable ones much encouraged. Email me!
MSR lattices for economic salts & LEU fuel

- Topic of the ICAPP-2014 paper which draft is available on the website.
- Infinite hexagonal lattices of graphite and salt fuel.
- Lattice parameters are channel pitch $p$ and salt fraction $f$.
- Channel radius: $r^2 = p^2 \frac{\sqrt{3}}{2\pi} f$
- Reflective unit cell:
Salt selection

- Salts composition differences impacts salt cost, tritium production, and neutronic performance.
- THD differences neglected.

<table>
<thead>
<tr>
<th></th>
<th>Salt composition</th>
<th>Melting point [C]</th>
<th>Density [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72%Li⁺F-16%BeF₂-12%UF₄</td>
<td>480</td>
<td>3.353</td>
</tr>
<tr>
<td>2</td>
<td>73%Li⁺F-27%UF₄</td>
<td>490</td>
<td>4.340</td>
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<tr>
<td>3</td>
<td>78%NaF-22%UF₄</td>
<td>618</td>
<td>4.056</td>
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<tr>
<td>4</td>
<td>49%NaF-38%ZrF₄-13%UF₄</td>
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<td>3.757</td>
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<td>5</td>
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<td>6</td>
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<td>500</td>
<td>3.437</td>
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<td>7</td>
<td>46%NaF-33%RbF-21%UF₄</td>
<td>470</td>
<td>4.026</td>
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</table>
Other material issues

- Li\textsuperscript{7} is 99.995% Li\textsuperscript{7}
- All salts at 650C using 900K ENDF/B-VII.0 libraries
- Graphite density is assumed as 1.8g/cm\textsuperscript{3}, temperature 700C, using 900K ENDF/B-VII.0 libraries. Impurities modelled as 2ppm of boron. Thermal scattering library is ENDF/B-VII.0sab at 1000K.
Criticality searches

- Parameters are channel pitch (1 to 60 cm) and fuel salt fraction (0.5% to 55%). ~900 points sampled/salt.

- For each point in the parameter space, criticality search is performed to find BoC criticality (1<k<1.001) using the iterative Secant method.

\[
e^{(n+1)} = e^{(n)} - \rho(e^{(n)}) \frac{e^{(n)} - e^{(n-1)}}{\rho(e^{(n)}) - \rho(e^{(n-1)})}
\]

- \(e\) = enrichment (x axis)
- \(\rho(e)\) = reactivity (y axis)
- upper index = iteration step
Presentation of results – values of interest

- Enrichment for critical lattice

- Conversion ratio (CR):

\[ CR = \frac{U^{238} \text{ captures}}{U^{235} \text{ captures} + U^{235} \text{ fissions}}. \]

- Reproduction factor:

\[ \eta = \frac{\nu}{1 + \alpha} = \frac{2.44}{1 + \frac{U^{235} \text{ captures}}{U^{235} \text{ fissions}}}. \]

- Fast fission bonus = \(238\text{U}\) fission fraction.

- Figure of Merit: CR/enrichment
72%LiF-16%BeF$_2$-12%UF$_4$.

73%LiF-27%UF$_4$.

78%NaF-22%UF$_4$. 
## Results in summary tables

Summary of the critical lattices properties: the minimum enrichment of 235U needed for criticality and its location in the parameter space of pitch versus salt fraction; the maximum CR and its position in the parameter space. Next tab: maximum FoM.

<table>
<thead>
<tr>
<th>Salt composition</th>
<th>$^{235}$U[%]</th>
<th>$p$[cm]</th>
<th>$f$[%]</th>
<th>CR</th>
<th>$p$[cm]</th>
<th>$f$[%]</th>
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<tbody>
<tr>
<td>72%Li$^7$F-16%BeF$_2$-12%UF$_4$</td>
<td>0.943</td>
<td>30.0</td>
<td>10.0</td>
<td>0.936</td>
<td>50.0</td>
<td>37.5</td>
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<tr>
<td>73%Li$^7$F-27%UF$_4$</td>
<td>0.817</td>
<td>26.0</td>
<td>6.0</td>
<td>0.984</td>
<td>55.0</td>
<td>32.5</td>
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<td>78%NaF-22%UF$_4$</td>
<td>1.181</td>
<td>26.0</td>
<td>6.0</td>
<td>0.876</td>
<td>60.0</td>
<td>40.0</td>
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<td>1.457</td>
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<td>10.0</td>
<td>0.831</td>
<td>1.0</td>
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<td>1.0</td>
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<td>0.789</td>
<td>1.0</td>
<td>10.0</td>
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<table>
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<tr>
<th>Salt composition</th>
<th>FoM</th>
<th>$p$[cm]</th>
<th>$f$[%]</th>
<th>$^{235}$U[%]</th>
<th>CR</th>
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<td>72%Li$^7$F-16%BeF$_2$-12%UF$_4$</td>
<td>0.829</td>
<td>30.0</td>
<td>14.0</td>
<td>0.986</td>
<td>0.817</td>
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<td>73%Li$^7$F-27%UF$_4$</td>
<td>1.031</td>
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<td>10.0</td>
<td>0.845</td>
<td>0.876</td>
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<td>78%NaF-22%UF$_4$</td>
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<td>18.0</td>
<td>1.616</td>
<td>0.648</td>
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<tr>
<td>58%NaF-30%BeF$_2$-12%UF$_4$</td>
<td>0.423</td>
<td>26.0</td>
<td>14.0</td>
<td>1.533</td>
<td>0.649</td>
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<tr>
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<td>0.425</td>
<td>28.0</td>
<td>14.0</td>
<td>1.525</td>
<td>0.648</td>
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<tr>
<td>46%NaF-33%RbF-21%UF$_4$</td>
<td>0.480</td>
<td>26.0</td>
<td>10.0</td>
<td>1.280</td>
<td>0.614</td>
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Note on lattice heterogeneity

- Molten Salt Reactor Experiment used the lattice pitch of 5.1 cm (2”), and the salt fraction of 22.5%
- Molten Salt Breeder Reactor used a similar pitch of ~5 cm and salt fractions of 13.2% and 37% in its two zones.
- Denatured Molten Salt Reactor's pitch ~15 cm, and the salt fraction of 13% in 95% of the core.
- These seem smaller pitches than optimal.
Comparison of enrichment

- The dependence of 235U enrichment on the lattice pitch for the salt fraction which maximizes FoM.
Impact of CR on power cost

- Conversion ratios in the lattice configuration investigated range between 0.6 – 0.9

- Say 800kg needs to fission for 1GWe.year → annual fresh fuel requirements range from 320 to 80 kg of fissile.

- Current cost of fresh U235 is below $40/g for LEU fuel.

- The total makeup fuel cost is thus $12.8M to $3.2M

- Which can be expressed as a part of the electricity cost in the range of 0.15 to 0.037 c/kWh.
Plutonium solubility and LWR SNF re-use

- All the salts discussed are expected to dissolve 1-2mol% of triflouride actinides, in particular PuF$_3$.

- Low fissile loadings, see below, seem to allow direct re-use of LWR SNF actinides in such hypothetical reactor.

Fraction of the fissile atoms for FoM maximizing lattices

<table>
<thead>
<tr>
<th>Salt composition</th>
<th>Fissile loading [%]</th>
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<tr>
<td>72%Li$^7$F-16%BeF$_2$-12%UF$_4$</td>
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<td>73%Li$^7$F-27%UF$_4$</td>
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<tr>
<td>78%NaF-22%UF$_4$</td>
<td>0.279</td>
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<tr>
<td>49%NaF-38%ZrF$_4$-13%UF$_4$</td>
<td>0.210</td>
</tr>
<tr>
<td>58%NaF-30%BeF$_2$-12%UF$_4$</td>
<td>0.184</td>
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<tr>
<td>74%NaF-12%BeF$_2$-14%UF$_4$</td>
<td>0.214</td>
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<tr>
<td>46%NaF-33%RbF-21%UF$_4$</td>
<td>0.267</td>
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Future work

- Look at Zr4H8 moderator (almost done, looks bad).
- Re-run several good configurations with the assumption of 1% and 2% leakage.
- Depletion studies for more realistic fuel cycle assessment.
- Temperature-reactivity feedbacks for finite cores.
Conclusions

- LEU fueled MSRs seem as an attractive proposition.
- Large selection of salts seem all feasible with surprising low enrichments.
- The data have been posted: [http://web.utk.edu/~ochvala/MSR/](http://web.utk.edu/~ochvala/MSR/)
- Stay tuned for more to come. The website will be updated with new results.