The Impact of Xenon-135 on a Load Following Transatomic Power Molten Salt Reactor

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Outline

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   - Molten Salt Reactors
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   - Full-core TAP MSR Serpent model
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   - ^{135}Xe/^{135}I balance
   - Neutron spectra
4. Conclusions

UIUC Project Overview

ARPA-E MEITNER Award 1798-1576

PI: Huff

Co-PIs: Brooks, Heuser, Kozlowski, Stubbins

Objective: This project will establish a xenon removal sparger design to enable load following in liquid-fueled MSRs at ramp rates comparable or superior to natural gas peaking generation, $\left(\frac{\pm 10\%}{\text{minute}}\right)$.

Motivation

- Load following Molten Salt Reactors are potentially transformative
- But, feasible online xenon removal system designs are absent.

The UIUC project will unlock the benefits of MSRs by bounding these designs

- **via simulation of multiple physics**
  - fluid dynamics,
  - neutronics,
  - and fuel cycle dynamics.
- **and with novel mass transport and sparging experiments.**

UIUC Project Thrusts

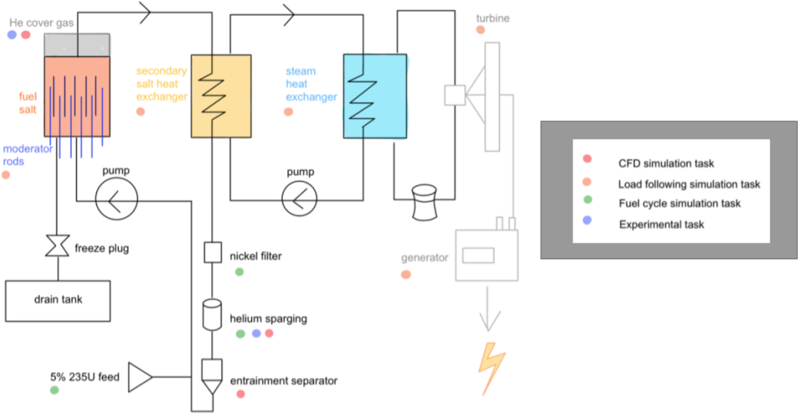
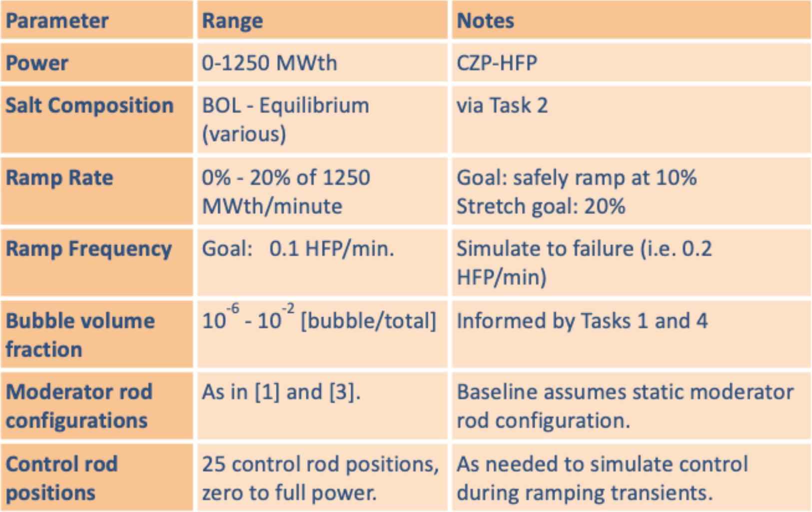


Figure 1: In **4 major thrusts** the project will establish a feasible design for the sparging system, an overlooked MSR component essential to load following in thermal MSRs.



Parameter	**Range**	**Notes**
Power	0-1250 MWth	CZP-HFP
Salt Composition	BOL - Equilibrium (various)	via Task 2
Ramp Rate	0% - 20% of 1250 MWth/minute	Goal: safely ramp at 10% Stretch goal: 20%
Ramp Frequency	Goal: 0.1 HFP/min.	Simulate to failure (i.e. 0.2 HFP/min)
Bubble volume fraction	10^{-6} - 10^{-2} [bubble/total]	Informed by Tasks 1 and 4
Moderator rod configurations	As in [1] and [3].	Baseline assumes static moderator rod configuration.
Control rod positions	25 control rod positions, zero to full power.	As needed to simulate control during ramping transients.

Table 1: Operating conditions and transients to be investigated and constraints that the core must meet.

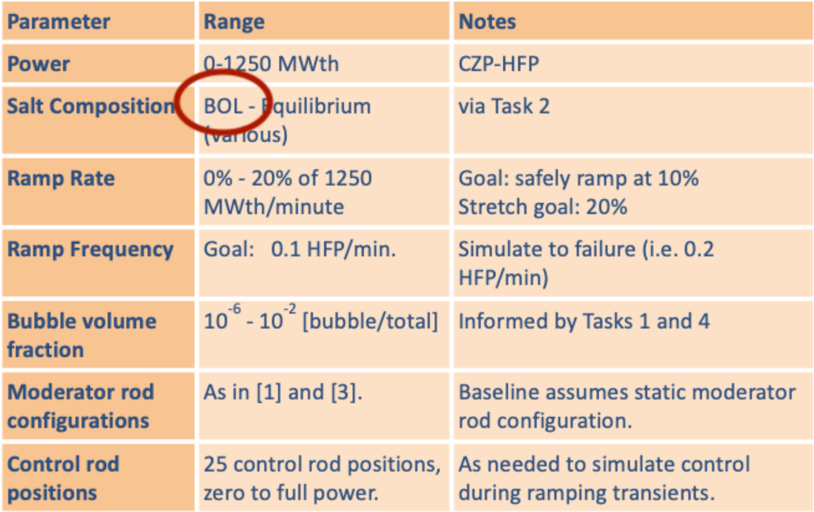


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Table 1: **This work** establishes that xenon removal may be unnecessary, even unadvisable, at BOL or for fast spectrum MSRs. Thermal and EOL reactors are expected to require xenon sparging.

Why is load following a game changer?

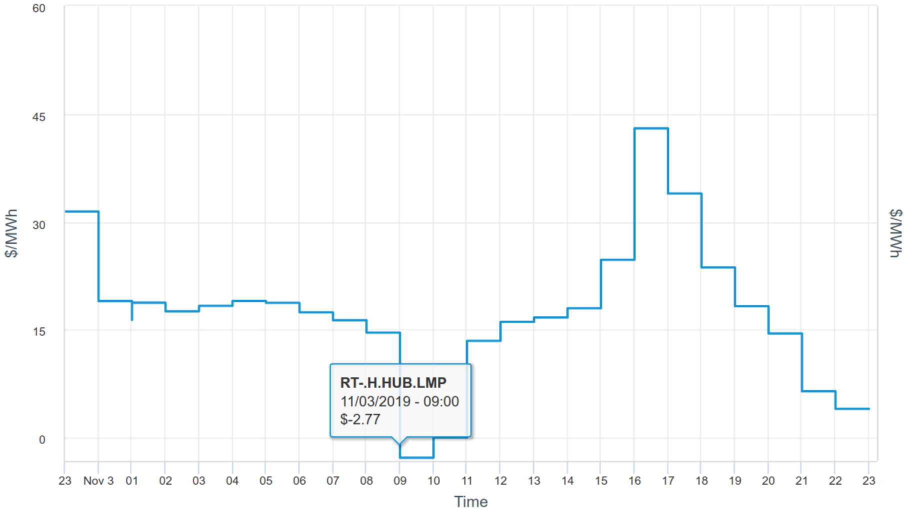

Figure 2: ISO New England hourly electricity price; November 3, 2019 from 00:00AM to 11:00PM (Source: https://www.iso-ne.com/).

Nuclear Power Plant Load-Following

Limitations to Light Water Reactor (LWR) power maneuvering [1]

1. Thermal strain and stress to fuel materials.
2. Moderator effect (primary coolant temperature change)
3. Doppler effect (fuel temperature change)
4. Fuel burnup (low excess reactivity at the end-of-cycle (EOC))
5. ^{135}Xe **poisoning (iodine pit)**

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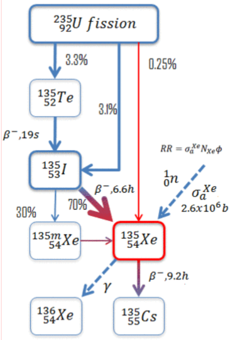
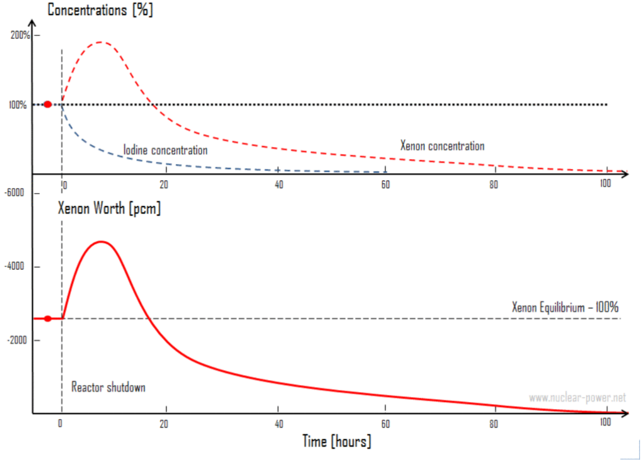
What is Xenon-135 poisoning? [2]



Source: www.nuclear-power.net
Data: JANIS 4.0 / NEA



MSR (Molten Salt Reactor) types

Stationary Fuel

1. Graphite block with TRISO fuel, clean salt works as coolant (Fluoride-Salt-Cooled High-Temperature Reactor (FHR))
2. Plate Fuel: hexagonal fuel assembly is similar in shape to a typical sodium-cooled reactor
3. Fuel Inside Radial Moderator (FIRM)

Mobile Fuel

1. **Solid**
    - Mobile solid fuel elements (pebbles) cooled by clean salt (PB-FHR)
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    - Without on-site fuel reprocessing facility (TerraPower Molten Chloride Fast Reactor (MCSFR))
    - With on-site fuel reprocessing (Transatomic Power (TAP) MSR, Molten Salt Breeder Reactor (MSBR))

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Mobile, Liquid Fuel with on-site reprocessing facility

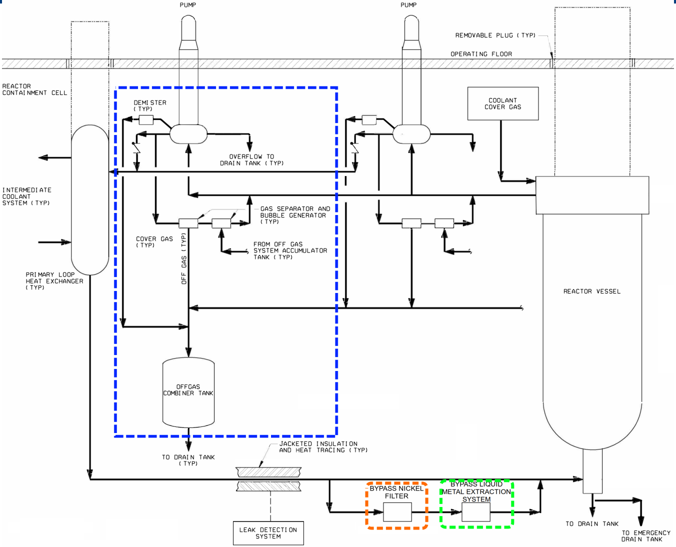

Figure 3: The TAP reactor conceptual schematic (including reprocessing system) [4].

Research objectives of this work

Analyze TAP MSR neutronic performance during load-following **at the Beginning of Life (BOL)** and **without online fission product removal**. The neutronics performance for the Middle of Life and End of Life will be different, and will require fission product removal.

Goals of current study

1. Create high-fidelity full-core 3-D model of TAP concept, without any approximations using Serpent [5]
2. Perform fuel salt depletion to study ^{135}**Xe/**^{135}**I balance dynamics during load-following**
3. Analyze k_{eff} dynamics during **load-following**
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Outline

TAP concept design

Table 2: Summary of principal data for the Transatomic Power (TAP) Molten Salt Reactor (MSR) [4, 6].

Thermal power	1250 MW_{th}
Electric power	520 MW_e
Gross thermal efficiency	44%
Outlet temperature	620°C
Fuel salt components	$LiF\text{-}UF_4$
Fuel salt composition	72.5-27.5 mole%
Startup fissile material	5% ^{235}U
Moderator	Zirconium Hydride ($ZrH_{1.66}$) rods (with silicon carbide cladding)
Neutron spectrum	**thermal/epithermal**
Moderator-to-fuel ratio (MFR)	**varies in (0.1099, 1.0)**

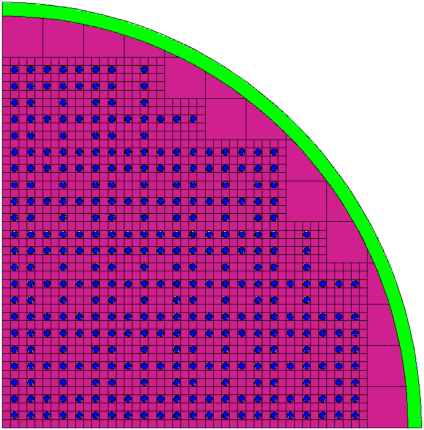


Figure 4: The TAP MSR schematic core view showing moderator rods configuration at Beginning of Life (BOL) [6].

TAP concept full-core high-fidelity Serpent model

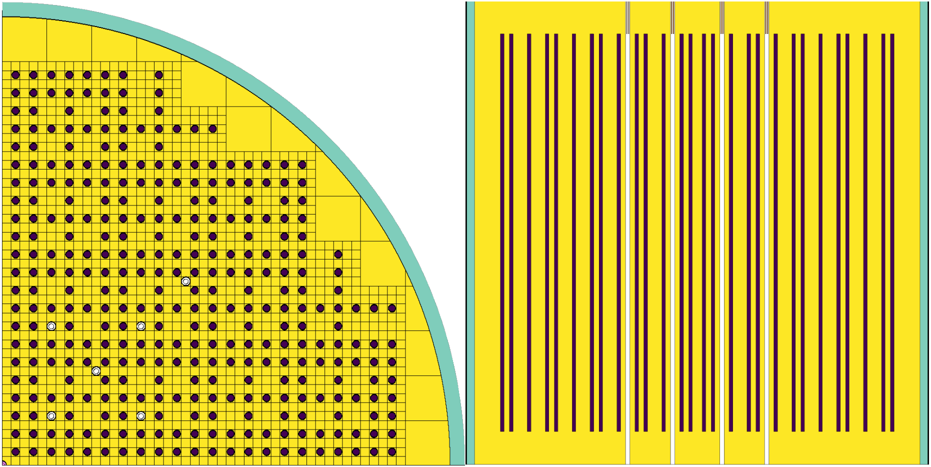


Figure 5: An *XY* (left) and *XZ* (right) section of the TAP model. The violet color represents zirconium hydride, the yellow represents fuel salt [7].

Postulated worst-case load-following scenario

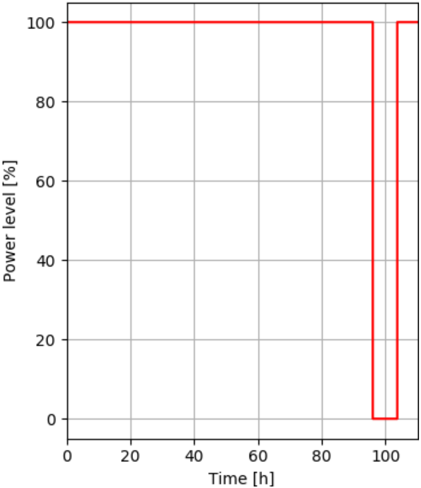


Figure 6: Assumed load-following power variation.

Power load

1. Startup with fresh fuel and operation on 100% power level for **96h** to reach ^{135}Xe/^{135}I equilibrium
2. **Instantaneous** power drop from 100% to 0%
3. Shutdown state for **7.66h** to reach the ^{135}Xe peak
4. Startup from 0 to 100%, and then operation on 100% for **16h**

Simplifying assumptions

- All control rods are fully withdrawn
- Online reprocessing system is **disabled**
- 15-min depletion steps in the transient

Outline

Multiplication factor dynamics after shutdown

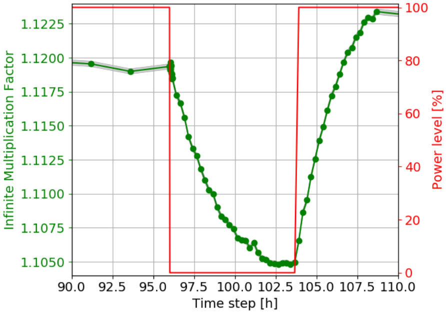
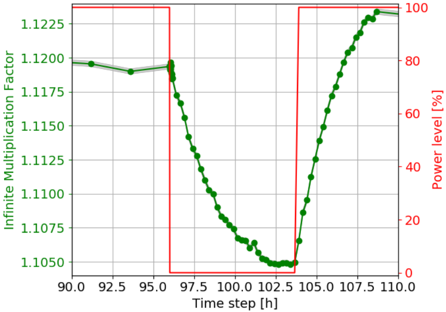


Figure 7: Multiplication factor for PWR assembly after shutdown ($\sigma \pm 20$pcm shaded).

1. $-1500pcm$ reactivity insertion due to ^{135}Xe poisoning
2. k_∞ reached local minima ≈ 7 hrs after shutdown
3. overall reactivity swing $1750pcm$

Multiplication factor dynamics after shutdown



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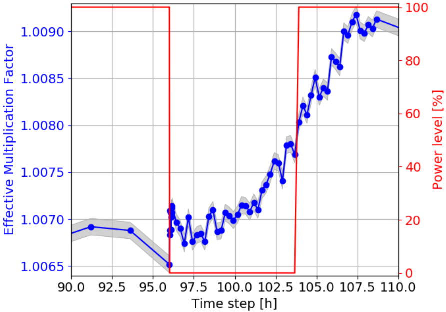

Figure 8: Multiplication factor for TAP after shutdown ($\sigma \pm 7.5$pcm shaded).

1. $-1500pcm$ reactivity insertion due to ^{135}Xe poisoning
2. k_∞ reached local minima $\approx$ 7 hrs after shutdown
3. overall reactivity swing $1750pcm$

1. $+130pcm$ reactivity insertion because loss of ^{135}Xe from decaying to ^{135}Cs is larger than gain from ^{135}I decay
2. k_∞ has no local minima
3. overall reactivity swing $270pcm$

Fuel salt composition dynamics

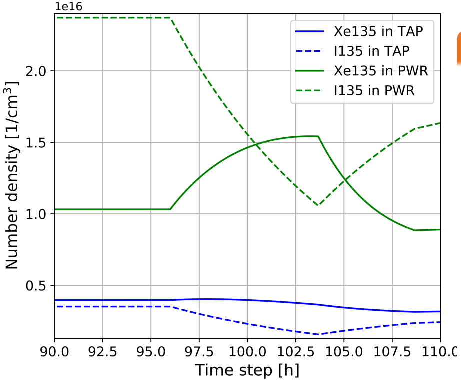

Figure 9: Atomic density of ^{135}Xe and its main precursor (^{135}I) after shutdown.

Why no poisoning effect?

1. ^{135}I/^{135}Xe number density ratio is 2.3 (PWR) and 0.9 (TAP)
2. ^{135}I half-life 6.6h $<$ ^{135}Xe half-life 9.2h
3. PWR accumulated significant ^{135}I inventory which caused large xenon concentration peak (150%)
4. In TAP, ^{135}Xe gain from ^{135}I decay did not overcome ^{135}Xe decay loss
5. Maybe because the neutron spectrum is different?

Neutron spectra of PWR vs TAP

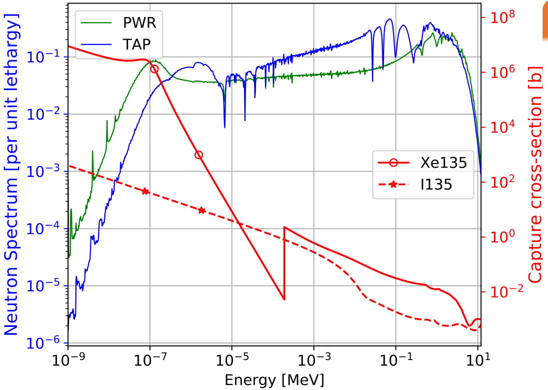

Figure 10: Neutron spectra normalized by lethargy for the PWR and TAP vs. ^{135}Xe and ^{135}I caption cross-section.

Why different ^{135}I/^{135}Xe balance?

1. TAP at beginning-of-life has much harder spectrum than PWR
2. Harder neutron spectrum leads to weaker ^{135}Xe transmutation to ^{136}Xe due to **strong energy dependence of the capture cross-section**
3. $\sigma_{(n,c)}$ slope is much steeper for ^{135}Xe than for ^{135}I

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Conclusions

Main outcomes

1. The neutron energy spectrum at the beginning-of-life (BOL) for the TAP eactor is **fast** ⇒ **gas removal system can be disabled** at BOL
2. The spectrum becomes **more thermal** during operation due to **increasing moderator-to-fuel ratio** ⇒ the xenon gas removal system **must operate** to enable load-following
3. Multiplication factor during depletion simulations for postulated load-following transient demonstrated following dynamics:
    - For PWR, dropped rapidly after shutdown; reached maximum poisoning effect $(-1500pcm) \approx 7$ hours after shutdown
    - For TAP concept, very small change in k_{eff}, no effect of ^{135}Xe poisoning was observed
4. **PWR**: the drop happened because $m_{^{135}I}/m_{^{135}Xe} = 2.3$ and ^{135}I decays to ^{135}Xe faster $(\tau_{1/2} = 6.6h)$ than ^{135}Xe decays to ^{135}Cs $(\tau_{1/2} = 9.17h)$
5. **TAP MSR**: no poisoning effect because $m_{^{135}I}/m_{^{135}Xe} = 0.9$

Future work

Future research effort

1. Investigate the impact of xenon poisoning for the TAP concept at the end-of-life (EOL), which night have softer neutron spectrum
2. Take into account gas removal system using the online reprocessing tool SaltProc [8, 9]
3. Take into consideration the TAP design adjustable moderator-to-fuel ratio
4. Develop a fuel processing system that enables load-following in a various commercial thermal molten salt reactors:
   - Terrestrial Energy Integral Small Modular Reactor
   - ThorCon Small Modular Reactor
5. Analyze multi-physics transients using the coupled neutronics/thermal-hydraulics code Moltres [10]

Acknowledgement

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- Anshuman Chaube, Alvin Lee (University of Illinois at Urbana-Champaign).

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