A Preconceptual Design of an Inverted Stable-Salt Reactor

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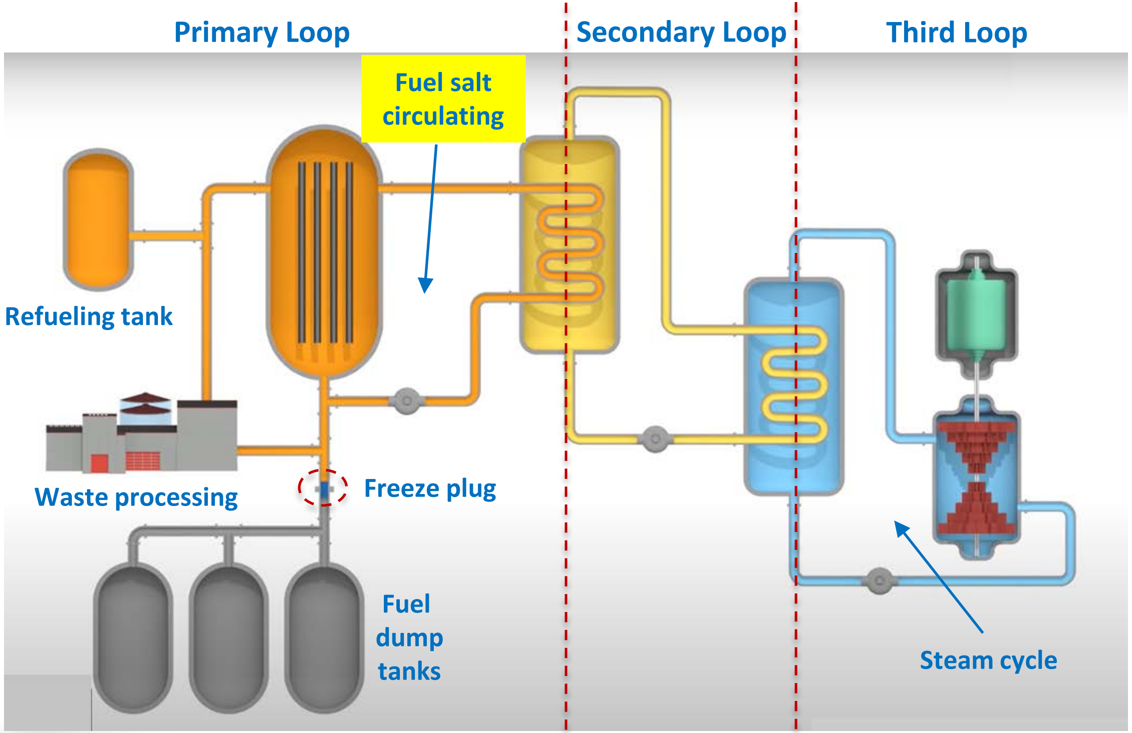
Molten Salt Reactor (MSR)

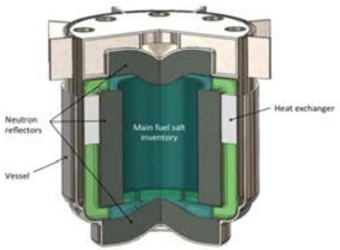


Advantages of MSR:

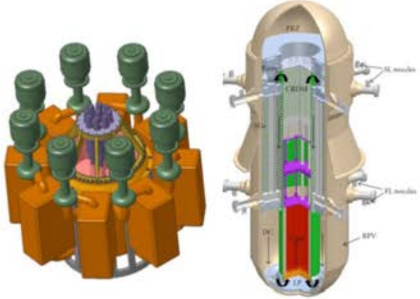
- High operation temperature
- Low operation pressure
- Fuel flexibility
- Versatile spectrum design (fast or thermal reactor)
- Burn TRU and MA
- Nonproliferation
- No fuel melting concern
- Homogeneous design
- Continuous online refueling

Figure courtesy of one undermined online resource

Concurrent MSR Designs by Industry



TerraPower
MCFR

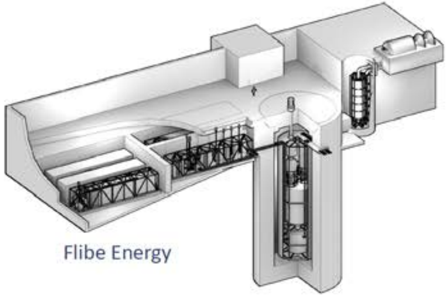


Elysium USA, MCSFR

Fast Reactors

Terrestrial Energy
IMSR

ThorCon Power



Flibe Energy

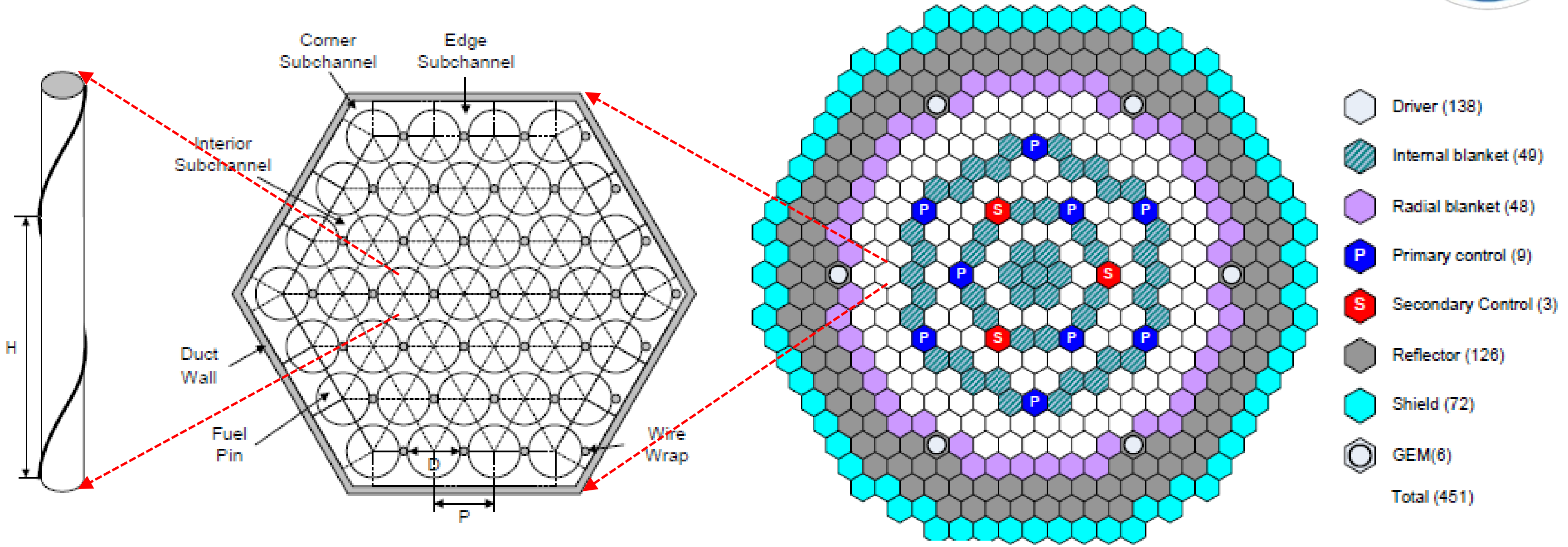
Thermal Reactors

Figure courtesy of the US DOE NEUP FY20 RC-1 Presentation

What is Stationary MSR and Why?

- Stationary MSR indicates the fuel salt is constrained in the core region.
- No radiative fuel outside of core, particularly the heat exchangers are not highly radioactive, which renders big maintenance advantage.
- No off-gas challenge: there is enough holdup in core to decay away the very short-lived radionuclides (such as xenon), so the off-gas system only deals with the longer-lived isotopes (such as krypton). These features help operations, which is a non-trivial challenge in the real world.
- Enables a traditional fast reactor design with a large prompt negative temperature coefficient due to expansion of the liquid fuel with temperature.

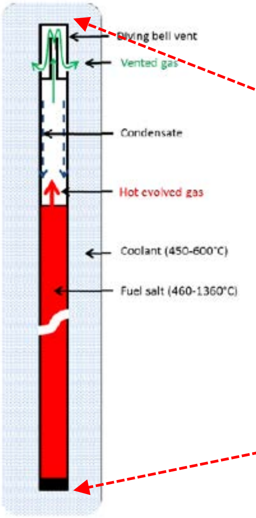
A Typical Sodium-cooled Fast Reactor (SFR)



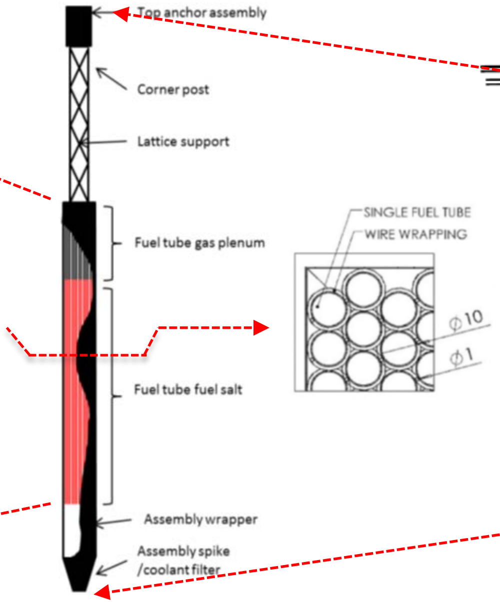
Fuel Rod **Fuel Assembly** **SFR Core Configuration (top-down view)**

Figures courtesy of one ANL Technical Report on SFR

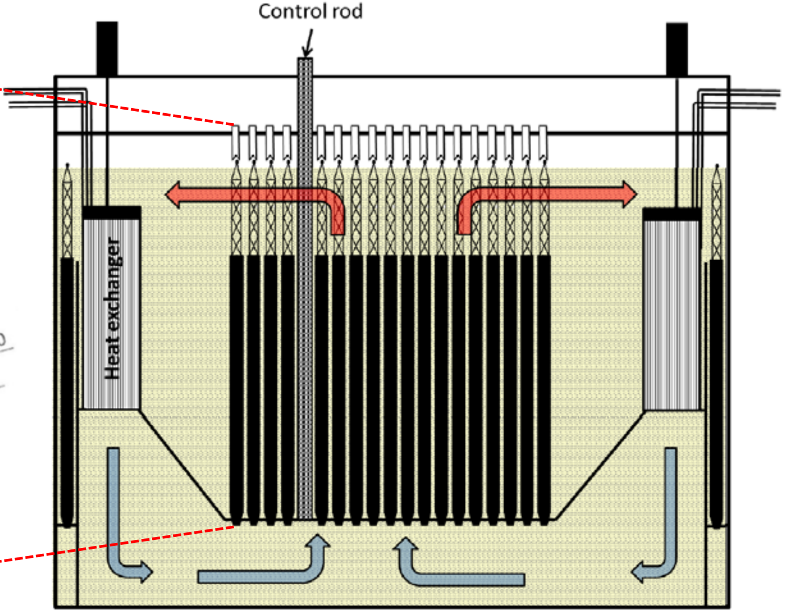
Moltex - Stable-Salt Reactor (SSR)



Fuel Tube



Fuel Assembly

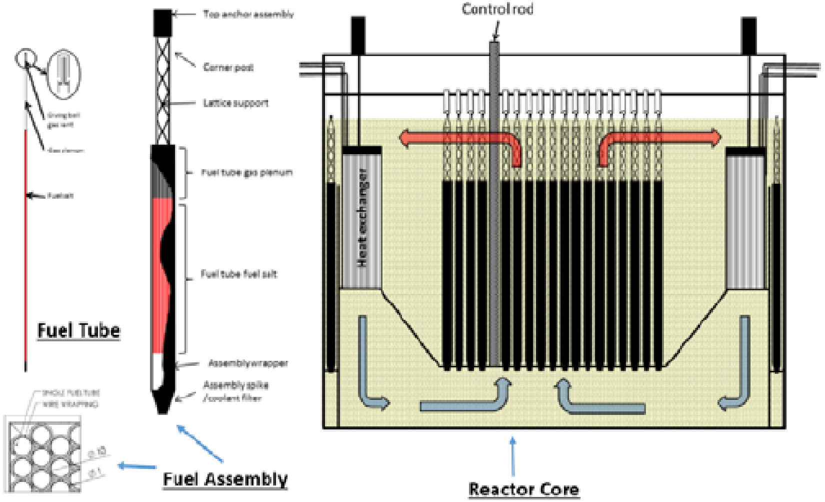


SSR Core Configuration (side view)

Figures courtesy of one IAEA Report on SMR

SSR basically Marries MSR and SFR

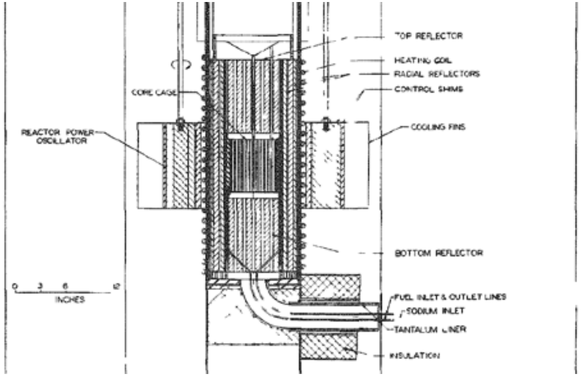
- Derived from the solid fueled SFR
- Represents the most cutting-edge technique in the realm of stationary MSR
- Costs of the SSR are envisioned to be extraordinarily high
- Completely heterogeneous design
- Hard to perform online refueling
- Fuel drain tank is not applicable



Non-Flowing Molten Metallic Fueled SFR

LAMPRE Project by LANL in 1950s - 1960s

- Los Alamos Molten Plutonium Reactor Experiment (LAMPRE).
- Initially designed with a tube-shell arrangement, in which the liquid plutonium fuel is located on the outside of the tubes in a single connected region, while the sodium coolant flows through the tubes welded to the top and bottom plates of a cylindrical container.
- Kiehn, "LAMPRE, A Molten Plutonium Fueled Reactor Concept," LA-2112, Los Alamos Scientific Laboratory (1957).



Re-visited by INL in 2000s

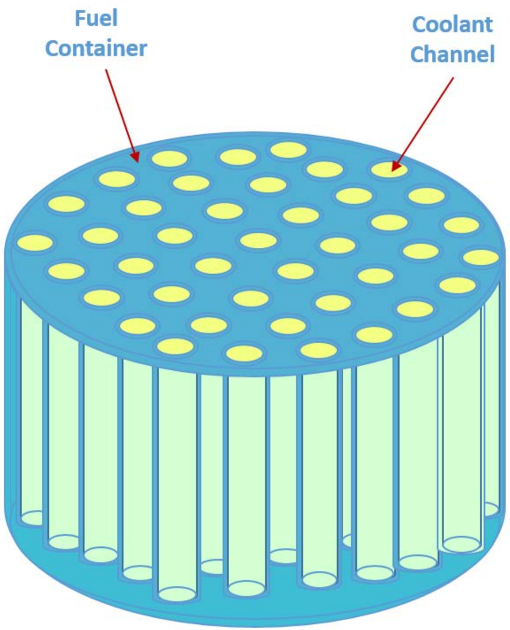
- Palmiotti & Feldman, "Fast Flux Fluid Fuel Reactor: A Concept for the Next Generation of Nuclear Power Production," *Trans. Am. Nucl. Soc.*, **81**, 279 (1999).

Most recently, SLFFR Project by Purdue University (2013-2015)

- Yang et al., "Stationary Liquid Fuel Fast Reactor," Final report, DOE NEUP Project (September 2015).

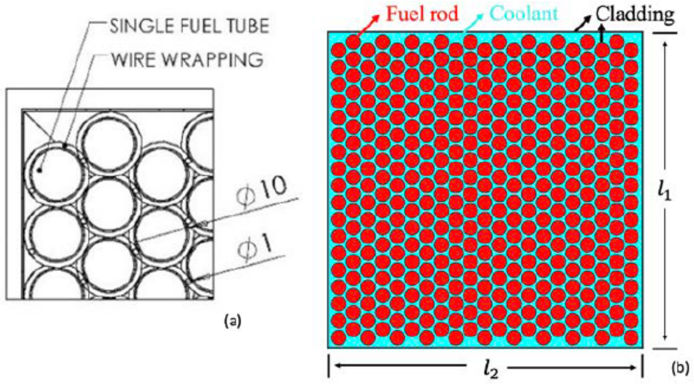
The Inverted SSR Design

- Inspired by the LAMPRE and SLFFR design
- Inverted SSR core is designed with a tube and shell heat exchanger pattern
- The molten fuel salt is constrained within a closed large volume container, while the coolant salt flows through the coolant channels penetrating the container
- It achieves a homogeneous core that enables online-refueling and fuel dumping safety features
- A much-simplified core configuration anticipating a decreased capital cost in fuel fabrication and structure manufacturing

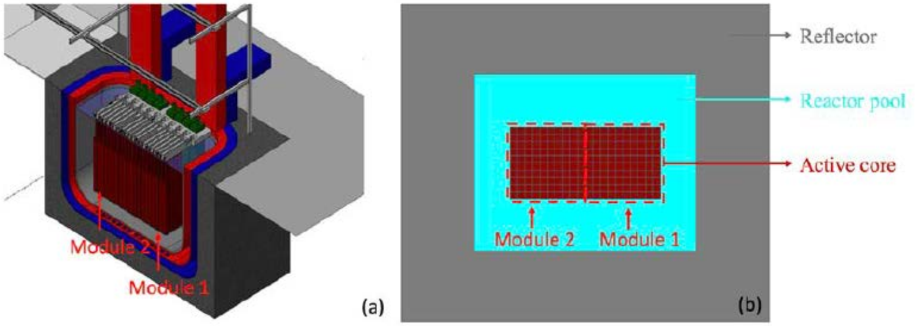


A schematic view of the inverted SSR

Neutronics Model – Reference SSR-W (Waste)



A schematic of (a) the SSR-W fuel assembly and (b) its Serpent model.

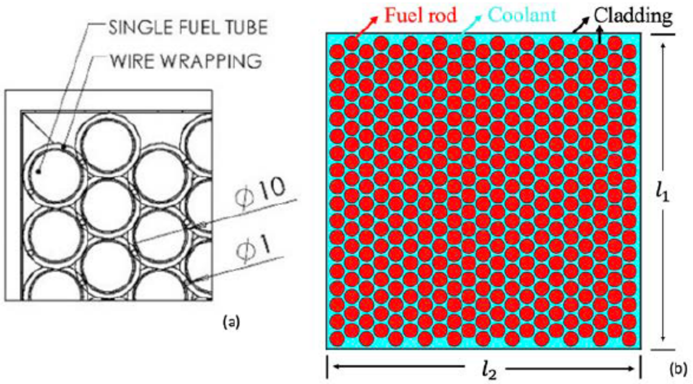


A schematic of (a) the SSR-W core and (b) the Serpent model (top view).

Materials used in the model:

- Fuel salt - consisted of 60 mol% of NaCl, 20 mol% of $PuCl_3$, and 20 mol% of UCl_3 . Uranium was modeled as pure ^{238}U for simplicity, and the abundance of different Pu isotopes in SNF of typical PWR was used
- Coolant salt - consisted of 48 mol% of KF, 10 mol% of NaF, 40 mol% of ZrF_4, and 2 mol% of ZrF_2
- HT-9 steel - fuel tube and fuel assembly cladding material
- SS-316L stainless steel (SS) - core module wall material

Neutronics Analysis Result – SSR-W



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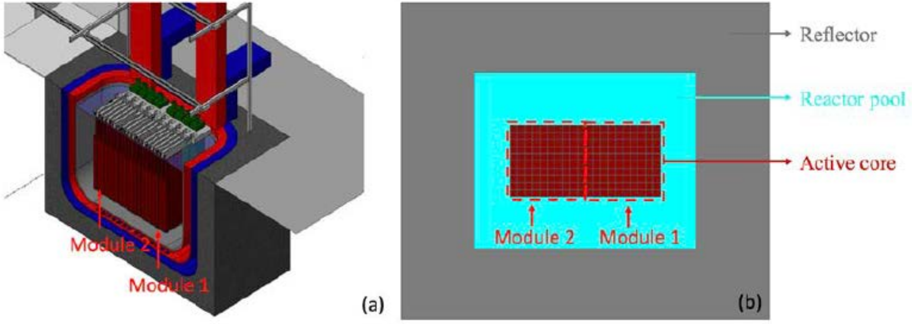

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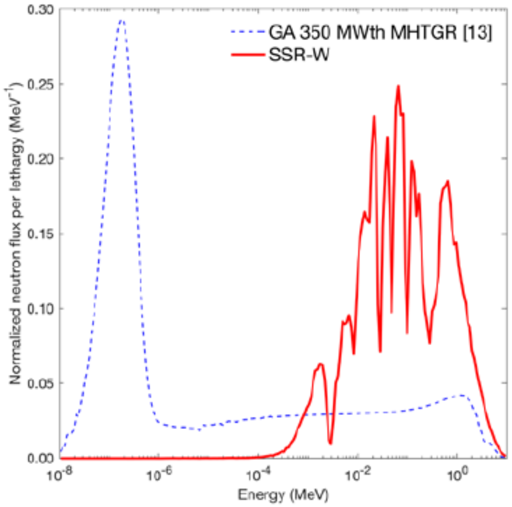
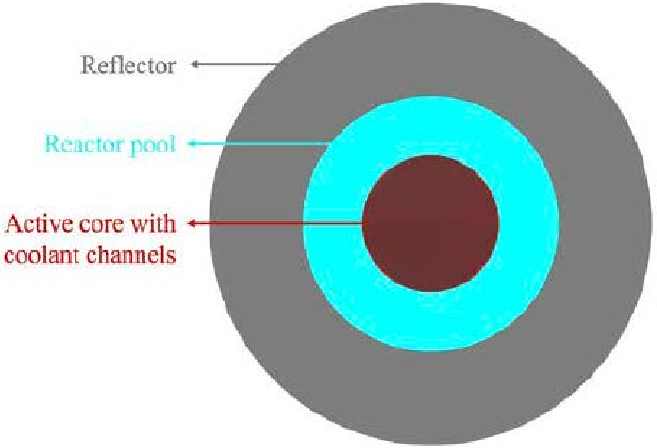
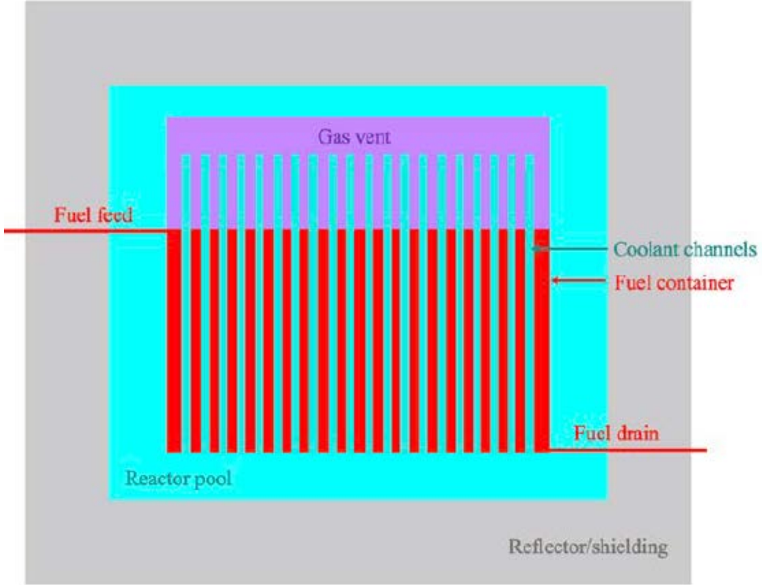


- The neutron spectra compared to HTGR clearly revealed the fast-spectrum nature of the SSR-W.
- Calculated k_{eff} = 1.44446 ± 0.00009

Neutronics Model – Inverted SSR



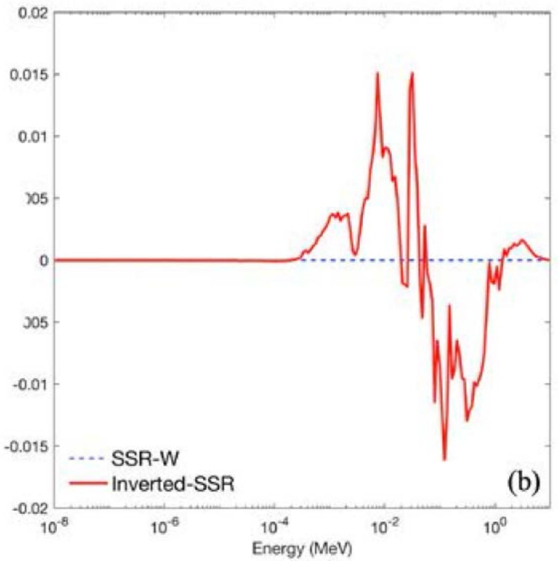
The Serpent neutronics model of the inverted SSR (top view)



The configuration inside the inverted SSR (side view).

Neutronics Analysis Result – Inverted SSR

- The k_{eff} of the inverted SSR was calculated to be 1.44816 ± 0.00009, which was 370 pcm larger than that of the SSR-W with same fuel components of SNF.
- The moderator-to-fuel ratio in the active core of the inverted SSR was ~0.6, while that in the active core of the SSR-W was ~0.5.
- The higher moderator-to-fuel ratio led to a softer neutron spectrum in inverted SSR (see the right figure), which partly contributes to the better neutron economy but may not be advantageous in SNF burning.



Spectra deviation between SSR-W and inverted SSR

T/H Analysis – Reference SSR-W

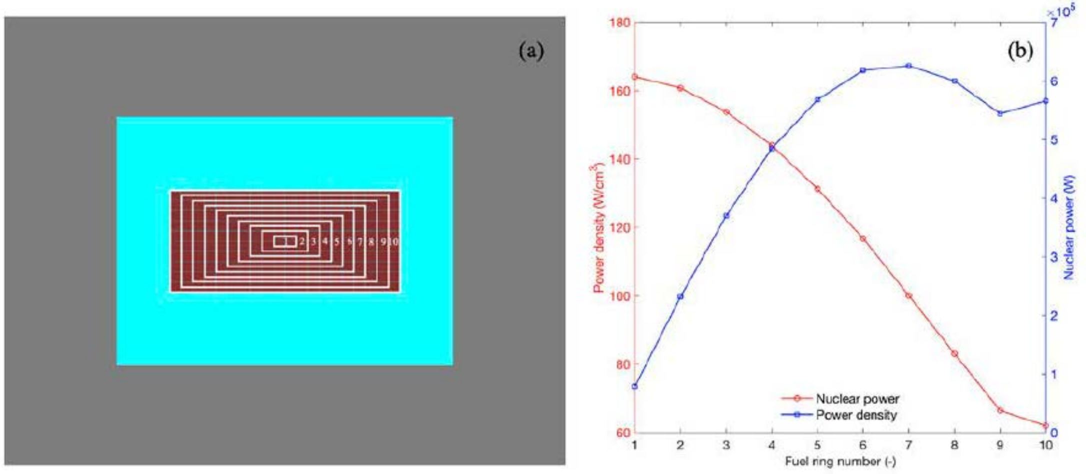
Maximum fuel temperature

- Analytic heat transfer models

$$T_{f,r} = T_{f,m} - \frac{q'''r^2}{4k_f},$$

$$q' = \frac{2\pi k_c (T_{c,i} - T_{c,o})}{\ln(1+b/a)}.$$

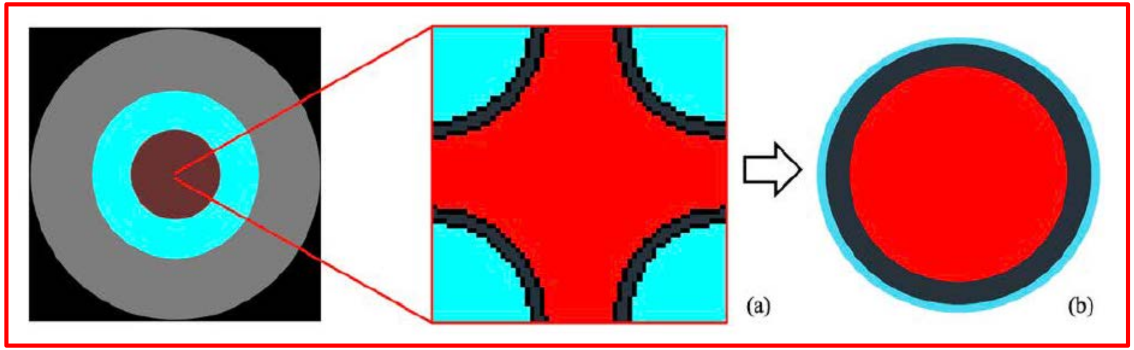
- $q'''$and q' calculated accordingly based on the 10 concentric fuel rings model (see the right figure)
- Max fuel temperature 2292 ℃.



(a) The 10 fuel rings of the SSR-W and (b) the corresponding nuclear power and the power density.

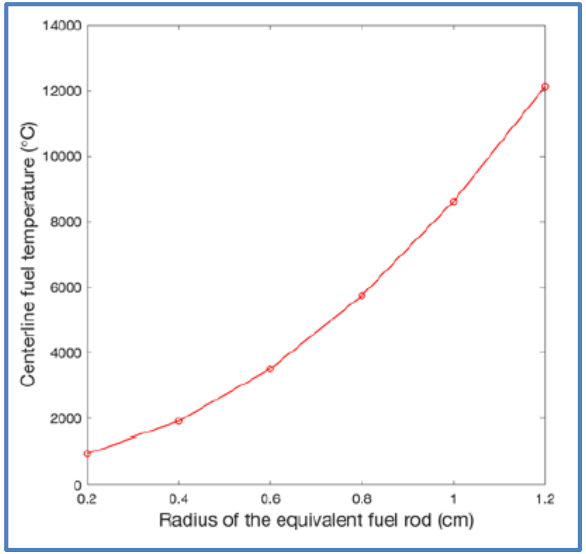
Maximum q'''=164 W/cm^3

T/H Analysis – Inverted SSR (1/2)



(a) The unit cell of the inverted SSR active core and (b) the equivalent fuel rod.

Centerline fuel temperature as a function of the radius of the equivalent fuel rod

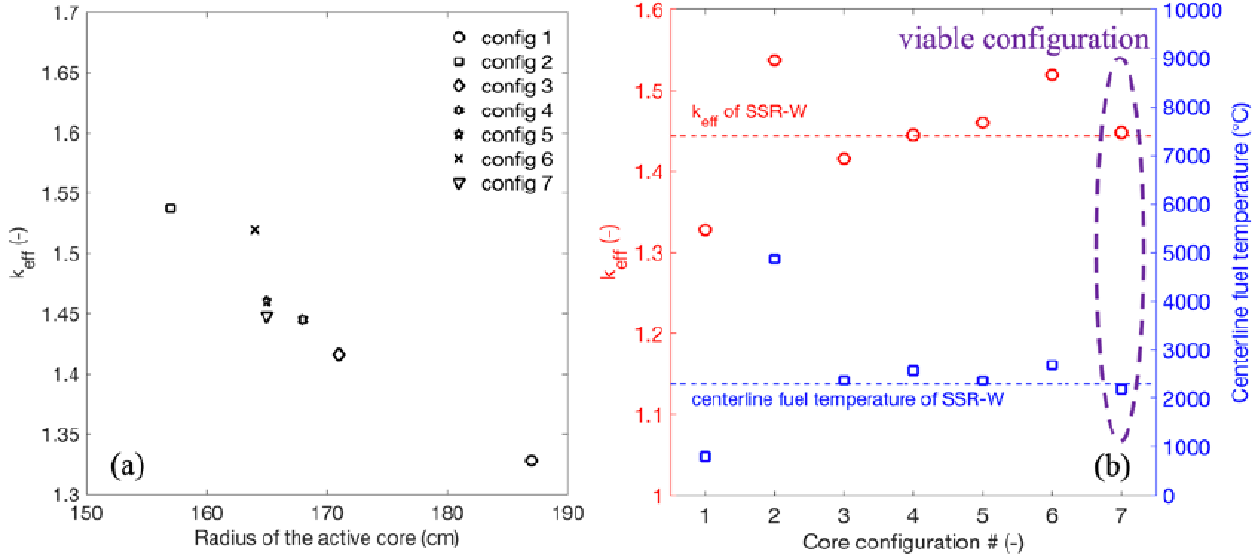


T/H Analysis – Inverted SSR (2/2)

Configuration Scoping for Inverted SSR Cores based on Max Fuel Temperature

Config.	Number of coolant channels (-)	Diameter of coolant channels (cm)	Pitch of coolant channels (cm)	Radius of equivalent fuel rods (cm)	Radius of active core (cm)	k_{eff}	Max. fuel temp. (°C)
1	30884	1.5	1.625	0.448	187	1.32791	808
2	30884	1.0	1.625	0.733	157	1.53763	4868
3	69453	0.8	1.15	0.467	171	1.41605	2375
4	69453	0.76	1.14	0.478	168	1.44515	2575
5	69453	0.72	1.1	0.466	165	1.46043	2367
6	69453	0.7	1.15	0.511	164	1.51945	2687
7	71901	0.715	1.08	0.453	165	1.44816	2193

A Trade-off between Neutronics and T/H



(a) k_{eff} as a function of the radius of the active core and (b) the k_{eff} and the maximum fuel temperature of the seven example inverted SSR core configurations.

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Conclusions

- A preconceptual design of one novel inverted stable-salt reactor is presented.
- One viable core configuration of the inverted SSR is identified based on a trade-off of neutronics and T/H analysis.
- Preliminary calculations are performed to demonstrate the physics feasibility of the design.
- Lower capital cost is anticipated for the novel design
- Many future investigations are needed for further justifcations