SnT 2023

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

HOFBURG PALACE - Vienna and Online

19 TO 23 JUNE

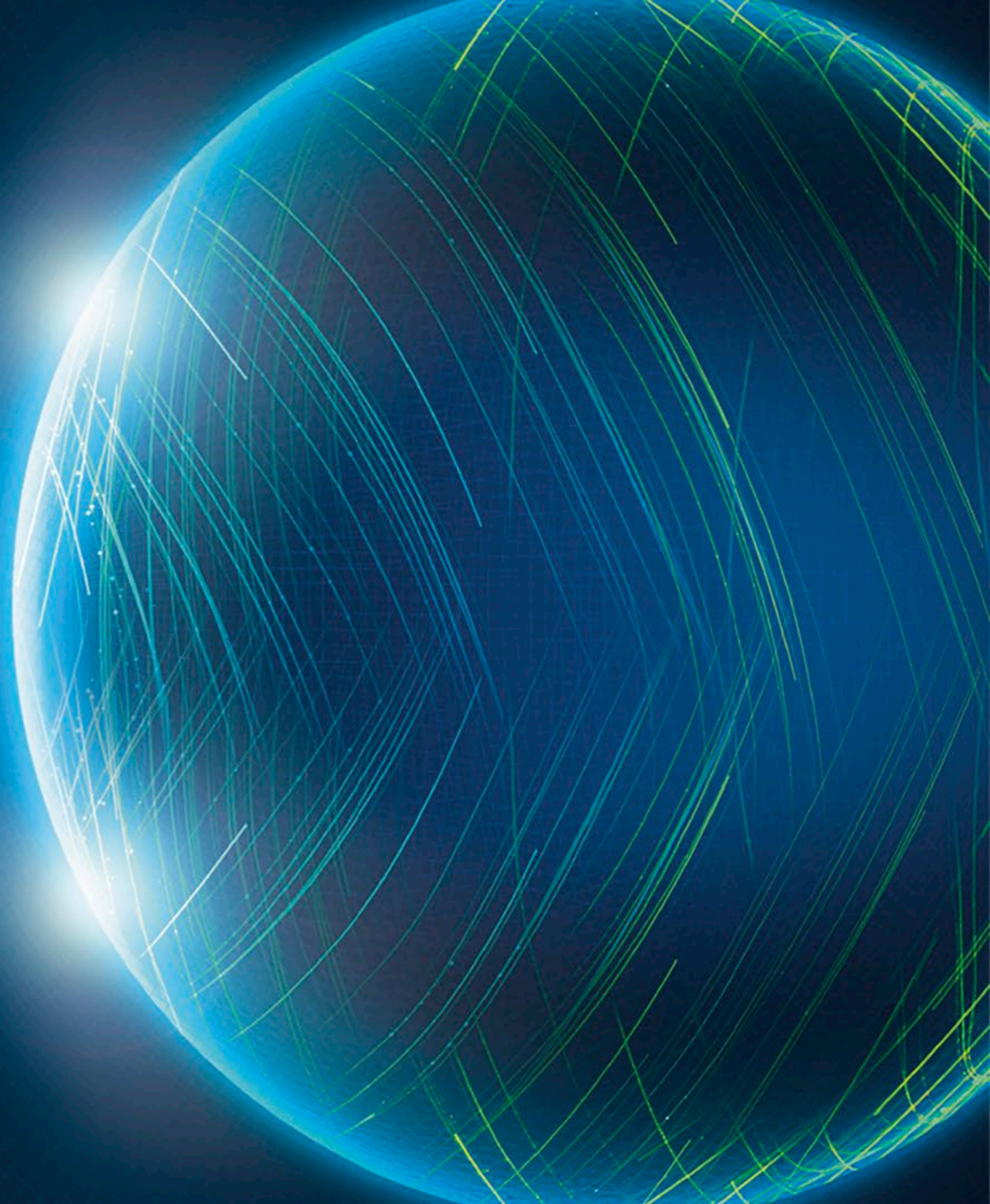
Potential impact of molten salt reactors on radionuclide stations of the International Monitoring System

Johnathan Slack, Christine Johnson, Manish Sharma, Cheslan Simpson, Jonathan Burnett

Pacific Northwest National Laboratory

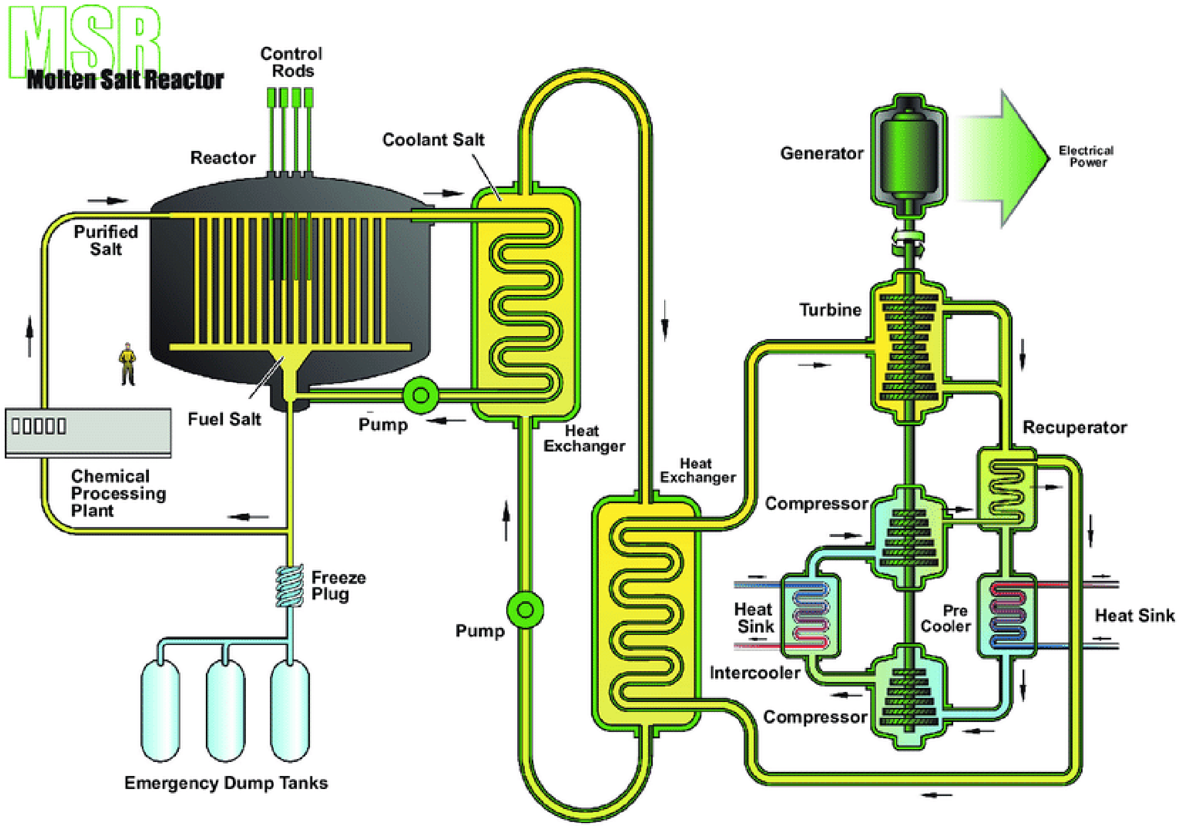
O2.4-393

20 June 2023



Abstract

Molten Salt Reactors (MSRs) are a Generation IV nuclear reactor design that are currently under development and testing in various countries around the world. The molten fuel provides an opportunity for continuous processing of gaseous fission products which may impact the International Monitoring System (IMS). Simulations were performed for four MSR designs to predict the production of IMS-relevant radionuclides during batch and continuous reprocessing schemes. Radioxenon and radioiodine signatures were drawn from these simulations and compared to current reactor designs (Boiling Water Reactor (BRW), Pressurized Water Reactor (PWR), High-Power Channel Type Reactor (RBMK)). For the case of continuous reprocessing of the fuel salt, the radioxenon and radioiodine signatures were found to be indistinguishable from a nuclear explosion.

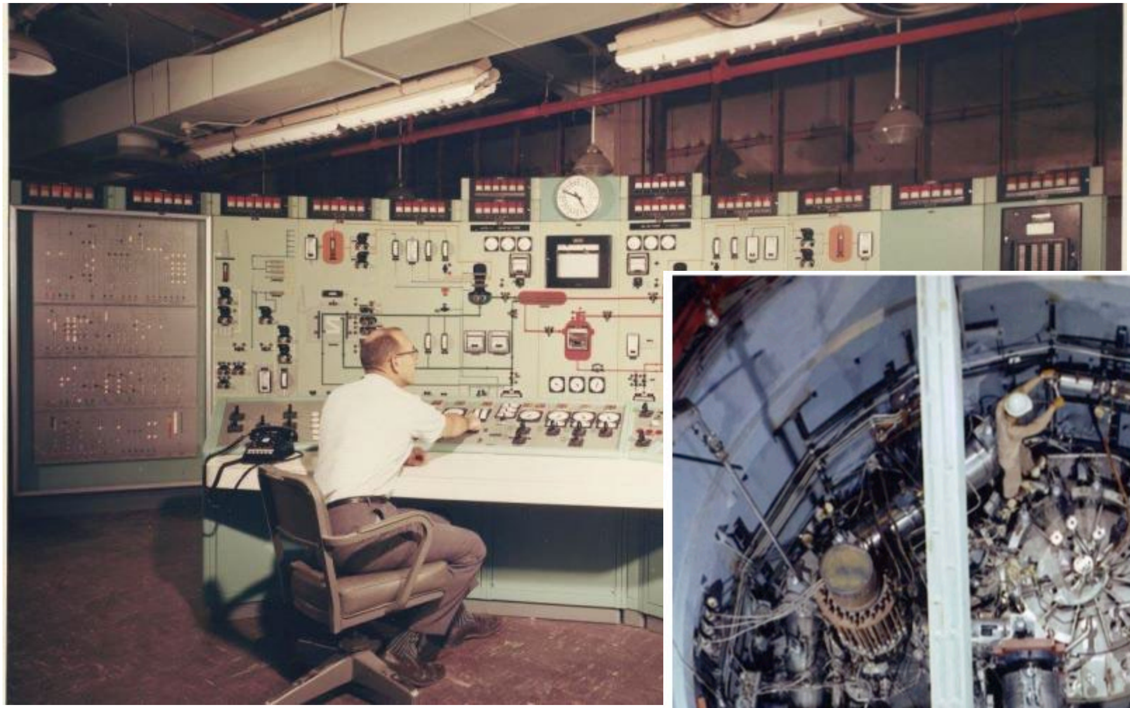


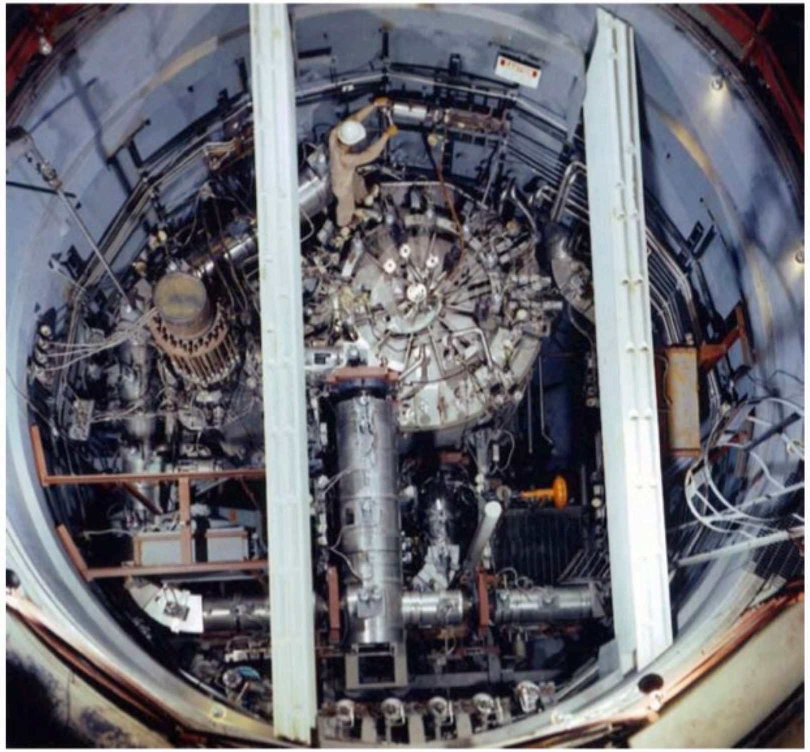
GenIV Forum generalized schematic

Historical Examples

Oak Ridge National Laboratory built and operated two MSR’s

- Aircraft Reactor Experiment (ARE)
  - Operational in 1954
  - Power levels up to 2.5 MW
  - Ran for 221 hours
- Molten Salt Reactor Experiment (MSRE)
  - Power output up to 7.4 MW
  - First campaign with ^{235}U starting in 1965
  - Second campaign with ^{233}U from 1968-1969
  - More than 13,000 hours of full power operation

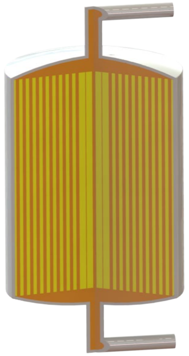




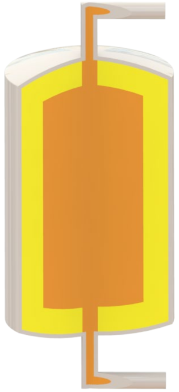
(Rosenthal, 2010)

Designs Under Consideration

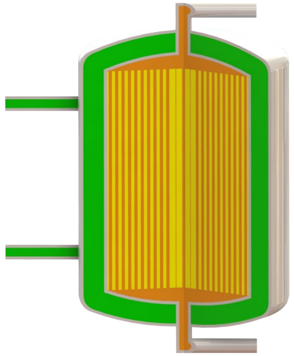
Graphite Moderated Thermal



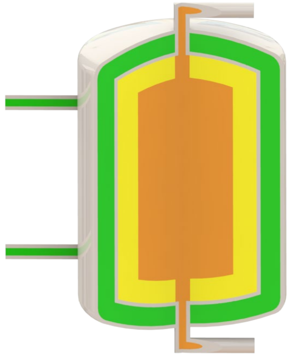
Graphite Reflected Fast



Dual Fluid Thermal



Dual Fluid Fast



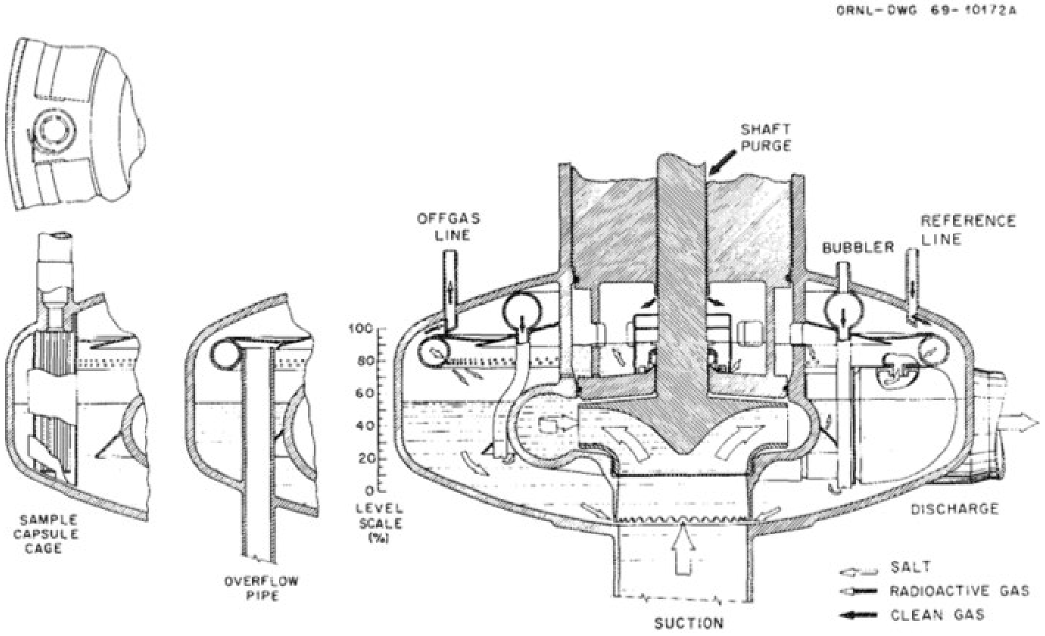
Reactor Category	Neutron Spectra	Thorium Breeding	TRU or MOX Burning	Examples	References
Graphite Moderated Thermal	Thermal	Optional (thorium in the fuel salt)	Potential	MSRE (USA) **TMSR (China)** ThorConIsle (USA)	(Haunbenreich and Engel,1970) (Zhou et al., 2020) (Lumbanraja and Liun, 2018)
Graphite Reflected Fast	Intermediate/Fast	Optional	Yes	**MOSART (Russia)** MSFR (EU) MCFR (USA)	(Ignatiev et al., 2015) (Lecce, 2018) (Sgro, 2018)
Dual Fluid Thermal	Thermal	Optional (thorium in a blanket salt)	Potential	LFTR (USA) CMSR (Denmark) **MSBR (USA)**	(IAEA, 2016) (Pater, 2019) (Rosenthal et al., 1972)
Dual Fluid Fast	Intermediate/Fast	Optional	Yes	IMSBR(India) **DFR (Germany)**	(Vijayan et al., 2015) (Huke et al., 2015)

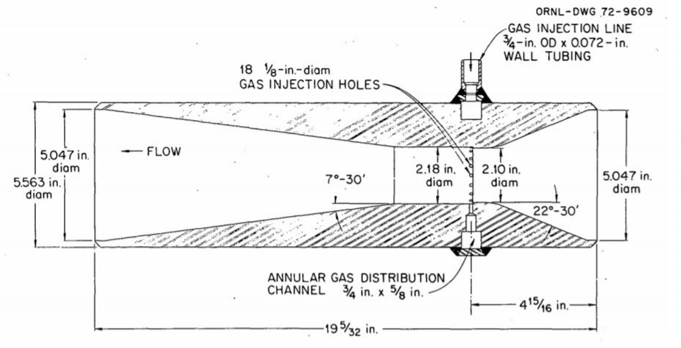
Gaseous Fission Product Sparging

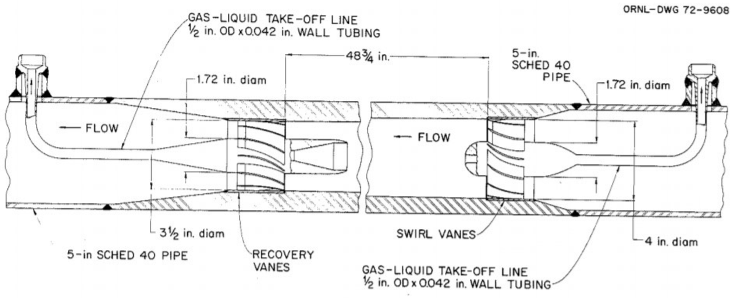
During the MSRE at Oak Ridge, fission products were sparged in the pump bowl in a parallel process with the sparge gas.

Fuel salt enters the pump bowl → Pumped upwards through the spray ring → Sprayed down into the pool of fuel salt → Cycled out through the discharge port

Helium enters in the head space → Entrained into the salt by the pressurized jet → Circulated through the system absorbing gaseous products → Bubbles are stripped by the pressurized jet







(Robertson, 1965)

Some newer designs create helium voids in the salt with a Venturi bubble generator. They are then stripped using a liquid-gas separator. Sparged gasses are then separated and held up in an abatement system.

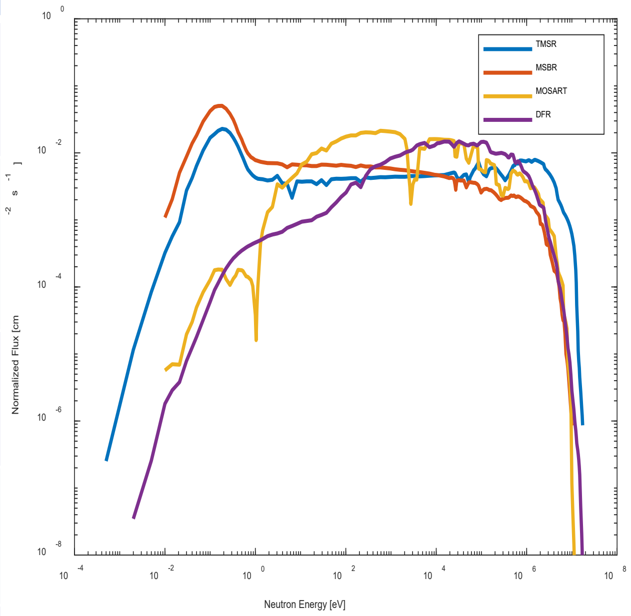
Reactor Simulations

The four MSR's of interest were modeled using parameters derived from the literature, where available.

- Simulations constructed using the COUPLE and ORIGEN modules of SCALE
- Only the fuel salt was considered
- Simulated with neutron spectrum at reactor equilibrium

Reactor	Fuel Salt Composition [mol %]	Fuel Salt Volume [m^3]	Fuel Salt Density [g/cc]	Neutron Flux in Fuel [n/cm^2 sec]	Power [MWth]	Reference
TMSR-LF1	65.39% ^{7}LiF (99.95% enriched ^{7}Li) 28.34% BeF_2 4.72% ZrF_4 1.55% UF_4 (19.75% enriched U)	2	2.307	1.3×10^{13}	2	(Liu et al., 2020; Zhou et al., 2020a)
TMSR-LF1 thorium	65.64% ^{7}LiF (99.95% enriched ^{7}Li) 27.27% BeF_2 4.54% ZrF_4 1.55% UF_4 (19.75% enriched U) 1% ThF_4	2	2.412	1.3×10^{13}	2	(Liu et al., 2020; Zhou et al., 2020a)
MSBR	71.75% ^{7}LiF (99.95% enriched ^{7}Li) 16% BeF_2 12% ThF_4 0.25% UF_4	48.7	3.35	1.5×10^{15}	2250	(Robertson, 1971; Rykhlevskii et al., 2019)
MOSART	15% ^{7}LiF (99.99% enriched ^{7}Li) 27% BeF_2 58% NaF 0.7% UF_3†	40.4	2.163	1×10^{15}	2400	(Ignatiev et al., 2007; Sheu et al., 2013)
DFR	75% ^{37}Cl 19.586% ^{238}U 5.414% Mixed Pu†	48.7*	3.532	1.5×10^{15}*	3000	(Huke et al., 2015; Wang and Macian-Juan, 2018)

***No value found in the literature. Uses the value for the MSBR from (Rykhlevskii et al., 2019).**
†Actinide breakdown can be found supplemental information of (Johnson, 2021).



Reactor Simulations (cont.)

Reprocessing

Liquid fuel can be removed in part or whole for chemical reprocessing and recycling

- Fluorination can separate out uranium from waste products
- Simulated MSBR and MOSART reprocessing fuel salt with removal rates calculated from literature values
- Assumed continuous reprocessing
- Rates listed are fractional of total inventory of the specified element

Sparging

Three of the four reactors included sparging (MSBR, MOSART, TMSR-LF1) for modeling.

- TMSR-LF1 removal rate of 7.84 x 10^{-4} 1/s for xenon and krypton
- Simulations assumed continuous removal

Comparison Reactors

Three traditional reactors were also simulated as a benchmark against the MSR designs.

-Boiling Water Reactor (BWR)
-Pressurized Water Reactor (PWR)
-High-Power Channel-Type Reactor (RBMK)

	Elements	Removal Rate [1/s]
MSBR		
Lanthanides (Rare Earths)	Y, La, Ce, Pr, Nd, Pm, Sm, Gd	2.32×10^{-7}
	Eu	2.32×10^{-8}
Transition Metals, Metalloids and Nonmetals	Se, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Sb, Te	5.00×10^{-2}
Transition Metals	Zr, Cd, In, Sn	5.79×10^{-8}
Gases	Kr, Xe	5.00×10^{-2}
Volatile Halogens	Br, I	5.00×10^{-2}
Actinides	Pa	3.86×10^{-6}
MOSART		
Transition Metals, Metalloids and Nonmetals	Ag, As, Cd, Ga, Ge, In, Mo, Nb, Pd, Rh, Ru, Sb, Se, Sn, Tc, Te, Zn	5.00×10^{-2}
Gases	He, Kr, Xe	5.00×10^{-2}
Soluble Fission Products	Ba, Ce, Cr, Cs, Dy, Er, Eu, Fe, Gd, Ho, I, La, Nd, Ni, Pm, Pr, Rb, Sm, Sr, Tb, Y, Zr	3.86×10^{-6}

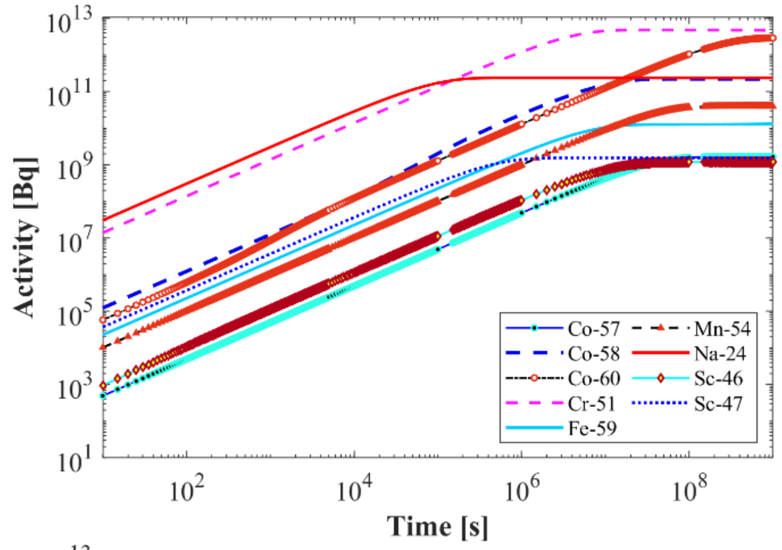
Activation Products

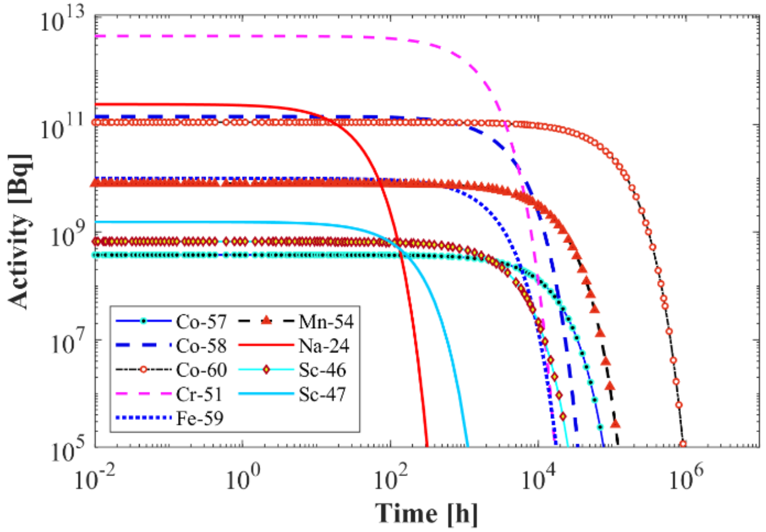
Activation of fuel salt corrosion products/impurities are an important consideration for MSR's

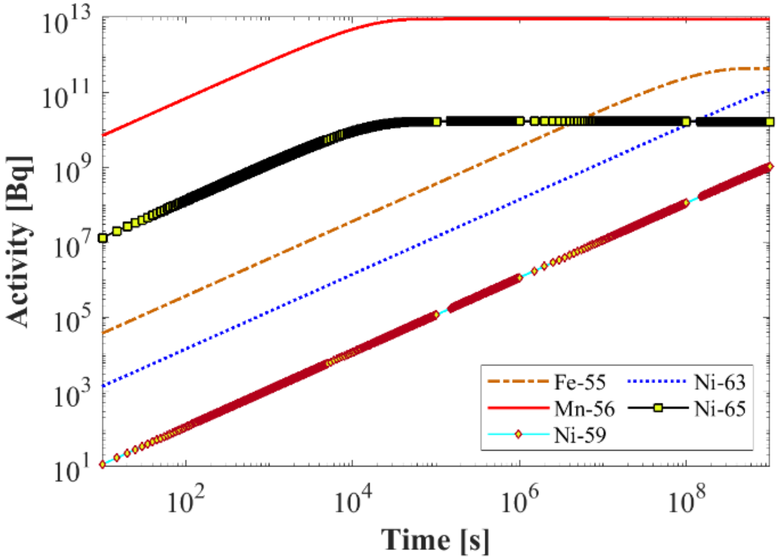
- Simulated values are for the TMSR-LF1

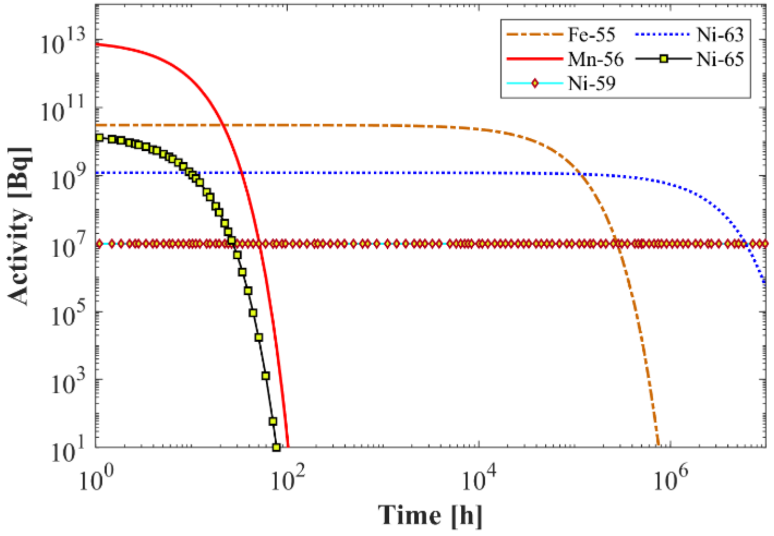
All figures are activity of activation products immediately after startup (left column) and cooldown after 100 days of irradiation (right column)

- Top Row – IMS relevant isotopes
- Bottom Row – Other activation products









Xenon and Iodine Ratios

Top left – Xenon ratios for all simulated reactors without reprocessing, refueling, or sparging

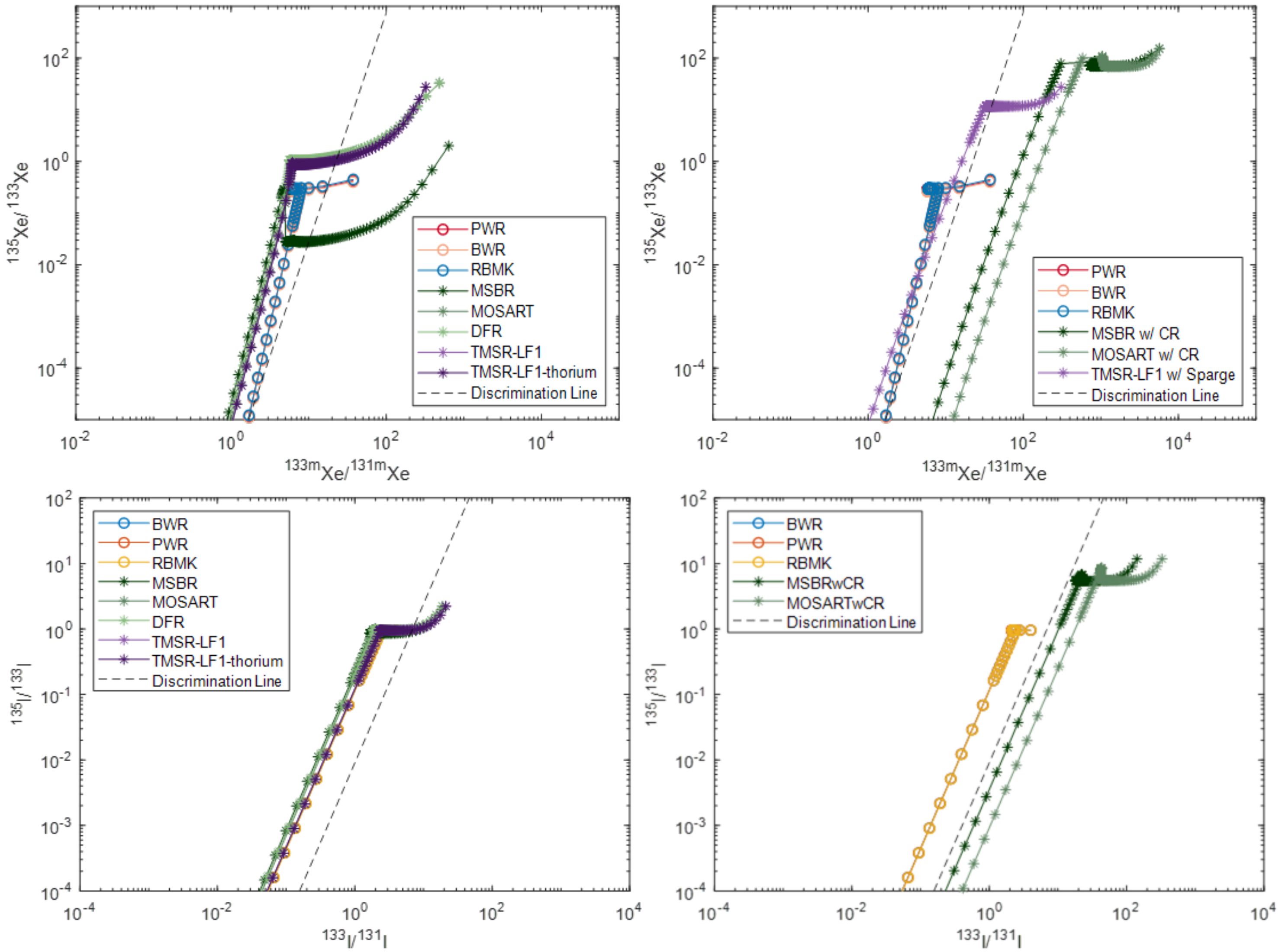
Top right – MSRs with continuous refueling and reprocessing (MSBR and MOSART) or sparging (TMSR-LF1)

Bottom left – Iodine ratios for all reactors without reprocessing or refueling

Bottom right – Iodine ratios for MSR's with reprocessing and refueling

(PWR, BWR, and RBMK lines overlap in most cases)

Conclusion: Continuous reprocessing and refueling in MSR's can create xenon and iodine ratios that remain over the discrimination line during equilibrium operation



Thank you

Published Works

Johnson, C. et al., 2021. “Modeling of Fission and Activation Products in Molten Salt Reactors and Their Potential Impact on the Radionuclide Monitoring Stations of the International Monitoring System.” *Journal of Environmental Radioactivity* 234. doi:10.1016/j.jenvrad.2021.106625.

Eslinger, P. W. et al., 2021. “Possible Impacts of Molten Salt Reactors on the International Monitoring System.” *Journal of Environmental Radioactivity* 234. doi:10.1016/j.jenvrad.2021.10662

References

Rosenthal, M. 2010. An Account of Oak Ridge National Laboratory's Thirteen Nuclear Reactors. Vol. 2009. Oak Ridge National Laboratory.

Robertson, R. C. 1965. “Msre Design and Operations Report. Part I. Description of Reactor Design.”   Oak Ridge, Tenn. pgs. 10.2172/4654707.