Safeguards assessments of Molten Salt Reactors

International Conference on SMRs & their Applications

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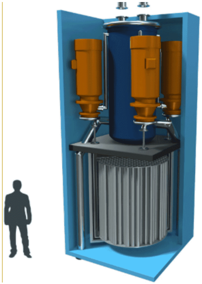
- Can function as breeders or burners; thermal, epithermal, or fast spectrum,
- Some designs may have online reprocessing achieved through removal of GVFPs.
- Conventional safeguards - adaptations for such SNF - **assess if one framework applies to all/most designs**.

The Seaborg CMSR



Images courtesy Seaborg Technologies

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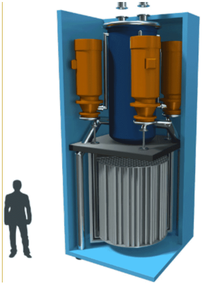

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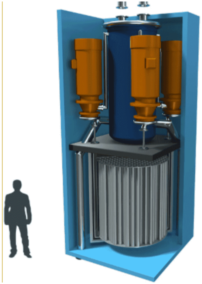

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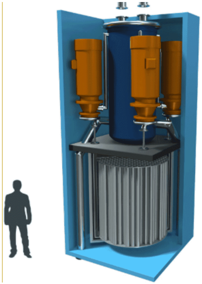

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- HA-LEU in NaF-KF_4-UF_4, NaOH as moderator,
- 250 MWth (100 MWe), thermal spectrum, converter-type, 12-year long irradiation,
- No mid-cycle refueling, on-line removal of GFPs by a designated system (OGS).

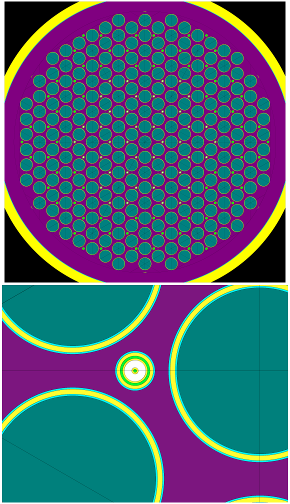
1 Introduction

2 MSR concept selection

3 Assessments
- Modeling and simulation
- Creation of datasets
- Radiation from MSR SNF
- Attractiveness of irradiated salts
- ML and MSR SNF

4 Conclusions

Calculations with Serpent



Top: Cross-section of the core. Bottom: Close-up of a fuel channel and a CR location.

- 3D model of CMSR core supplied by Seaborg,

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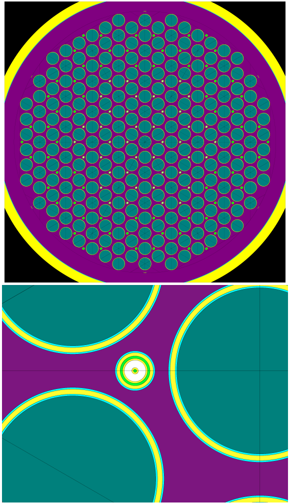

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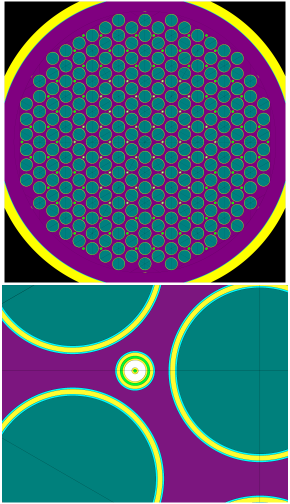

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- 3D model of CMSR core supplied by Seaborg,
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- Removal of GVFP - `reprocessor` feature in Serpent - materials moved across regions at user-defined rates.

Calculations with SOURCES 4C

Listing 1: SOURCES 4C input file structure

```
Fresh molten salt
1 2 1
5 0 ##salt composition
    3  0.3340366305
    4  0.0966776017
    9  0.5609068090
    40  0.0080008774
    92  0.0003780815
500 12.00 0.00
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Methodology

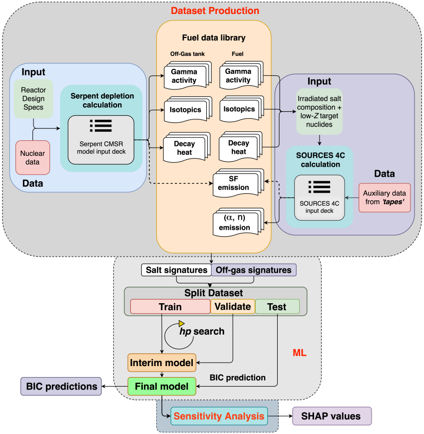

Figure 1: Methodology used for the development of the dataset(s) and subsequent analyses.

Dataset description

Table 1: Key features of the CMSR fuel dataset (with removal of GVFP).

BU ··	**IE** ··	**CT**··	**FMI**	..$\mathbf{m}_{f1}$	..$\mathbf{m}_{fM}$	..$\mathbf{m}_{t1}$	..$\mathbf{m}_{tM}$	..**SF**	..**(**α**, n)**	..**GS**$_f$	..**GS**$_t$	..**DH**$_f$	..**DH**$_t$	..**fl**$_i$	..**fl**$_k$
BU_1 ·	IE_1 ·	CT_1··	FMI_1	.m_{f11}	.m_{f1M}	.m_{t11}	.m_{t1M}	.SF_1	.$(\alpha, \mathrm{n})_1$	.GS_{f1}	.GS_{t1}	.DH_{f1}	.DH_{t1}	.fl_{i1}	.fl_{k1}
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
BU_N ·	IE_N ·	CT_N··	FMI_N	.m_{fN1}	.m_{fNM}	.m_{tN1}	.m_{tNM}	.SF_N	.$(\alpha, \mathrm{n})_N$	.GS_{fN}	.GS_{tN}	.DH_{fN}	.DH_{tN}	.fl_{iN}	.fl_{kN}

FMI: Flow Multiplier Index - removal rate multiplier for each of the 42 isotopes removed from the primary salt and moved to the off-gas tank,

m_{ij}: i^{th} isotopic mass density for j^{th} BIC combination in g/cm^3, subscripts ***f*** and ***t*** denote presence of isotope in the fuel salt and the off-gas tank resp.

SF_j: total spontaneous fission neutron emission rate from the primary salt for j^{th} BIC combination in $\frac{neutrons}{sec*cm^3}$,

$(\alpha, \mathrm{n})_j$: total (α, n) neutron emission rate from the primary salt for j^{th} BIC combination in $\frac{neutrons}{sec*cm^3}$,

GS_j: total gamma emission rate for the j^{th} BIC combination in $\frac{photons}{sec*cm^3}$, subscripts ***f*** and ***t*** denote presence of isotope in the fuel salt and the off-gas tank resp.

DH_j: total decay heat for the j^{th} BIC combination in Watts, subscripts ***f*** and ***t*** denote presence of isotope in the fuel salt and the off-gas tank resp.

fl_{ij}: removal rate for the i^{th} isotope and j^{th} BIC combination in sec^{-1}.

Gamma emissions

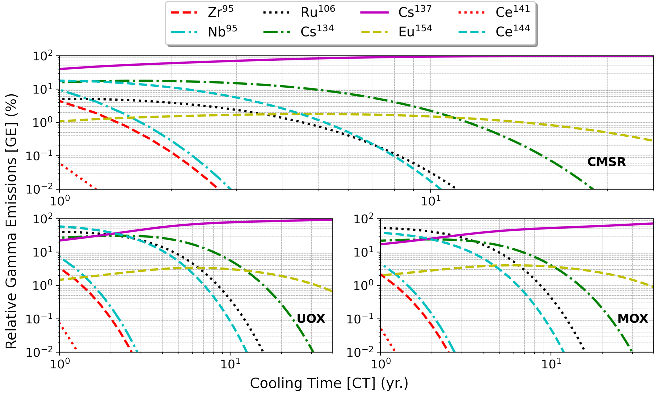

Figure 2: Percentage contributions to gamma emissions in irradiated CMSR, PWR-UOX, and PWR-MOX fuels as a function of CT.

Neutron emissions

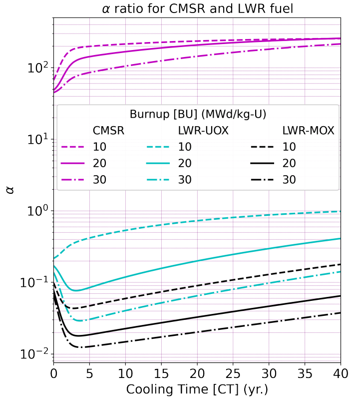

Figure 3: Comparison of α-ratio and overall neutron emission rates between fuel types.

Attractiveness metric

Formulation of an attractiveness quantifier as follows:

$$Metric = f(p_1, p_2, p_3, ..., p_N) \tag{1}$$

$$Metric \propto \sum_{i=0}^{4} M_i * \sum_{i=0}^{n} \gamma_i * \sum_{i=0}^{n} H_i * \sum_{i=0}^{n} (\eta_{SF+\alpha,n}) \tag{2}$$

Where, M_i : quantities of $^{235}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Am}$, $^{237}\mathrm{Np}$,
γ_i : total gamma emissions from the SNF material,
H_i : total decay heat produced in the SNF material &,
$(\eta_{SF+\alpha,n})$: neutron production rates from SF and (α, n).

Quantifying material attractiveness of salts

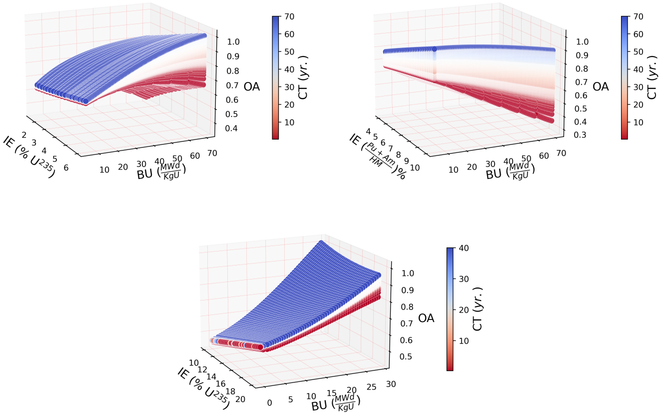

Figure 4: Comparison of the attractiveness of irradiated salts (bottom) against UOX (top left) and MOX fuels (top right).

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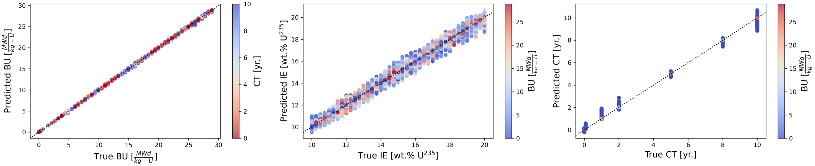
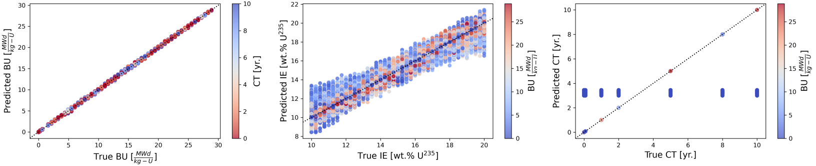
- A tree-based model was trained on one of these datasets - predict fuel salt parameters,
- Models trained separately on 1. fuel salt parameters and 2. on gaseous effluent properties.

BIC prediction with fuel salt signatures



Figures showing prediction of fuel salt **Left:** BU, **Middle:** IE, and **Right:** CT using salt signatures as input features in the ML model.

BIC prediction with off-gas signatures



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Conclusions

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- Datasets available for public use - could be useful for future work with similar reactors,
- Assessments of radiation from MSR SNF instrumental for evaluating suitability of existing NDA instrumentation,
- ML techniques - demonstrated the feasibility of verifying fuel material without directly conducting NDA on fuel,
- Other MSR concepts worth investigating (for land-based/sea-based use) - assessments related to safeguardability needed.

Thank You