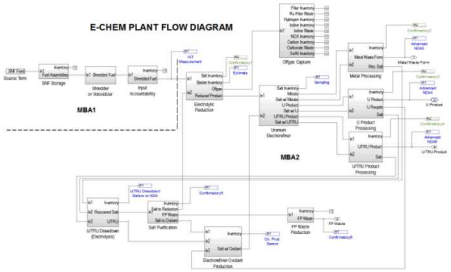
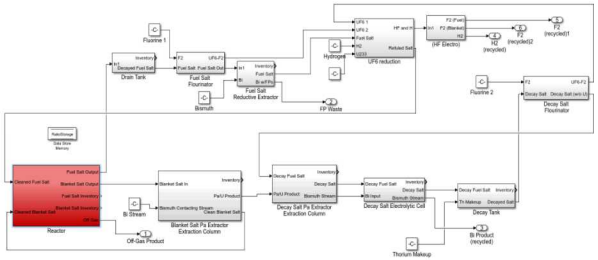
SAND2018-3074PE

Safeguards Modeling and Advanced Integration Update





PRESENTED BY

Ben Cipiti & Nathan Shoman

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Advanced Integration (Facility Models) Overview

- **Integration of SSPM-EChem with other MPACT capabilities**

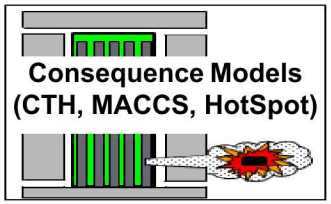
  This task focuses on how the safeguards modeling fits into the 2020 Milestone. Our plan is to use the ANL flowsheet as the baseline, adjust the SSPM based on that, include the latest data on measurement technology performance, and re-calculate the safeguards metrics.

- **Safeguards modeling expansion**

  The safeguards modeling capability was extended to Molten Salt Reactor (MSR) safeguards. Depletion was added to the Simulink modeling in order to generate more accurate results. This work is focused on liquid-fueled designs that perform salt processing on-site.

Virtual Facility Distributed Test Bed

High Fidelity Capabilities

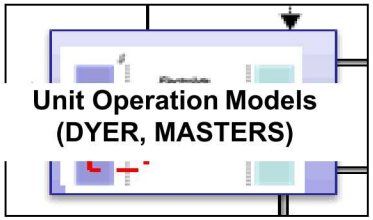


Measurement Technologies (Bubbler, Voltammetry, Microfluidic Sampler, Microcal, High Dose Neutron, Electrochemical Sensor)

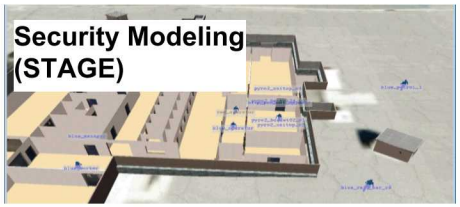
Measurement Models (NDA, MIP, etc.)

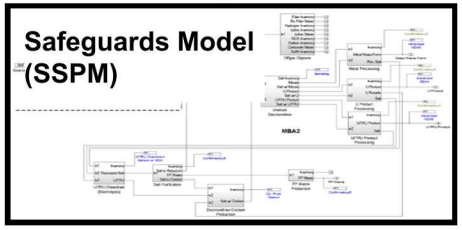
Experimental Data (IRT, Laboratory Research)

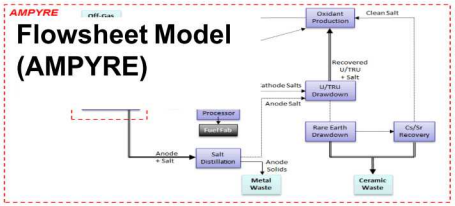
Statistical Methods (Page, Multivariate, Pattern Recognition)



Systems Level Models







Key Metrics

Probability of Success
Timeliness
Consequence

Facility Layout
Batch Timing

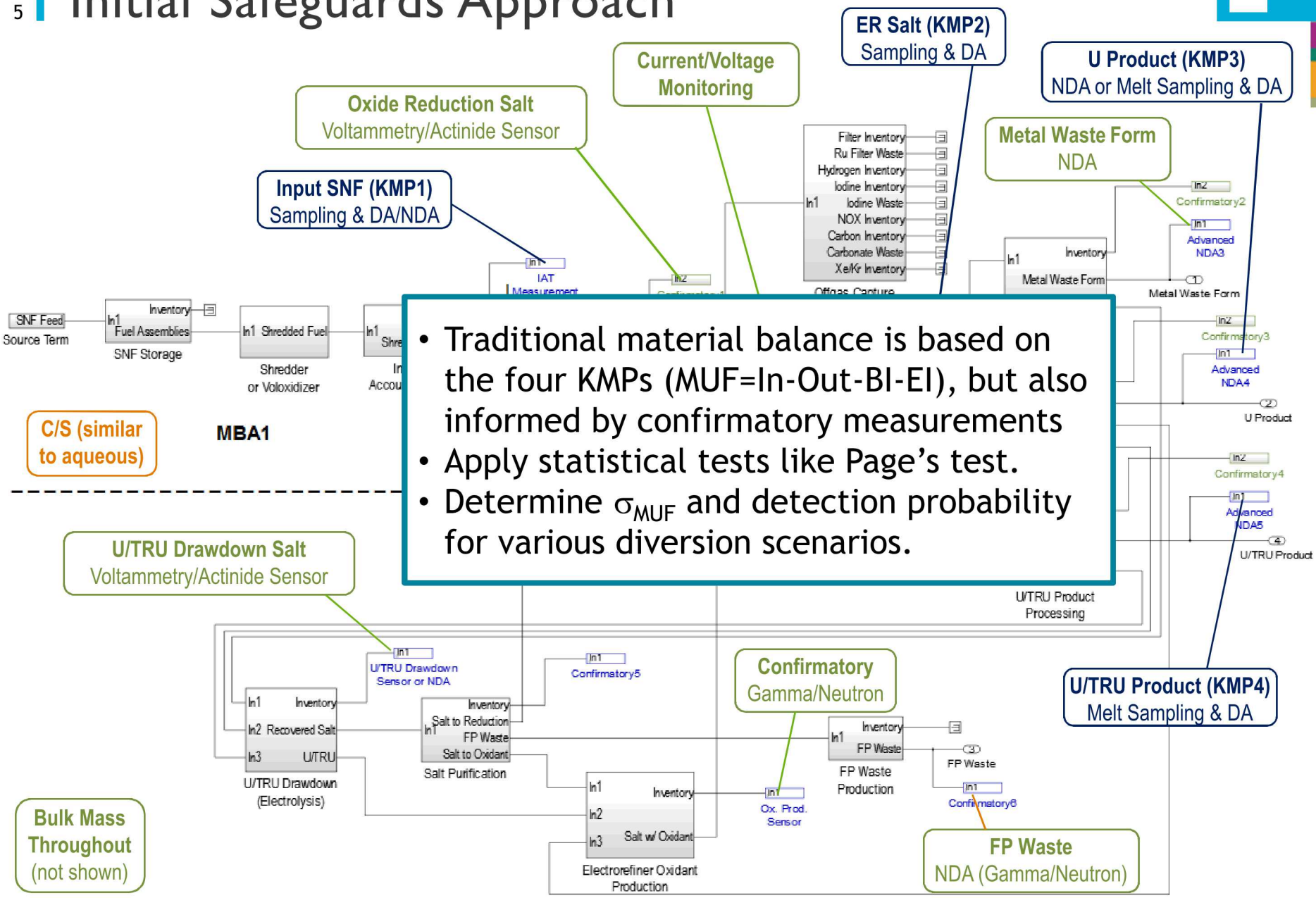
SEID (σ_{MUF})
Probability of Detection
Timeliness

Flowrates
Inventories
Separation Efficiencies

Safeguards Approach for Echem

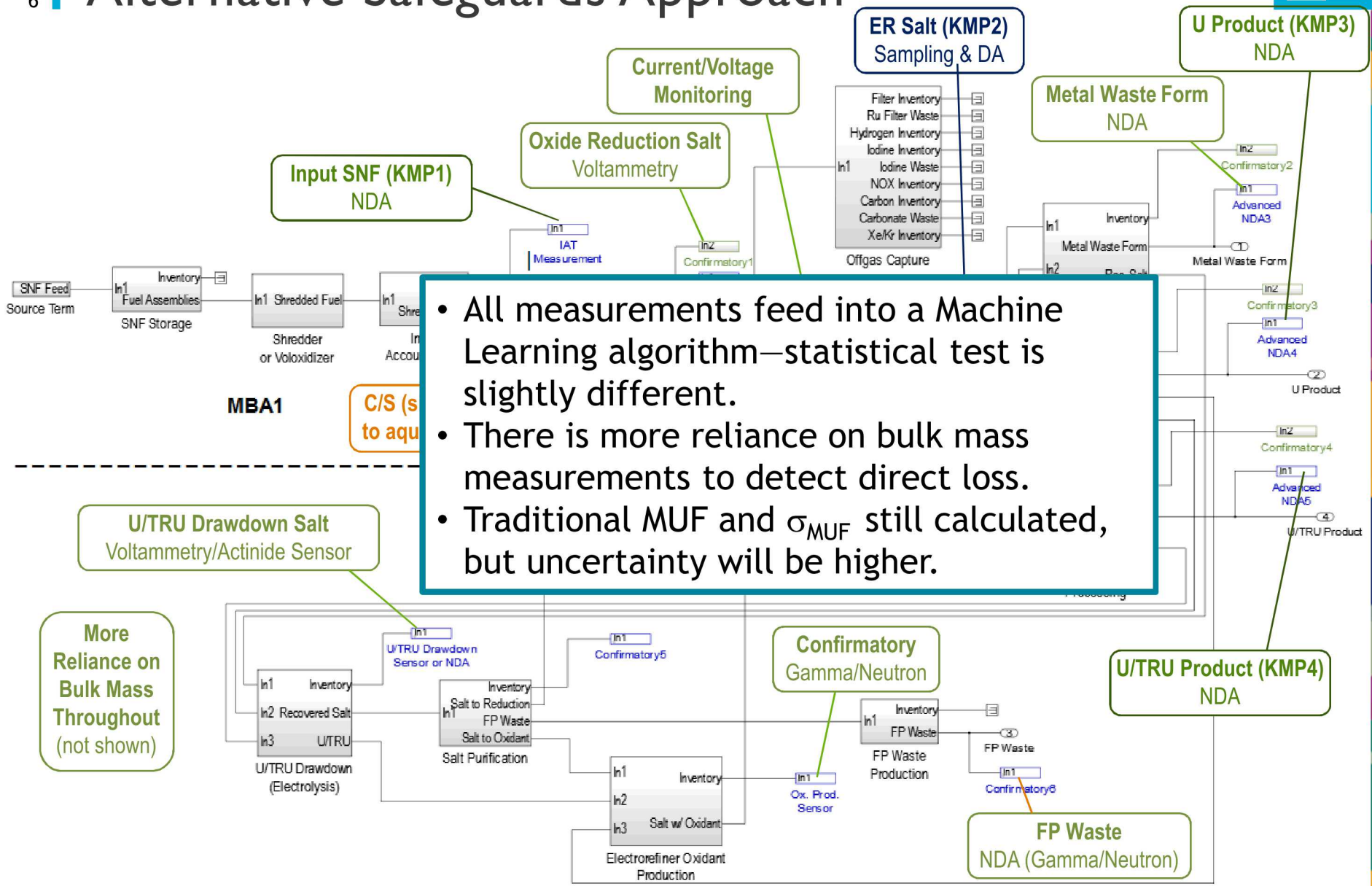
- Past work developed a Safeguards Approach based on Sampling and DA, but measurement uncertainties are still unknown and there are concerns about representativeness of samples.
- We are examining other approaches that make more use of NDA measurements along with Machine Learning techniques to provide an alternative safeguards approach.
- We also need to work with other labs to incorporate the new measurement technologies into the approach.

Initial Safeguards Approach



- Traditional material balance is based on the four KMPs (MUF=In-Out-BI-EI), but also informed by confirmatory measurements
- Apply statistical tests like Page's test.
- Determine σ_{MUF} and detection probability for various diversion scenarios.

Alternative Safeguards Approach



- All measurements feed into a Machine Learning algorithm—statistical test is slightly different.
- There is more reliance on bulk mass measurements to detect direct loss.
- Traditional MUF and σ_{MUF} still calculated, but uncertainty will be higher.

Echem Safeguards Modeling Next Steps

- Receive an updated baseline flowsheet and associated data from ANL.
- Make minor modifications to the SSPM to be consistent with the baseline flowsheet.
- Update the safeguards results (as presented in past MPACT meetings) based on the new flowsheet.
  - Continue to perform a parametric analysis as a function of measurement uncertainty for the traditional safeguards approach
  - Provide new results using the alternative safeguards approach.

Safeguards Modeling Expansion (MSRs)

- Renewed interest in Molten Salt Reactors (MSRs) is being driven by nuclear startups.
- Depending on the design, MSRs can have more safeguards challenges than a typical LWR.
- The safeguards modeling approach used in the SSPM is being used to generate an MSR safeguards model.

Three Types of MSRs

- **Liquid-fueled, drop-in design, with centralized salt processing**

  Cores are designed to be self-contained for ease of installation and replacement. This design shifts some of the accountancy requirements to a centralized facility.

- **Liquid-fueled design with on-site salt processing**

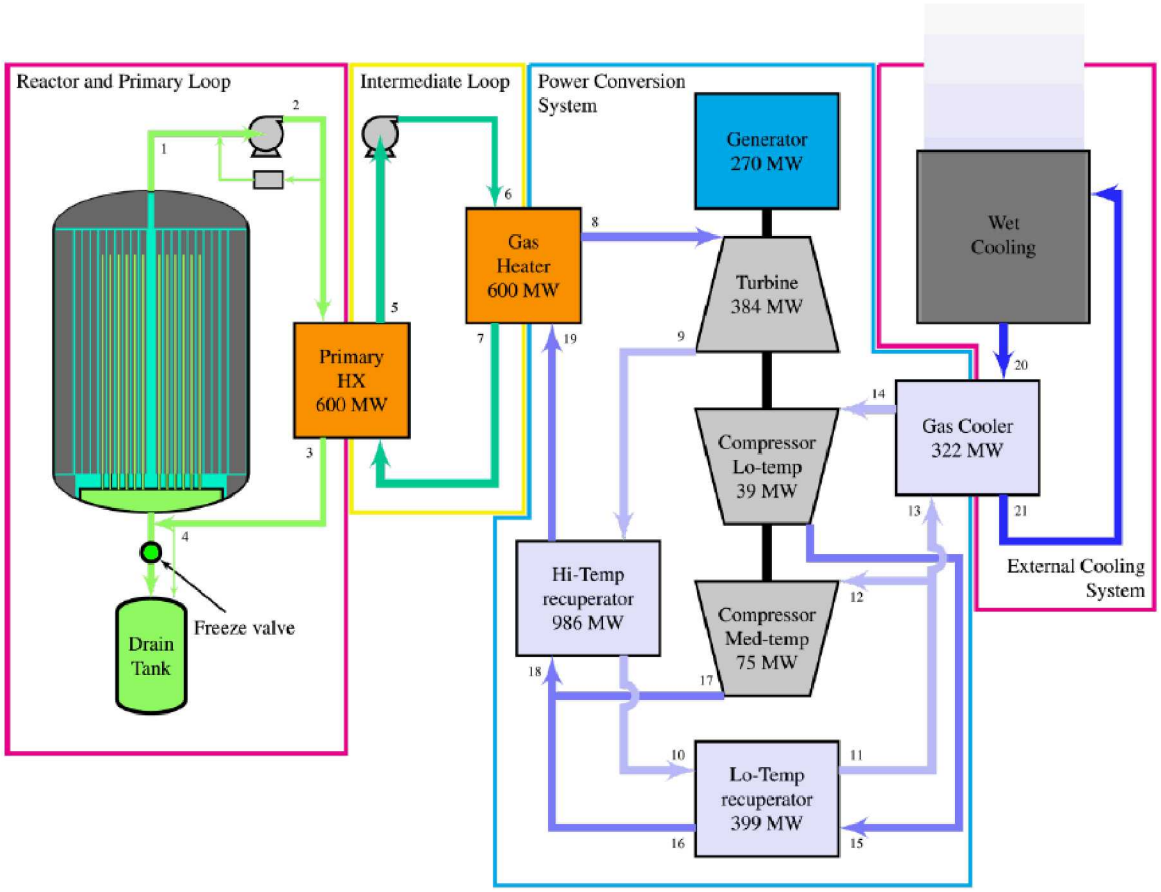
  Modeling Focus

  Salt processing on-site may have advantages since the processed amount is smaller, there is no need to remove actinides, and requires much less transportation of nuclear material.

- **Solid TRISO fuel elements (either pebble bed in MS or fixed assemblies)**

  Fixed assemblies would have no greater safeguards challenge than with LWRs. Pebble beds have the added complication of accounting of pebbles (though huge numbers need to be diverted for a significant quantity).

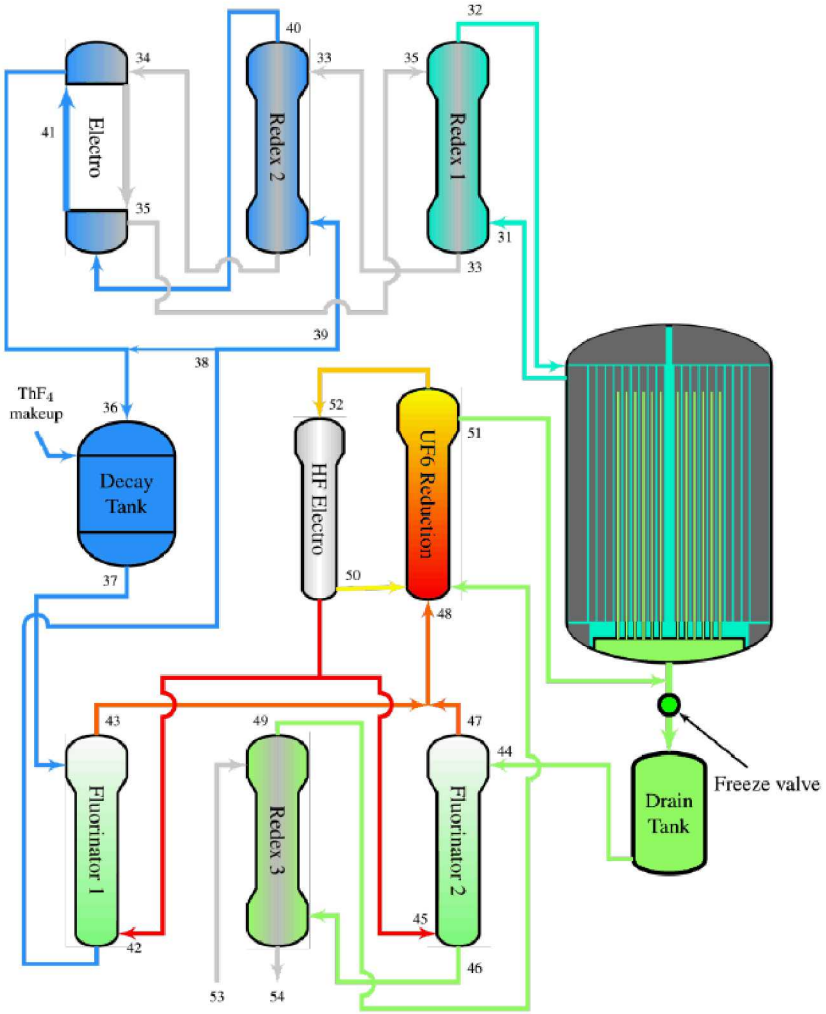
LFTR Primary Loop and Power Conversion



- Flibe based salt as primary coolant, contains fuel.
- Primary loop flow rate ~ 1700 kg/s
- Fission product gas removal is necessary since Xe-135 is a strong neutron poison. A sparging process is included on the primary loop.

Reference: A. Sowder, "Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design: The Liquid-Fluoride Thorium Reactor (LFTR)," Electric Power Research Institute (October 2015).

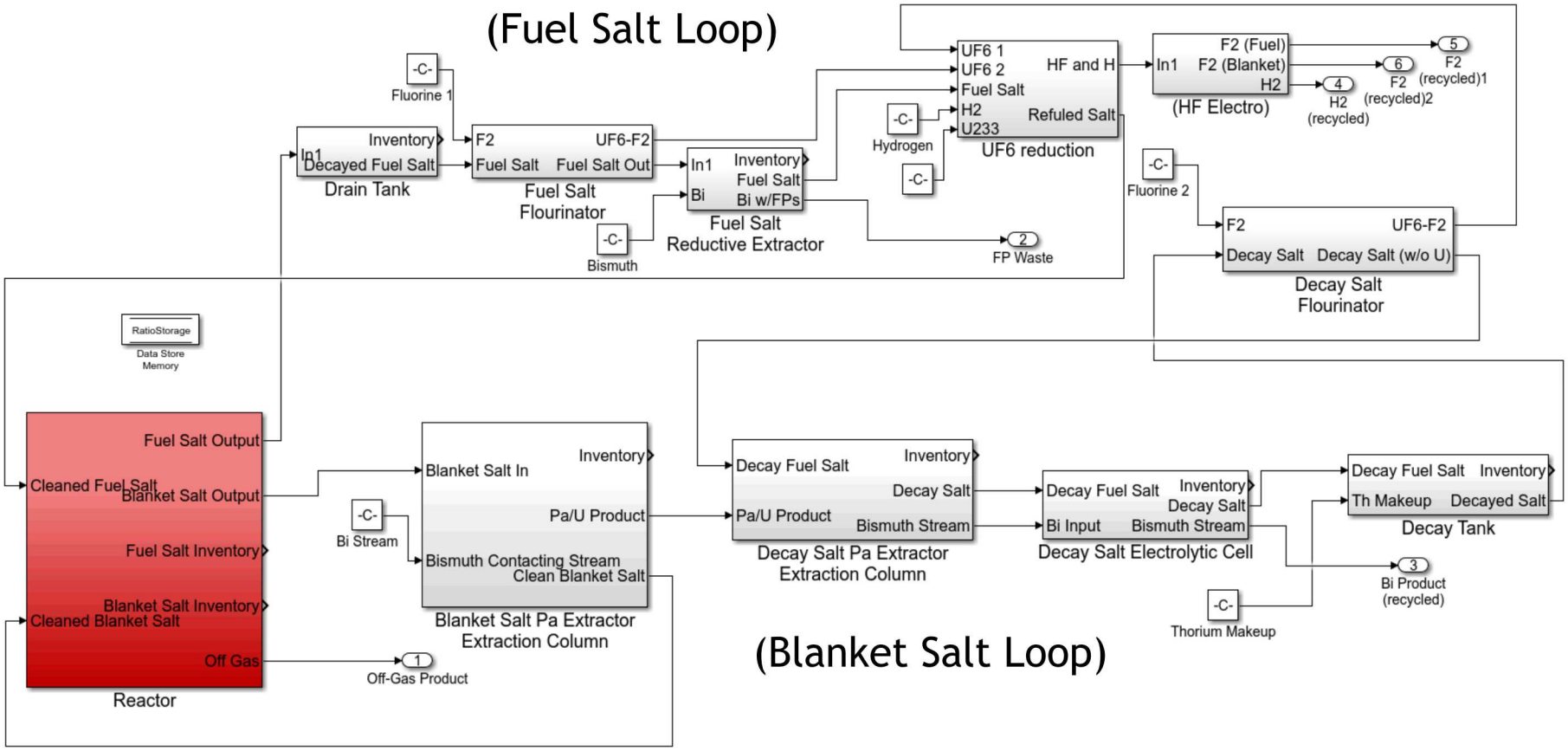
LFTR Chemical Processing System



- Mass flow rate of the fuel salt ~ 0.8 g/s.
- Mass flow rate of the blanket salt ~ 380 g/s.
- Metallic bismuth is used for the extraction processes.
- The blanket contains Th to breed $^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$. The decay tank must hold the material for about 100 days to allow time for Pa-233 to decay. The ^{233}U is transferred to the fuel salt.
- The fuel salt decays in the drain tank for about 30 days for short-lived species to decay. Then fission products are removed and ^{233}U is added.

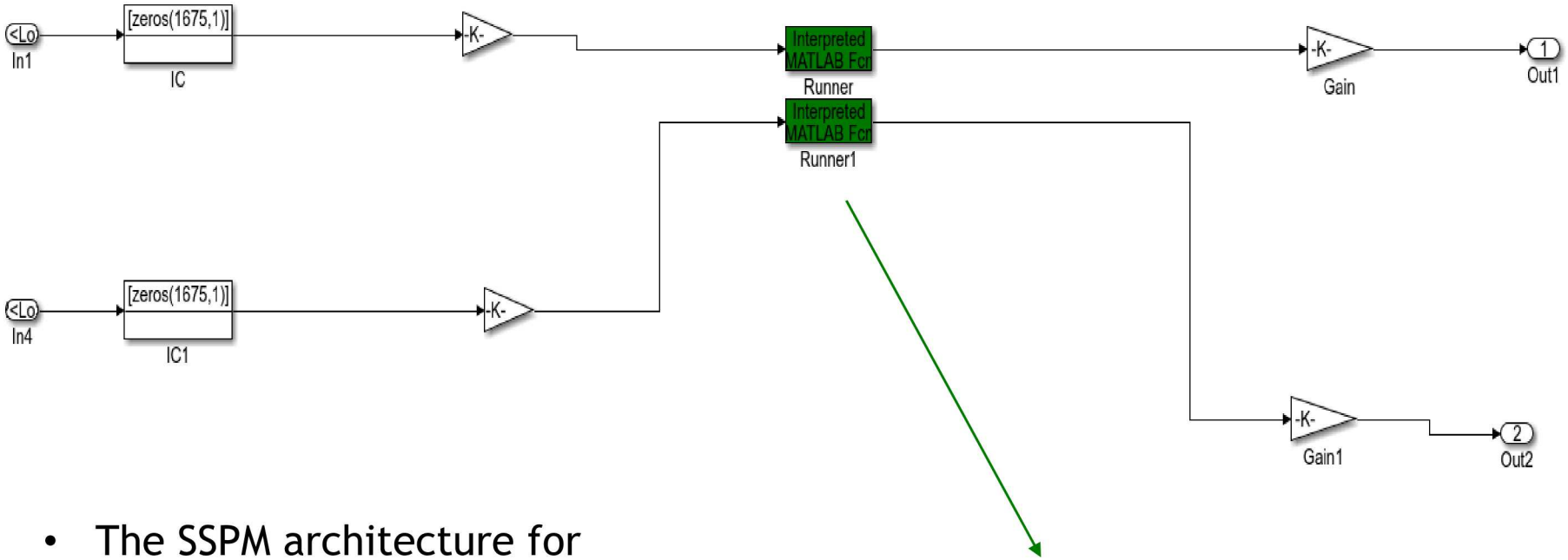
Reference: A. Sowder, "Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design: The Liquid-Fluoride Thorium Reactor (LFTR)," Electric Power Research Institute (October 2015).

MSR Safeguards Model



Reference: A. Sowder, “Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design: The Liquid-Fluoride Thorium Reactor (LFTR),” Electric Power Research Institute (October 2015).

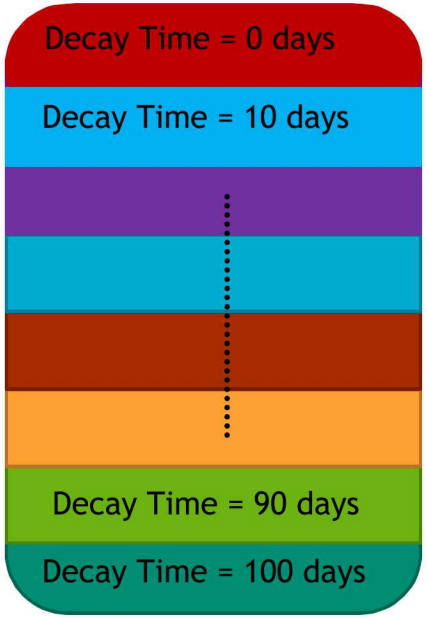
Reactor Block



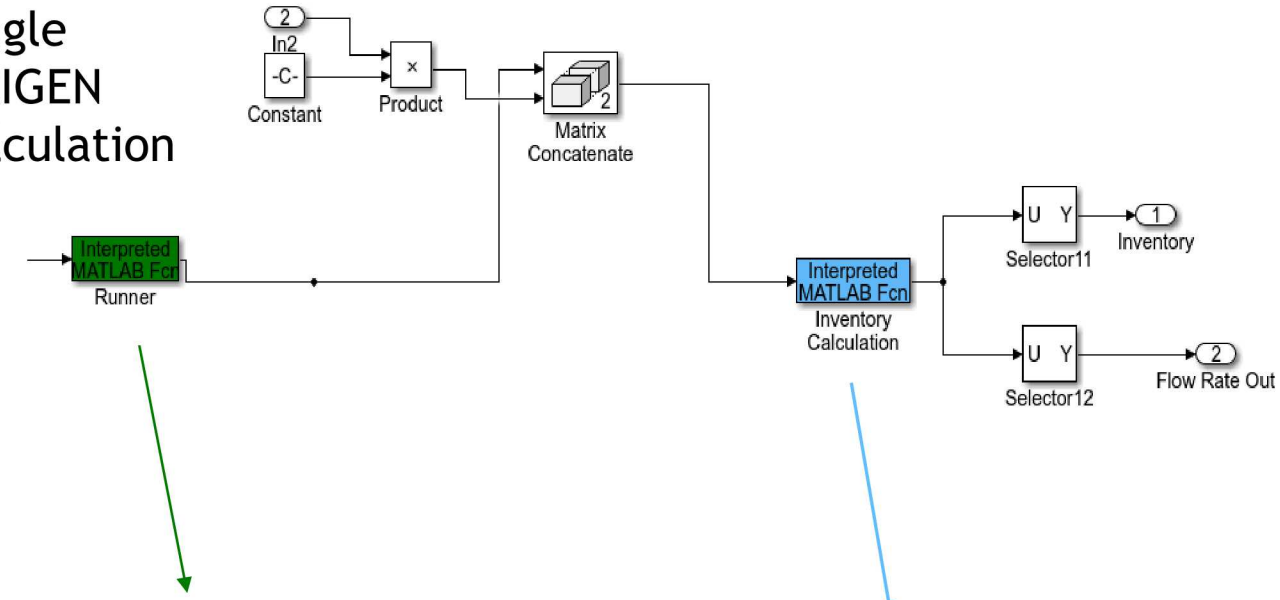
- The SSPM architecture for reprocessing tracks total elemental quantities as a function of time, and calculates isotopic ratios for each element group based on mixing.
- For the MSR model, the architecture was changed to track full isotopic mass flow rates.

Runner: Writes isotopic masses from the process model to **ORIGEN** or **TRITON** template and executes. Output is then passed back to model. Two calculations are performed, one for blanket salt and one for fuel salt.

Decay and Drain Tank Calculation



Single ORIGEN calculation



Decay of materials in tank simulated and stored in “slices” to approximate continuous change in input material.

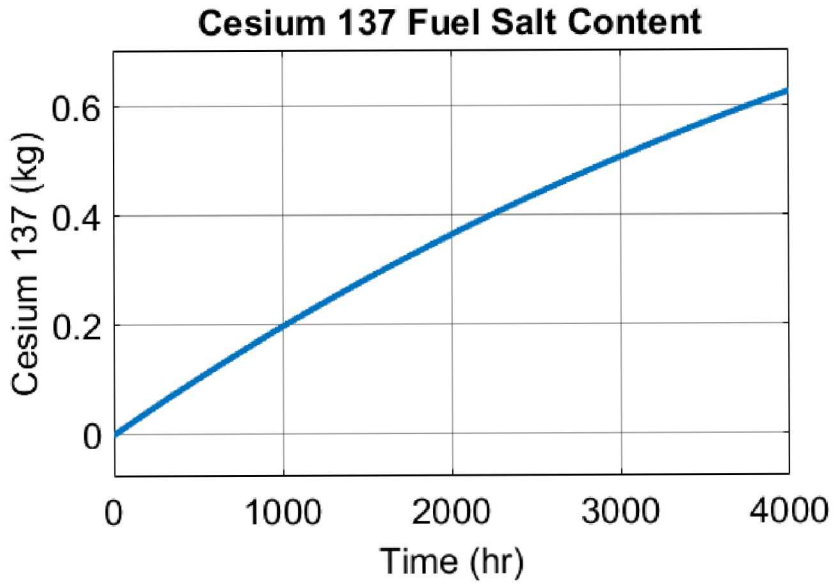
Runner: Writes isotopic masses to **ORIGEN** decay template and executes. Output is passed to inventory calculation module.

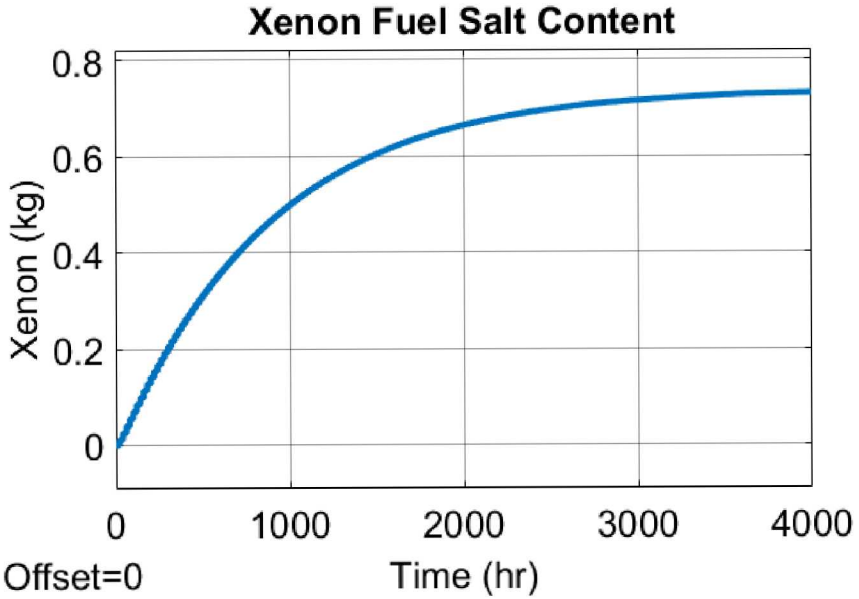
Inventory Calculation: Stores **ORIGEN** output to calculate inventory for subsequent calls. Calculates inventory and output.

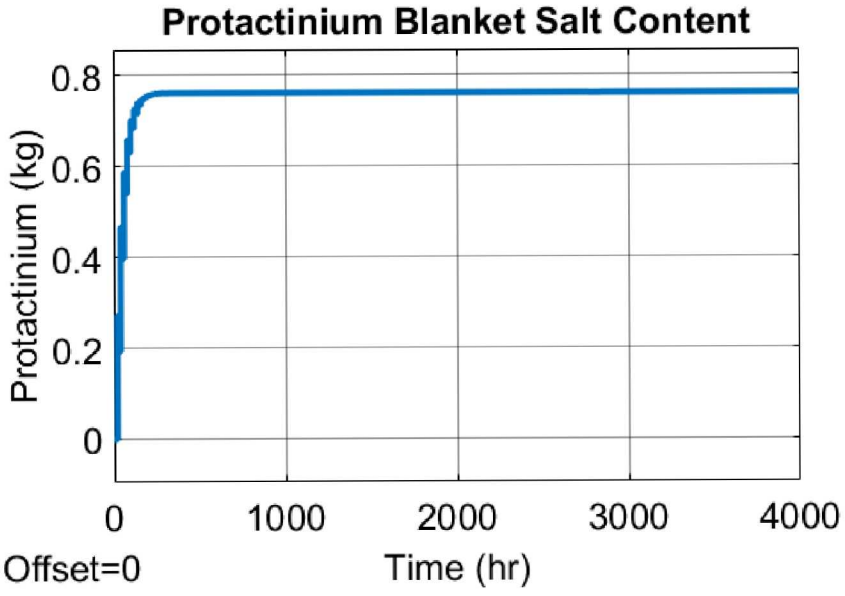
Isotopic Tracking with Time

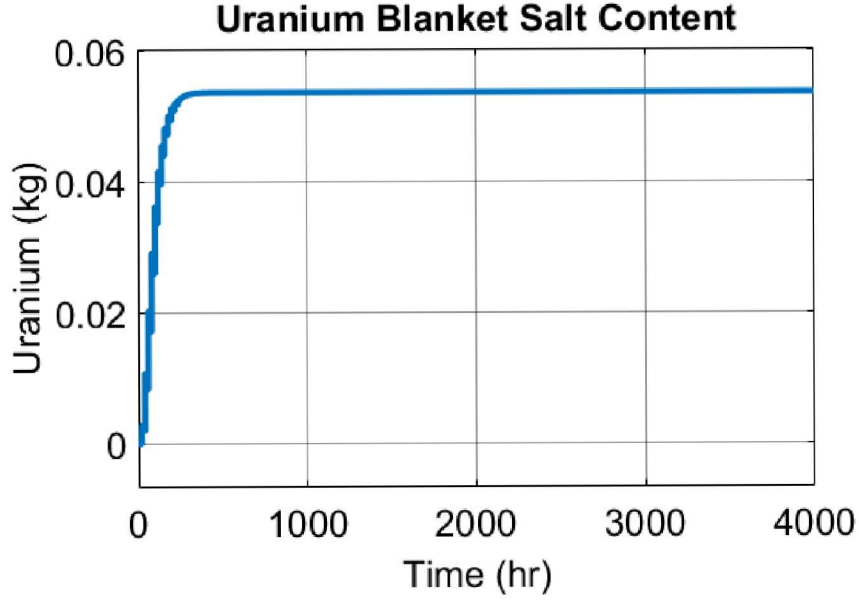
Time (h)	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360
'he4'	0.000313	0.000619	0.000917	0.001209	0.001493	0.001771	0.002043	0.002308	0.002567	0.00282	0.003067	0.003309	0.003545	0.003775	0.004001	0.004221	0.004436	0.004646
'se80'	8.67E-05	0.000173	0.000259	0.000345	0.000431	0.000516	0.000601	0.000686	0.00077	0.000854	0.000938	0.001022	0.001106	0.001188	0.001271	0.001354	0.001436	0.001517
'br81'	0.000134	0.000272	0.000409	0.000545	0.000681	0.000817	0.000952	0.001087	0.001221	0.001355	0.001489	0.001621	0.001754	0.001886	0.002018	0.002149	0.00228	0.00241
'kr85'	0.000163	0.000375	0.000583	0.000786	0.000985	0.001179	0.001369	0.001553	0.001734	0.001911	0.002083	0.002251	0.002415	0.002575	0.002731	0.002883	0.003033	0.003178
'kr86'	0.001132	0.002239	0.003319	0.004374	0.005404	0.006411	0.007395	0.008355	0.009293	0.010204	0.011102	0.011972	0.012821	0.013651	0.014462	0.015253	0.016035	0.016797
'sr90'	0.00282	0.00564	0.008449	0.011252	0.014043	0.016824	0.019594	0.022355	0.025106	0.027847	0.030578	0.033299	0.03602	0.038731	0.041432	0.044123	0.046804	0.049476
'y91'	0.00121	0.003554	0.006138	0.008752	0.011341	0.013903	0.016434	0.018936	0.021398	0.023829	0.026231	0.028603	0.030936	0.033238	0.03551	0.037753	0.039965	0.042148
'zr94'	0.002908	0.005872	0.008827	0.011771	0.014701	0.017621	0.020532	0.023442	0.026343	0.029233	0.032114	0.034984	0.037845	0.040695	0.043536	0.046366	0.049187	0.051998
'nb95'	1.21E-05	4.86E-05	0.000109	0.000191	0.000296	0.000423	0.00057	0.000737	0.000923	0.001128	0.001351	0.001592	0.001849	0.002123	0.002412	0.002717	0.003036	0.003369
'mo98'	0.002352	0.004697	0.007035	0.009364	0.011689	0.014001	0.016304	0.018606	0.020899	0.023181	0.025454	0.027726	0.029989	0.032241	0.034484	0.036726	0.038959	0.041181
'mo99'	0.002031	0.003671	0.004995	0.006063	0.006925	0.007621	0.008183	0.008636	0.009002	0.009296	0.009534	0.009727	0.009882	0.010007	0.010107	0.010187	0.010256	0.010306
'mo100'	0.002068	0.004127	0.006179	0.008225	0.010263	0.012296	0.014319	0.016343	0.018356	0.020359	0.022353	0.024346	0.02633	0.028313	0.030287	0.03225	0.034214	0.036167
'ru101'	0.001436	0.002917	0.004393	0.005865	0.007331	0.008792	0.010251	0.011706	0.013151	0.014597	0.016032	0.017467	0.018892	0.020318	0.021733	0.023148	0.024554	0.025959
'pd105'	2.32E-05	0.000108	0.000239	0.0004	0.000578	0.000768	0.000965	0.001167	0.001371	0.001576	0.001782	0.001988	0.002193	0.002399	0.002604	0.002808	0.003012	0.003215
'sn126'	0.000131	0.000262	0.000393	0.000523	0.000652	0.000781	0.00091	0.001038	0.001166	0.001293	0.00142	0.001546	0.001672	0.001797	0.001923	0.002048	0.002172	0.002296
'te132'	0.002663	0.004878	0.006721	0.008253	0.009527	0.010589	0.011465	0.012202	0.01281	0.013318	0.013736	0.014085	0.014374	0.014613	0.014812	0.014981	0.015121	0.01524
'i129'	0.000489	0.001266	0.002056	0.002846	0.003637	0.004426	0.005215	0.006005	0.006794	0.007583	0.008371	0.009158	0.009946	0.010737	0.011525	0.012312	0.013099	0.013887
'i131'	0.001451	0.003066	0.004696	0.006295	0.007834	0.009299	0.010679	0.011975	0.01319	0.014326	0.015383	0.016359	0.017276	0.018123	0.01891	0.019638	0.020315	0.020943
'xe132'	0.000276	0.001008	0.0021	0.003479	0.005088	0.006877	0.008805	0.010835	0.012948	0.015119	0.017318	0.019547	0.021775	0.024003	0.026221	0.02843	0.030608	0.032767
'xe133'	0.000866	0.002846	0.005209	0.007601	0.009864	0.011931	0.013783	0.015419	0.016861	0.018128	0.019238	0.020212	0.021059	0.0218	0.022452	0.023017	0.023514	0.023942
'xe134'	0.003552	0.007387	0.011129	0.014792	0.018366	0.021863	0.025272	0.028602	0.031854	0.035039	0.038144	0.041182	0.044151	0.047052	0.049884	0.052648	0.055344	0.057981
'xe135'	0.000375	0.000416	0.00042	0.000421	0.000421	0.000421	0.000421	0.000421	0.000421	0.000421	0.000421	0.00042	0.00042	0.00042	0.00042	0.00042	0.00042	0.00042
'xe136'	0.00613	0.013369	0.02058	0.027642	0.034538	0.041277	0.04786	0.054287	0.060567	0.0667	0.072687	0.078538	0.084252	0.089828	0.095278	0.100581	0.105758	0.110837
'cs137'	0.004272	0.008544	0.012802	0.017048	0.021274	0.02549	0.029686	0.033872	0.038048	0.042204	0.046351	0.050477	0.054593	0.05869	0.062776	0.066853	0.070909	0.074956
'ba138'	0.003582	0.007351	0.011106	0.014843	0.018571	0.022289	0.025996	0.029684	0.033362	0.03703	0.040688	0.044336	0.047964	0.051582	0.05519	0.058788	0.062376	0.065944
'ba140'	0.004056	0.00792	0.011594	0.015102	0.01844	0.021619	0.024649	0.027529	0.030269	0.03288	0.035372	0.037743	0.040005	0.042158	0.044201	0.046154	0.048008	0.049782
'la139'	0.003629	0.007677	0.011705	0.015721	0.019728	0.023715	0.027692	0.031659	0.035606	0.039543	0.04347	0.047377	0.051274	0.055161	0.059038	0.062895	0.066742	0.07058
'ce141'	0.002965	0.007063	0.011107	0.015063	0.01894	0.022728	0.026435	0.030073	0.033631	0.037109	0.040518	0.043856	0.047125	0.050325	0.053454	0.056514	0.059514	0.062444
'ce142'	0.003859	0.008235	0.012593	0.016938	0.021274	0.02559	0.029896	0.034191	0.038467	0.042733	0.046979	0.051215	0.055441	0.059647	0.063843	0.068029	0.072196	0.076352
'ce144'	0.003149	0.006282	0.009397	0.012499	0.015579	0.018649	0.021698	0.024728	0.027748	0.030748	0.033729	0.036699	0.039649	0.042589	0.045509	0.04842	0.05131	0.054181
'pr143'	0.000692	0.002442	0.004823	0.007562	0.010485	0.013475	0.016456	0.019386	0.022236	0.024997	0.027658	0.030209	0.03266	0.035002	0.037245	0.039387	0.04143	0.043383
'nd145'	0.00141	0.003629	0.005918	0.008205	0.010483	0.012755	0.015018	0.01727	0.019513	0.021756	0.023988	0.026211	0.028424	0.030626	0.032829	0.035022	0.037204	0.039377
'nd146'	0.001671	0.003415	0.005154	0.006887	0.008615	0.010342	0.012056	0.01377	0.015475	0.017179	0.018873	0.020568	0.022252	0.023937	0.025611	0.027285	0.02895	0.030614
'pm147'	2.96E-05	0.000118	0.000262	0.000457	0.000701	0.000991	0.001323	0.001695	0.002103	0.002547	0.003024	0.003531	0.004066	0.004629	0.005216	0.005826	0.006458	0.00711
'sm151'	4.45E-05	0.000155	0.000303	0.000471	0.00065	0.000833	0.001017	0.0012	0.001378	0.001553	0.001725	0.001891	0.002054	0.002212	0.002366	0.002515	0.002661	0.002802
'u233'	53.16151	53.14686	53.13662	53.12665	53.11668	53.10671	53.09675	53.08678	53.07681	53.06685	53.05688	53.04691	53.03695	53.02698	53.01701	53.00704	52.99708	52.98711
'u234'	0.01288	0.025698	0.038465	0.051183	0.063851	0.076469	0.089038	0.101506	0.113965	0.126424	0.138783	0.151142	0.163401	0.175661	0.18782	0.19998	0.21204	0.2241
'u235'	4.13E-06	1.67E-05	3.76E-05	6.68E-05	0.000104	0.00015	0.000204	0.000265	0.000335	0.000412	0.000497	0.00059	0.000691	0.000799	0.000915	0.001038	0.001169	0.001306

Initial Results









MSR Model Next Steps

- Work with ORNL to ensure consistent results. The model can be setup to work with ORIGEN or TRITON, or just use pre-generated data sets.
- Develop a safeguards approach—add measurements to the model and determine the appropriate approach for setting up a material balance.
- Examine the alternative MSR designs.