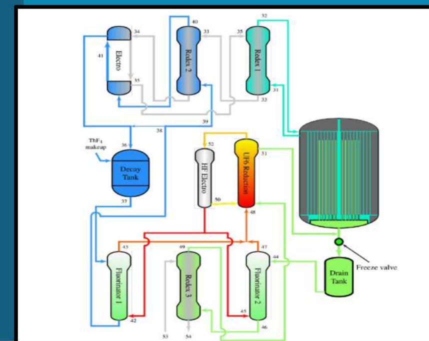
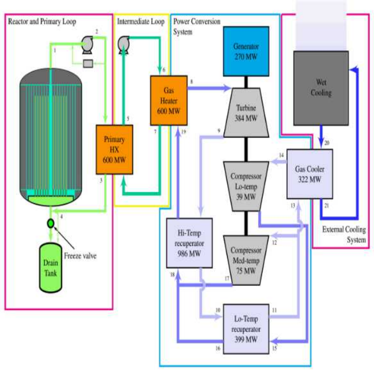
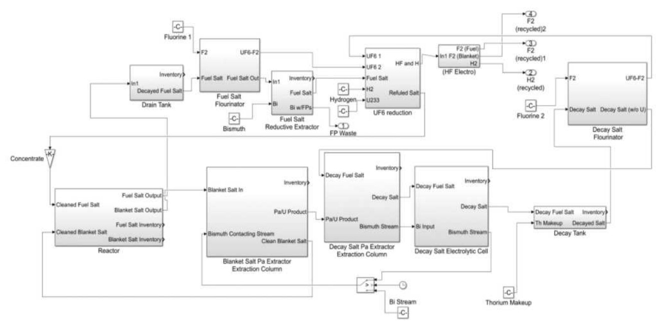
SAND2018-9582PE

Development of a Two-Fluid Molten Salt Reactor Safeguards Model







PRESENTED BY

Nathan Shoman and Ben Cipiti

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MPACT MSR Safeguards Analysis

- The goal of the MPACT program is to address safeguards and security challenges for the DOE NE program.
- Due to renewed interest in MSRs, we began developing an MSR safeguards model in FY18.
  - Modeling architecture is based on the Separation and Safeguards Performance Model (SSPM) in MATLAB Simulink.
  - The SSPM was originally developed for reprocessing plant safeguards modeling, including pyroprocessing.
- Our focus is addressing materials accountancy, so we needed to model the reactor and salt processing loop inventories to reasonably approximate the changing isotopics as a function of time.

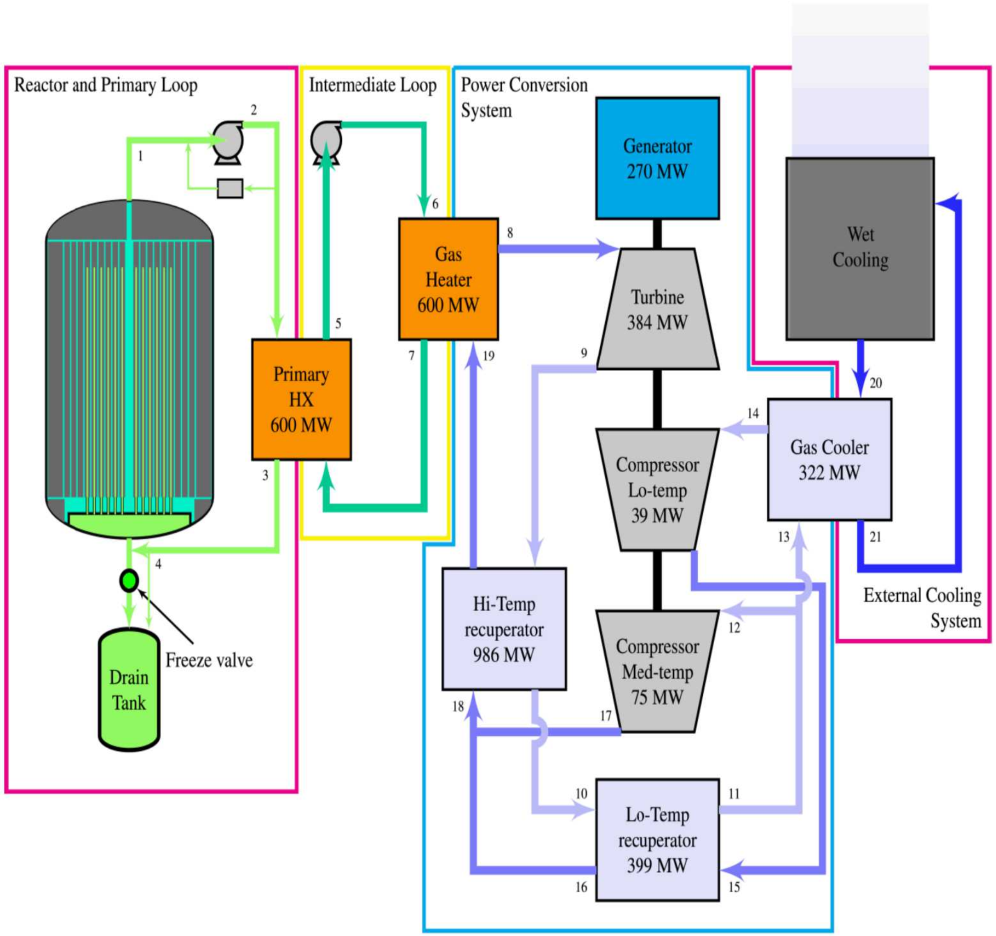
Three Types of MSRs

- 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
  - Salt processing on-site only removes fission products, but does not separate out actinides. Requires much less transportation of nuclear material at the expense of more accountancy challenges.

Modeling Focus

- 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).

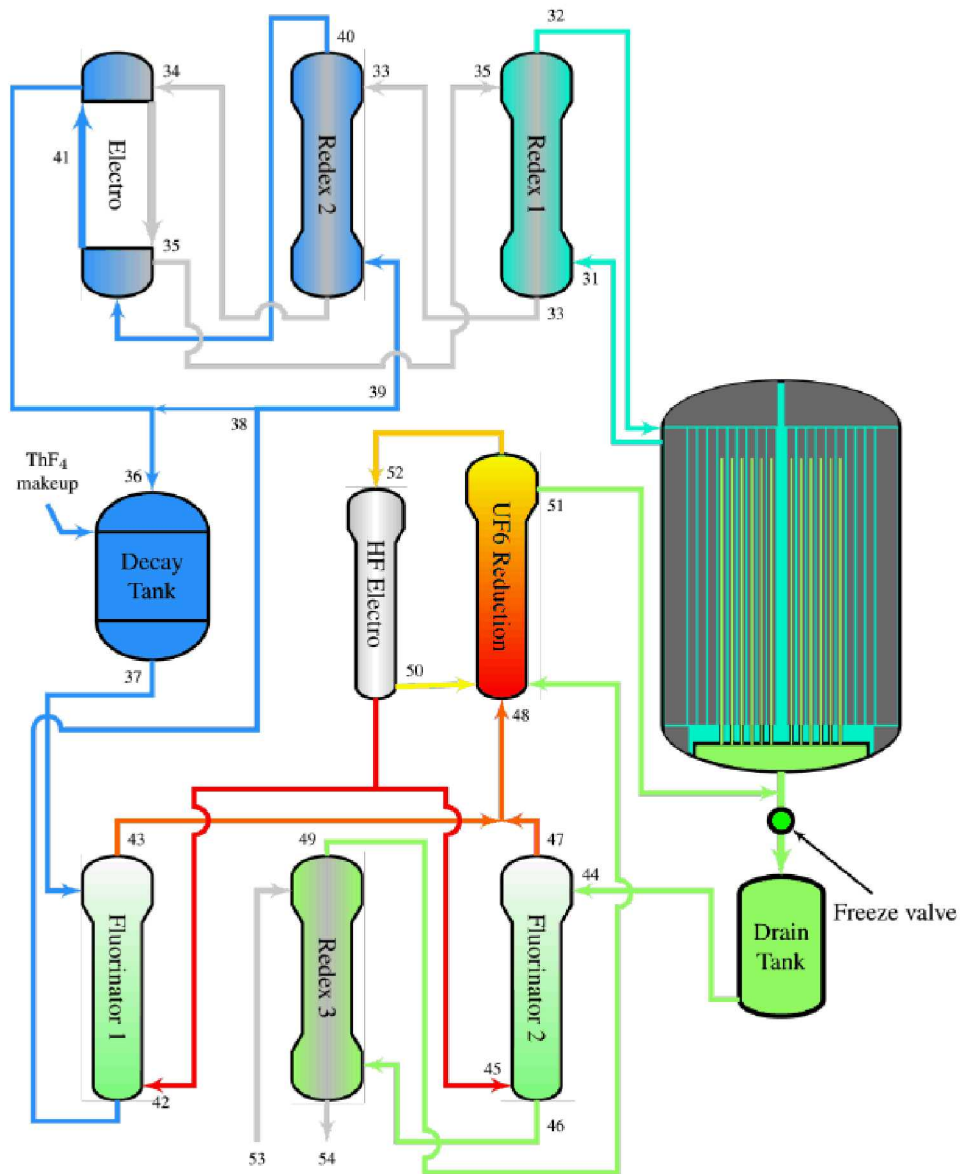
Reference Design – Flibe Energy Liquid-Flouride Thorium Reactor (LFTR)



- Separate breeder and fuel salts
- Thorium fuel cycle
- Onsite salt processing
- 600 MWth / 200MWe

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



Fuel salt ~ 0.8 g/s.

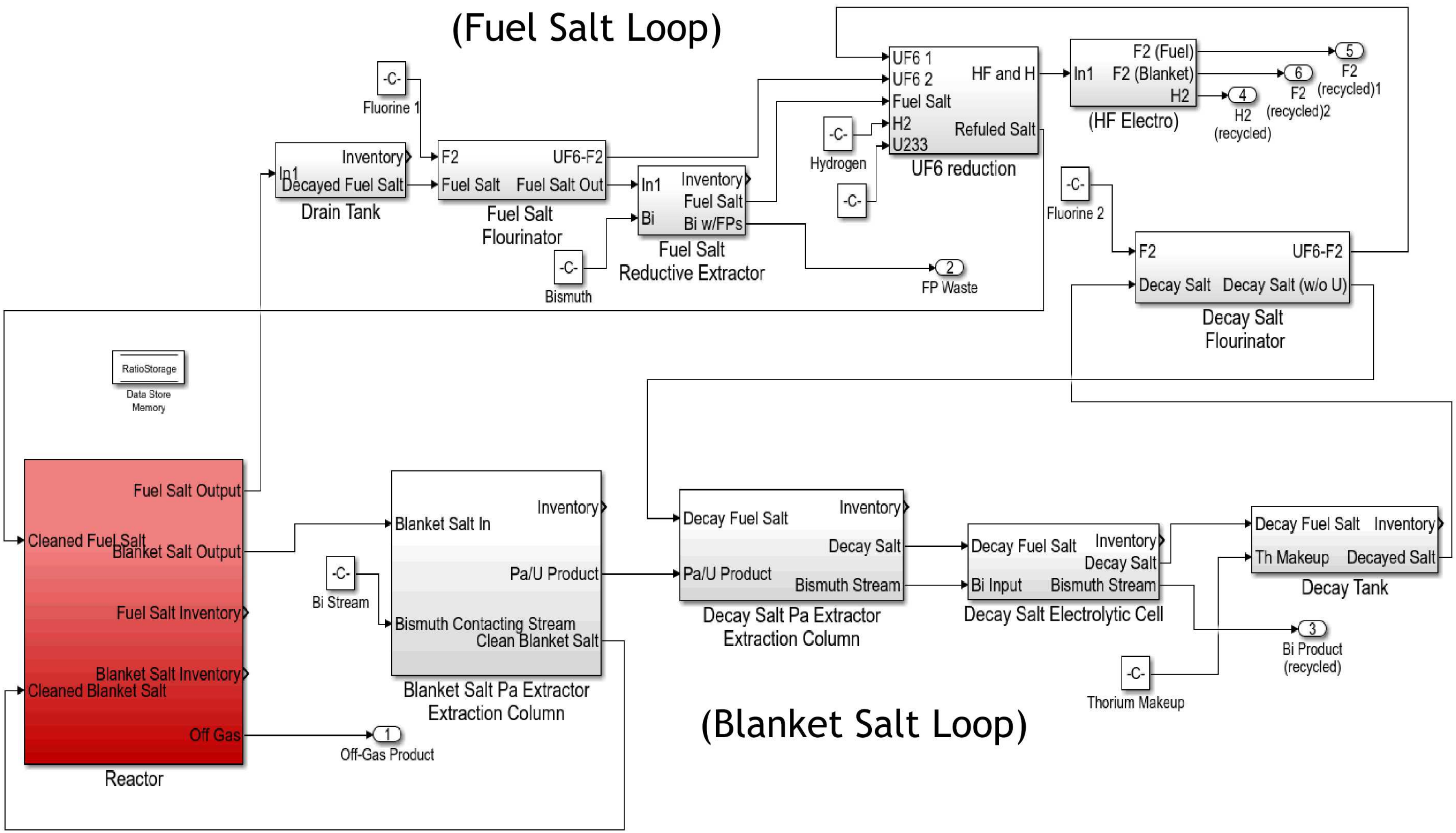
Blanket salt ~ 380 g/s.

Metallic bismuth is used for the extraction processes.

The blanket contains Th to breed ^{233}Th → ^{233}Pa → ^{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.

MSR Safeguards Model



Modeling Approach – Reactor Subsystem Assumptions

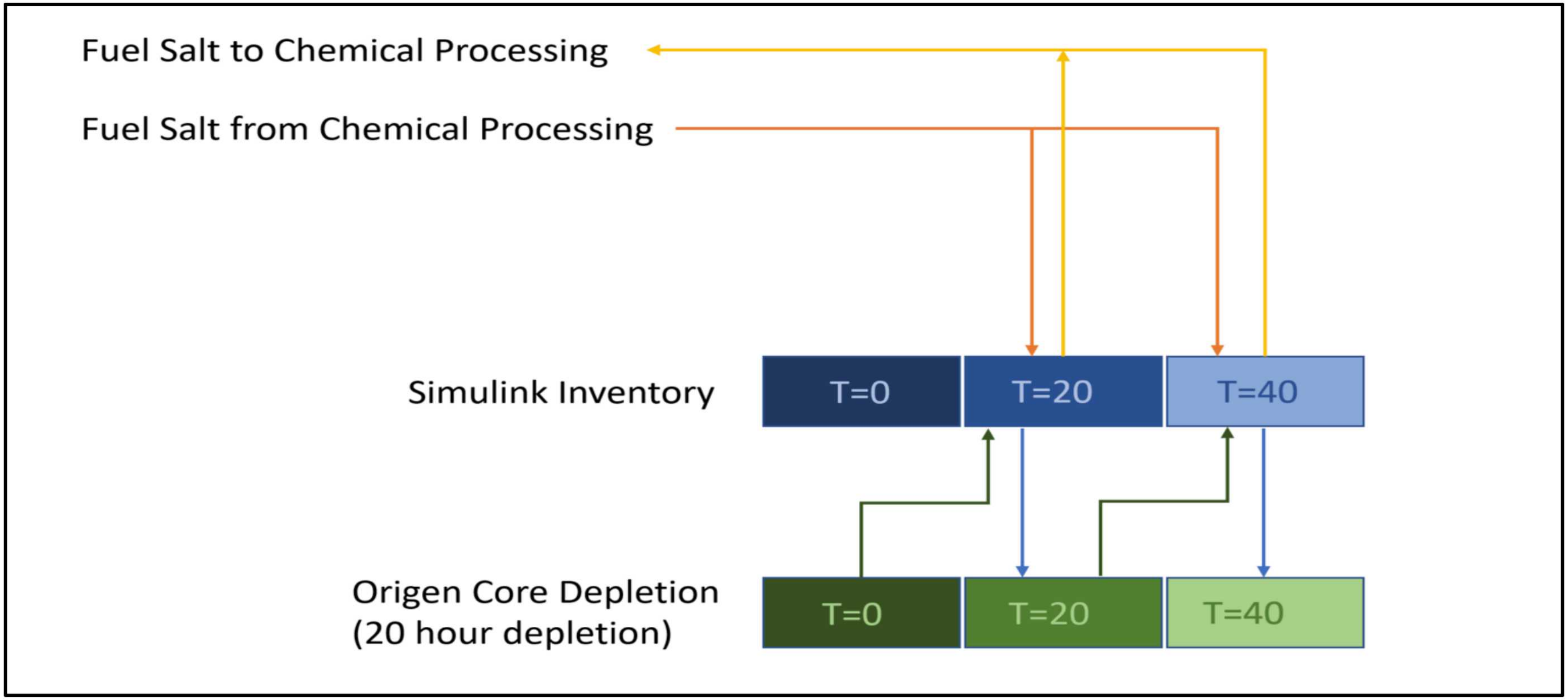
	Flibe Design	ORNL-4528 (20 kW/L)	Assumption Used
Thorium	N/A	54,000 kg	30,000 kg
Uranium	N/A	315 kg	50 kg
Salt Composition	(Blanket) $LiF-BeF_2-ThF_4$ (Fuel) $LiF-BeF_2-UF_4$	(Blanket) $LiF-BeF_2-ThF_4$ (Fuel) $LiF-BeF_2-UF_4$	(Blanket) $LiF-BeF_2-ThF_4$ (Fuel) $LiF-BeF_2-UF_4$

- Assumptions for uranium content based on energy released per fission, does not account for energy lost due to neutron leakage, capture, etc.
- Thorium content was based on educated guess before obtaining ORNL-4528.
- The fuel salt flow rate to the primary heat exchanger is large compared to the total fuel salt—this led to computational issues when modeled directly.
  - "Dilute" the fission products and activation products in the fuel salt going to chemical processing by 139/355, the fraction of fuel salt in the core compared to the total as specified by ORNL-4528.

Modeling Approach – Reactor Subsystem Depletion

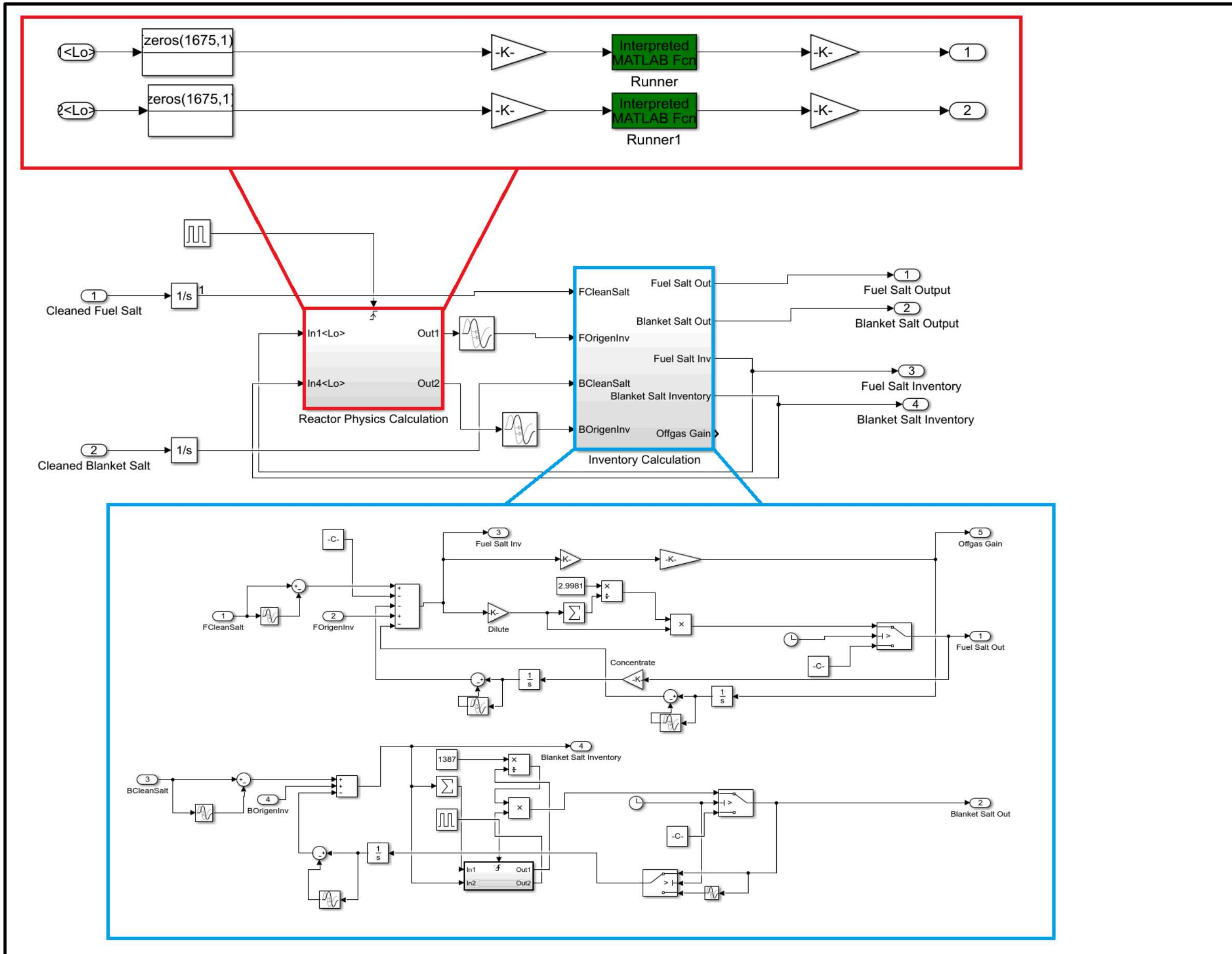
- Depletion of fuel and blanket salt estimated using ORIGEN
- Westinghouse 17x17 cross-sections (incorrect for this application) – 2.5% enrichment
  - Pick more appropriate cross-section library for future
  - Flibe doesn't have enough publicly available information to do 2-D transport/depletion
- Depletion every 20 hours
  - Does not account for the impact of buildup of fission products on the flux (first ORIGEN library position used for duration of simulation)
- Specific powers tuned to provide the correct uranium consumption and thorium consumption in the fuel and blanket respectively
  - 10 MWD/MT currently for fuel, about 12 MWD/MT for blanket

Modeling Approach – Reactor Subsystem

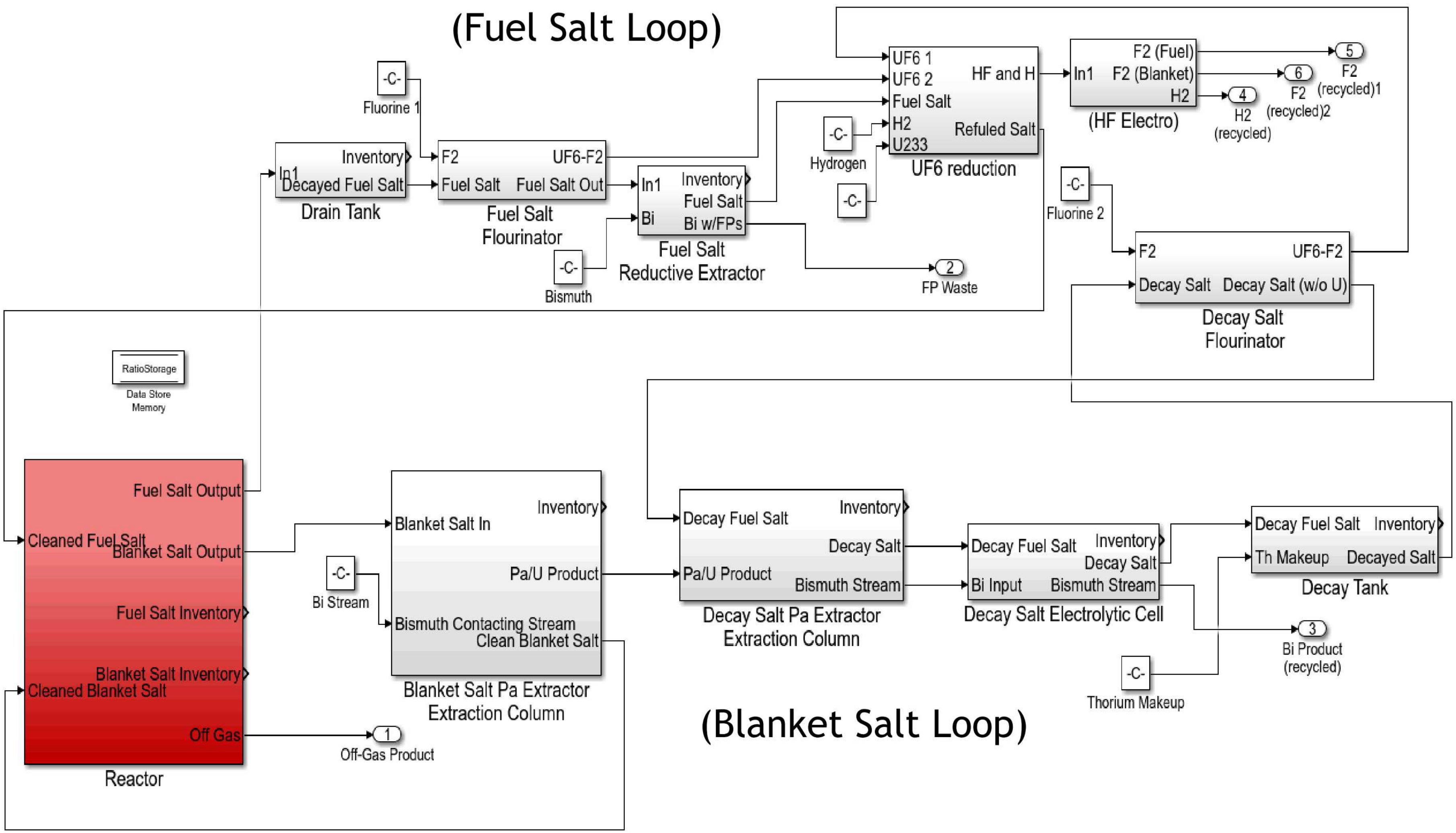


- The Simulink model tracks inventory at every location.
- The reactor core requires a special calculation.
- Delays needed to "sync" model time with depletion time.

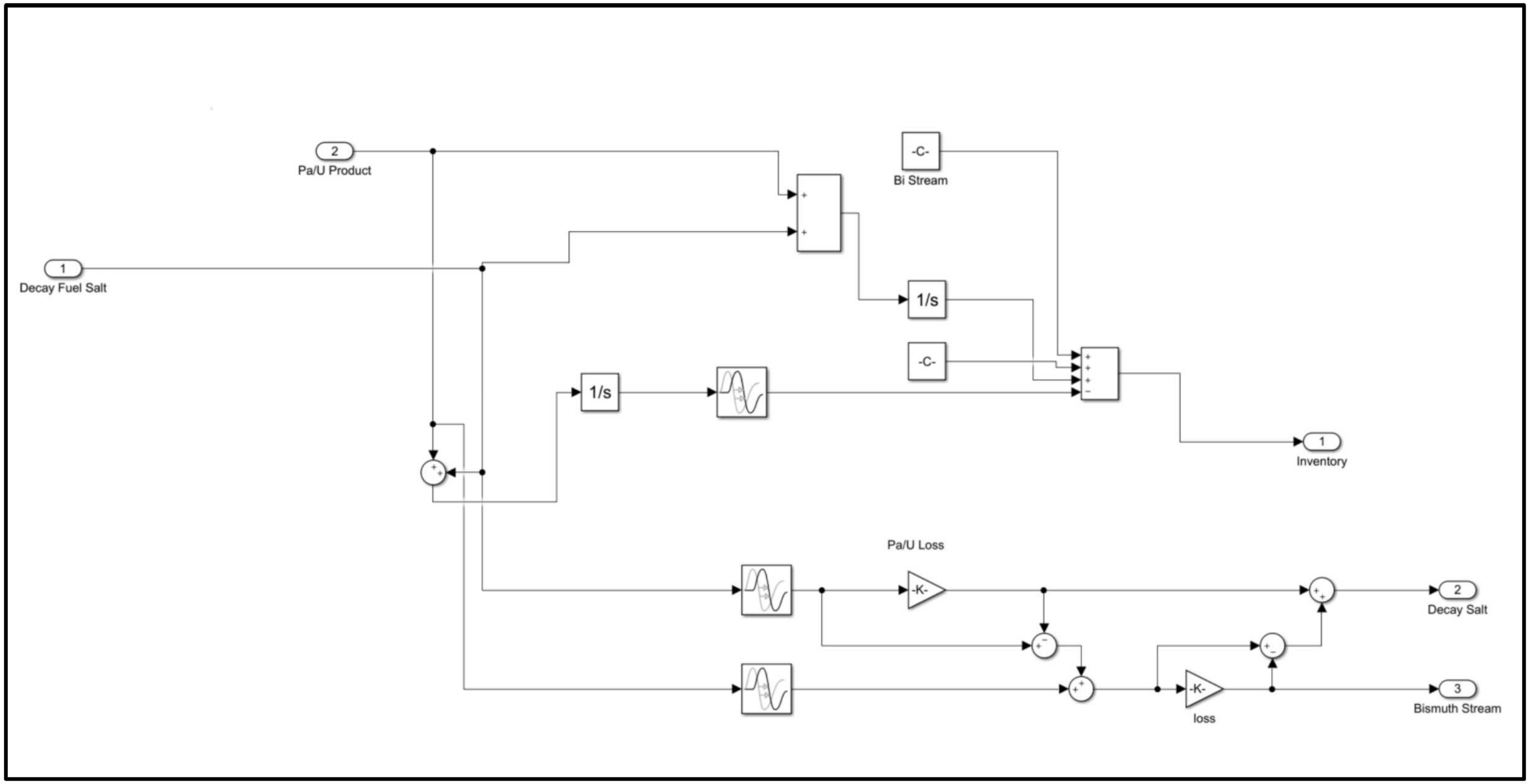
Modeling Approach – Reactor Physics and Inventory Calculation



MSR Safeguards Model

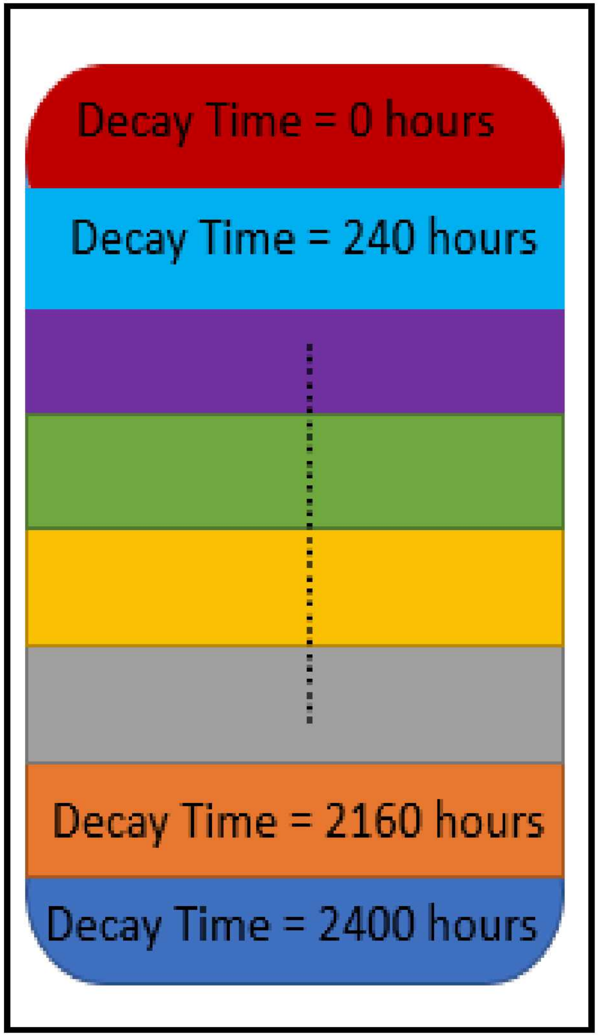


Modeling Approach – Salt Processing Operations



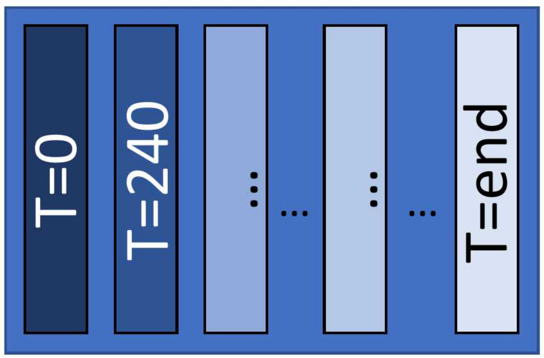
- Most of the salt processing unit operations are chemical separations that can be modeled using simple gain blocks. Assumptions are used for the extraction fractions going into the metallic or salt streams.

Modeling Approach – Decay and Drain Tanks

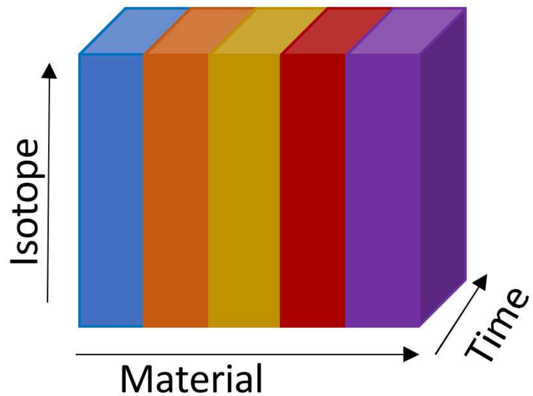


- Purpose is to allow protactinium to decay to uranium (blanket salt) or allow fission products to decay (fuel salt).
- The decay tank must let material decay for a specific amount of time, but the input material to the decay tank is changing due to constant core depletion.
- The decay tanks were discretized into 10 “slices”.

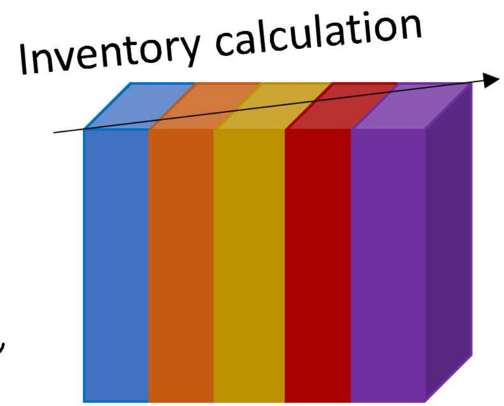
Modeling Approach – Decay Tanks (cont.)



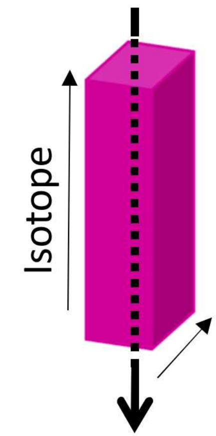
A single ORIGEN calculation is run on a "slice" of material.



All ORIGEN calculated time-dependent isotopics are stored in a persistent array.

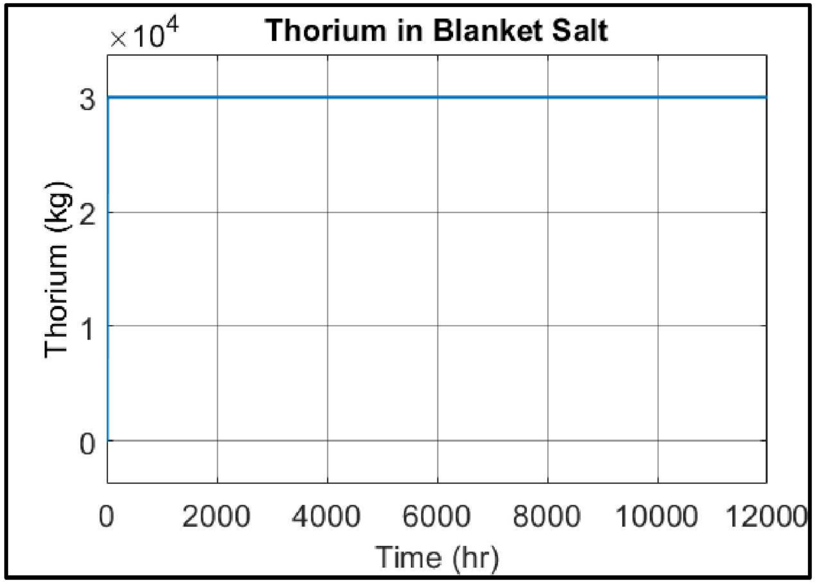


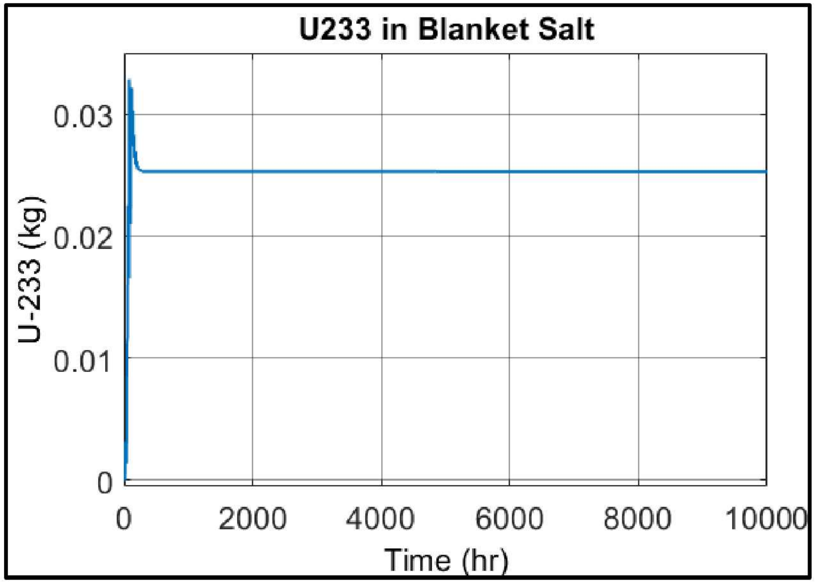
The Inventory for the decay tank is the diagonal of the persistent array – material 1 at t=0, material 2 at t=240 and so on.

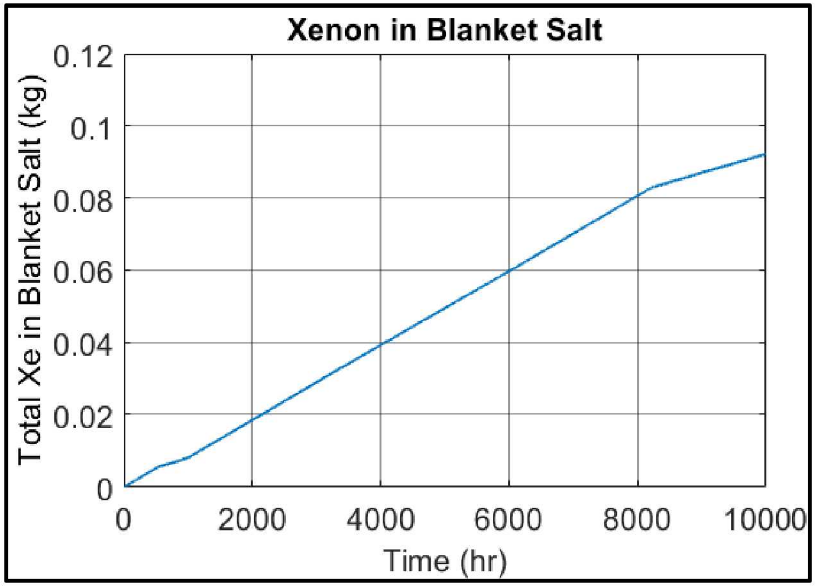


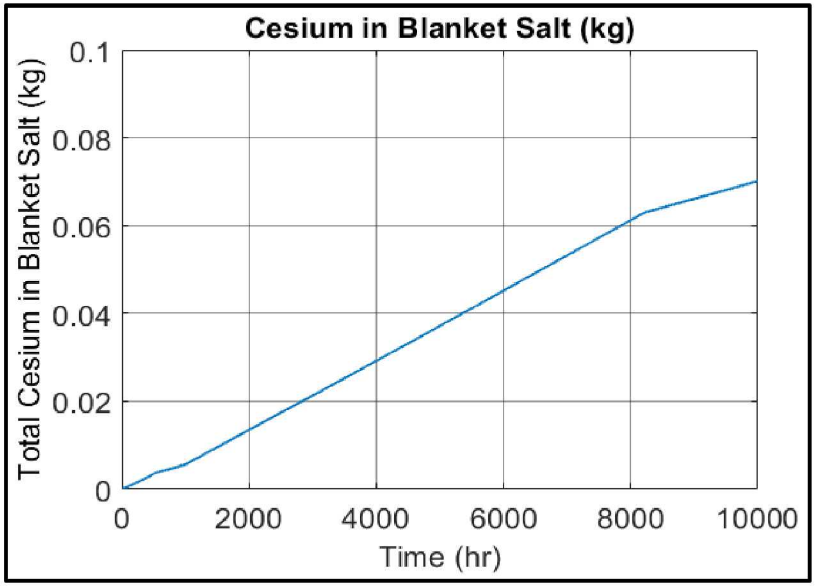
Output for the decay tank is the last material at the final decay time

Initial Results (Blanket Inventories)

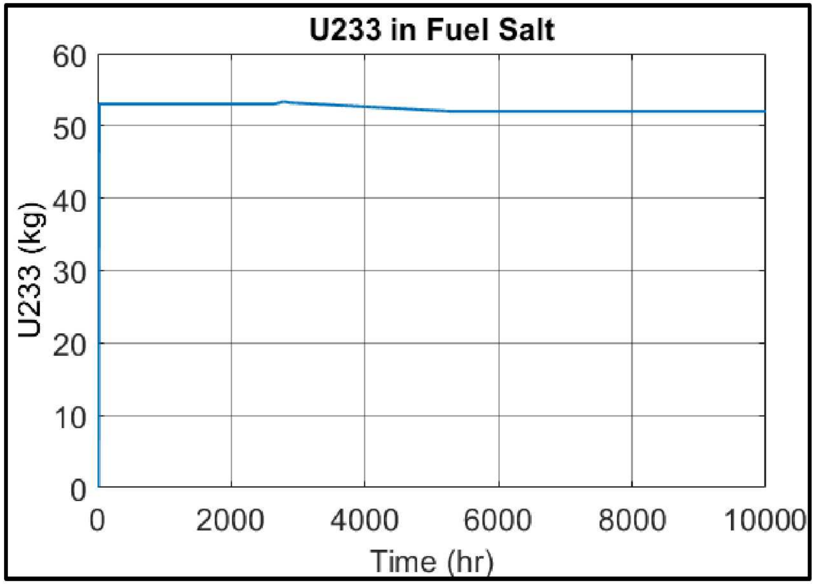


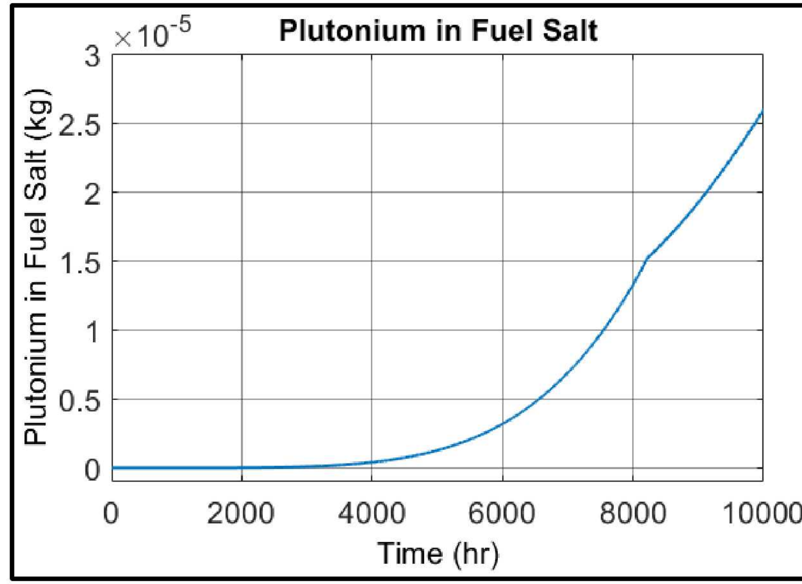


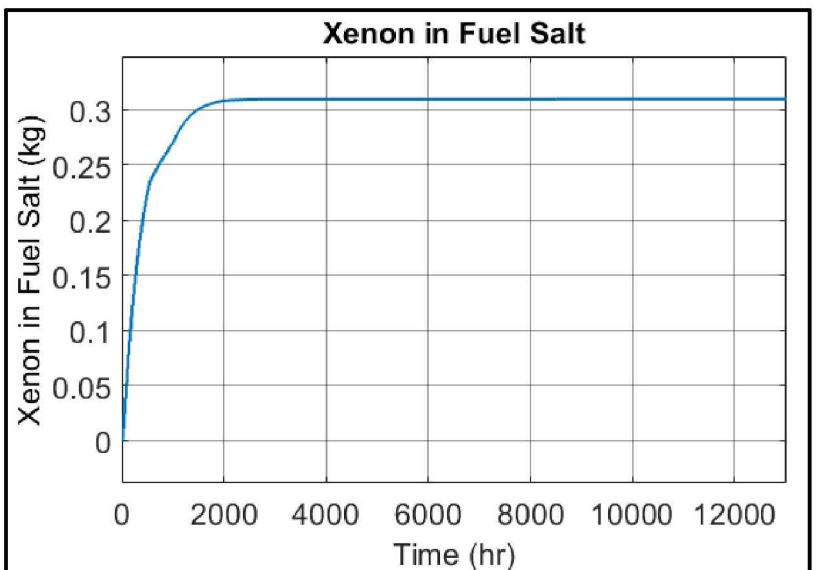


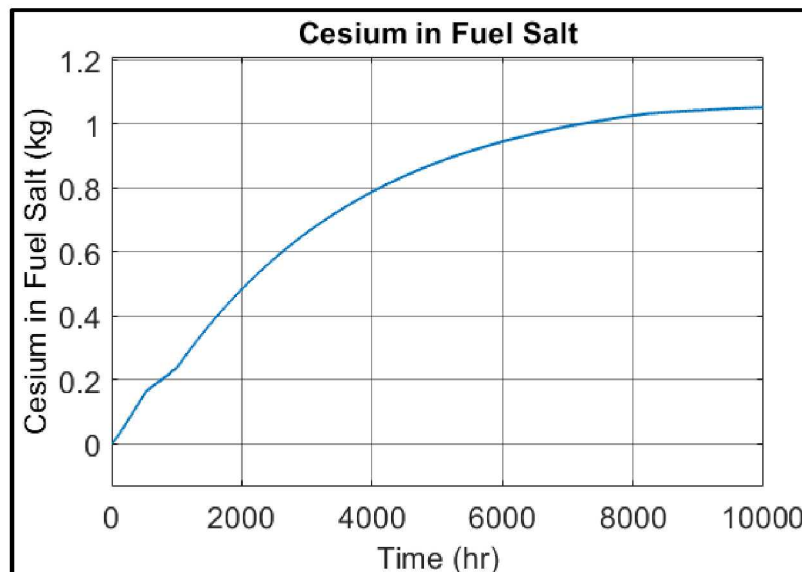


Initial Results (Fuel Inventories)

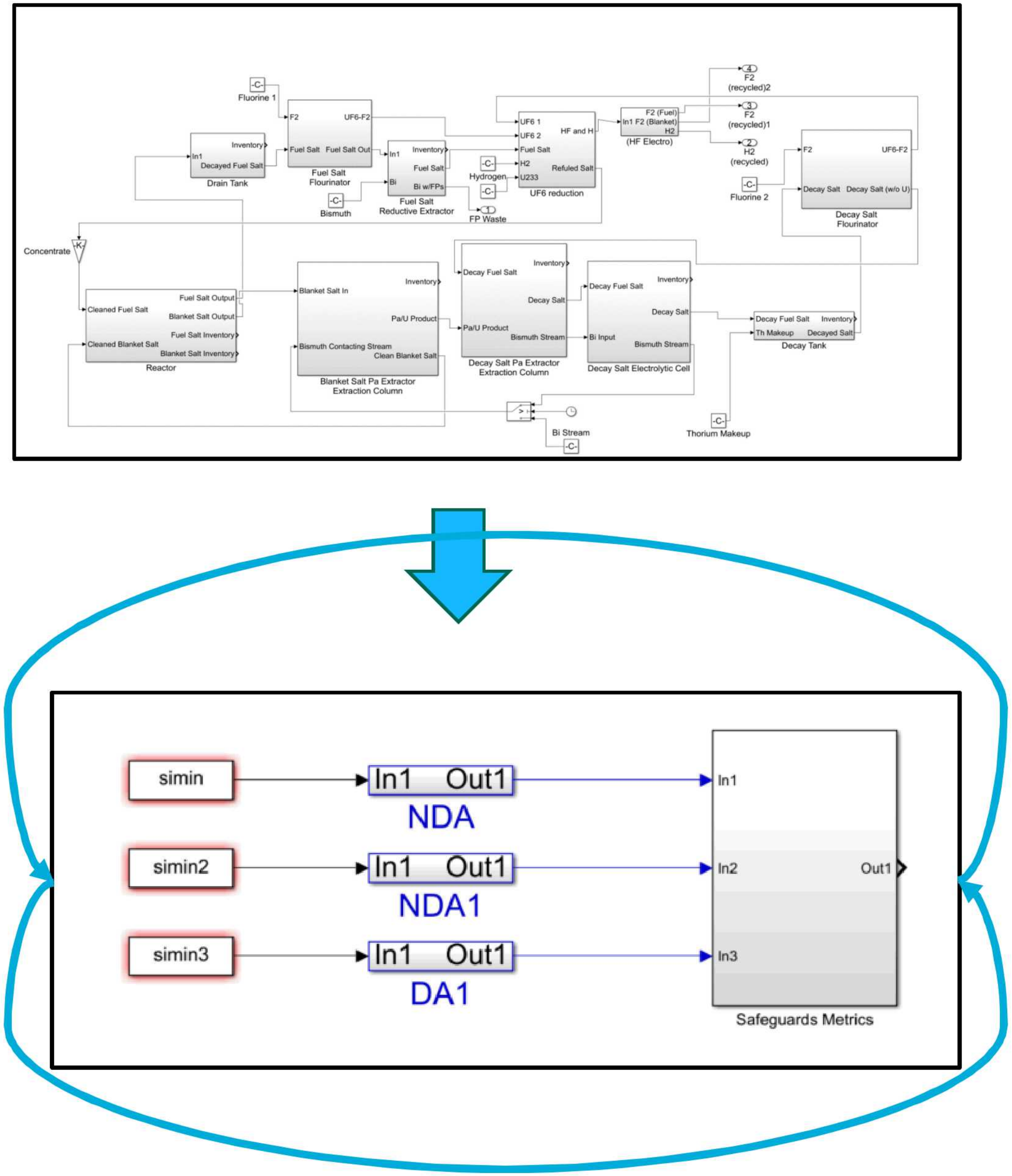








Modeling Approach – Safeguards Model



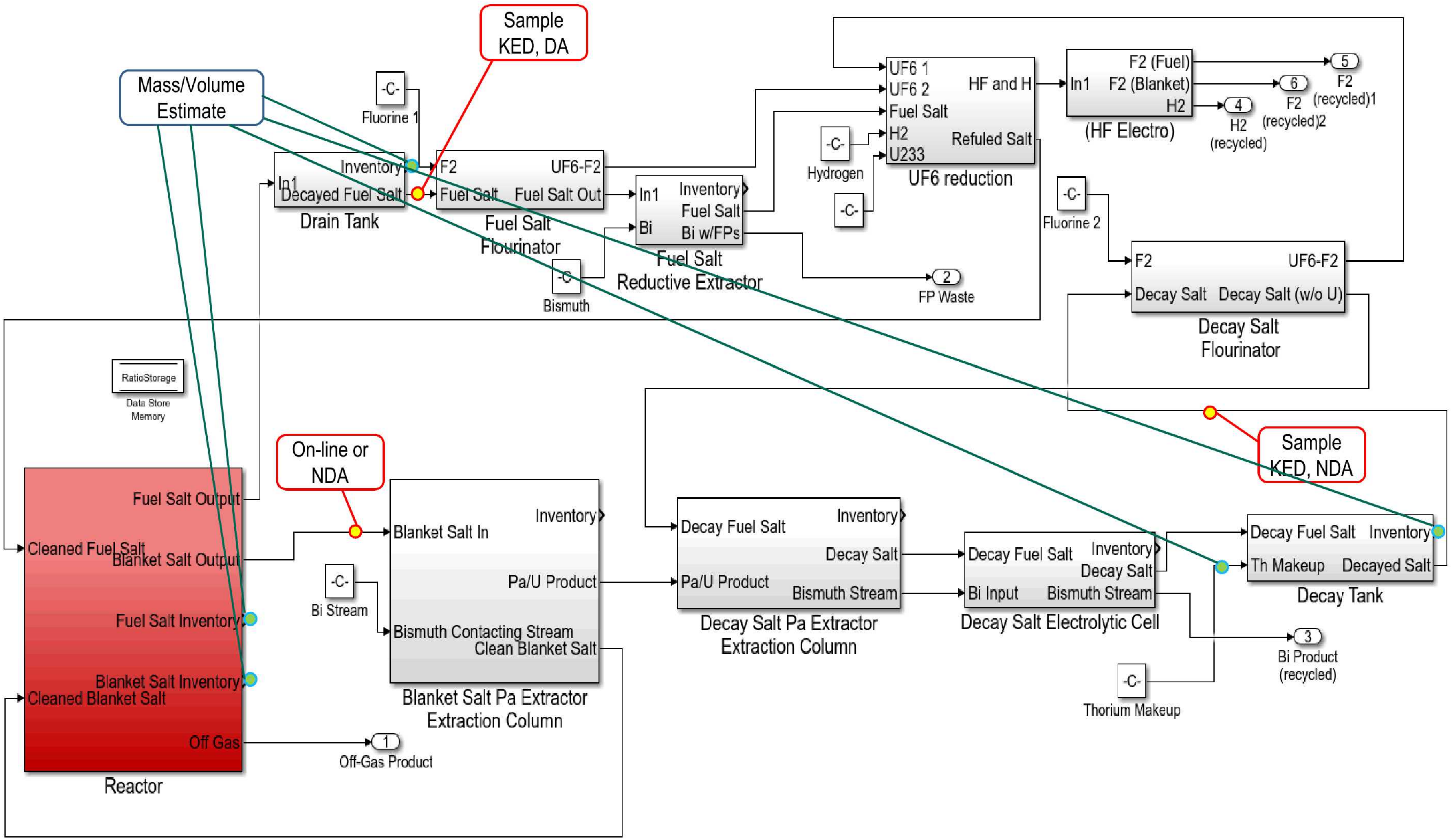
- For reprocessing SSPM models, the safeguards system is modeled as part of the process model.
- The safeguards aspects include the materials accountancy measurements and material balance calculation.
- However, the MSR model is more computationally intense, so it makes sense to separate the safeguards model from the process model.
- Can process the 1000's of runs needed to generate safeguards metrics with good statistics.

Initial Safeguards Analysis

(kg)	Fuel Salt Loop	Drain Tank	Blanket Salt Loop	Decay Tank
Total Mass	9067	239.8	49000	3571
Thorium	2.50E-06	6.60E-08	30000	2158
Protactinium	2.50E-06	6.60E-08	0.52	16.92
Uranium	132.5	3.5	0.025	23.22

- Reprocessing plants have much larger quantities of material in a given balance period compared to MSRs
- Radioactivity in molten salts for MSRs will be considerably higher which will make measurements more challenging
- Reprocessing plants are throughput-dominated – precision measurements required on high flow rates
- MSRs will likely track inventory measurements
- MSR safeguards may require taking into account depletion and decay unlike reprocessing

Proposed Measurement Locations



Additional Comments

- The Fuel salt contains the majority of fissionable material – good estimate/measurement will be key.
- Optimal measurement location is after decay/drain tanks.
- Volume measurements could be challenging due to core geometry and plant piping, level measurements and volume estimates of piping and core may be needed.
- The blanket salt has a low concentration of U and Pa due to the high flow rate to the chemical processing plant.
- Pa and U from the blanket are concentrated in the decay tank, but measurement would be difficult. A decay calculation combined with flows in and out of the decay tank will likely be needed.

Discussion

- FY19 work will focus on the development of the safeguards model.
- We would like to discuss how to better collaborate with ORNL so that we are using consistent data sets (use data sets directly from ORNL?, benchmark our results?, integrate capabilities?)
- How do we address other MSR design types?
- Modeling problems that need to be resolved:
  - Solve issues with numerical error over long simulation time (round-off error can cause numerical instability over many timesteps)
  - Update code with OBIWAN to read ORIGEN binaries (Change in thorium is so low per cycle that ORIGEN rounds the number even with long format)

Regulatory Requirements

- Accounting and control of material at traditional LWRs is covered under 10CFR74.
  - Parts 13, 15, 17 cover material status reports, transaction reports, and physical inventories.
  - Item accounting is also covered as part of physical security under 10CFR73
  - This has less applicability to MSRs with liquid fuels.
- For liquid fueled reactors, 10CFR74 can form a basis, but it should be noted that reprocessing is specifically excluded.
  - 10CFR74.59(f) requires a six-month shut-down and flushout to calculate an inventory difference (ID). The standard error of the inventory difference (SEID) must be estimated, and any SEID >0.1% of the active inventory must be examined. 10CFR74.53 requires a statistical test with a 95% probability of detecting the abrupt