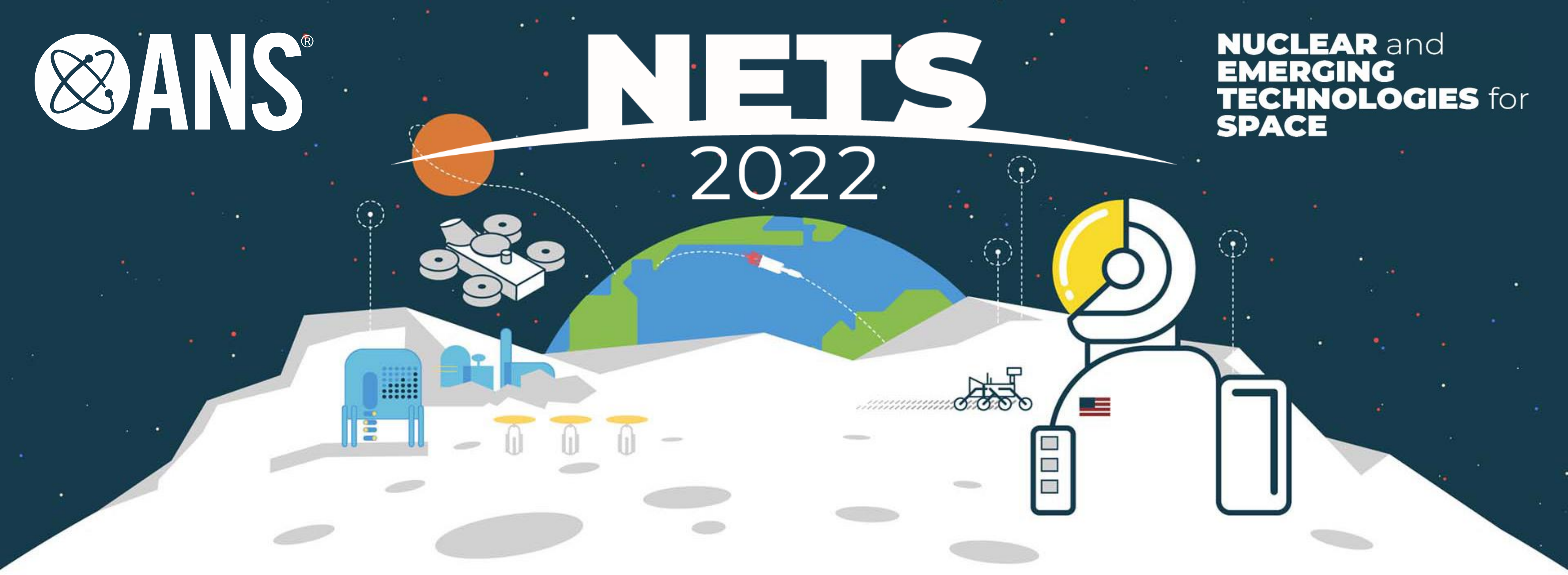


Nuclear Thermal Propulsion (NTP) Fission Product and Source Term Analysis

Reed Herner (Analytical Mechanics Associates, Inc.)

Kelsa Palomares, Adam Boylston, Lindsey Holmes (Analytical Mechanics Associates, Inc.)

Acknowledgements

This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) Project

Contract No. 80LARC17C0003

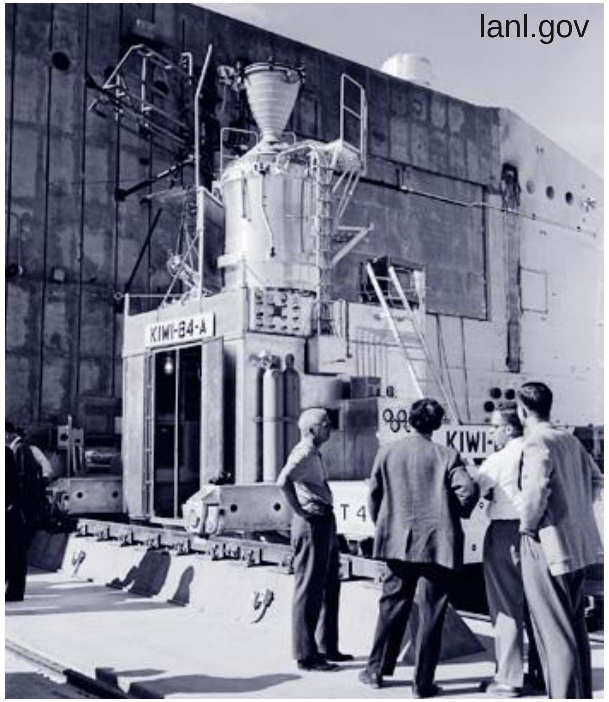
Task No. 10.020.000

Agenda

- Motivation
- Background
- Methodology
- Results
- Conclusions
- Future Work

Motivation

Planning for the safe ground testing of NTP engines requires an accurate estimation of fission product inventories, incident flux, and dose resulting from reactor operation.



The Kiwi-B4A Reactor awaiting testing at the Nevada Test Site, 1962 [1]

Nuclear Rocket Testing (Nerva Reactor) at Test Cell A at Nevada Test Site [2]

The goal of this work is to determine the fission product inventory due to reactor operation and resulting dose at candidate demonstration test sites.

Background

Fission products produced from reactor operations are unstable and result in release of radiation as they decay. High energy radiation is harmful to any person in proximity and must be mitigated.

- Activity is a measurement of the rate of decay. It is dependent on the total initial concentration of unstable isotopes and the half life ($t_{1/2}$) of each isotope.
  - The total fission product inventory is directly dependent on reactor operating power and duration.
  - Fission products will decay into daughter products which can also decay, leading to changes to total radioactivity and is time dependent.

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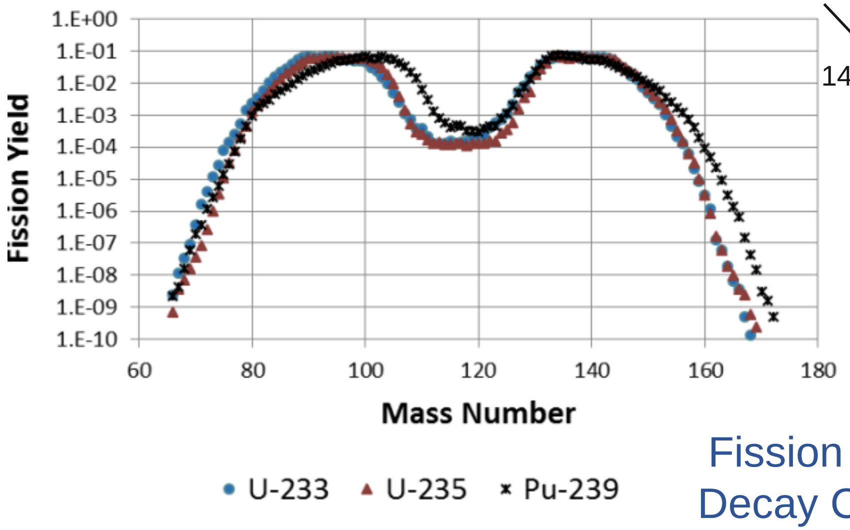

$^{140}Xe \rightarrow \beta$ T = 14s

$^{140}Cs \rightarrow \beta$ T = 64s

$^{140}Ba \rightarrow \beta$ T = 13d

$^{140}La \rightarrow \beta$ T = 40hr

^{140}Ce Stable

Fission Product Yield and Decay Chain Examples [3]

$$N(t) = N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

$$N(t) = N_0\, e^{\frac{-t}{\tau}}$$

$$N(t) = N_0\, e^{-\lambda t}$$

$N(t)$ = quantity of the substance remaining
N_0 = initial quantity of the substance
t = time elapsed
$t_{1/2}$ = half life of the substance
τ = mean lifetime
λ = decay constant

Background

Fission products produced from reactor operations are unstable and result in release of radiation as they decay. High energy radiation is harmful to any person in proximity and must be mitigated.

- Dose is the amount of energy deposited in a material due to a radiation source. The dose equivalent is a modified calculation of dose which takes into account the local impact of radiation interactions due to radiation type and unique biological effects
  - Dose equivalent units: roentgen equivalent man (rem) and sievert (Sv)
  - Dose equivalent can be calculated based upon the test series and compared to existing limits for exposure to onsite personnel or the public.

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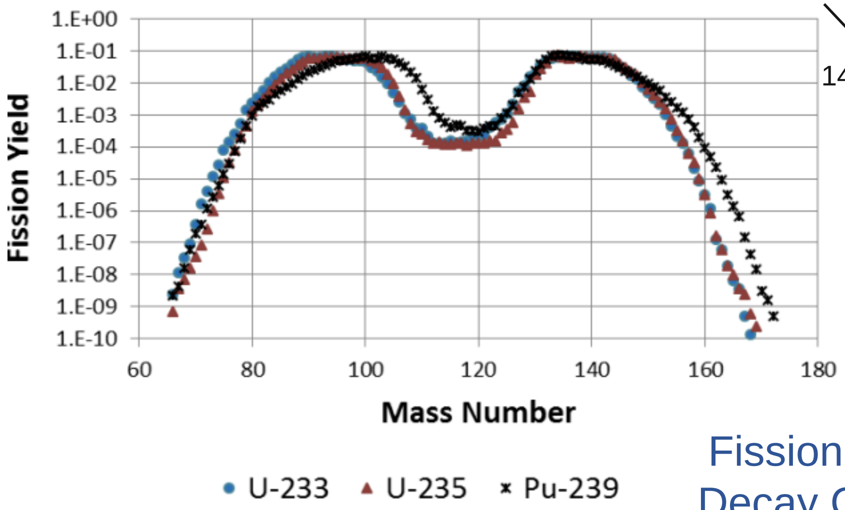

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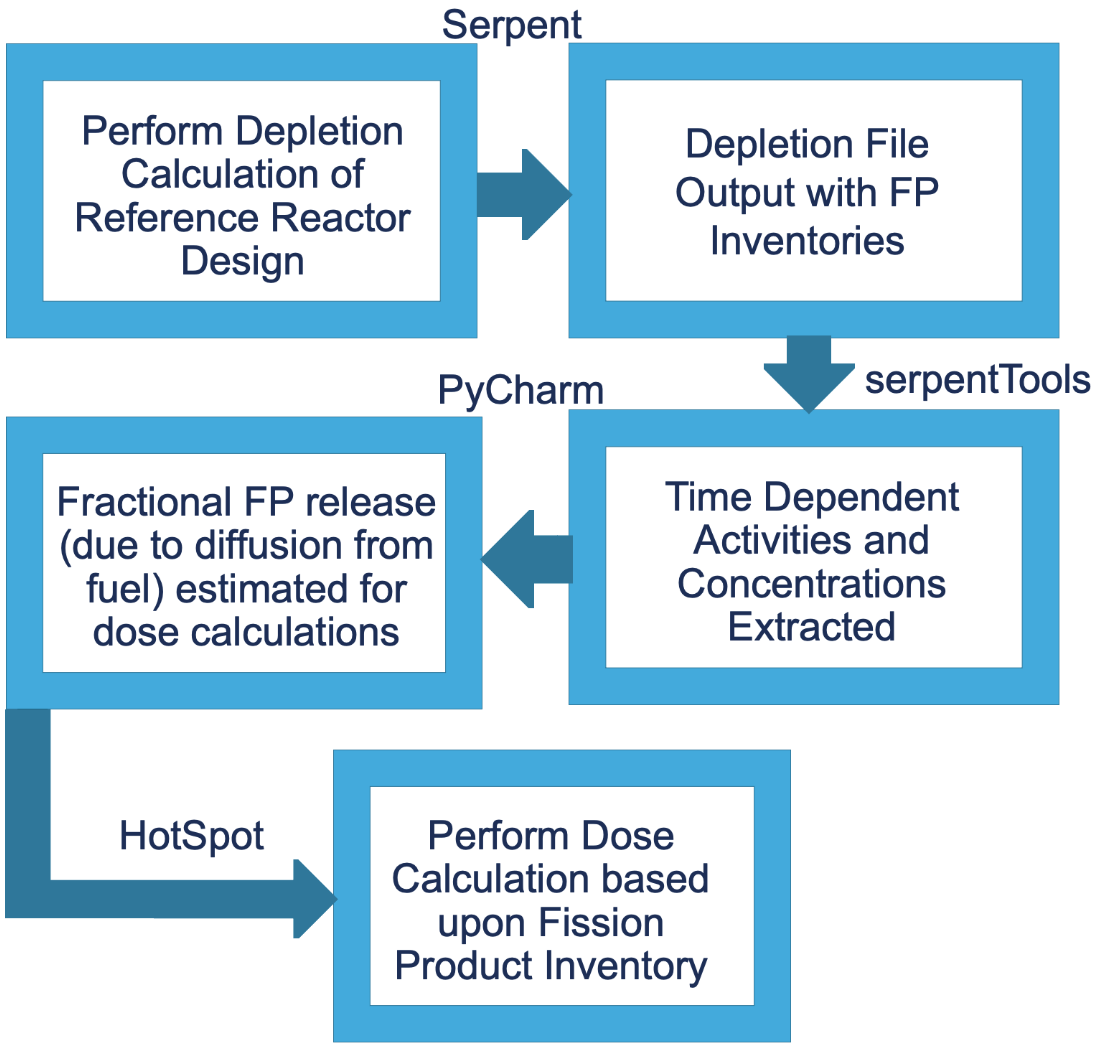
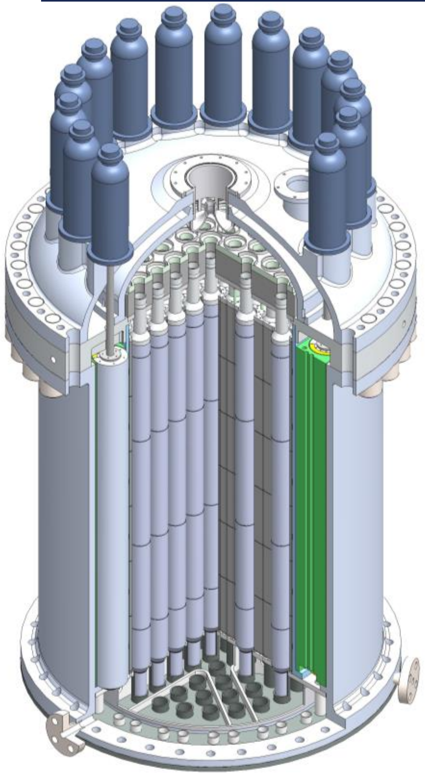
Methodology

The generation of fission product inventory and source term, requires analysis using specialized tools to accurately perform dose and depletion analysis.



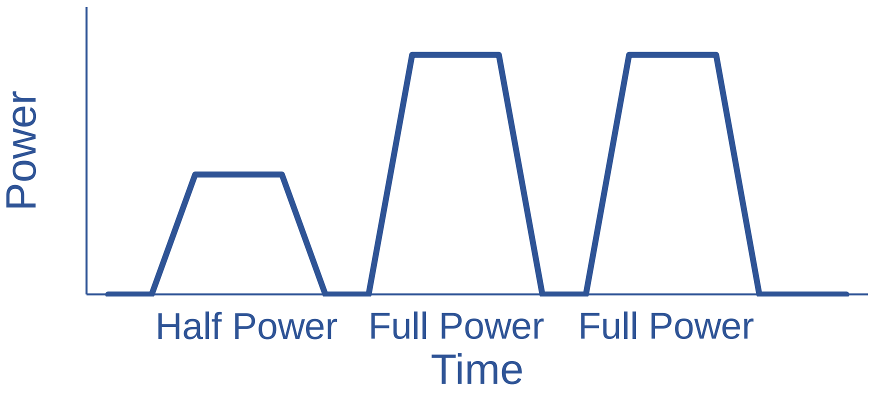
Methodology: Depletion and Fission Product Inventory

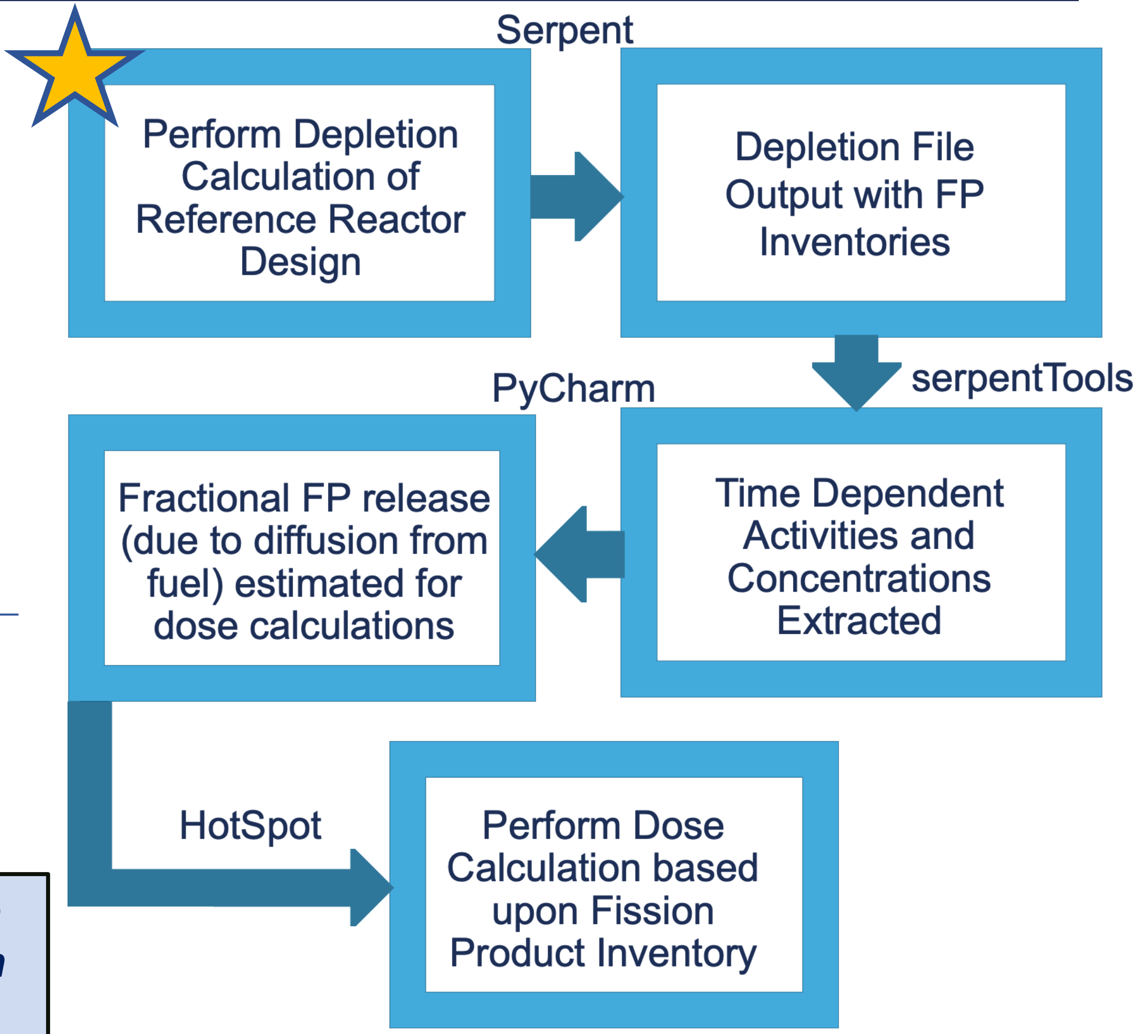
Depletion analyses were performed in Serpent to calculate fission product inventory using the SNP project testing reference design (TRD).



Reactor Subsystem Cross Section from BWXT [4]

Example Burn ConOps for Ground Test Series





The depletion analysis varied several inputs such as fuel type (cercer vs cermet), power level, and burn times with cooldown to simulate test series scenarios

Methodology: Depletion and Fission Product Inventory

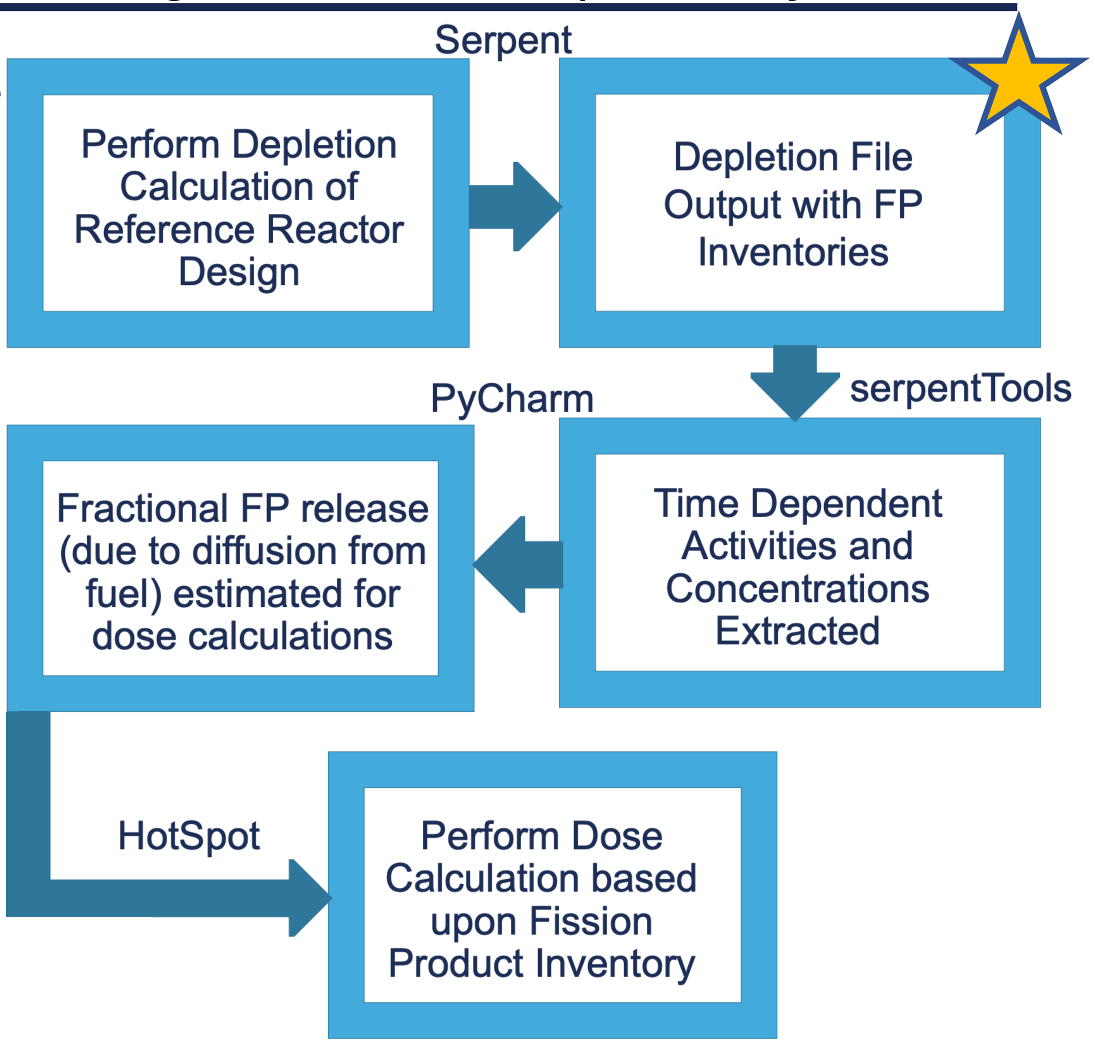
The Serpent MC code produces output depletion files containing all needed isotope activity data.

Activity Level | Each column is a depletion time step | Isotope Name

0.00000E+00	2.77451E-26	5.53853E-26	8.27577E-26	1.09857E-25	1.36863E-25	9.05939E-26	% Zr87
0.00000E+00	4.20401E-24	8.42089E-24	1.26259E-23	1.68178E-23	2.10237E-23	2.10164E-23	% Zr88
0.00000E+00	7.40051E-14	1.62472E-13	2.54400E-13	3.55699E-13	4.66464E-13	4.62358E-13	% Zr89
0.00000E+00	3.80345E-22	3.80891E-22	3.80555E-22	3.79595E-22	3.79440E-22	0.00000E+00	% Zr90m
0.00000E+00	3.78181E-10	7.80000E-10	1.18148E-09	1.58189E-09	1.98132E-09	1.92312E-09	% Zr97
0.00000E+00	1.93230E-10	2.44885E-10	2.58235E-10	2.61248E-10	2.61600E-10	0.00000E+00	% Zr98
0.00000E+00	1.80242E-11	1.80360E-11	1.80368E-11	1.79963E-11	1.79568E-11	0.00000E+00	% Zr99
0.00000E+00	6.03391E-11	6.05541E-11	6.05573E-11	6.04218E-11	6.02892E-11	0.00000E+00	% Zr100
0.00000E+00	1.08275E-11	1.08346E-11	1.08350E-11	1.08107E-11	1.07871E-11	0.00000E+00	% Zr101
0.00000E+00	9.05271E-12	9.05866E-12	9.05906E-12	9.03870E-12	9.01898E-12	0.00000E+00	% Zr102
0.00000E+00	1.00635E-12	1.00701E-12	1.00706E-12	1.00479E-12	1.00263E-12	0.00000E+00	% Zr103
0.00000E+00	1.57011E-13	1.57115E-13	1.57123E-13	1.56764E-13	1.56439E-13	0.00000E+00	% Zr104
0.00000E+00	1.05875E-13	1.05944E-13	1.05949E-13	1.05711E-13	1.05479E-13	0.00000E+00	% Zr105
0.00000E+00	7.75367E-18	7.78047E-18	7.75625E-18	7.72822E-18	7.76096E-18	0.00000E+00	% Zr106

Example Fission Product Inventory

Fission products can be tracked by contribution to dose, isotope type, and other factors. All activities are reported as Bequerels (Bq), are converted to Curies (Ci)

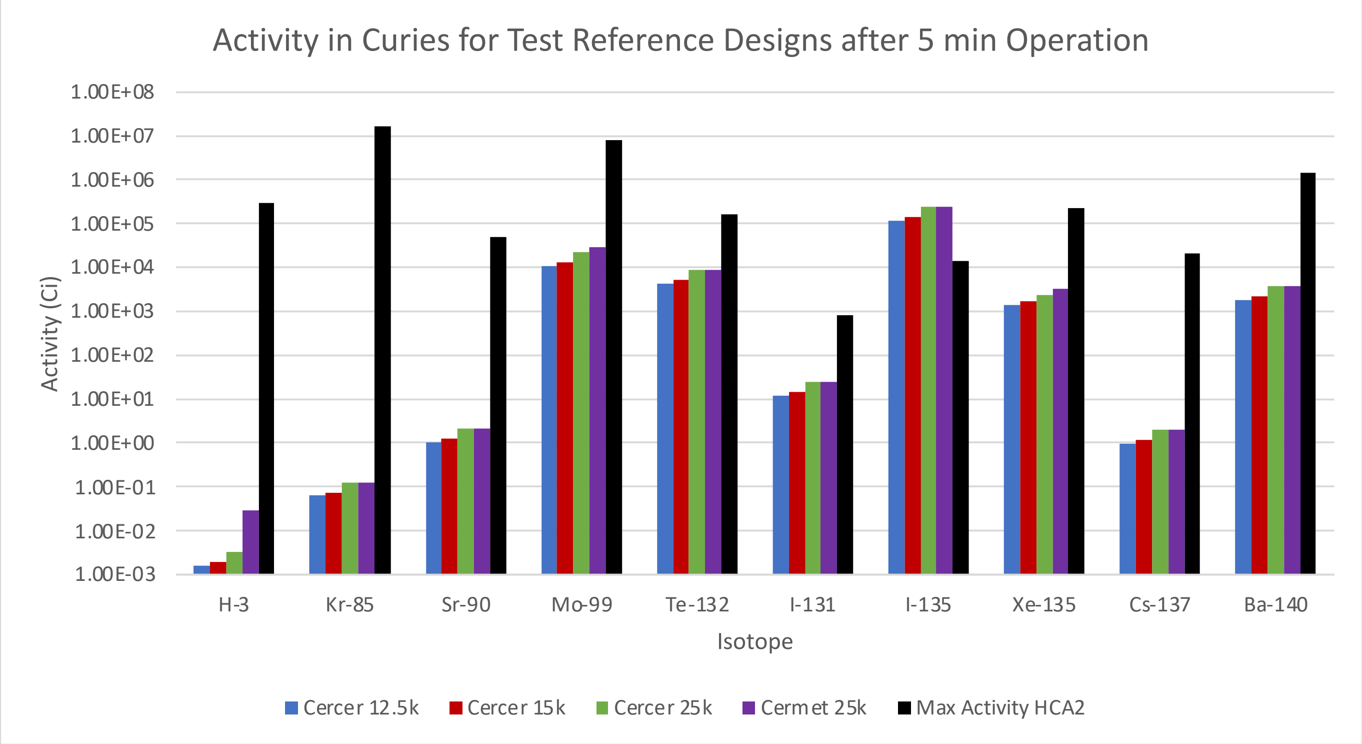


Results: Predicted Activity from TRD Operations

Activity from fission product inventory is compared to HCA Limits. Shown below are the contributions from isotopes with the highest activity after reactor operations.

TABLE I. Reproduction of Table 1 in Appendix A of Subpart B of 10 CFR Part 830 [5]

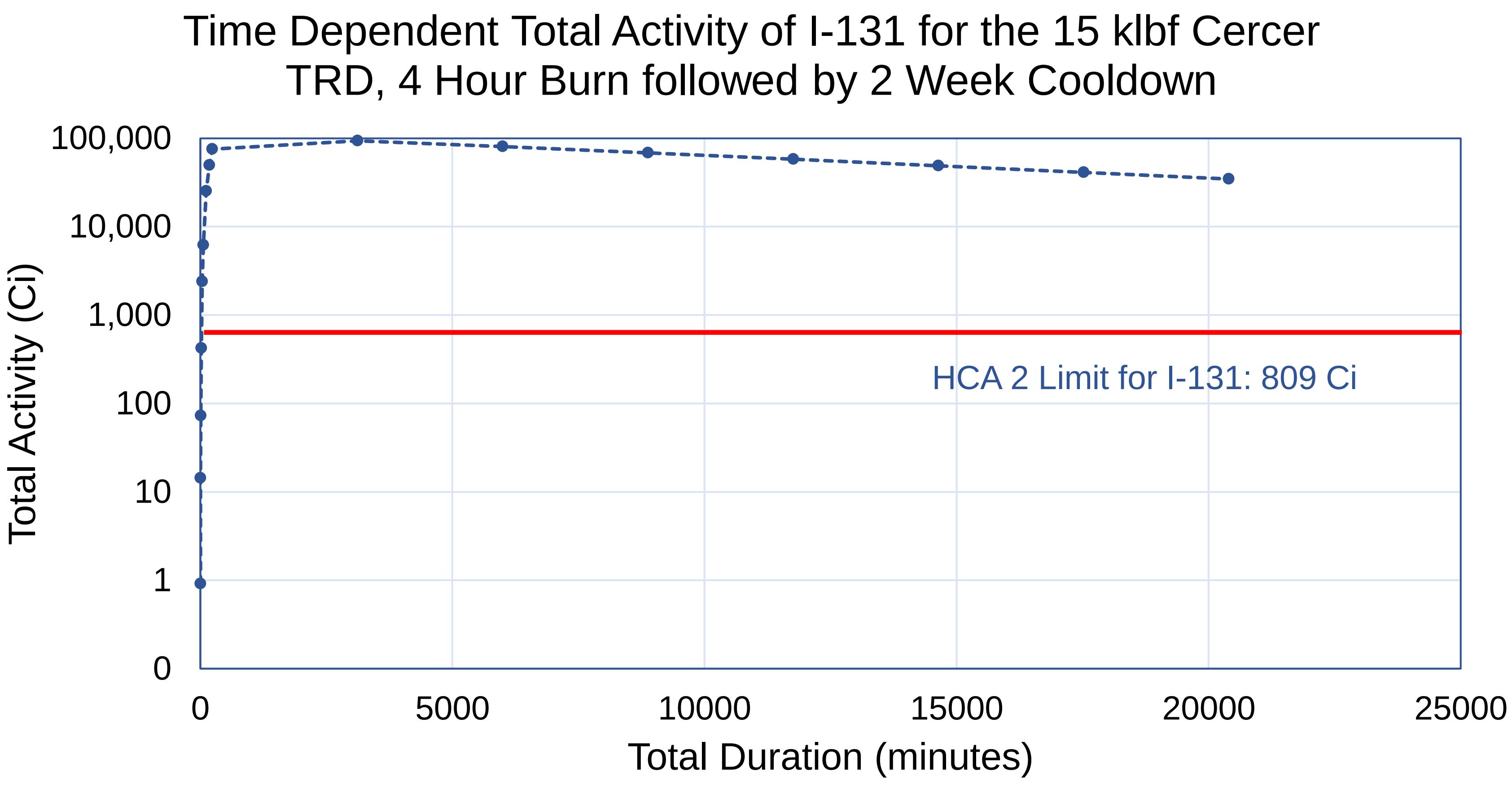
A DOE nuclear facility categorized as…	Has the potential for…
Hazard Category 1	Significant off-site consequences
Hazard Category 2	Significant on-site consequences beyond localized consequences
Hazard Category 3	Only local significant consequences
Below Hazard Category 3	Only consequences less than those that provide a basis for categorization as a hazard category 1, 2, or 3 nuclear facility

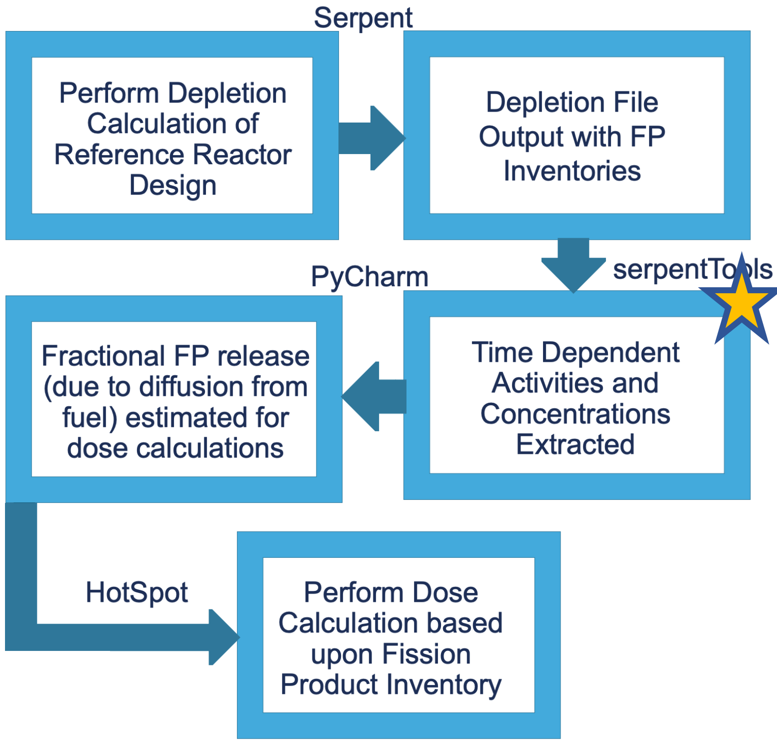


Hazard Category Analysis from the Department of Energy (DOE) is used to categorize nuclear facilities, and direct comparisons to current restrictions will highlight isotopes above limits and set margins for facility trades

Methodology: Activity Analysis

Depletion data is interpreted in the Pycharm interface and post processed for maximum activity levels and levels over time. Activities are compared to the set Hazard Category definitions to observe which isotopes are above or below set limits.





Isotopes of interest can be isolated and behavior over time can be analyzed, identifying needed time of cooldown to ensure lowest activity level and how activity compares to HCA levels

Methodology: Fission Product Release

During operation, a fraction of fission products may be released. Using data collected by Cleary and Rymer (1964), temperature dependent diffusion coefficient-based fractional release formulas were developed to estimate FP release.

WANL-TME-958 [6]

TABLE II

Classification of Elements for FIPDIF in Type II Fuel

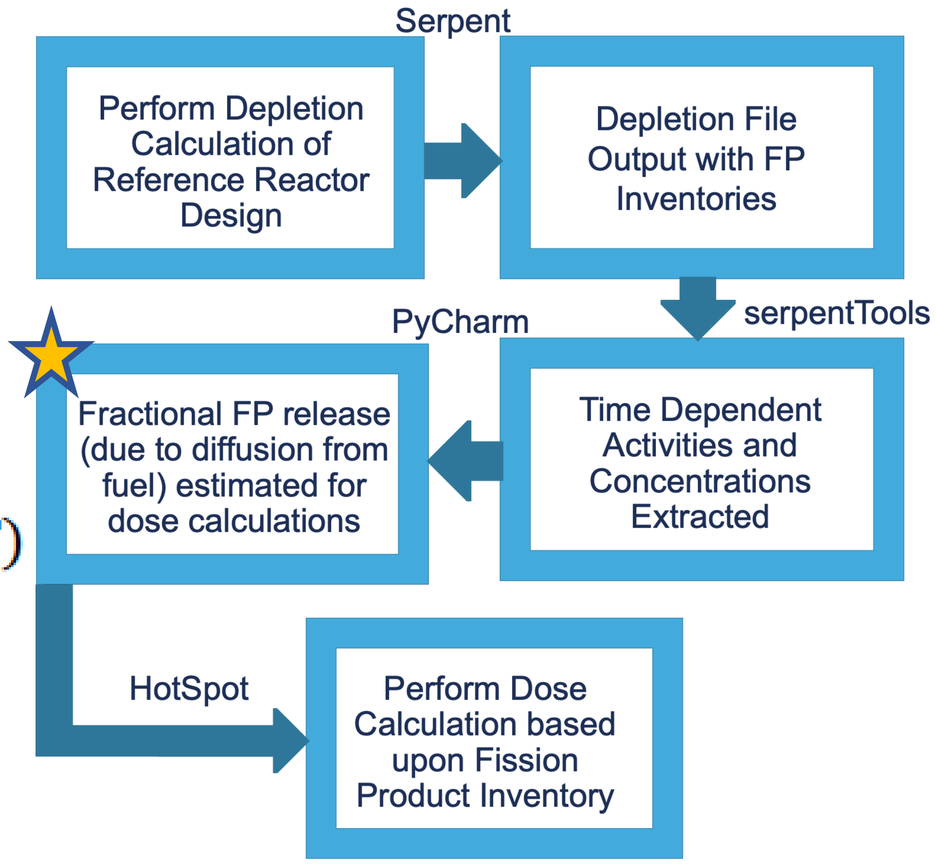
Diffusion Group	f	Do	E/R	Element					
1	0.855	3.977×10^{2}	3.32×10^{4}	Sr*	Sn	Sb	Br		
2	0.145	8.70	1.55×10^{4}	Sr*-0	Sn-0				
3	0.855	1.80×10^{-3}	6.00×10^{3}	Ba*					
4	0.145	9.17×10^{-3}	2.50×10^{3}	Ba*-0					
5	1	1.215	3.22×10^{4}	Ce*	Y*	La*	Kr	Xe	
6	1	5.383×10^{10}	8.72×10^{4}	I*	Cs*	Te*	Se	Rb	As
7	1	0	0	Mo*	Zr*	Ru*	Nb		

* Nuclides analyzed for were:

Sr^{89}, Ba^{140}, Ce^{144}, Y^{91}, La^{140}, I^{131}, Te^{129}, Cs^{137}, Mo^{99}, Zr^{95}, Ru^{103}

$$1 - f = f_0 \, e^{-Dt}$$

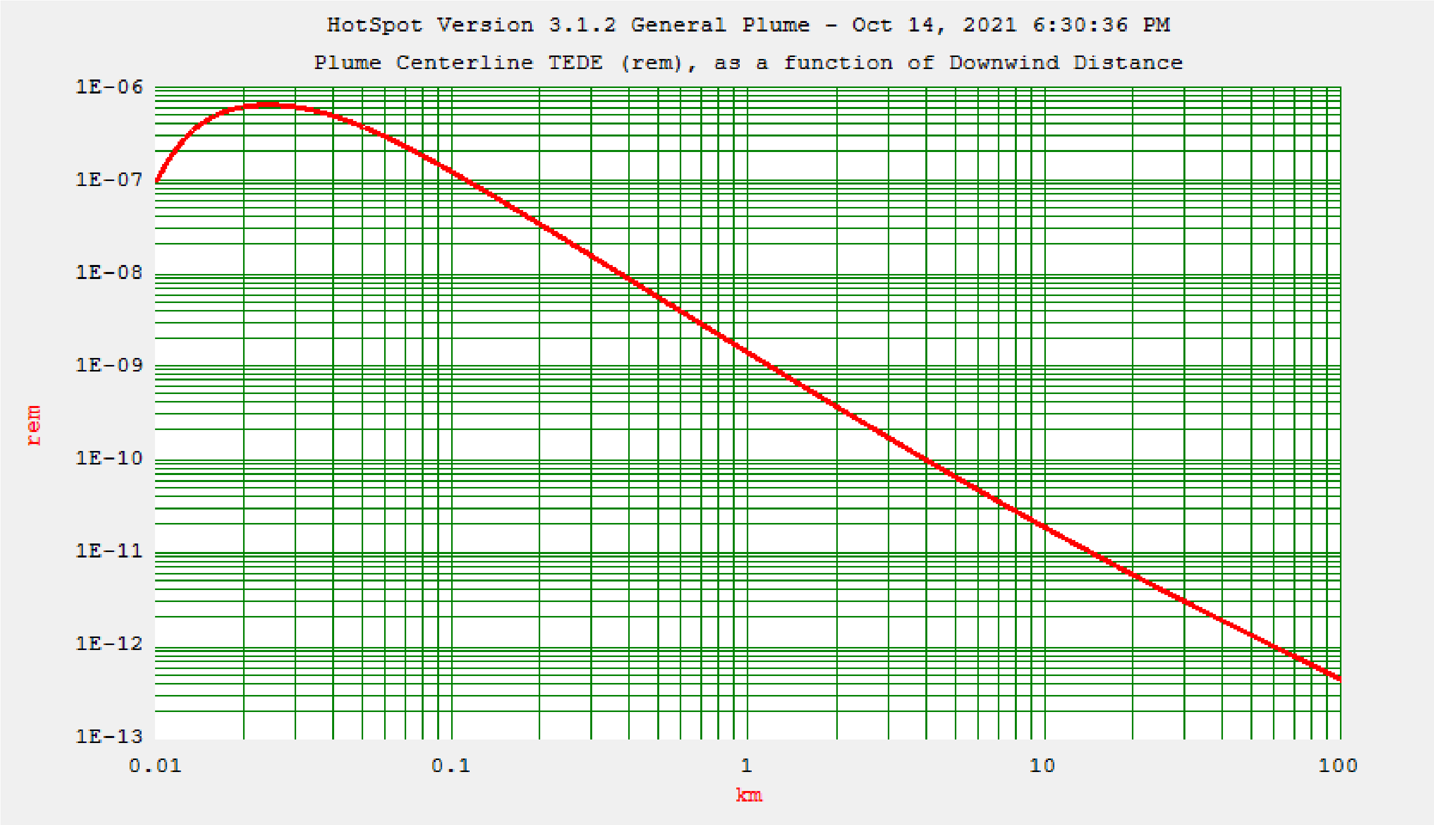
$$D = D_0 \, e^{-E/(RT)}$$

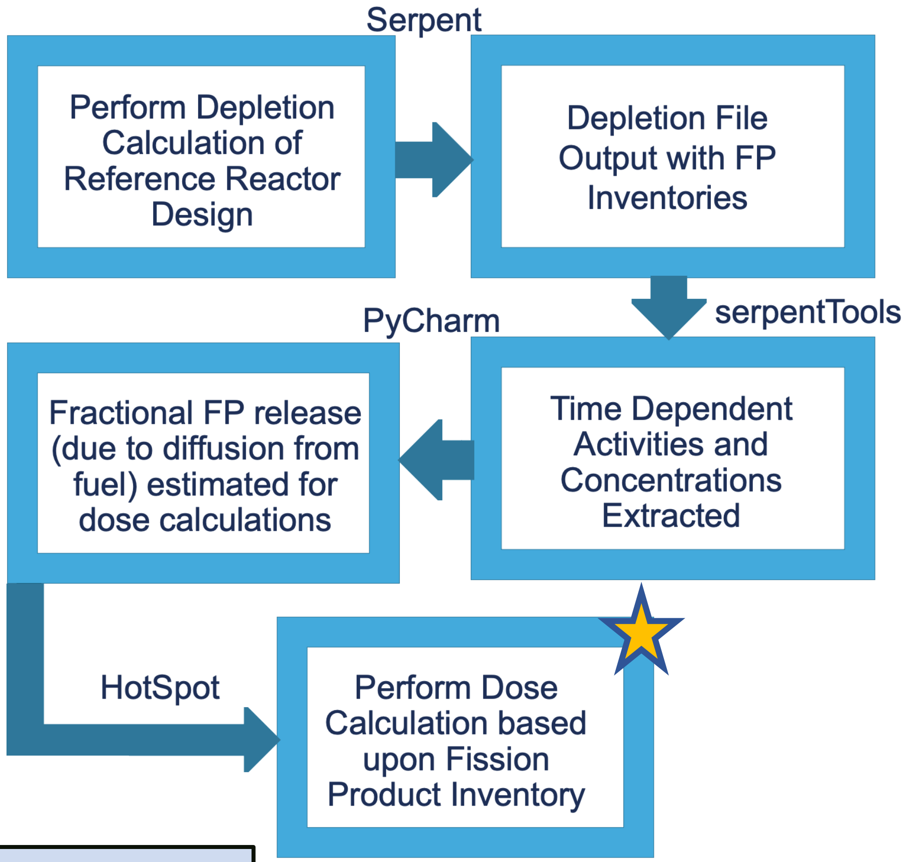


Significant data gaps present in fractional release data. Type II Fuel from NERVA different than contemporary designs in geometry and fuel design

Methodology: Source Term Calculation

Using HotSpot for source term calculations, isotope activities can be used for determination of dose and the impact to workers and the general public.





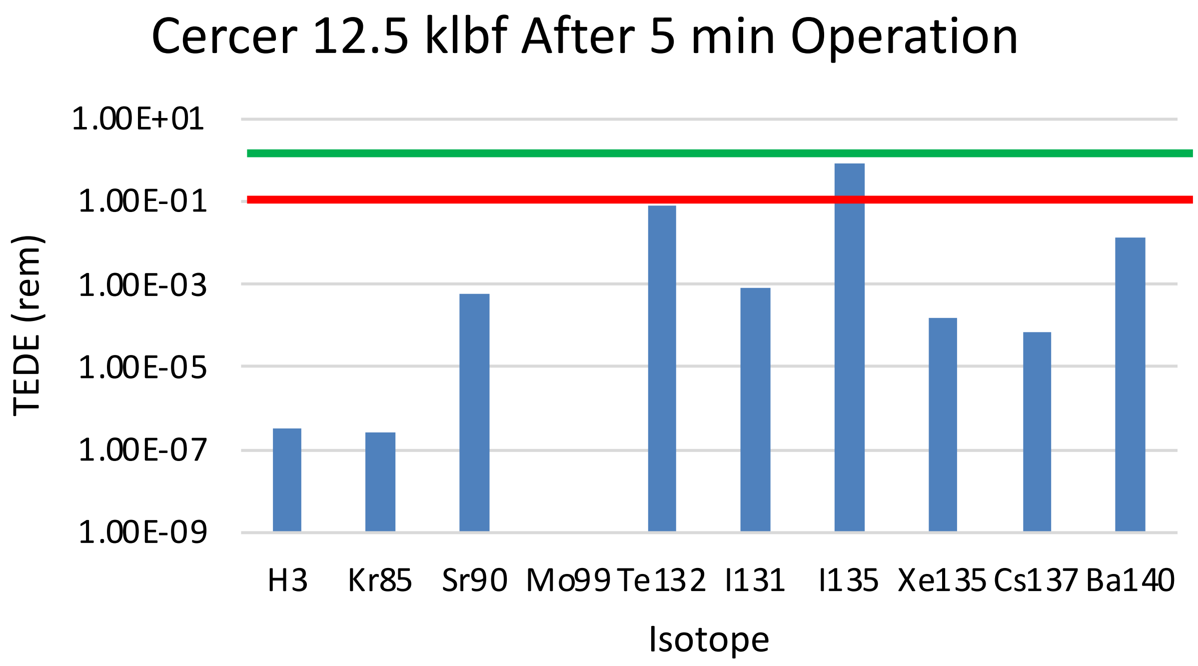
HotSpot can simulate different test sites and conditions for the source term. Meteorological factors like release height, wind speed and direction, ground shine, breathing rate, and more can be adjusted as needed

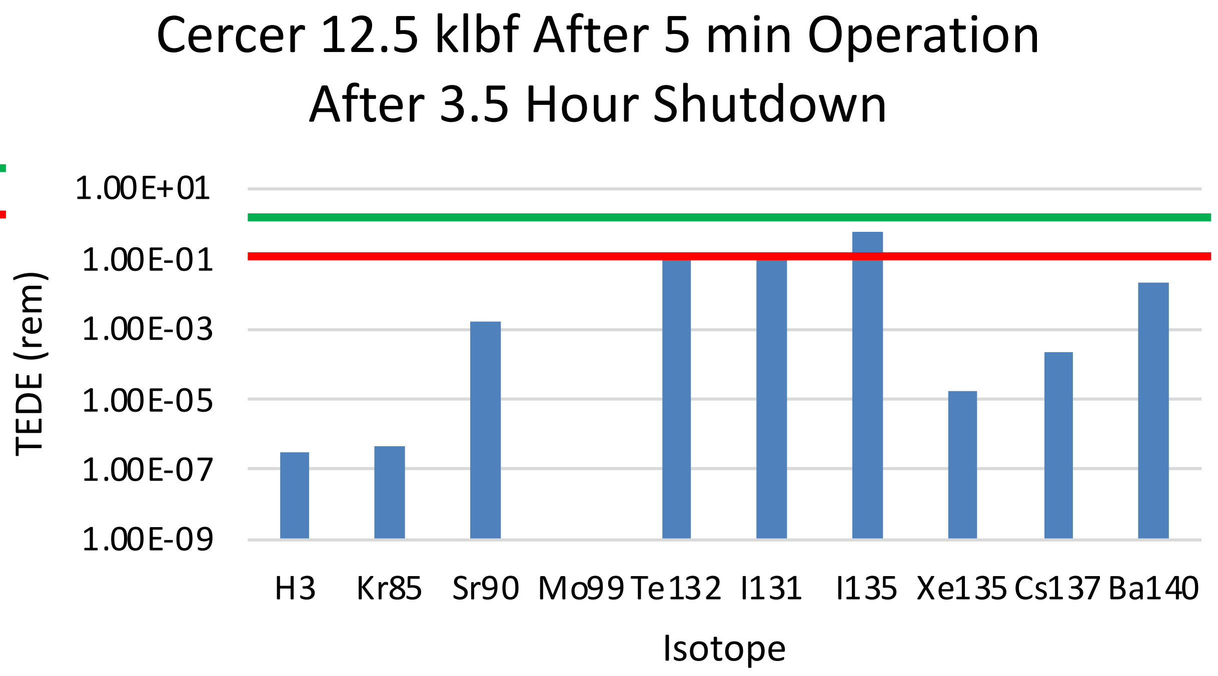
Results: Predicted Dose from TRD Operations

Fractional release is applied to the activity levels of the fission products. These activities are uploaded to the HotSpot source term code to determine dose impact per isotope.

Total Effective Dose Equivalent in rem is shown for 5 minutes of operation and shutdown to observe behavior. Fractional release was applied based on temperature dependent diffusion coefficient formulas. Isotopes that did not have relevant data were given 60% fractional release

- Occupational Dose Limit (0.1 rem per year) General Public in Controlled Area
- Occupational Dose Limit (5 rem per year) General Employees





Conclusions and Recommendations

- Only Iodine-135 was found to be above Occupational Dose Limit for General Public in a Controlled Area (0.1 rem) for the reference case of a 5-minute burn at 12.5 klbf.
  - This indicates additional mitigations are still needed to allow for NTP engine operations at the test site.
  - At maximum fuel temperature of 2860 K, I-135 had a fractional release of 93.8%.
- Fuels with high fission product retention (>90%) will reduce fission product release allowing for longer operations during a demonstration.
  - Fractional release is a key sensitivity for dose analysis and is fuel form dependent (governed by geometry and diffusion). There does not exist accurate fission product diffusion data for the testing reference design fuel form.
- Filtration or capture systems can further play a role in preventing fission product release to the environment.
  - Fission product release may not be mitigated through fuel design alone as it is inherently governed by diffusion through the fuel form.

Future Work

- Future work aims to update HotSpot analyses with site specific meteorological conditions to evaluate the impact on predicted dose to inform facility trades.
  - Benchmarking in-house models to results from site personnel focus for improving AMA source term generation capabilities.
- Shielding and activation analyses using radiation flux data are currently underway.
  - This analysis will inform updated dose calculations based on flux fields of neutrons, gammas, and other incident particles

Thank you for your time.
Questions?

A special thanks to the Nuclear Team at Analytical Mechanics Associates, Lindsey Holmes, Jim Werner, Marc Neely, Jarvis Caffery, the CORE Lab at Georgia Tech, and the organizers of NETS 2022.

Backup Slides

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6. Cleary, J. D., Rymer, G. T. “Interim Report on Fission Product Diffusion Code (FIPDIF)”. AEC Research and Development Report, WANL-TME-958, Jan. 9 1982.

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Reference Clarification

References in Presentation cite all third-party images included in slides, References from Paper cite all acknowledgements of codes and documents supporting work and not explicitly shown, not related to any images

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