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Pacific Northwest
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Fission Product Inventory Modeling

Fall 2020 RAMP USERS GROUP MEETING

October 30, 2020

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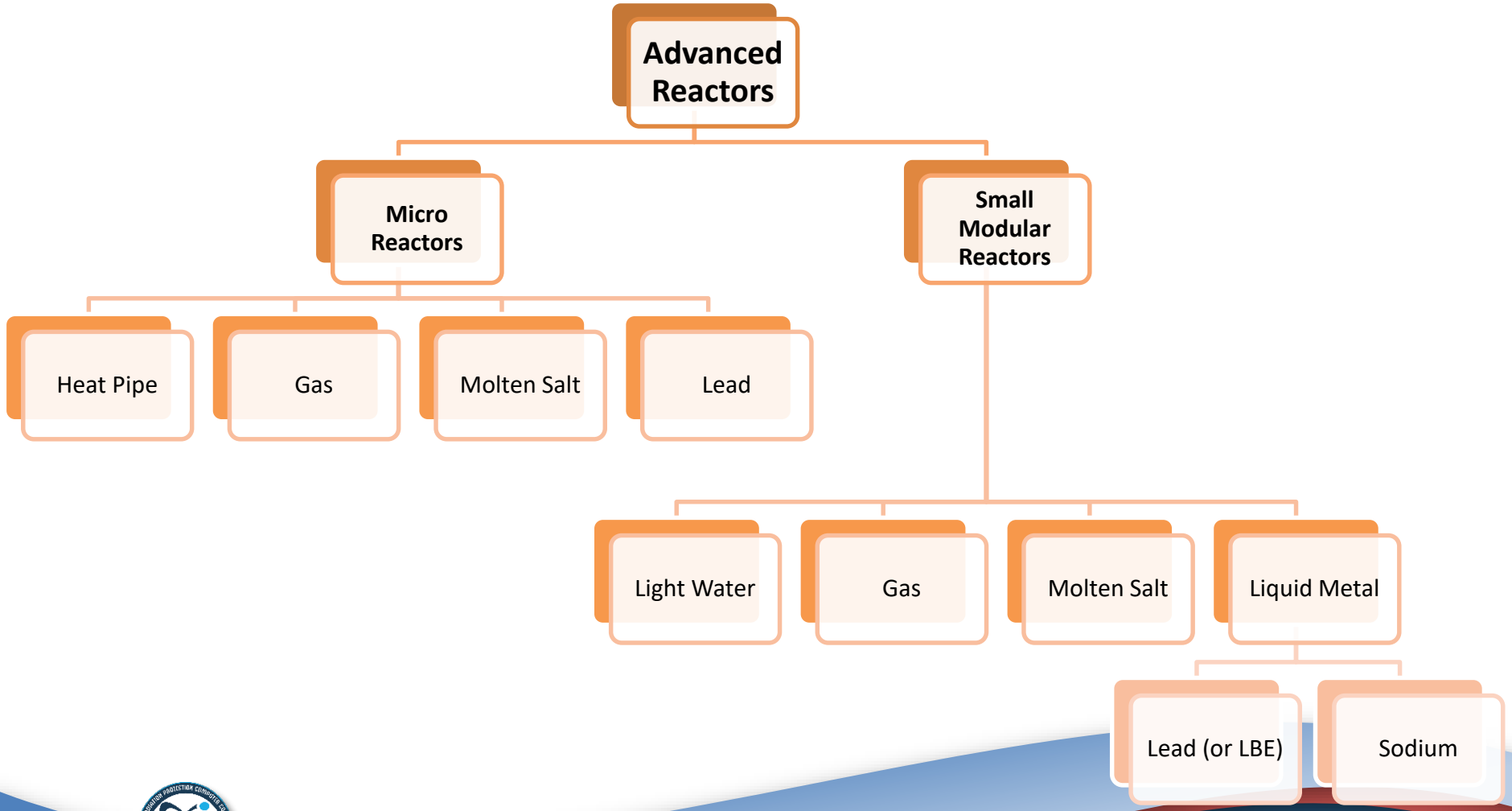
Pacific Northwest National Laboratory

Introduce Advanced Reactors

Describe Reactors Under Design

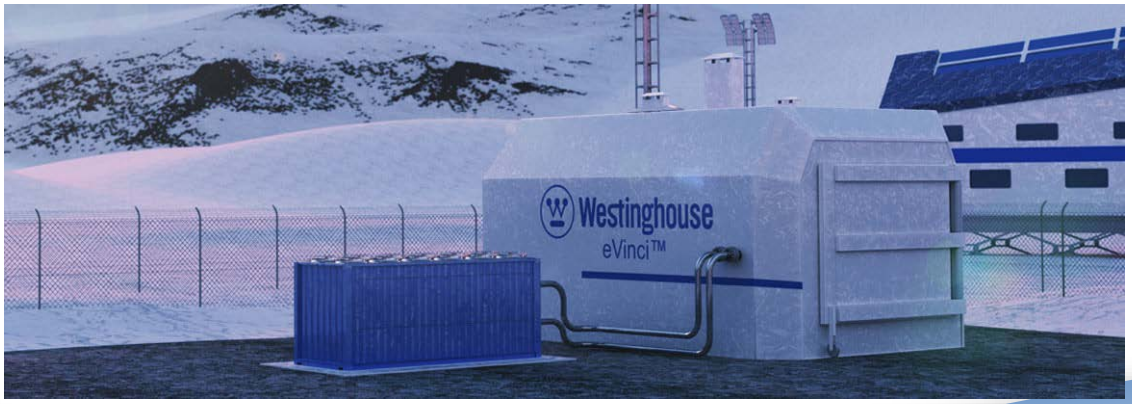
Describe Fission Product Modeling Approach

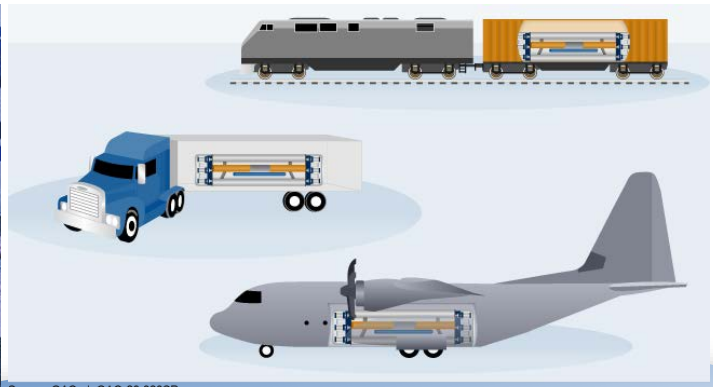
Hierarchy of Advanced Reactors



What are the general characteristics of a Micro Reactor?

- Defined by a power range (1 MWe to 30 MWe) rather than specific technology
- Small footprint: fit on a flatbed truck, housed within 1000 ft^2
- Potentially mobile/deployable
- Semi-autonomous operation
- Operate for several years without refueling

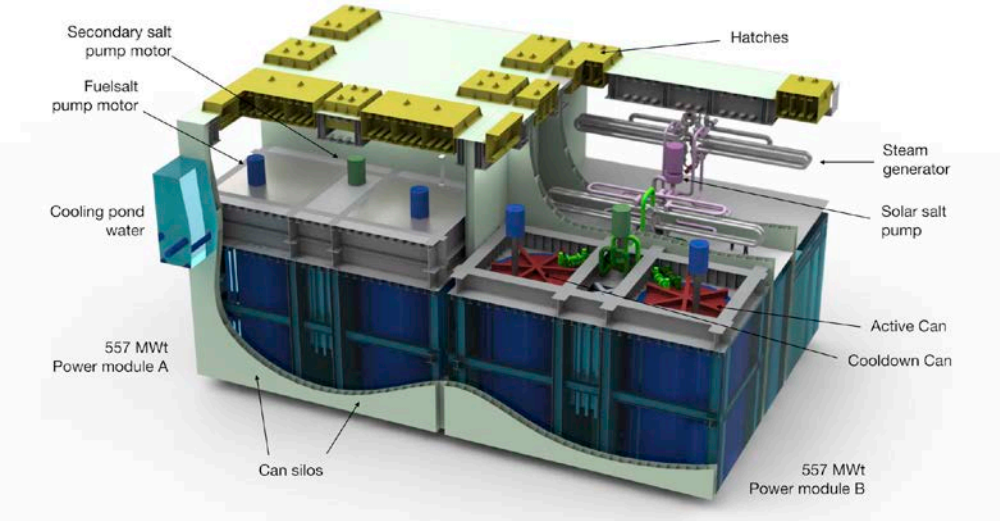


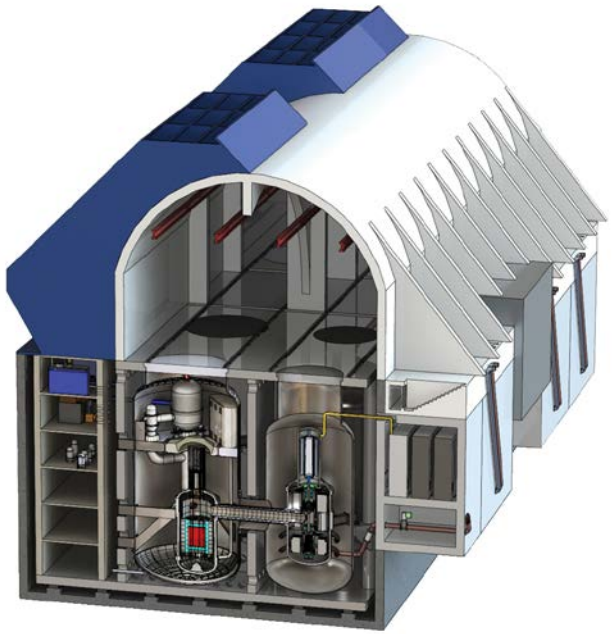


Source: GAO. | GAO-20-380SP

What are the general characteristics of an SMR?

- Again defined by power range (~30 MWe to 500 MWe)
- Smaller footprint than large light water designs
- Modular
- Safety by design





US-Based Vendors and Designs

Vendor	Design	Vendor	Design
Framatome	High Temperature Gas Reactor	Alpha Tech Research Group	Molten Salt Reactor
General Atomics (EM2)	High Temperature Gas Reactor	Elysium Industries	Molten Salt Reactor
HolosGen	High Temperature Gas Reactor	Flibe Energy (LFTR)	Molten Salt Reactor
NuGen	High Temperature Gas Reactor	Kairos Power	Molten Salt Reactor
Ultra Safe Nuclear Corporation	High Temperature Gas Reactor	Terrapower (MCFR)	Molten Salt Reactor
X-Energy	Liquid Metal-cooled Fast Reactor	Terrestrial Energy USA (IMSR)	Molten Salt Reactor
Advanced Reactor Concepts (ARC-100)	Liquid Metal-cooled Fast Reactor	ThorCon Power	Molten Salt Reactor
Columbia Basin Consulting Group	Liquid Metal-cooled Fast Reactor	Atlas Energy Systems	Nuclear Battery
General Electric-Hitachi (PRISM)	Liquid Metal-cooled Fast Reactor	CityLabs (NanoTritium)	Nuclear Battery
Hydromine Nuclear Energy	Liquid Metal-cooled Fast Reactor	MicroNuclear	Nuclear Battery
Niowave	Liquid Metal-cooled Fast Reactor	Global Energy Research Associates (GERA)	Small Modular Reactor
Oklo*	Liquid Metal-cooled Fast Reactor	Holtec (SMR-160)	Small Modular Reactor
Terrapower (TWR)	Liquid Metal-cooled Fast Reactor	**Nuscale Power (NuScale)***	Small Modular Reactor
Westinghouse	Liquid Metal-cooled Fast Reactor	Westinghouse (SMR)	Small Modular Reactor
Westinghouse (eVinci)	Liquid Metal-cooled Fast Reactor		
General Atomics Mobile Micro-Reactor	Mobile Micro Reactor		
Westinghouse Mobile Micro-Reactor	Mobile Micro Reactor		
X-Energy Mobile Micro-Reactor	Mobile Micro Reactor		
BWX Technologies (BWXT) Mobile Micro-Reactor	Mobile Micro Reactor or Space Reactor		

* Have submitted Design Certification Application to NRC

More information on international vendors available in publication developed by Nuclear Power Technology Development Section of the IAEA

How did we approach modeling fission products?

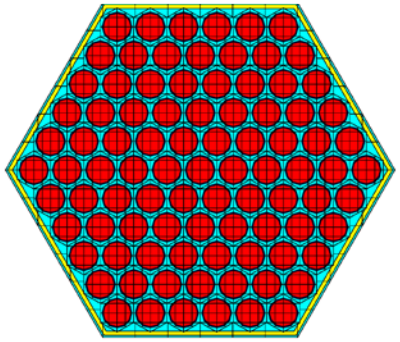
Reactors of interest were categorized by general reactor type

- Helium-cooled prismatic reactor with TRISO fuel (based on High-Temperature Engineering Test Reactor [HTTR])
- Helium-cooled pebble-bed reactor with TRISO fuel (based on HTR 10)[1]
- Lead-cooled fast reactor with UO_2 fuel (based on LeadCold Reactor)[2]
- Heat-pipe fast reactor with UO_2 fuel (based on Special Purpose Reactor)[3, 4]
- Molten salt thermal reactor with liquid fuel (based on ThorCon Reactor)[5, 6]
- Molten salt fast reactor with liquid fuel (simplified design)
- Sodium-cooled Fast Reactor (based on GE PRISM)

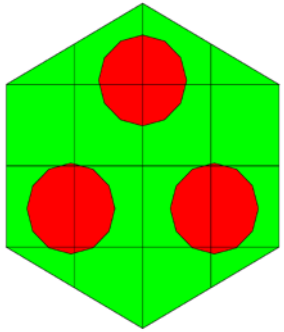
[1] IAEA 2004
[2] Wallenius et al. 2018
[3] INL 2017
[4] Hernandez et al. 2018
[5] Fei et al. 2019
[6] EPRI 2015
[7] Triplett 2018

TRITON Models

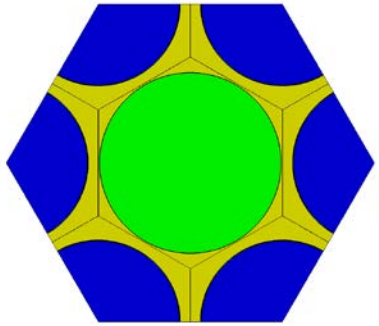
LeadCold



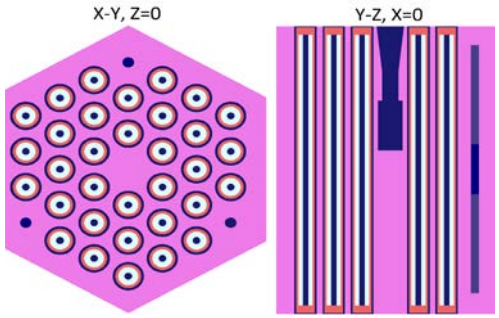
ThorCon



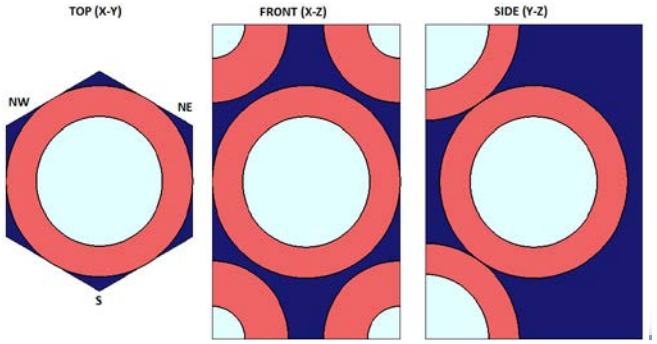
SPR



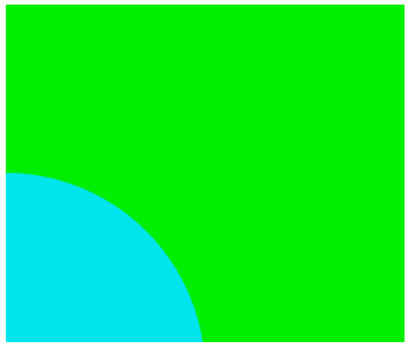
HTTR



HTR-10



Molten Salt - Fast



What model runs were conducted?

- Depletion models using TRITON (Transport Rigor Implemented with Time-dependent Operation for Neutronic depletion) in SCALE (Standardized Computer Analyses for Licensing Evaluation)
  - Create library files for later use
  - Run a defined number of depletion cases based on power level (MW/MTHM)
- Radionuclide inventories calculated from TRITON libraries using ORIGEN (Oak Ridge Isotope Generation Code)
- Decay-only calculations performed using ORIGEN
  - Up to 20 years

Comparing Inventories

- Summary data set includes reactor source term inventories by radionuclide
  - Time 1 day, Time 1 year
- Minimum, maximum, and average activity for each radionuclide deduced from comparison across reactor types
- Focused summary data limited to radionuclides with high mobility potential
- Molten salt reactors exhibited highest activities for most radionuclides and had highest total activities

Example Results

Summary files for reactor type and enrichment (excerpt)

	240500000	240500000	240500000	240500000	240500000	240500000	240500000	240500000	240500000	240500000	240500000	240500000	240600000	240600000	241600000	272100000
np239	6.632E+17	6.632E+17	6.632E+17	6.632E+17	6.632E+17	6.632E+17	6.632E+17	6.632E+17	6.631E+17	6.622E+17	6.589E+17	6.437E+17	5.981E+17	4.976E+17	1.956E+16	702900000
u239	6.649E+17	6.649E+17	6.646E+17	6.639E+17	6.616E+17	6.551E+17	6.455E+17	6.085E+17	5.096E+17	3.176E+17	1.129E+17	3.252E+15	7.78E+10	0.2178	0	0
xe133	4.164E+16	4.164E+16	4.164E+16	4.164E+16	4.164E+16	4.164E+16	4.164E+16	4.164E+16	4.165E+16	4.165E+16	4.165E+16	4.165E+16	4.149E+16	4.029E+16	1.051E+16	0.00005691
xe135	4.502E+16	4.502E+16	4.502E+16	4.502E+16	4.502E+16	4.502E+16	4.502E+16	4.501E+16	4.499E+16	4.491E+16	4.464E+16	4.305E+16	3.522E+16	1.597E+16	49120000	0
i133	4.328E+16	4.328E+16	4.328E+16	4.328E+16	4.328E+16	4.328E+16	4.327E+16	4.327E+16	4.324E+16	4.309E+16	4.255E+16	4.016E+16	3.297E+16	2E+16	3.022E+12	0
mo99	3.992E+16	3.992E+16	3.992E+16	3.992E+16	3.992E+16	3.992E+16	3.992E+16	3.991E+16	3.987E+16	3.976E+16	3.952E+16	3.869E+16	3.633E+16	3.103E+16	1.938E+15	0
la140	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.714E+16	3.713E+16	3.712E+16	3.703E+16	3.666E+16	2.202E+16	102600000
nb95	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.598E+16	3.597E+16	3.549E+16	1.494E+15
zr95	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.599E+16	3.598E+16	3.595E+16	3.585E+16	3.561E+16	3.161E+16	6.923E+14
ba140	3.676E+16	3.676E+16	3.676E+16	3.676E+16	3.676E+16	3.676E+16	3.676E+16	3.676E+16	3.675E+16	3.673E+16	3.668E+16	3.652E+16	3.602E+16	3.482E+16	1.915E+16	89060000
i134	4.816E+16	4.816E+16	4.816E+16	4.815E+16	4.815E+16	4.812E+16	4.808E+16	4.787E+16	4.698E+16	4.358E+16	3.443E+16	1.086E+16	1.398E+14	1094000000	0	0
ce141	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.506E+16	3.504E+16	3.493E+16	3.451E+16	2.729E+16	1.47E+13

Focused reactor summary at 1 year (excerpt)

		lead_e1000	lead_e1500	lead_e1995	spr_e1000	spr_e1500	spr_e1995	msr_fast_Th_e2000	msr_fast_e1500	msr_thermal_Th_e1000	msr_thermal_e1000	httr_e100	httr_e1500	httr_e1995	pbr_e1000	pbr_e1500	pbr_e1995	Min	Max	Average	% Difference (Min/Max)	Max Design
Noble Gases	kr81	1.60E+04	9.18E+03	5.70E+03	7.18E+02	3.78E+02	2.40E+02	2.30E+06	1.49E+05	2.28E+06	4.73E+05	6.63E+03	4.57E+03	3.53E+03	4.02E+03	2.61E+03	1.99E+03	2.40E+02	2.30E+06	3.28E+05	200.0	msr_fast_Th_e2000
	kr83m	4.14E+06	2.53E+06	1.58E+06	1.19E+06	6.25E+05	3.87E+05	9.02E+06	9.84E+06	9.32E+06	1.08E+07	3.20E+06	2.21E+06	1.68E+06	2.39E+06	1.55E+06	1.17E+06	3.87E+05	1.08E+07	3.85E+06	186.1	msr_thermal_e1000
	kr85	5.44E+14	5.95E+14	6.24E+14	1.83E+14	1.91E+14	1.96E+14	2.21E+15	1.16E+15	2.05E+15	9.39E+14	5.40E+14	5.63E+14	5.75E+14	5.65E+14	5.81E+14	5.88E+14	1.83E+14	2.21E+15	7.57E+14	169.5	msr_fast_Th_e2000
	rn217							4.26E+05		1.43E+05								1.43E+05	4.26E+05	2.85E+05	99.3	msr_fast_Th_e2000
	rn218	2.25E+00	2.85E+00	3.31E+00	5.68E-01	7.08E-01	8.22E-01	4.56E+03		5.00E+03		1.81E-01	2.36E-01	2.87E-01	4.02E-02	5.51E-02	6.95E-02	4.02E-02	5.00E+03	6.84E+02	200.0	msr_thermal_Th_e1000
	rn219	2.15E+05	3.08E+05	3.95E+05	2.27E+04	3.38E+04	4.48E+04	3.34E+09	7.16E+04	7.00E+08		2.94E+05	4.58E+05	6.13E+05	1.92E+05	3.12E+05	4.28E+05	2.27E+04	3.34E+09	2.69E+08	200.0	msr_fast_Th_e2000
	rn220	1.17E+09	8.52E+08	6.53E+08	2.21E+07	1.58E+07	1.25E+07	7.66E+12	7.67E+08	1.24E+13	1.46E+08	2.66E+08	3.14E+08	3.53E+08	1.18E+08	1.34E+08	1.52E+08	1.25E+07	1.24E+13	1.25E+12	200.0	msr_thermal_Th_e1000
	rn222	2.27E+04	3.51E+04	4.76E+04	2.86E+03	4.34E+03	5.80E+03	4.63E+06		2.99E+06		1.51E+04	2.36E+04	3.22E+04	1.70E+04	2.62E+04	3.53E+04	2.86E+03	4.63E+06	5.63E+05	199.8	msr_fast_Th_e2000
	xe127	3.56E+06	2.01E+06	1.27E+06	1.63E+05	8.63E+04	5.53E+04	1.54E+07	5.75E+05	2.47E+07	2.06E+06	3.95E+04	2.79E+04	2.28E+04	5.13E+03	3.60E+03	2.98E+03	2.98E+03	2.47E+07	3.12E+06	200.0	msr_thermal_Th_e1000
	xe129m	2.06E-01	1.08E-01	6.13E-02	1.08E-02	4.95E-03	2.73E-03	7.45E+00	7.49E-01	9.92E+00	4.36E+00	2.20E-02	1.30E-02	9.59E-03	8.28E-03	3.99E-03	2.68E-03	2.68E-03	9.92E+00	1.43E+00	199.9	msr_thermal_Th_e1000
	xe131m	3.89E+05	3.75E+05	3.67E+05	3.60E+05	3.56E+05	3.56E+05	5.80E+05	5.50E+05	6.02E+05	5.76E+05	3.67E+05	3.60E+05	3.56E+05	3.62E+05	3.56E+05	3.53E+05	3.53E+05	6.02E+05	4.16E+05	52.2	msr_thermal_Th_e1000
	xe133	5.69E-05	5.70E-05	5.72E-05	5.88E-05	5.92E-05	5.95E-05	7.98E-05	8.06E-05	7.91E-05	7.85E-05	5.65E-05	5.68E-05	5.69E-05	5.69E-05	5.71E-05	5.72E-05	5.65E-05	8.06E-05	6.30E-05	35.1	msr_fast_e1500

Questions?