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Laboratory Analysis of the Cooling Time Requirements and Criticality Safety Requirements Prior to Transporting Commercial Spent Nuclear Fuel

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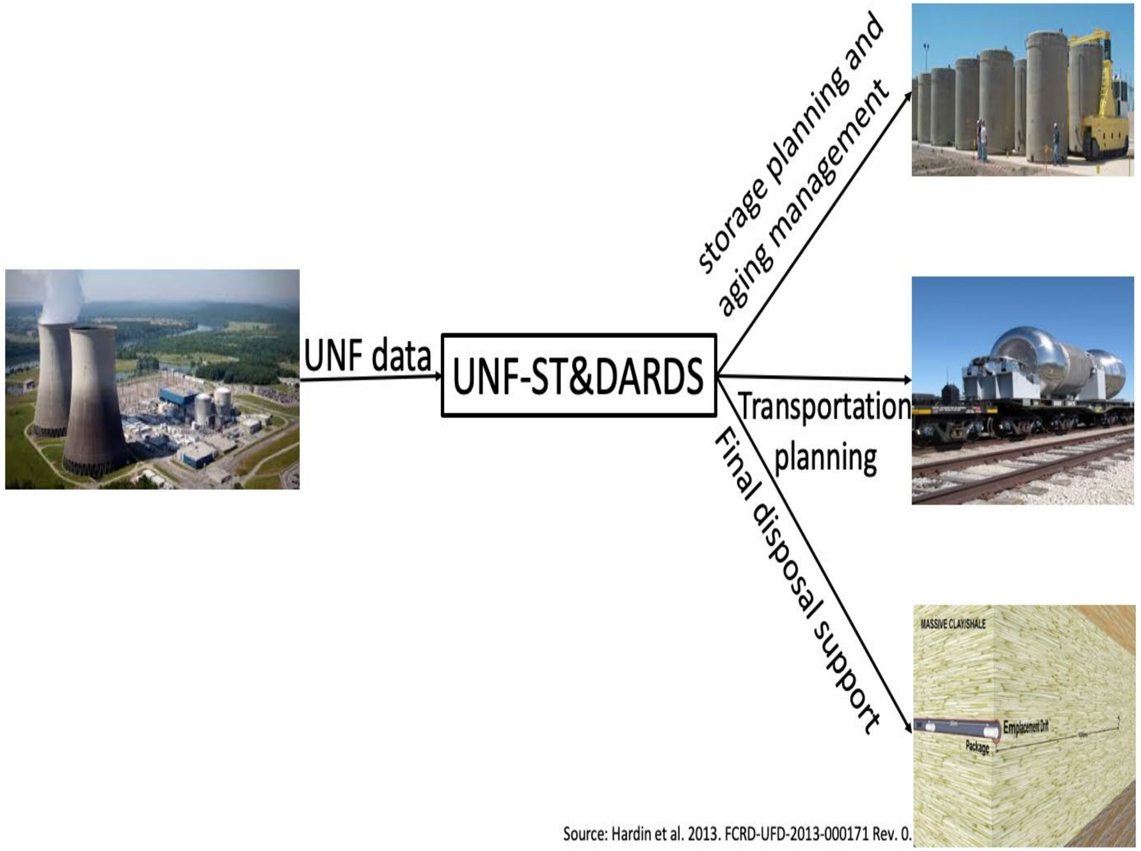
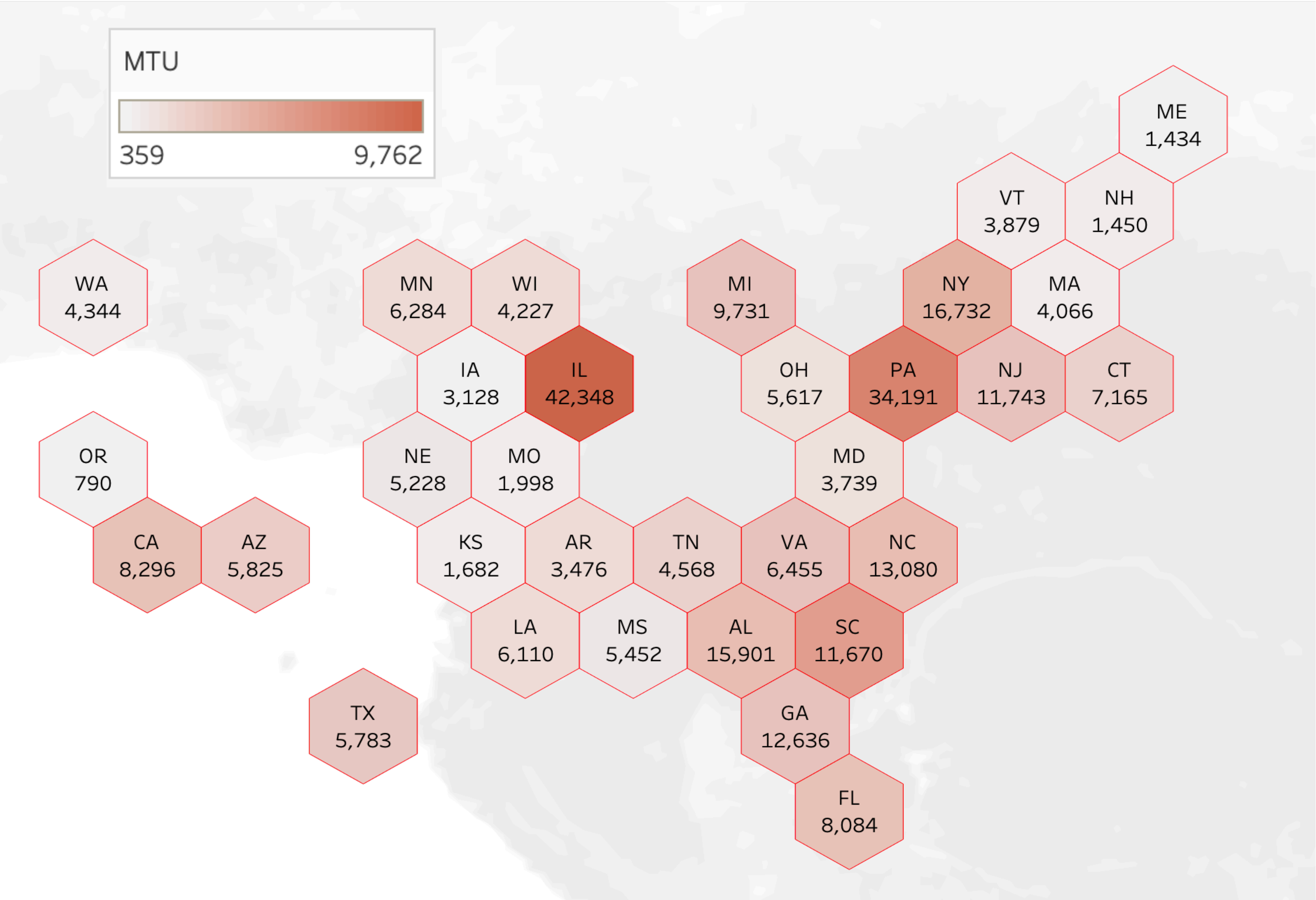
UNF-ST&DARDS is being developed as an integrating (storage, transportation, and disposal) foundational resource

- Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) provides a spent nuclear fuel (SNF) database and integrated analysis tools
- Objective is to develop a comprehensive system for analysis of the SNF from the time it is discharged from the reactor to the time it is disposed of in a geologic repository
- Current and potential future applications include:
  - Identification of potential issues and prioritization of R&D
  - Supply of fundamental data for informed decision making at various stages of SNF management
  - Fuel cycle analysis as well as safeguard and security determination
  - Various licensing/certification activities (e.g., integration between storage and transportation licensing practices)



Source: Hardin et al. 2013. FCRD-UFD-2013-000171 Rev. 0.

Data Source GC-859 2018 (Discharges through 2017)



The large spent nuclear fuel (SNF) volumes and diverse systems in the United States make system-wide planning a complex undertaking

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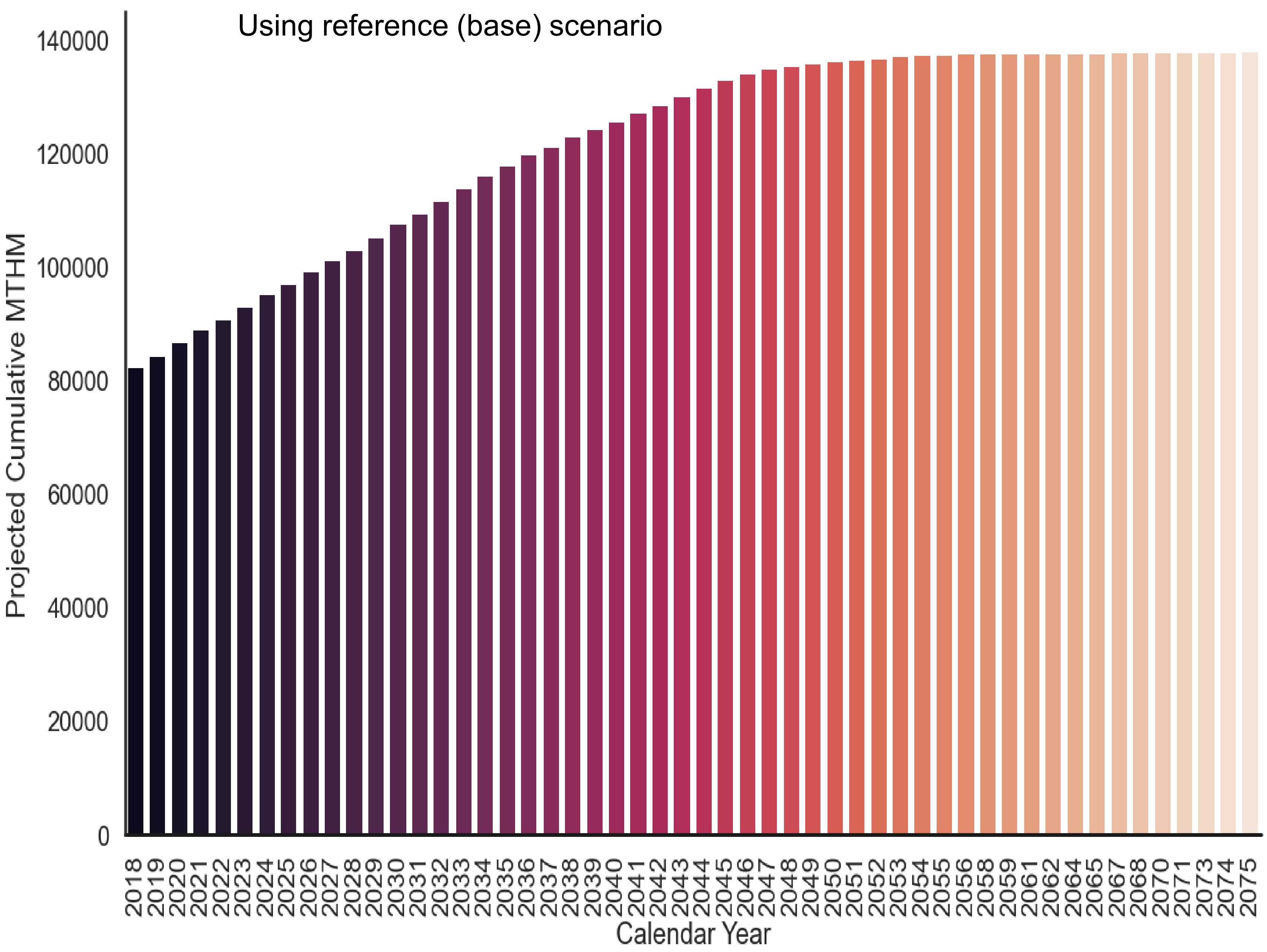

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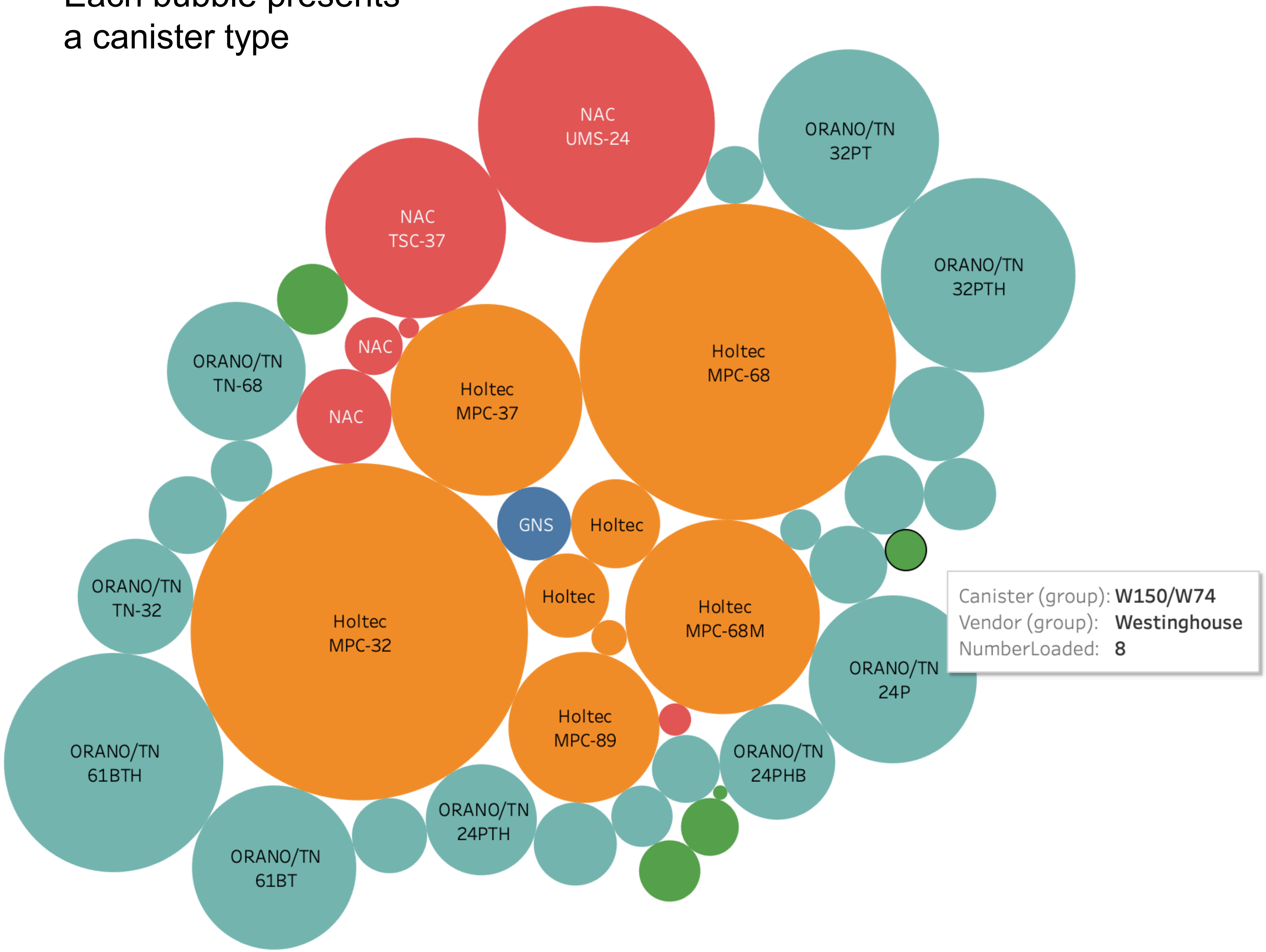
Each bubble presents a canister type



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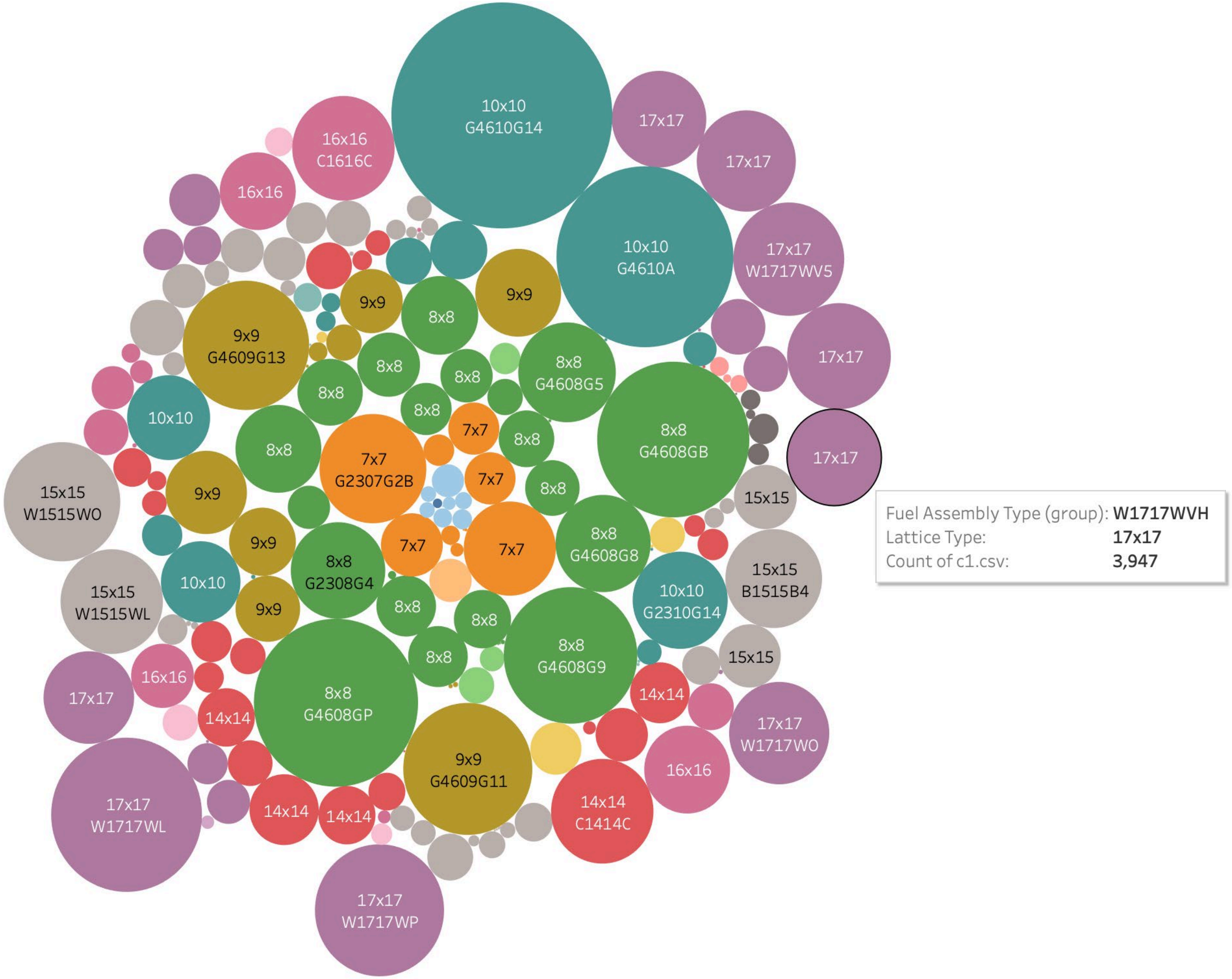
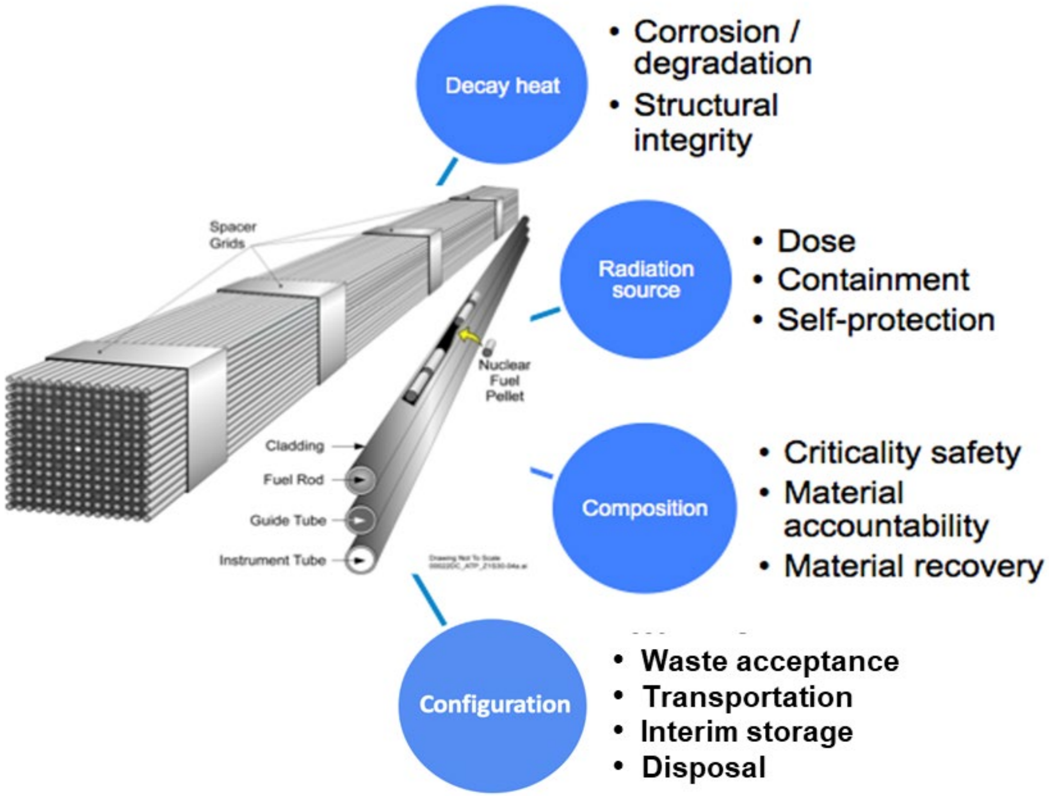


The large spent nuclear fuel (SNF) volumes and diverse systems in the United States make system-wide planning a complex undertaking

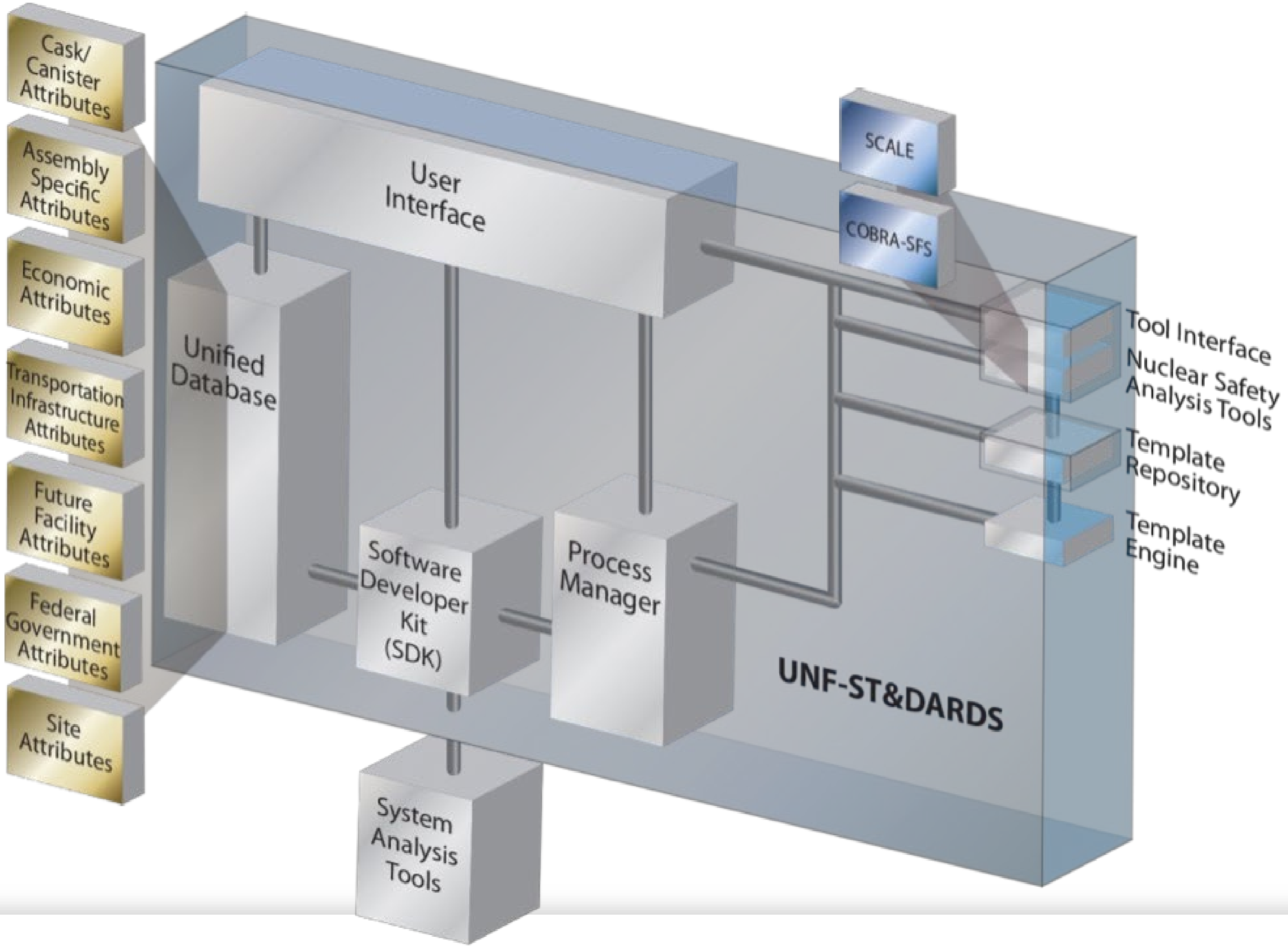
Any SNF related activity starts with understanding the SNF characteristics

- **SNF and related systems characteristics can be categorized into:**
  - **<u>Base Characteristics:</u>** fuel geometry, materials, reactor irradiation histories (e.g., cycle length, specific power etc.), cask system, cask loading patterns used to store SNF
  - **<u>Derived Characteristics:</u>** decay heat, isotopic composition, radiation sources, cask criticality, transportation cask dose rates



UNF-ST&DARDS integrates data with analysis capabilities to simplify SNF characterization process

- **Unified Database consolidates key information from multiple sources and preserves data**
- **Data relations facilitate analysis automation**



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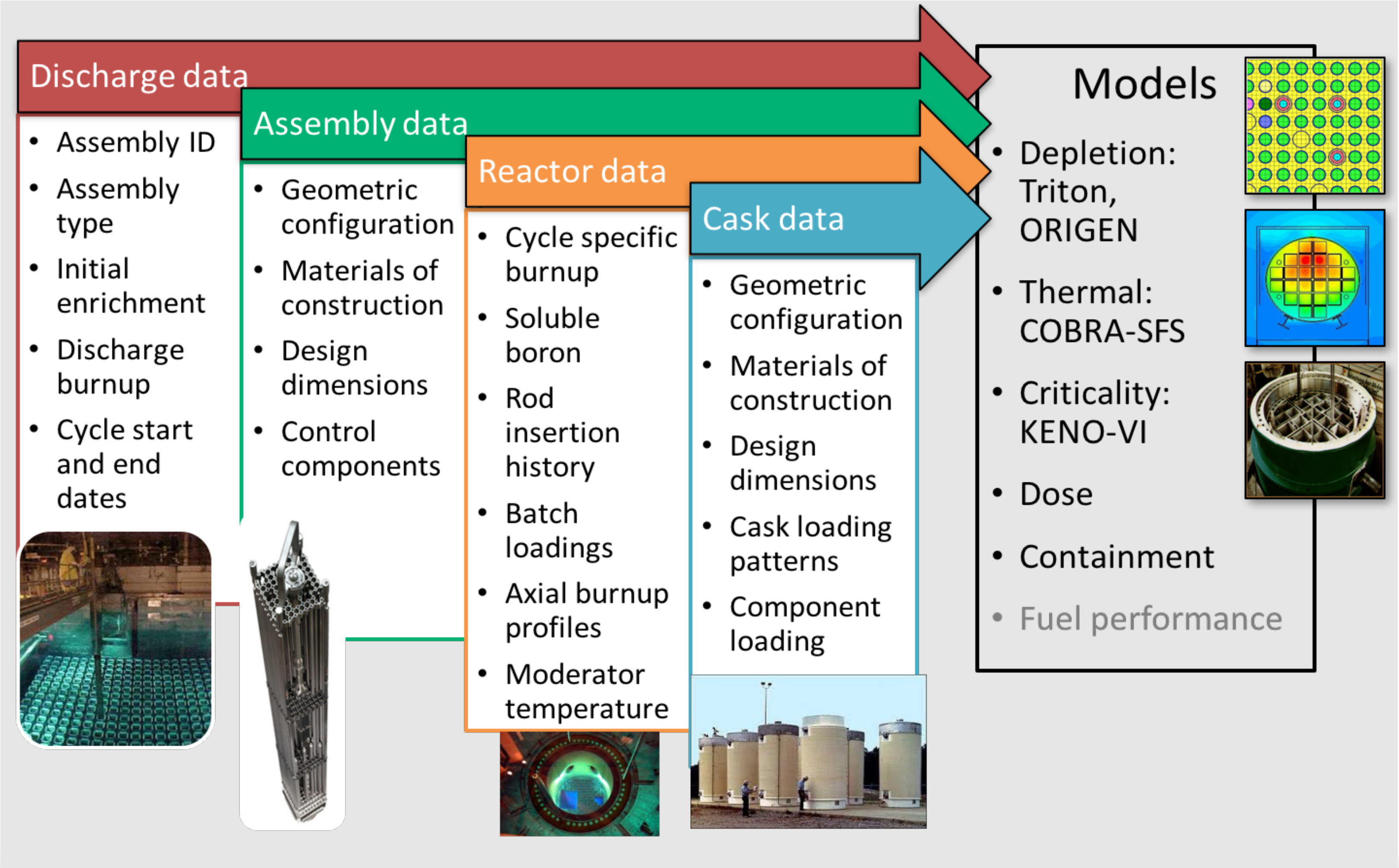

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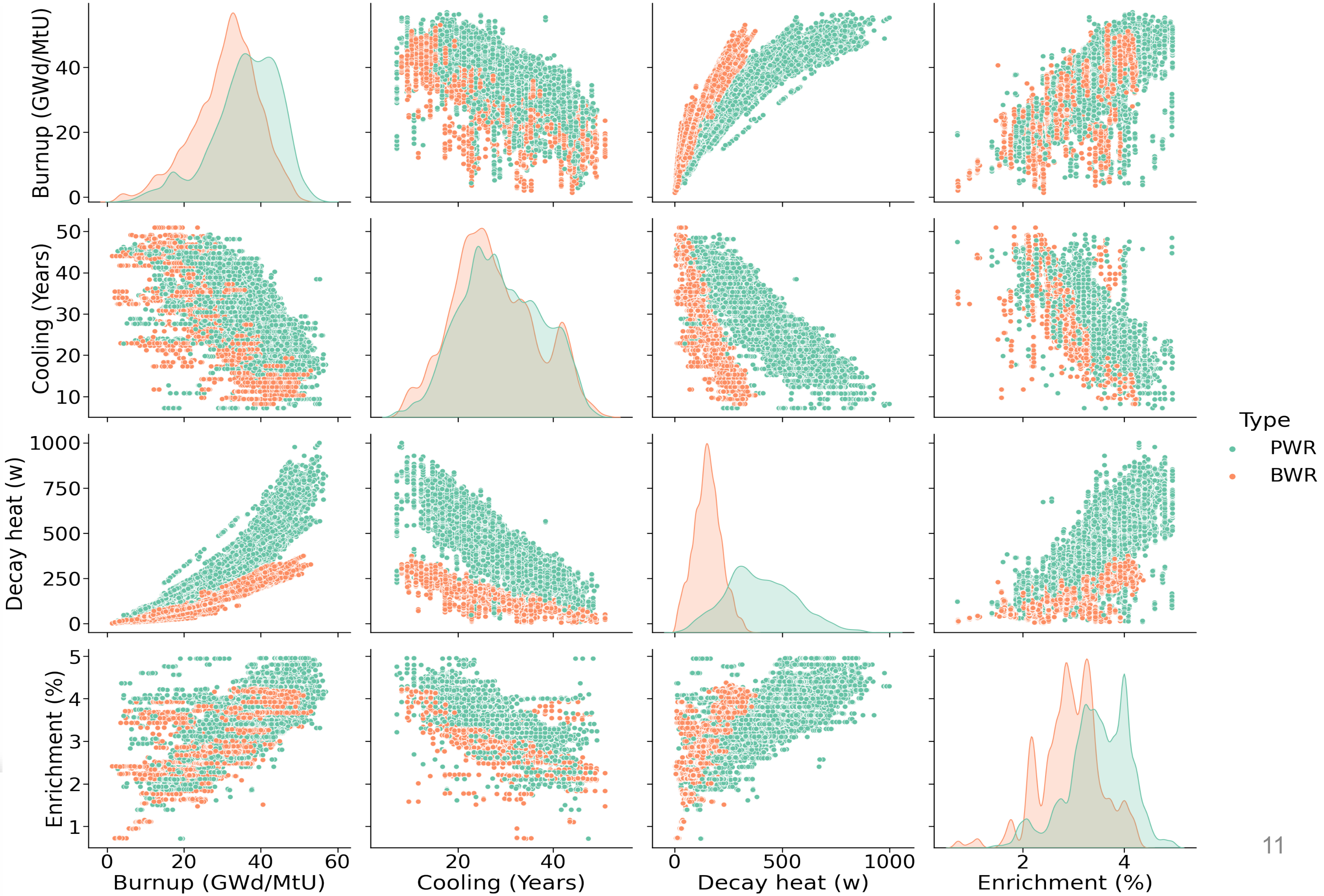
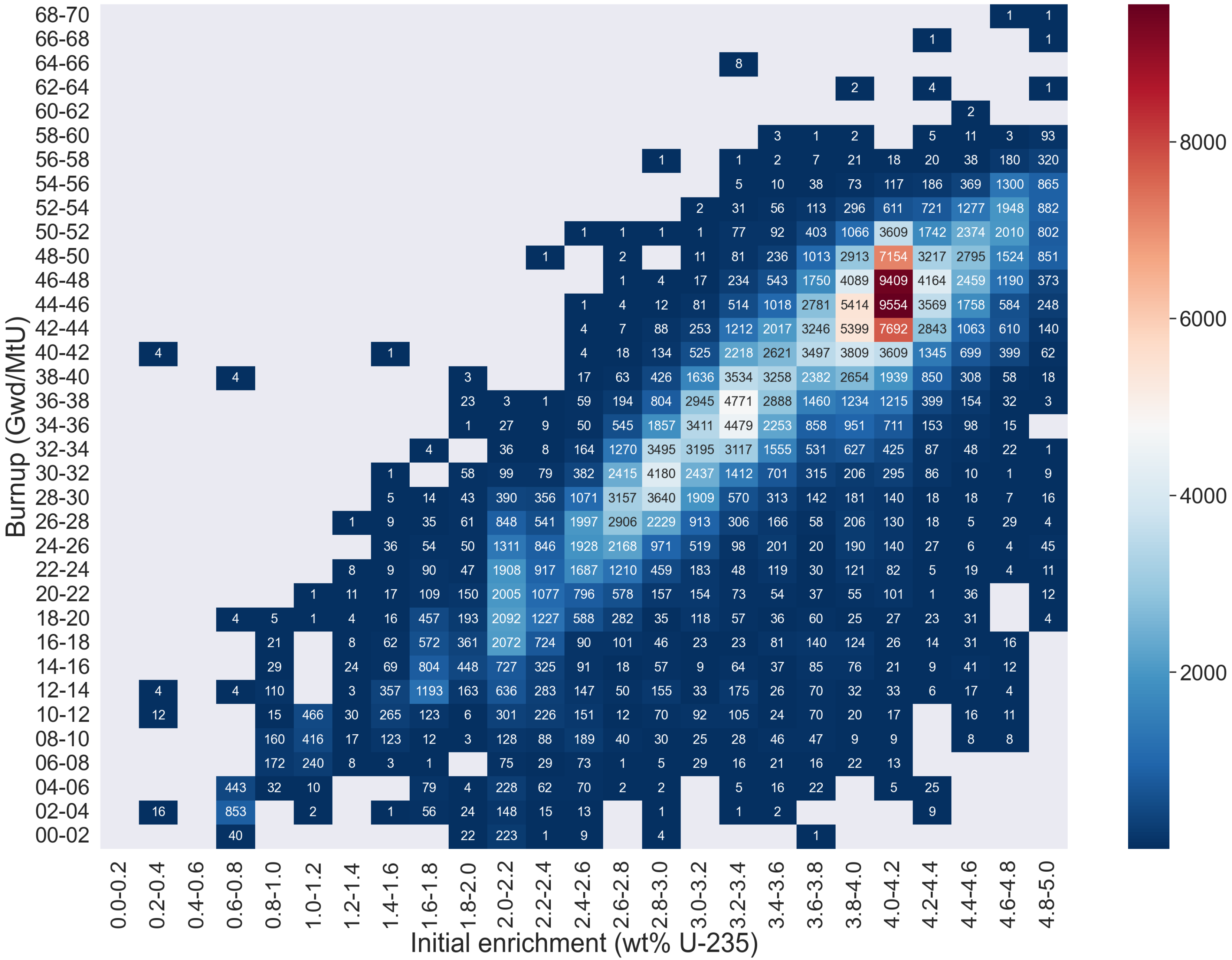


The UNF-ST&DARDS database contains SNF and related systems inventory data



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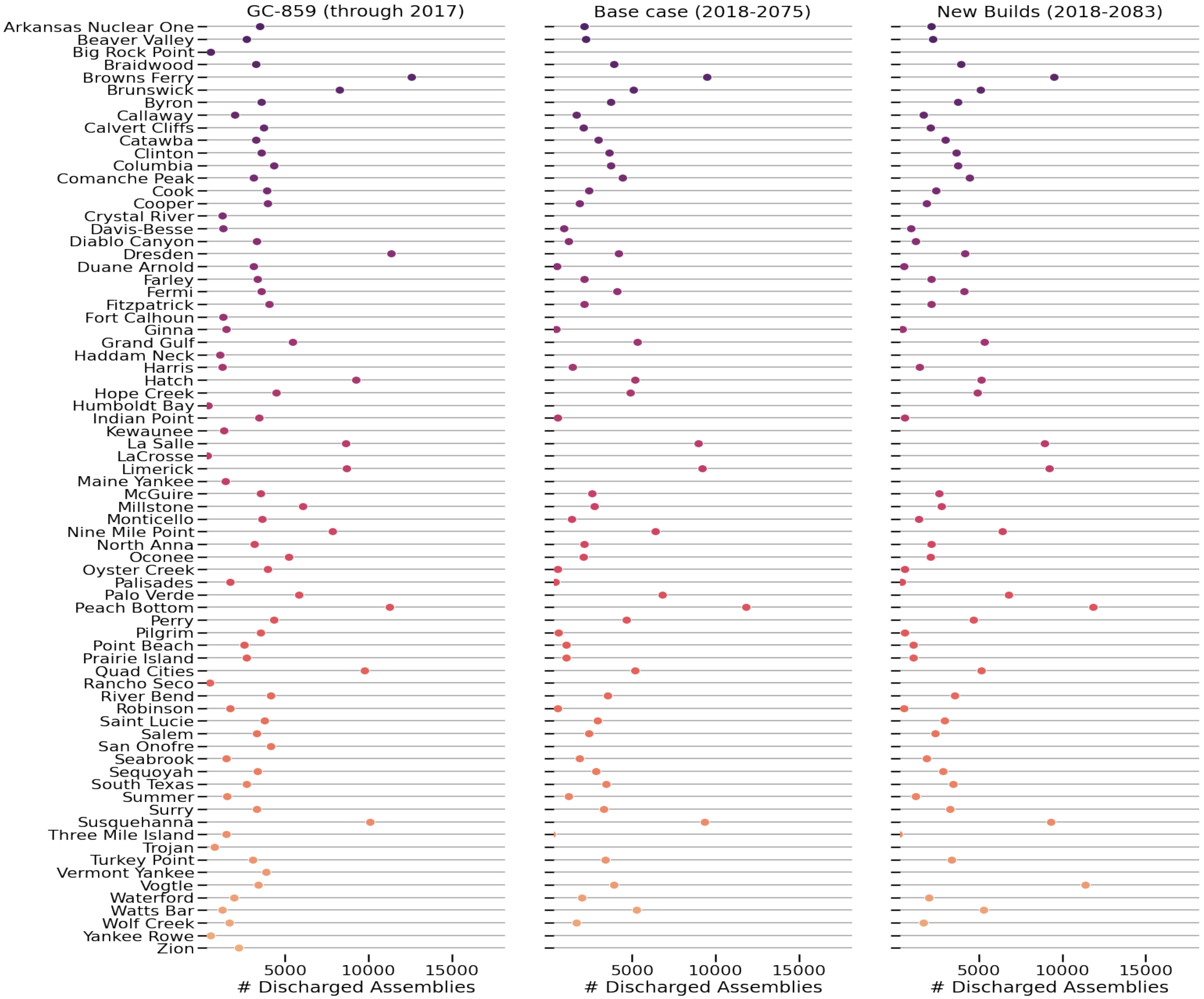

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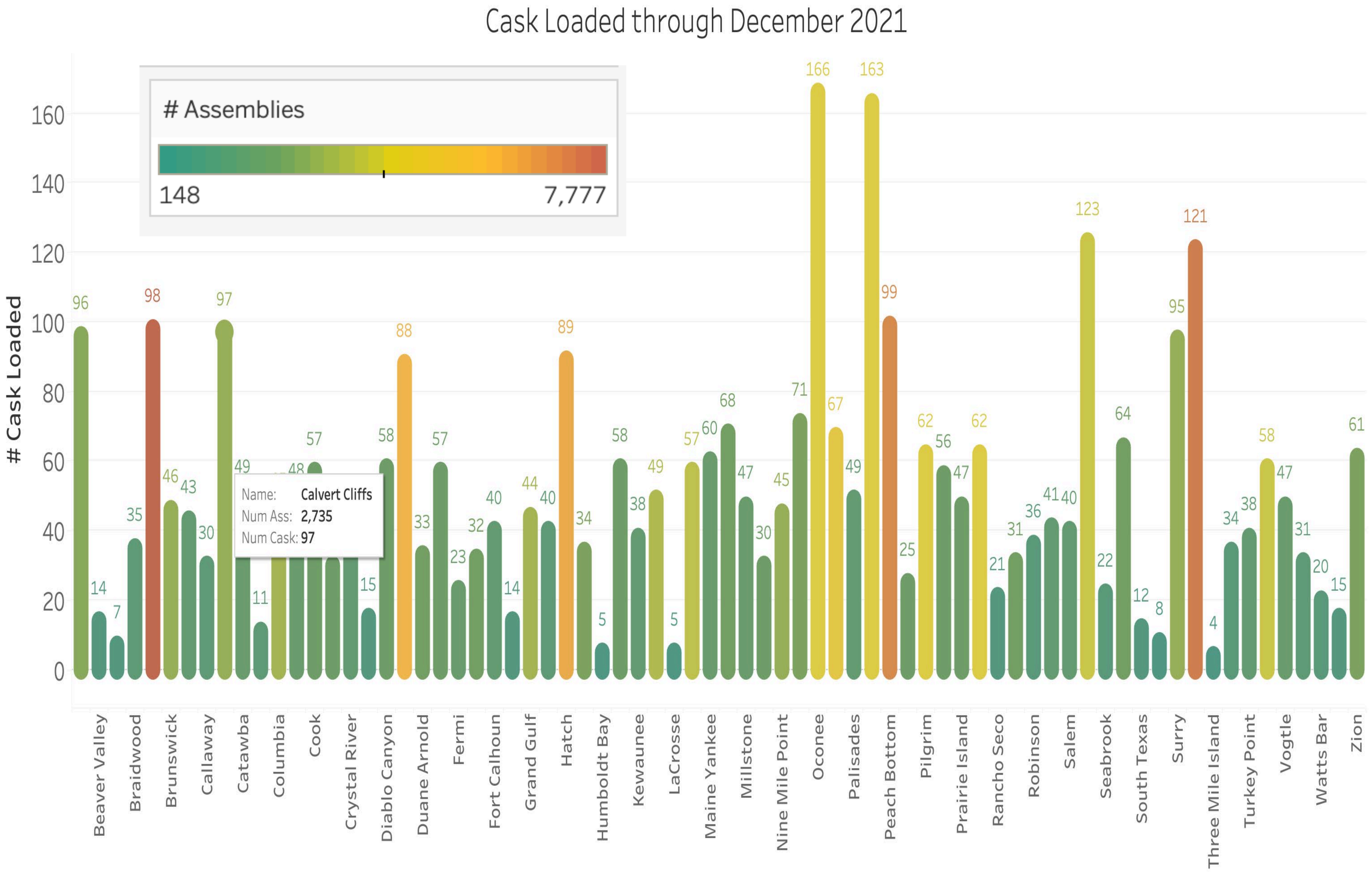
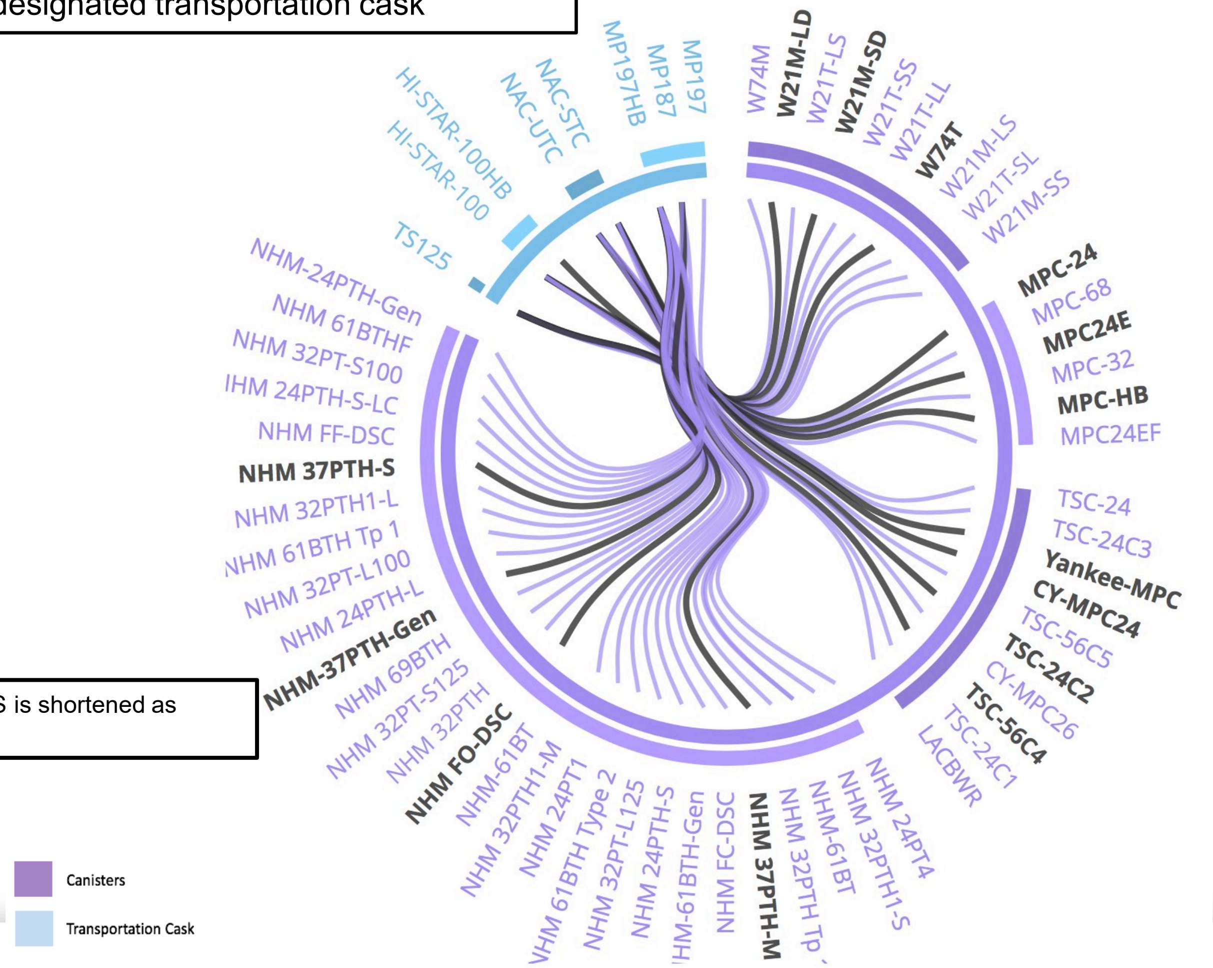


The UNF-ST&DARDS database contains base SNF and related systems characteristics

- **Base characteristics data include**
  - fuel geometry, dimensions, and materials
  - reactor irradiation histories (e.g., cycle length, specific power etc.)
  - cask system (e.g. various cask/canister attributes, certificate of compliance [CoC])
  - Site attributes (e.g., facility, reactor, pool, ISFSI)
  - Economic attributes (e.g., transportation infrastructure, ISFSI, and facility estimated costs)
  - Transportation infrastructure attributes (e.g., rail, heavy haul, legal weight truck, and barge related data, and transfer times between these transportation modes)
  - Potential future facility attributes (e.g., interim storage, repackaging)
- **Base characteristics data are used for various analyses**

Various canisters (grouped by vendors) and their designated transportation cask

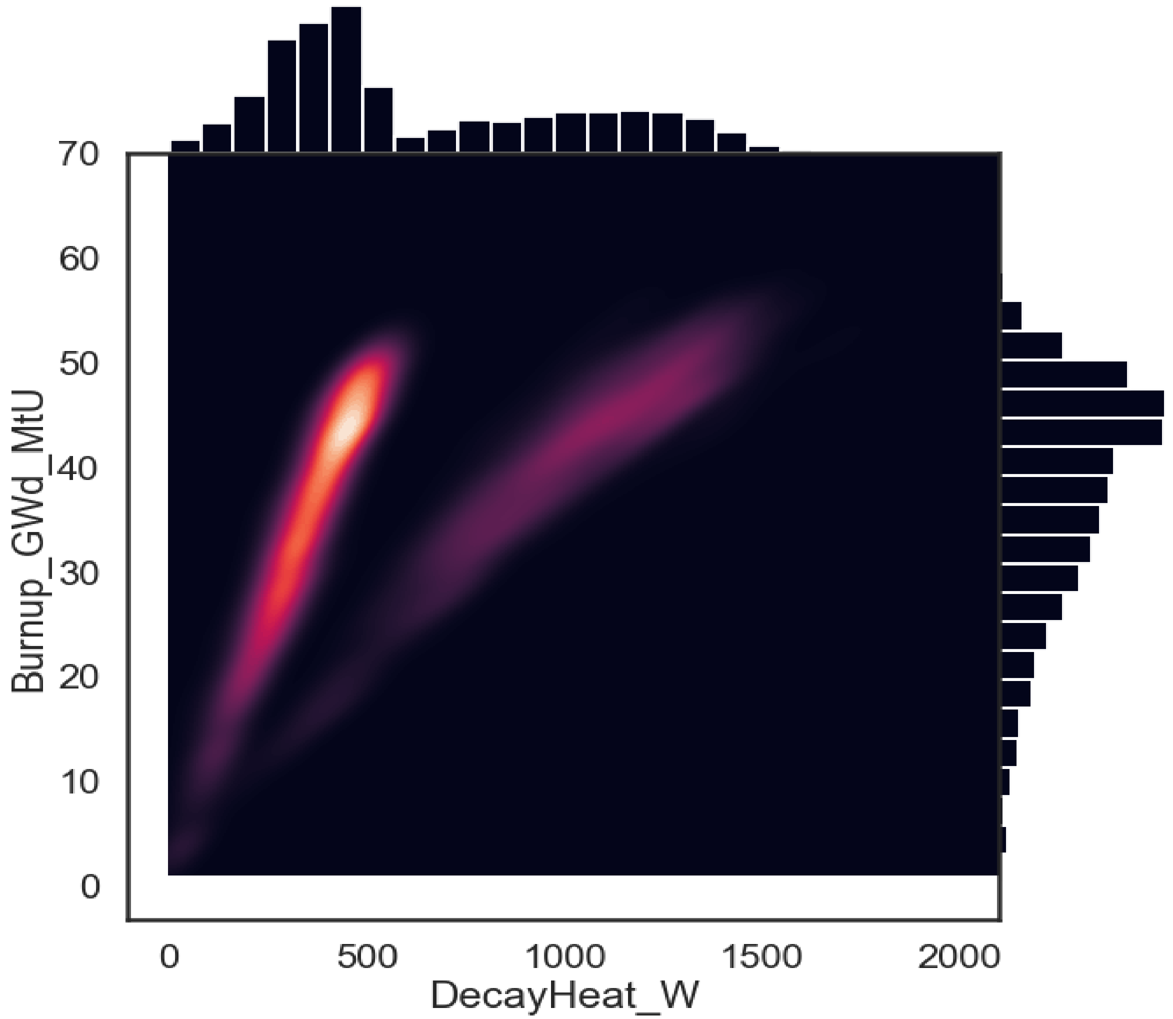
NUHOMS is shortened as NHM



ISFSI: Independent Spent Fuel Storage Installation

The UNF-ST&DARDS database contains derived SNF and related systems characteristics

- **Derived characteristics are calculated data based on SNF and related systems inventory and base characteristics data**
- **Derived characteristics include**
  - Assembly-specific decay heat
  - Assembly-specific isotopic composition
  - Assembly-specific radiation sources
  - Cask-specific criticality
  - Cask-specific thermal attributes (e.g., clad temperature, canister surface temperature)
  - Cask-specific transportation dose rates



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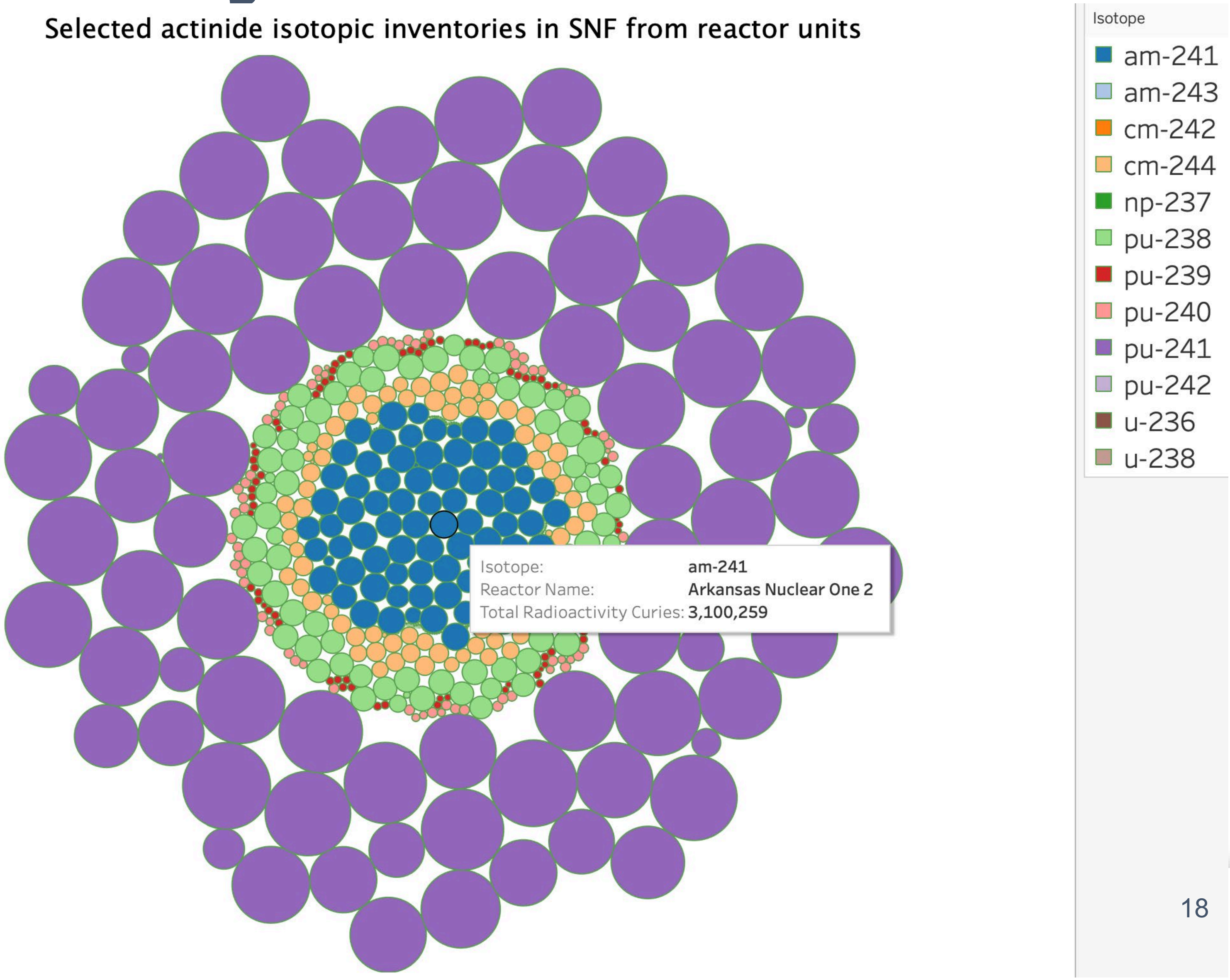

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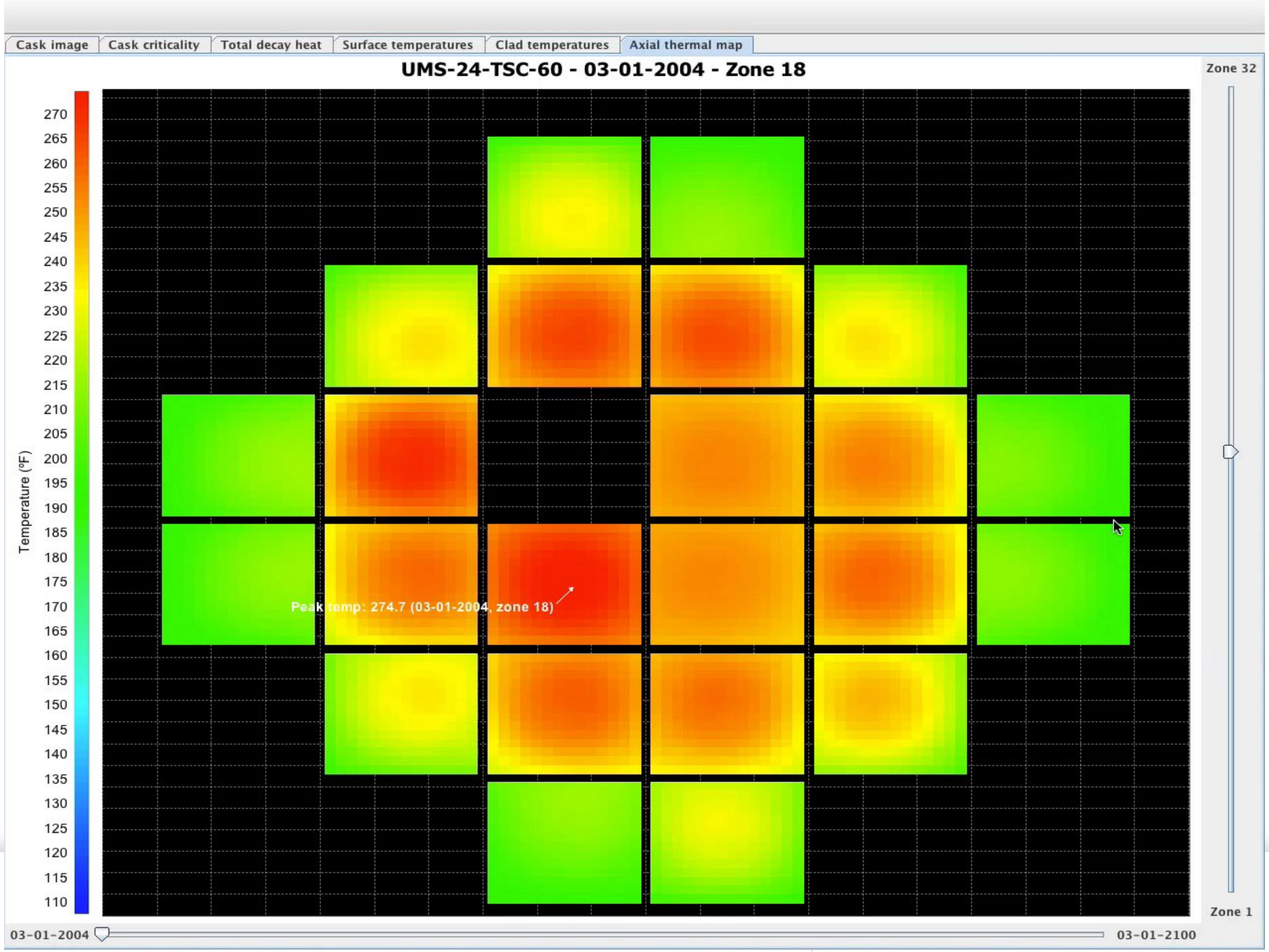
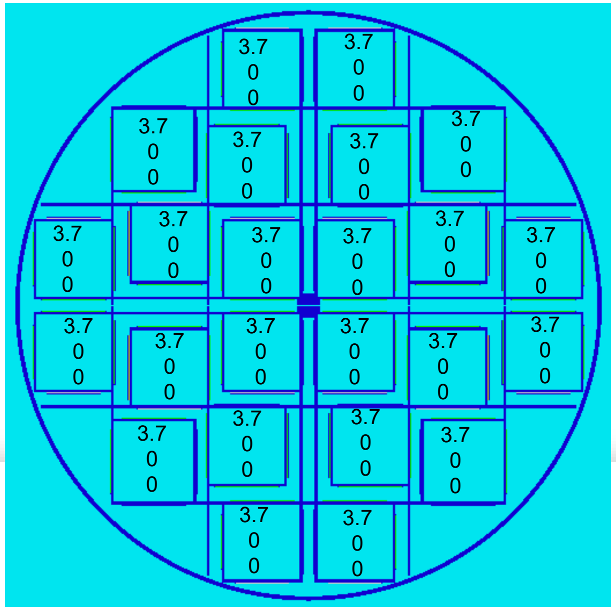


A Few potential applications of UNF-ST&DARDS data and as-loaded analyses

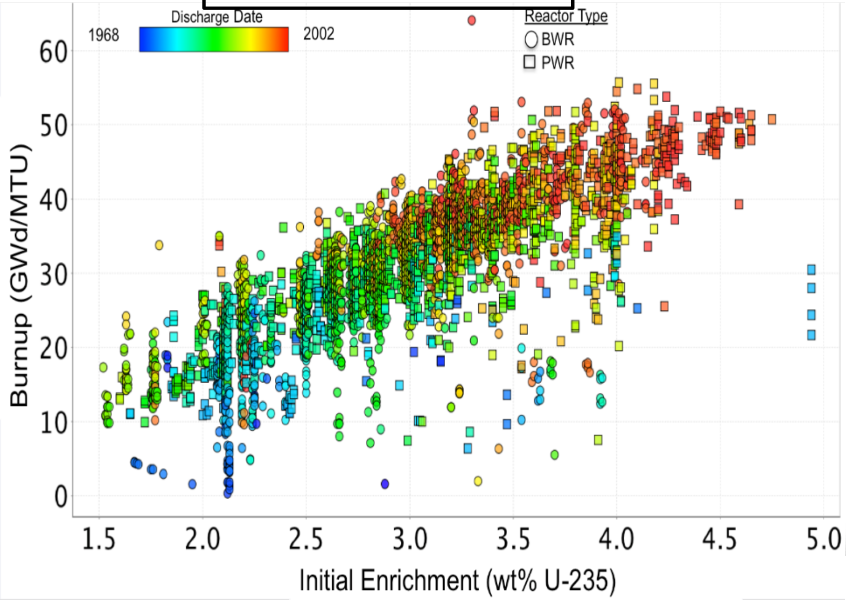
A unique capability within UNF-ST&DARDS is the performance of actual assembly-specific and cask-specific evaluations

- **Current design-basis approach uses bounding fuel characteristics (e.g., fuel type, initial enrichment, and discharge burnup) for spent nuclear fuel (SNF) storage and transportation systems certification process**
- **In practice, discharged SNF assemblies available for loading are diverse (e.g., wide variation in SNF assembly burnup values)**

Design-basis k_{eff} = 0.90

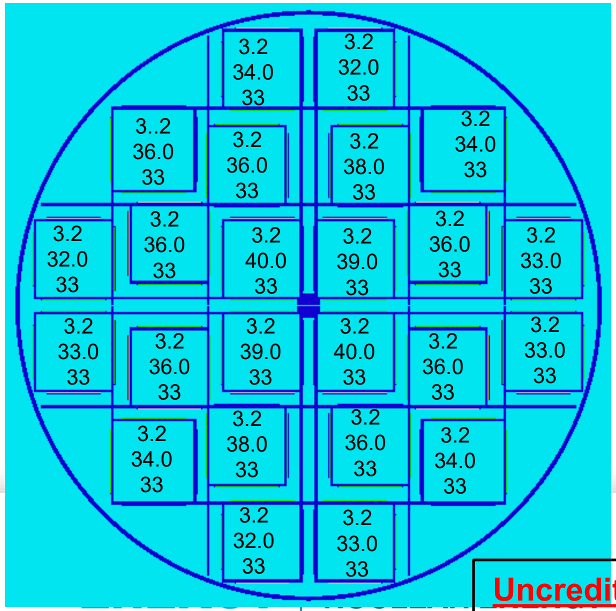


Discharged inventory



X	Assembly average initial enrichment (wt %)
Y	Assembly average burnup (GWd/MTU)
Z	Cooling (years)

As-loaded k_{eff} = 0.66



Uncredited margin = 0.90-0.66 = 0.24 Δk_{eff}

UNF-ST&DARDS data and as-loaded analyses can be used to determine if and when a loaded canister is transportable

- **Canisters currently in storage may or may not be immediately transportable**
- **Transportability can be determined by comparing the loaded canister (in storage) content with the allowable content in the transportation CoC***
  - Major content parameters: assembly types, design parameters, and conditions (damaged/intact), non-fuel component types, burnup, initial enrichment, and cooling time

*CoC: Certificate of Compliance

UNF-ST&DARDS data and as-loaded analyses can be used to determine if and when a loaded canister is transportable (Contd.)

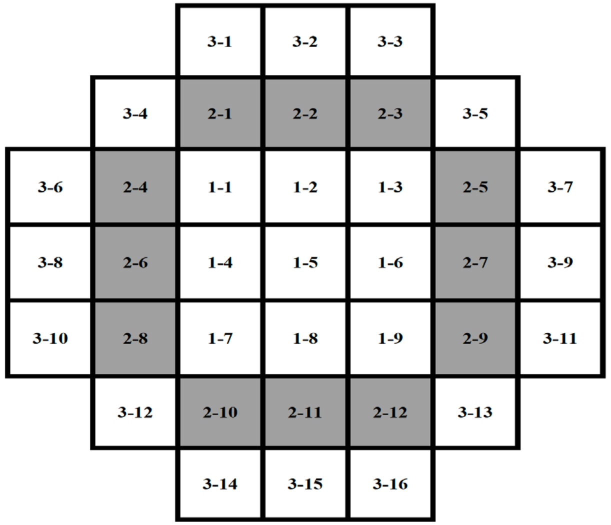
- **Additional cooling on the storage pad makes many canisters transportable**
  - Mainly to meet transportation decay heat and dose requirements
  - Additional cooling time can be determined from the CoC’s minimum cool time requirements
  - UNF-ST&DARDS assembly-specific decay heat and transportation package-specific dose calculations can also be used to determine additional cooling time requirement
    - Expected to be more realistic
- **A few canisters may need CoC amendment to make them transportable**
  - UNF-ST&DARDS can help to identify these canisters and streamline the CoC amendment process

Transportability from decay heat perspective: CoC requirements

e.Decay heat per assembly:

i. ZR Clad:	≤272 Watts, except for array/class 8X8F fuel assemblies, which shall have a decay heat ≤183.5 Watts.

Simple requirement for MPC-68 in HI-STAR 100 transportation cask from HI-STAR SAR, Rev 20 (June 2019)



MPC-37 Loading Regions

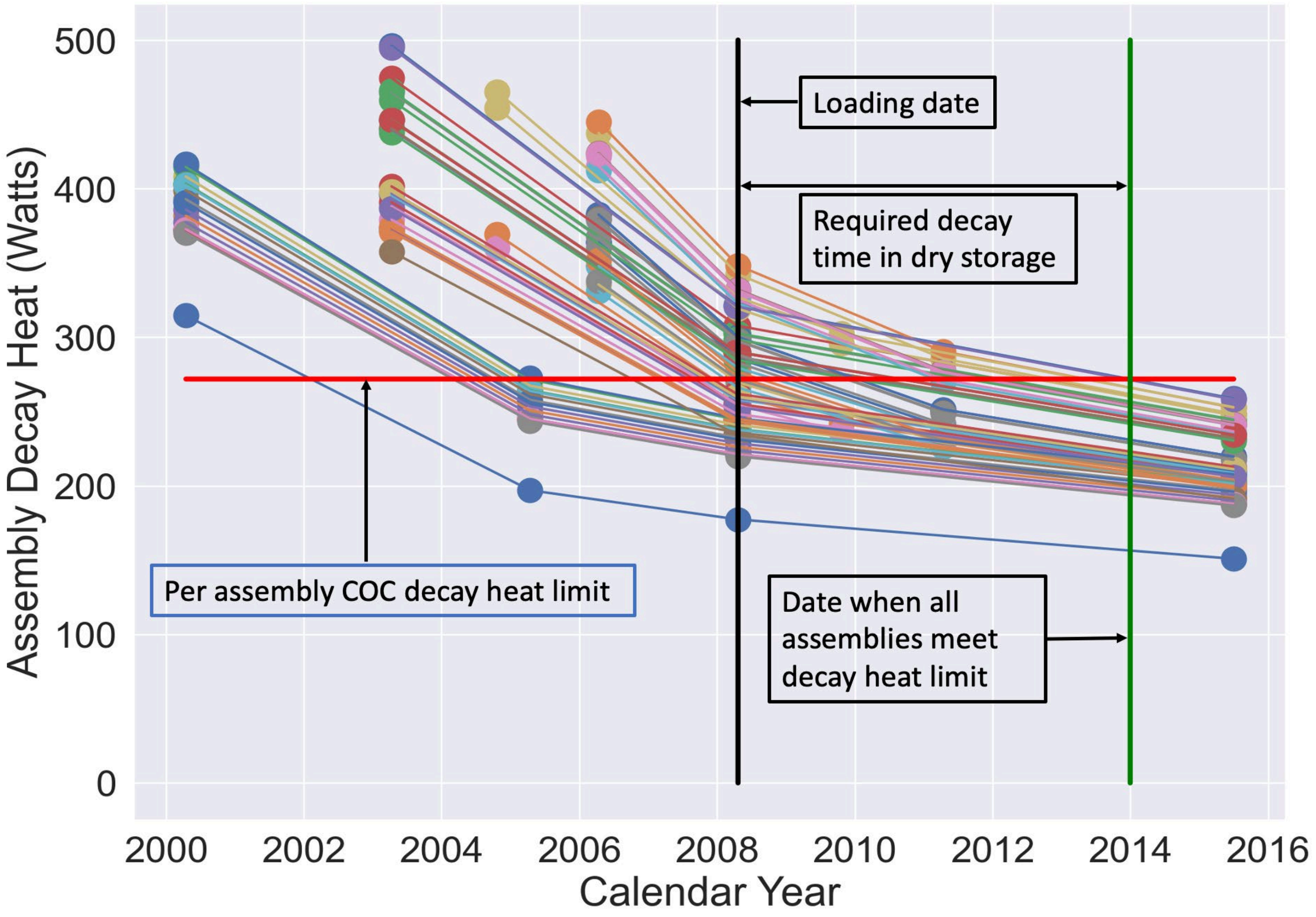
Table 7.C.7

LOADING PATTERNS FOR MPC-37

Pattern	Region (Note 1)	Maximum Decay Heat Load per Assembly (kW) (Note 2)
1	1	0.38
	2	1.7
	3	0.50
2	1	0.42
	2	1.54
	3	0.61
3	1	0.61
	2	1.23
	3	0.74
4	1	0.74
	2	1.05
	3	0.8
5	1	0.8
	2	0.95
	3	0.84
6	1	0.95
	2	0.84
	3	0.8

Complex requirements for MPC-37 in HI-STAR 190 from HI-STAR 190 SAR, Rev 3 (Nov 2018)

Simple MPC-68 example



Transportability from decay heat perspective: using UNF-ST&DARDS decay heat analysis

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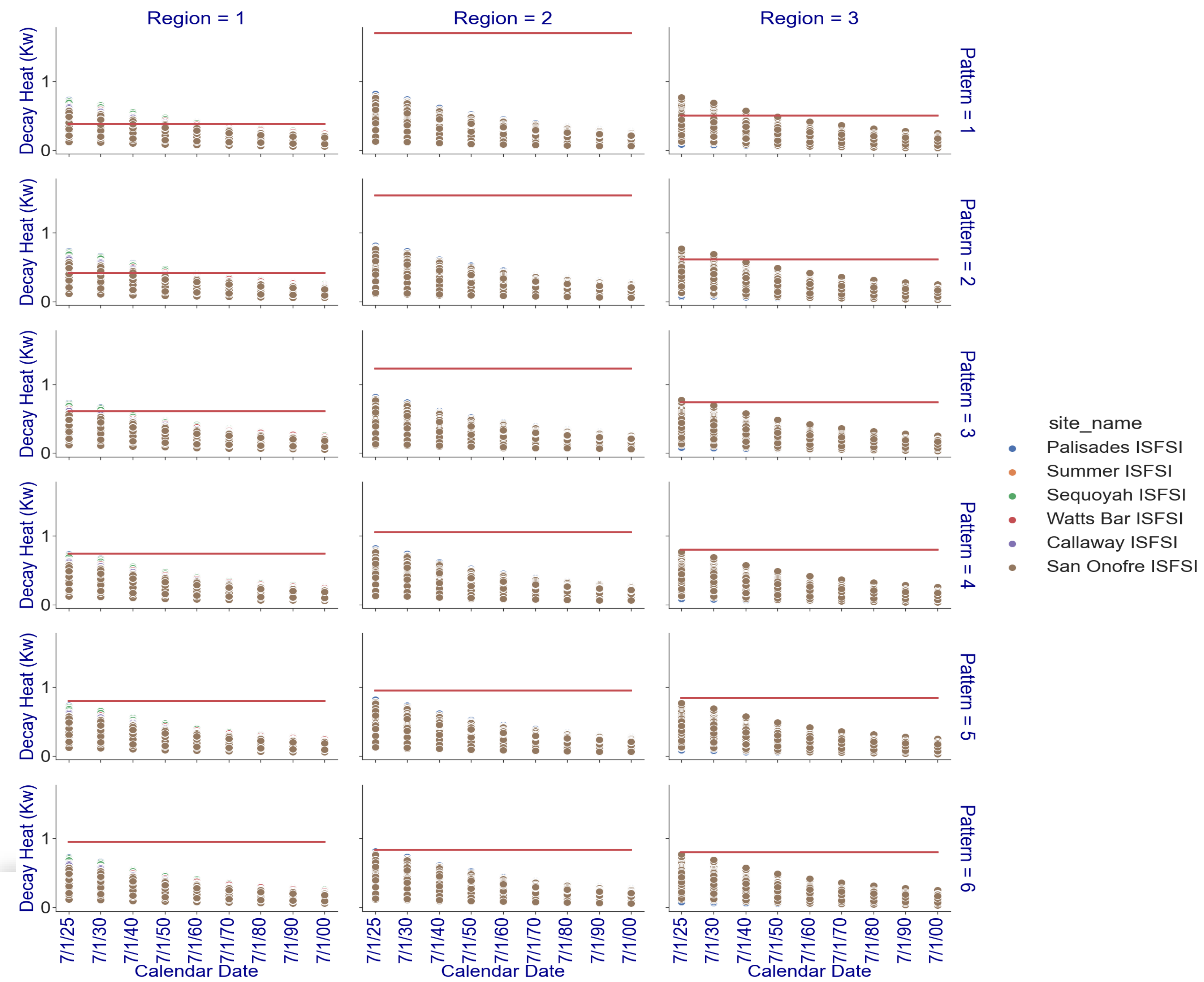

Complex MPC-37 example

Transportability from dose perspective: CoC requirements

Table 7.A.10 (Sheet 1 of 2)

FUEL ASSEMBLY COOLING, AVERAGE BURNUP, AND MINIMUM ENRICHMENT MPC-32 PWR FUEL WITH ZIRCALOY CLAD AND WITH NON-ZIRCALOY IN-CORE GRID SPACERS

Post-irradiation cooling time (years)	Assembly burnup (MWD/MTU)	Assembly Initial Enrichment (wt. % U-235)
WITHOUT NON-FUEL HARDWARE		
≥12	≤24,500	≥2.3
≥14	≤25,000	≥1.7
≥14	≤29,500	≥2.6
≥16	≤30,000	≥2.3
≥16	≤34,500	≥2.9
≥19	≤39,500	≥3.2
≥20	≤40,000	≥3.0
≥20	≤42,500	≥3.4
≥22	≤42,500	≥3.2
≥24	≤45,000	≥3.6
≥26	≤45,000	≥3.2

From HI-STAR SAR, Rev 20 (June 2019)

canister_id	position	assembly_id	initial_enrichment	bu_gwd_mtu
MPC-32-TSC 073	1	D23	3.65	39.66
MPC-32-TSC 073	2	N30	3.1	34.69
MPC-32-TSC 073	3	N42	3.1	35.22
MPC-32-TSC 073	4	N44	3.1	35.44
MPC-32-TSC 073	5	N19	3.1	29.72
MPC-32-TSC 073	6	N23	3.1	36.41
MPC-32-TSC 073	7	F04	3.49	40.98
MPC-32-TSC 073	8	F72	3.79	41.55
MPC-32-TSC 073	9	N13	3.1	36.48
MPC-32-TSC 073	10	N17	3.1	37.32
MPC-32-TSC 073	11	M34	2.62	36.53
MPC-32-TSC 073	12	F69	3.79	41.65
MPC-32-TSC 073	13	F29	3.48	42.2
MPC-32-TSC 073	14	P52	3.5	41.51
MPC-32-TSC 073	15	P14	3.5	34.81
MPC-32-TSC 073	16	M29	2.62	36.64
MPC-32-TSC 073	17	N36	3.1	29.71
MPC-32-TSC 073	18	R58	3.61	38.73
MPC-32-TSC 073	19	F02	3.49	38.31
MPC-32-TSC 073	20	E42	3.73	38.32
MPC-32-TSC 073	21	E33	3.74	38.25
MPC-32-TSC 073	22	M37	2.62	36.72
MPC-32-TSC 073	23	M55	2.62	36.9
MPC-32-TSC 073	24	M53	2.62	37.11
MPC-32-TSC 073	25	F49	3.79	38.93
MPC-32-TSC 073	26	P18	3.52	41.04
MPC-32-TSC 073	27	N21	3.1	37.31
MPC-32-TSC 073	28	M08	2.62	30.03
MPC-32-TSC 073	29	N34	3.1	37.69
MPC-32-TSC 073	30	N38	3.1	38.31
MPC-32-TSC 073	31	N11	3.1	40.27
MPC-32-TSC 073	32	N26	3.1	40.54

First example loading maps for canisters at storage: Highlighted assemblies indicate assemblies in storage currently do not satisfy transportation CoC.

Transportability from dose perspective: CoC requirements

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≥16	≤34,500	≥2.9
≥19	≤39,500	≥3.2
≥20	≤40,000	≥3.0
≥20	≤42,500	≥3.4
≥22	≤42,500	≥3.2
≥24	≤45,000	≥3.6
≥26	≤45,000	≥3.2

From HI-STAR SAR, Rev 20 (June 2019)

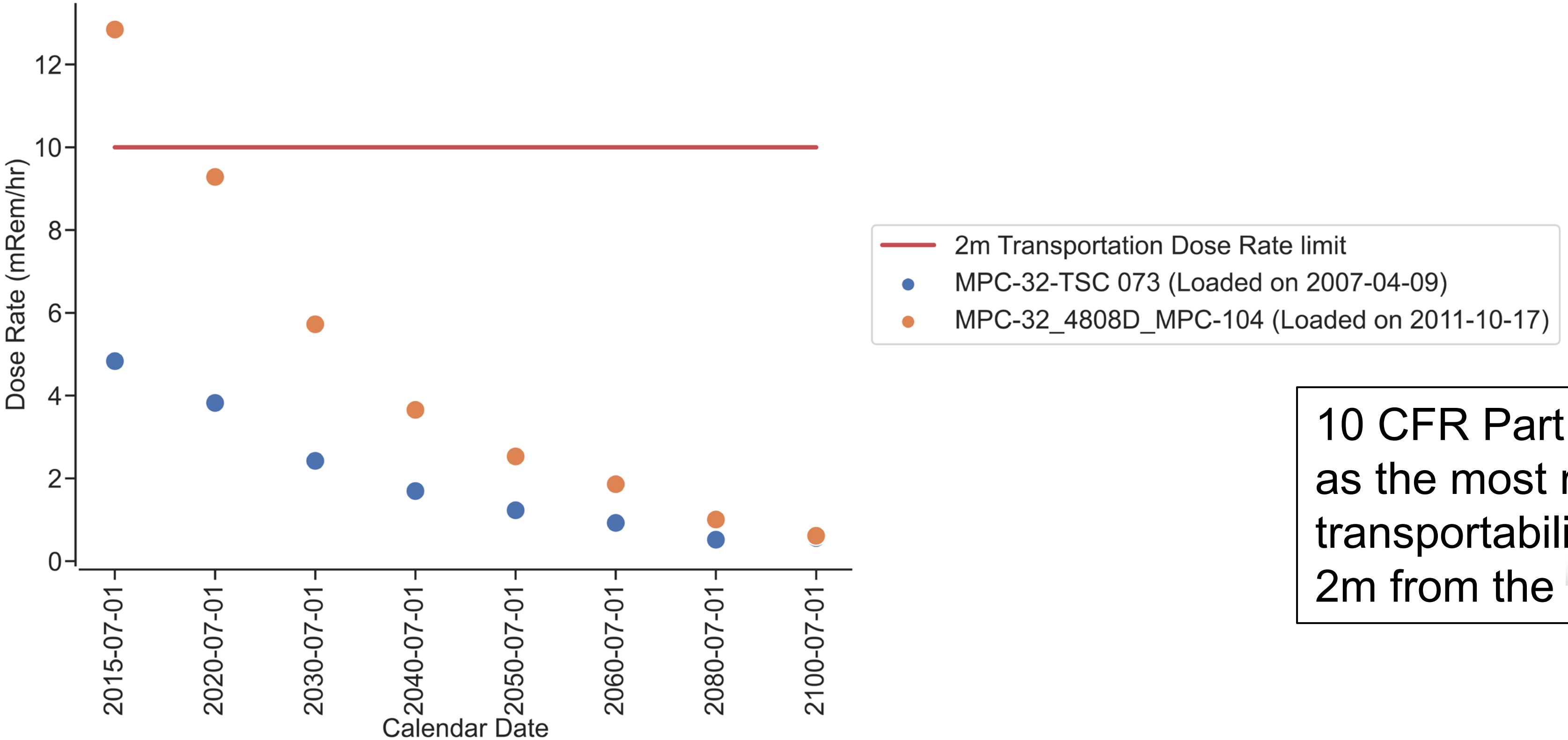
canister_id	position	assembly_id	initial_enrichment	bu_gwd_mtu
MPC-32_4808D_MPC-104	1	U44	4.01	43.24
MPC-32_4808D_MPC-104	2	U67	4.03	43.29
MPC-32_4808D_MPC-104	3	U62	4.01	43.23
MPC-32_4808D_MPC-104	4	U64	4.01	43.14
MPC-32_4808D_MPC-104	5	V39	3.81	52.8
MPC-32_4808D_MPC-104	6	G44	3.91	46.92
MPC-32_4808D_MPC-104	7	AC44	4.24	48.49
MPC-32_4808D_MPC-104	8	Y09	4.11	47.3
MPC-32_4808D_MPC-104	9	T59	4.19	46.25
MPC-32_4808D_MPC-104	10	U59	4.02	43.03
MPC-32_4808D_MPC-104	11	W54	4.21	35.03
MPC-32_4808D_MPC-104	12	AC43	4.24	43.41
MPC-32_4808D_MPC-104	13	K78	4.2	51.22
MPC-32_4808D_MPC-104	14	Y83	4.36	48.52
MPC-32_4808D_MPC-104	15	Y31	4.08	47.1
MPC-32_4808D_MPC-104	16	V48	3.81	52.72
MPC-32_4808D_MPC-104	17	W62	4.2	35.16
MPC-32_4808D_MPC-104	18	Y56	4.39	46.29
MPC-32_4808D_MPC-104	19	K74	4.2	50.71
MPC-32_4808D_MPC-104	20	Y28	4.1	48.18
MPC-32_4808D_MPC-104	21	AC19	3.92	47.34
MPC-32_4808D_MPC-104	22	V40	3.81	52.88
MPC-32_4808D_MPC-104	23	U49	4.01	39.56
MPC-32_4808D_MPC-104	24	U26	3.61	43.24
MPC-32_4808D_MPC-104	25	Y54	4.39	46.42
MPC-32_4808D_MPC-104	26	AC25	3.92	47.27
MPC-32_4808D_MPC-104	27	T62	4.2	46.1
MPC-32_4808D_MPC-104	28	W65	4.21	39.36
MPC-32_4808D_MPC-104	29	U45	4.01	39.68
MPC-32_4808D_MPC-104	30	U51	4.01	39.94
MPC-32_4808D_MPC-104	31	T77	4.2	41.97
MPC-32_4808D_MPC-104	32	W56	4.21	39.22

Second example loading maps for canisters at storage: Highlighted assemblies indicate assemblies in storage currently do not satisfy transportation CoC.

Both example canisters (MPC-32) will require CoC amendments to make them transportable

Transportability from dose perspective: using UNF-ST&DARDS as-loaded dose analysis

- **UNF-ST&DARDS as-loaded time-dependent dose analysis can be used to show transportability (meeting regulatory limits)**
  - May support potential future CoC amendments or different licensing approach

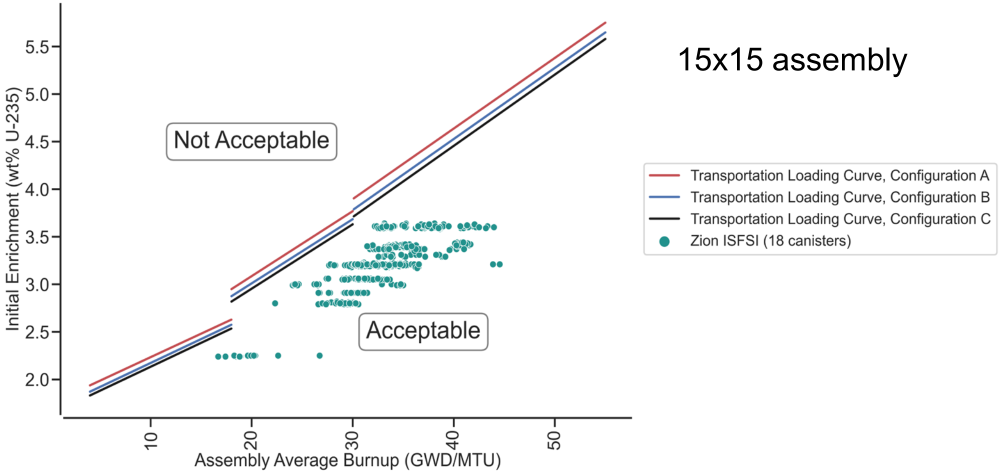


10 CFR Part 71.47 2m dose limit (known as the most restrictive) is used to show transportability. The plot slows max dose at 2m from the radial surface of the cask.

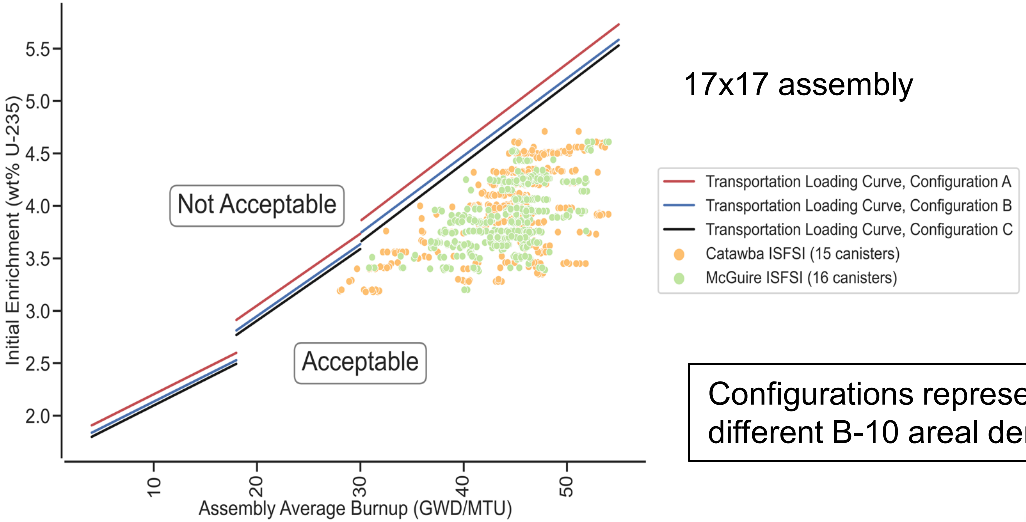
Transportability from criticality perspective: CoC requirements

Table 3 — Maximum Initial Enrichment – 37-Assembly Undamaged Fuel 15 Year Minimum Cool Time									
Assembly ID	^{10}B Absorber (g/cm^2)	Zero (0) Burnup Maximum Enrichment (wt %)	Max Initial Enrichment (wt % ^{235}U) = C_4 × Burnup (GWd/MTU) + C_5						
			Burnup (GWd/MTU) < 18		18 ≤ Burnup (GWd/MTU) ≤ 30		Burnup (GWd/MTU) > 30		
			C_4	C_5	C_4	C_5	C_4	C_5	
BW15	0.036	1.9	0.0501	1.69	0.0693	1.65	0.0748	1.60	
BW17		1.9	0.0502	1.72	0.0687	1.70	0.0742	1.66	
CE14		2.1	0.0473	2.04	0.0675	2.03	0.0759	1.93	
CE16		2.1	0.0464	2.03	0.0657	2.06	0.0733	1.99	
WE14		2.2	0.0496	2.08	0.0672	2.21	0.0725	2.29	
WE15		1.9	0.0494	1.74	0.0683	1.72	0.0742	1.67	
WE17		1.9	0.0494	1.71	0.0685	1.68	0.0749	1.61	
BW15	0.030	1.8	0.0507	1.61	0.0687	1.59	0.0745	1.48	
BW17		1.9	0.0503	1.66	0.0683	1.63	0.0733	1.59	
CE14		2.1	0.0468	1.95	0.0664	1.97	0.0738	1.90	
CE16		2.1	0.0470	1.95	0.0649	1.99	0.0727	1.90	
WE14		2.1	0.0492	2.03	0.0680	2.10	0.0728	2.19	
WE15		1.9	0.0503	1.67	0.0675	1.66	0.0747	1.54	
WE17		1.9	0.0494	1.64	0.0685	1.58	0.0737	1.53	
BW15	0.027	1.8	0.0508	1.58	0.0686	1.52	0.0754	1.41	
BW17		1.8	0.0503	1.62	0.0683	1.59	0.0748	1.47	
CE14		2.1	0.0471	1.92	0.0666	1.92	0.0729	1.87	
CE16		2.1	0.0462	1.93	0.0657	1.92	0.0747	1.75	
WE14		2.1	0.0499	1.98	0.0667	2.10	0.0743	2.07	
WE15		1.9	0.0503	1.63	0.0677	1.60	0.0749	1.46	
WE17		1.9	0.0497	1.60	0.0683	1.54	0.0749	1.41	

MAGNATRAN CoC, Rev 4, 71-9356, NAC International (March 2022)



15x15 assembly



17x17 assembly

Configurations represent different B-10 areal density

These loaded canisters are transportable from criticality perspective

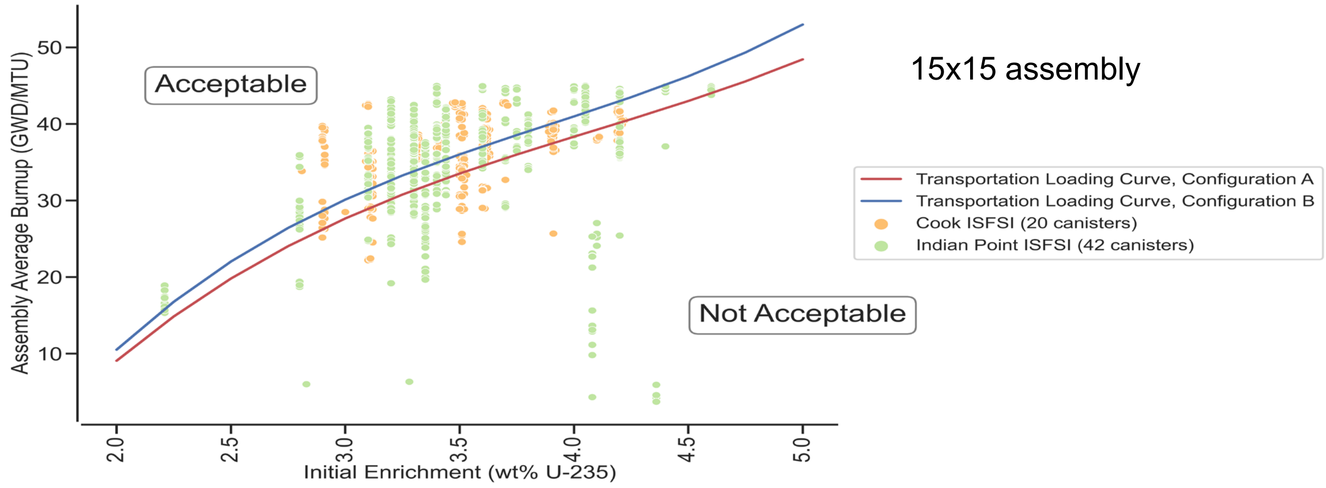
Transportability from criticality perspective: CoC requirements (Contd.)

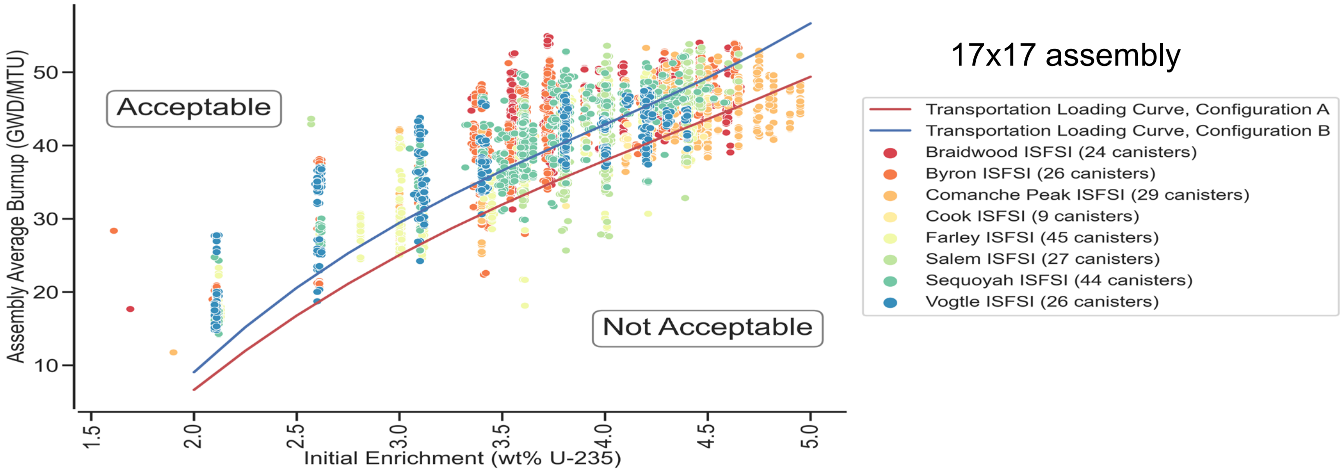
Table 7.A.12

FUEL ASSEMBLY MAXIMUM ENRICHMENT AND MINIMUM BURNUP REQUIREMENTS FOR TRANSPORTATION IN MPC-32

Fuel Assembly Array/Class	Configuration (Note 2)	Minimum Burnup (B) as a Function of Initial Enrichment (E) (Note 1) (GWD/MTU)
Standard MPC-32		
15x15D, E, F, H	A	B = +(1.2222) * E^3 – (14.9530) * E^2 + (70.1230) * E - 81.1400
	B	B = +(1.6446) * E^3 – (19.1690) * E^2 + (84.1940) * E - 94.3490
17x17A, B, C	A	B = +(0.6704) * E^3 – (8.7858) * E^2 + (49.6000) * E – 62.7720
	B	B = +(1.2284) * E^3 – (14.5450) * E^2 + (69.7780) * E – 82.1460
Diablo Canyon MPC-32		
17X17A (Note 3)	A	See SAR Table 6.III.4
17x17B (subclasses 17X17B01 and 17X17B06) (Note 4)	A	See SAR Table 6.III.4.

MPC-32 in HI-STAR 100 (Holtec International), from HI-STAR SAR, Rev 20 (June 2019)
Note: (a) Configurations represent assembly core position and operating history. (b) currently no loading curve for 16x16 type (already loaded in MPC-32) , and (c) currently damaged fuels are not allowed for transportation in MPC-32.





CoC amendment is needed to make some canisters transportable

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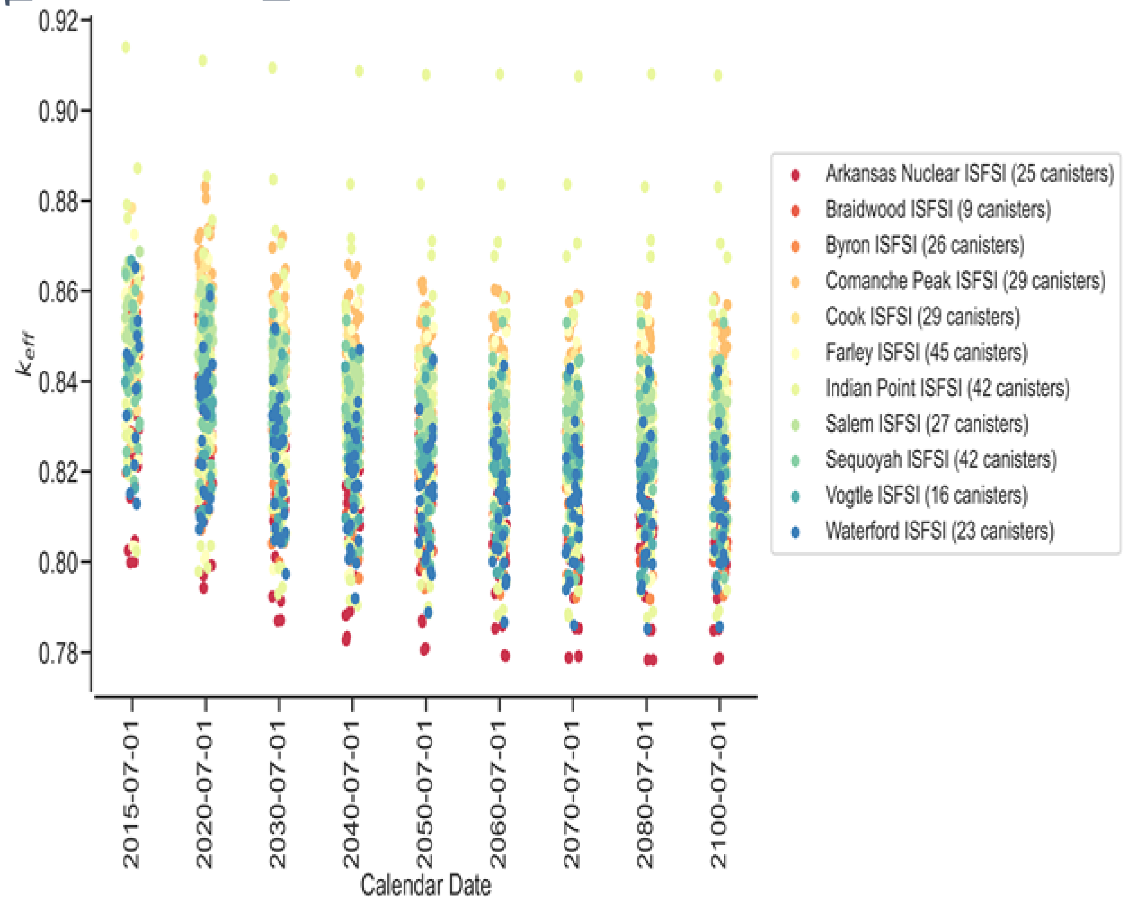
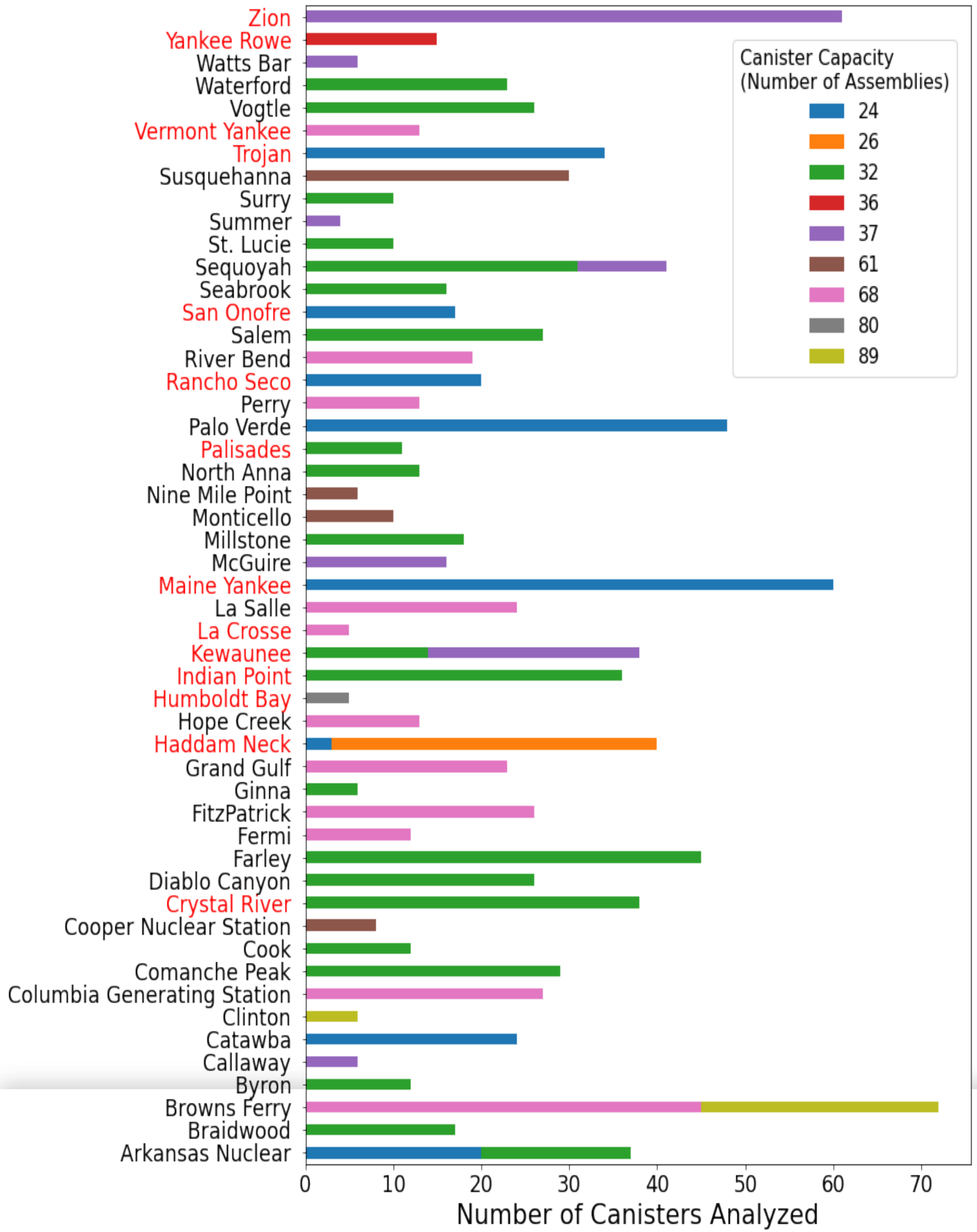
Transportability from criticality perspective: using UNF-ST&DARDS as-loaded criticality analysis

- **Some loaded canisters are not currently transportable from criticality perspective due to two different analysis approaches**
  - Storage: soluble boron credit with fresh fuel assumption
  - Transportation: Burnup credit and loading is restricted by the loading curves in CoC
- **As-loaded criticality analysis can be used for license amendment and integrating storage and transportation analysis approaches**



As-loaded criticality analysis shows canisters that are currently not transportable using MPC-32 loading curve (previous slide) could be safely transported in MPC-32



UNF-ST&DARDS as-loaded criticality analysis related activities

- **Currently analyzed ~1100 loaded canisters at 51 sites**
- **There are three main activities in the criticality areas**
  - Development of models/templates for analyzing as loaded canisters
    - Criticality safety margin quantification during transportation to offset uncertainties related to fuel/basket integrity
    - Direct disposability evaluation
  - Validation of various criticality related assumptions using detailed data
    - Reactor operational history
    - Data (e.g., declared burnup) uncertainties
  - Validation of various analysis codes and biases and uncertainties quantification
    - Depletion code
    - Criticality code

A few relevant conference and journal articles

- **As-loaded analysis approach**
  - J. B. Clarity, K. Banerjee, H. K. Liljenfeldt, W. J. Marshall, "As-Loaded Criticality Margin Assessment of Dual-Purpose Canisters Using UNF-ST&DARDS," *Nuclear Technology,* **199(3)**, 245-275 (2017).
- **As-loaded analysis assumption validation**
  - J. B. Clarity, H. K. Liljenfeldt, K. Banerjee, and P. L. Miller, "Validation of UNF-ST&DARDS As-Loaded Safety Analysis Methods for BWR Decay Heat Calculations," *Progress in Nuclear Energy,* **143(3)**, January 2022
  - K. Banerjee, P. Miller, S. Bhatt, J. B. Clarity, and G. Radulescu, "UNF-ST&DARDS: A Unique Tool for Spent Nuclear Fuel Characterization and Long-Term Fuel Database Management," *TopFuel*, 24-28 October 2021 (Santander, Spain).
- **Criticality analysis validation, bias and uncertainty determination**
  - J. B. Clarity, A. M. Saw, W. J. Marshall, L. P. Miller, and K. Banerjee, "Validation of UNF-ST&DARDS As-loaded Criticality Calculations," American Nuclear Society, Nuclear Criticality Safety Division Topical Meeting, Anaheim, CA (June 2022).
- **Loading optimization from criticality perspective**
  - J. B. Clarity, L. P. Miller, G. G. Davidson, and K. Banerjee, "Development of an Artificial Neural Network for Rapid Post-Closure Reactivity Analysis," American Nuclear Society, Nuclear Criticality Safety Division Topical Meeting, Anaheim, CA (June 2022).

Conclusion: UNF-ST&DARDS analysis and data integration capabilities have many potential applications

- **UNF-ST&DARDS is a comprehensive, integrated data and analysis system**
  - Preserves the SNF information for decades during which SNF related issues will be addressed (**Knowledge Management**)
- **UNF-ST&DARDS provides ready access to characteristics of all SNF assemblies enabling informed large-scale transportation planning**
  - Ready access to assemblies and related systems (e.g., canister) characteristics including CoC limits
    - Can be used to identify systems that require CoC amendments for transportation
    - As-loaded analysis can support CoC amendments for transportation systems
    - Can be used to evaluate when a loaded canister is eligible for transportation
- **ORNL and PNNL are partnering with EPRI to commercialize UNF-ST&DARDS**

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Thank you!

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Backup Slide

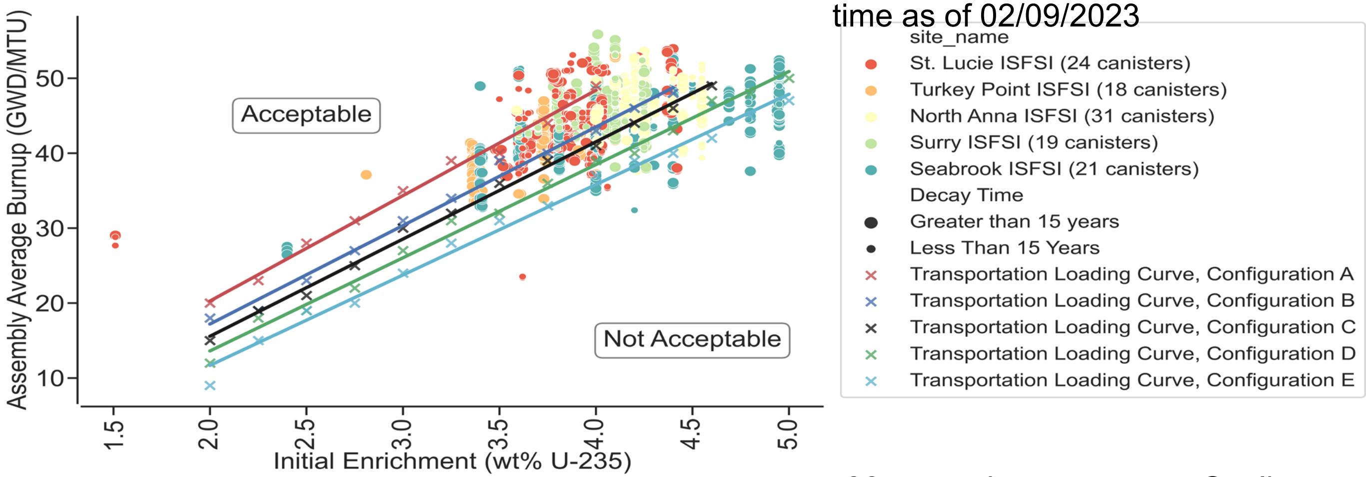
Transportability from criticality perspective: CoC requirements (Contd.)

Table A.1.4.4-7
Maximum Planar Average Initial Enrichment/Minimum Burnup Combinations - NUHOMS®-32PTH –Intact Fuel Assemblies

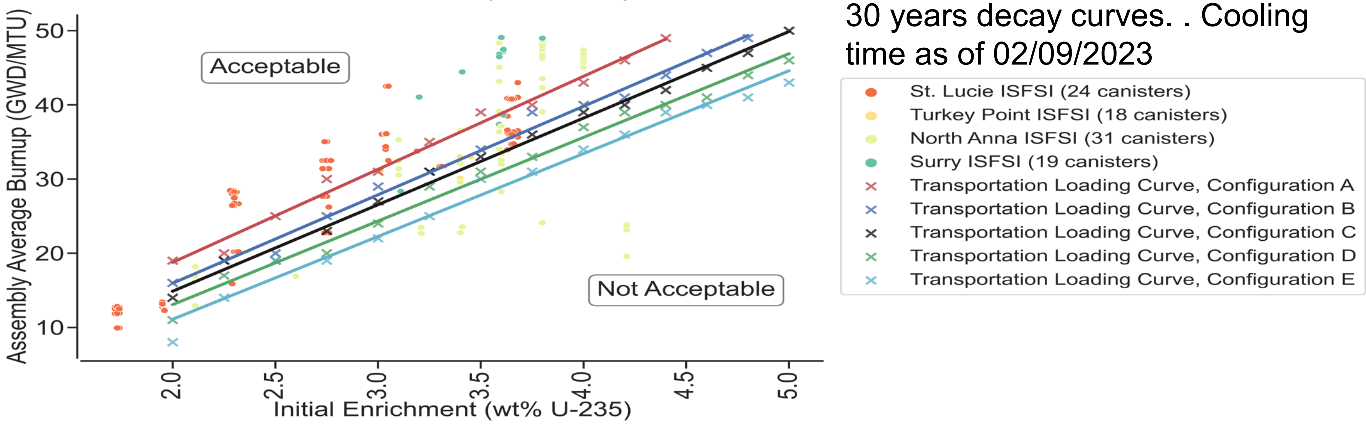
Enrichment (wt. % U-235)	WE 17x17, WE 15x15, CE 14x14 and CE 16x16 fuel assembly classes									
	Type A	Type B	Type C	Type D	Type E	Type A	Type B	Type C	Type D	Type E
1.55	fresh	–	–	–	–	fresh	–	–	–	–
1.70	–	fresh	–	–	–	–	fresh	–	–	–
1.75	–	–	fresh	–	–	–	–	fresh		–
1.80	–	–	–	fresh	–	–	–	–	fresh	–
1.90	–	–	–	–	fresh	–	–	–	–	fresh
	Burnup (GWd/MTU), 15 years decay					Burnup (GWd/MTU), 30 years decay				
2.00	20	18	15	12	9	19	16	14	11	8
2.25	23	19	19	18	15	20	19	19	17	14
2.50	28	23	21	19	19	25	20	19	19	19
2.75	31	27	25	22	20	30	25	23	20	19
3.00	35	31	30	27	24	31	29	27	24	22
3.25	39	34	32	31	28	35	31	31	29	25
3.50	40	39	36	32	31	39	34	33	31	30
3.75	44	40	39	36	33	40	39	36	33	31
4.00	49	43	41	39	37	43	40	39	37	34
4.20	–	46	44	40	39	46	41	40	39	36
4.40	–	48	46	43	40	49	44	42	40	39
4.60	–	–	49	47	42	–	47	45	41	40
4.80	–	–	–	48	45	–	49	47	44	41
5.00	–	–	–	50	47	–	–	50	46	43

NUHOMS-32PTH in MP197 (TN/ORANO), from MP197 transportation packaging safety analysis report, Rev 21 (11/2022)
Note: (a) Configurations represent B-10 areal density of the basket neutron absorber, (b) only intact assemblies are considered, (c) No burnup requirement for enrichment below 2%, (d) minimum burnup requirements are different for assemblies exposed to control rod insertion

15 years decay curves. Cooling time as of 02/09/2023



30 years decay curves. . Cooling time as of 02/09/2023



CoC amendment is needed to make some canisters transportable