

Summary of Nuclear Waste Inventory in the U.S.

EINSTEIN Milestone 1.1

Prepared for:
ARPA-E NEWTON
(DE-FOA-0003418)

CONTRACT
EINSTEIN
(DE-AR0002080)

Prepared by:
Samar Abdelkawy
Madeleine Wallman

Principal Investigator:
Prof. Angela Di FULVIO
Co-Investigator:
Prof. Kathryn D. HUFF

UIUC-ARFC-2025-01

ADVANCED REACTORS AND FUEL CYCLES
DEPT. OF NUCLEAR, PLASMA, & RADIOPHYSICAL ENGINEERING
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

I ILLINOIS

This research was performed using funding received from the Department of Energy, 'Enhanced Integrated Nuclear Systems for Transmutation and Efficient Isolation of Nuclides,' Award Number DE-AR0002080.

cite a
federal
database
here

1 Introduction

This summary consolidates U.S. spent nuclear fuel (SNF) and high level waste (HLW) inventory information from federal databases and national reports [1]. This summary serves to inform isotopic composition analysis and strategic scenario development for modeling fuel cycles enabled by accelerator driven and fusion-source driven transmutation systems (XDS)¹. It provides (1) current commercial SNF inventory, (2) Department of Energy (DOE)-managed SNF from research and defense programs, (3) research reactor SNF, and (4) reprocessing waste inventories.

This report will describe the current U.S. inventories at a high level, emphasizing data to be incorporated into CYCLUS [2] facility archetypes and scenarios developed in support of the Enhanced Integrated Nuclear Systems for Transmutation and Efficient Isolation of Nuclides (EINSTEIN) project [?].

2 Geospatial Information

Transportation of feed material to XDS facilities and transportation of product material from the XDS facilities can be modeled using geographical data from the available datasets coupled with the geospatial mapping capabilities in CYCLUS. Figure 1 shows the geographic distribution of sites storing SNF and reprocessing waste across the United States based on data from [1]. The map shows the locations of commercial nuclear power plants, Independent Spent Fuel Storage Installations (ISFSIs), and DOE-managed facilities. Notable concentrations of SNF storage sites are observed in the northeastern United States, the Midwest, the Southeast, and along the West Coast, reflecting the historical deployment of the nation's light water reactor fleet. This spatial distribution is an important consideration for future fuel consolidation strategies, transportation planning, and repository siting analyses.

cite UDB

¹This report will refer to all accelerator-driven subcritical systems (ADSs) and fusion source-driven subcritical systems (FDSs) as fusion source or accelerator-driven subcritical system (XDS).

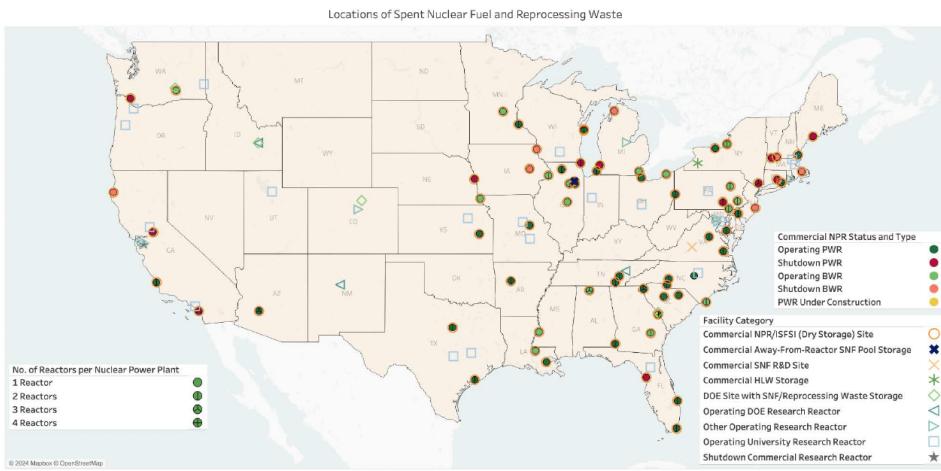


Figure 1: Sites Storing Spent Nuclear Fuel and Reprocessing Waste at the End of 2022

Commercial Spent Nuclear Fuel at Nuclear Power Reactor and ISFSI Sites (excluding DOE)	90.963 MTHM ^a
Total Amount of Commercial Discharged PWR Spent Nuclear Fuel ^b	135,645 Assemblies 59,013 MTHM ^a
Total Amount of Commercial Discharged BWR Spent Nuclear Fuel ^b	179,466 Assemblies 32,023 MTHM ^a
Total Number of Commercial Spent Nuclear Fuel Canisters/Casks in Dry Storage (See Section 2.1)	3,862
Spent Nuclear Fuel at DOE Sites (includes SNF from DOE Research Reactors)	2,479 MTHM ^{a,c}
Spent Nuclear Fuel at Other Sites (University and Other Government Research Reactors, Commercial R&D Centers) ^d	1 MTHM ^a
Number of Sites Having One or More Commercial Nuclear Power Reactors and/or ISFSIs with SNF Stored Onsite (excluding DOE Sites) ^e	73
Number of Sites Having All Nuclear Power Reactors Shutdown with SNF Stored Onsite (excluding DOE Sites, See Section 2)	20
Number of Operating Nuclear Reactors	92
Number of Shutdown Nuclear Power Reactors with SNF Stored Onsite (excluding DOE sites)	27
Number of DOE Sites with SNF storage and/or DOE research reactors (see Section 3)	6
Number of University Research Reactor Sites (see Section 4.1) ^f	20
Number of Other Government Agency Research Reactors (see Section 4.2)	4
Number of Commercial Research and Development Centers with SNF (see Section 4.3)	4
Number of Primary Reprocessing Waste or HLW Storage Sites (see Section 5.1) ^g	4
Number of Vitrified Reprocessing Waste Canisters at DOE Sites	4,346 ^h
Number of Vitrified Reprocessing Waste Canisters at West Valley Site	278 ⁱ

Table 1: U.S. SNF and Reprocessing Waste Inventory Summary as of December 31, 2022.

CITE THE SOURCE

Table notes:

^a Values are rounded to the nearest metric ton of heavy metal (MTHM).

^b Commercial SNF includes permanently discharged Pressurized Water Reactor (PWR) and boiling water reactor (BWR) fuel through December 31, 2022, excluding fuel reprocessed at West Valley, removed from Three Mile Island Unit 2, or discharged from the Fort St. Vrain reactor.

^c DOE SNF includes fuel from DOE research and production reactors, naval reactors, and the Fort St. Vrain gas-cooled reactor.

^d Other sites include university research reactors, government research reactors, and commercial R&D facilities.

^e Site counts exclude DOE-owned ISFSIs but include the Morris away-from-reactor pool; co-located plants are counted as single sites.

^f Excludes critical facilities and very-low-power AGN-201 university reactors that are not expected to generate discharged fuel.

^g Includes three DOE reprocessing waste sites and one commercial HLW storage site.

^h Includes only vitrified waste canisters produced through December 31, 2022.

ⁱ Includes all West Valley vitrified HLW canisters, including melter-drain and end-of-process canisters.

As summarized in Table 1, at the end of 2022, the U.S. inventory of SNF and primary reprocessing waste was distributed across more than 100 sites in 39 states. These include 73 commercial nuclear power reactor and ISFSI sites, 6 DOE facilities with SNF or research reactors, and 28 Research and Development (R&D) sites encompassing universities, government laboratories, and commercial research centers. Four major locations manage HLW and vitrified reprocessing waste, including 3 DOE facilities and one commercial site at West Valley, NY.

Commercial SNF inventories include permanently discharged PWR and BWR assemblies reported through 2022. Quantities exclude reprocessed fuel from the West Valley and Fort St. Vrain reactors. DOE totals include SNF from research, naval, and production programs. Other noncommercial sources include university and government research reactors. Reprocessing waste totals reflect vitrified HLW canisters produced through 2022.

3 U.S. Commercial Spent Nuclear Fuel Inventory

Commercial nuclear power reactors have operated in the United States since 1960, during which time a total of 131 civilian Nuclear Power Reactors (NPRs) were constructed, excluding several experimental or non-power demonstration units. Nine of the early demonstration reactors, including Peach Bottom Unit 1, Shippingport, and Fermi 1, have been fully decommissioned, and the remaining SNF from these reactors is managed by the DOE. The Fort St. Vrain high temperature gas cooled reactor, although also decommissioned, has its SNF under DOE custody at the Idaho National Laboratory (INL). Of the remaining fleet, 121 are light water reactors (LWRs). Shoreham never entered commercial service, and Three Mile Island Unit 2 was permanently disabled in 1979, with both now under DOE management. As of the end of 2022, 92 reactors remain operational and 27 are permanently shut down. Nearly every plant hosts a co-located ISFSI, which becomes the primary storage facility after plant decommissioning.

To facilitate inventory analysis, reactor sites are assigned to four categories based on operational status and onsite storage configuration. Group A consists of sites where all reactors have been permanently shut down, while Group B contains sites with a mixture of operating and shutdown units. Group C includes sites where all reactor units remain operational, and Group F consists of away from reactor ISFSI facilities such as the Mor-

ris, Illinois wet storage pool. A numeric suffix is used to indicate whether SNF storage at the site is entirely dry (1), a mixture of wet and dry storage (2), or entirely wet (3). For example, Yankee Rowe is classified as Group A1 because all SNF at the site is stored in dry casks, while Surry is classified as Group C2 because it contains both pool and dry storage systems. Diablo Canyon Units 1 and 2 are currently classified under Group C but are expected to transition to shutdown status before 2030.

Table 2 summarizes the distribution of commercial SNF by reactor category, illustrating the growth of Group A sites as more reactors retire. This grouping framework underpins the spatial and temporal distribution of discharged fuel and the corresponding storage infrastructure needed across the United States.

Commercial SNF data originate primarily from the DOE's GC-859 Nuclear Fuel Data Survey, which provides assembly level discharge information including assembly type, physical dimensions, enrichment, and burnup. As of December 2022, approximately 91,000 MTU of commercial SNF had been discharged nationally. These discharge records reflect only the initial removal from reactor cores and do not include subsequent transfers. Historically, small quantities of fuel were shipped to other facilities prior to the year 2000, including limited reprocessing at West Valley, New York, and transfers to the Morris, Illinois away from reactor wet storage pool. Approximately 73 MTU of fuel was transferred to DOE facilities for research programs involving rod consolidation, dry storage demonstration, and vitrification studies; 68 MTU of this material remains in DOE custody today. SNF from Fort St. Vrain and Three Mile Island Unit 2 is also stored at INL. Since 2000, however, virtually all discharged commercial SNF has remained onsite at the generating reactor facilities. In total, 73 commercial locations, including Morris, currently store SNF. Notably, as of 2021, the national inventory stored in dry casks surpassed the inventory remaining in spent fuel pools, reflecting both aging reactor infrastructure and the expansion of dry storage systems across the fleet.

CITE
THIS

Group A: All Units Shutdown Sites (# of Units) – 25 Reactors/20 Sites					
A1 (Dry Storage)		A2 (Dry and Pool Storage)	A3 (Pool Storage)		
Reactors Shutdown Prior to 2000					
Big Rock Point (1)	Rancho Seco (1)	Indian Point (3)			
Haddam Neck (1)	Trojan (1)	Palisades (1)			
Humboldt Bay (1)	Yankee Rowe (1)				
La Crosse (1)	Zion (2)				
Maine Yankee (1)					
Reactors Shutdown Post 2000					
Crystal River (1)	Vermont Yankee (1)				
Keweenaw (1)	Fort Calhoun (1)				
San Onofre (3)	Oyster Creek (1)				
Pilgrim (1)	Duane Arnold (1)				
Three Mile Island (1) ††					
Group B: Mixed Status Sites (# of Units) – Total 6 Reactors (4 Operating, 2 Shutdown) /2 Sites					
Currently All Group B Sites have both Dry and Wet Storage Capabilities	B2† (Dry and Pool Storage)				
	Dresden (3)				
	Millstone (3)				
Group C: All Units Operating (# of Units)– 88 Reactors/52 Nuclear Power Plants/50 Sites (Note: All Group C Sites have Wet Storage Capabilities)					
C2 (Dry and Pool Storage)			C3 (Pool Storage)		
Arkansas Nuclear (2)	Fitzpatrick (1)‡‡	Prairie Island (2)	Shearon Harris (1)		
Beaver Valley (2)	Fermi (1) ††	Quad Cities (2)			
Braidwood (2)	Ginna (1)	River Bend (1)			
Browns Ferry (3)	Grand Gulf (1)	Robinson (1)			
Brunswick (2)	Hatch (2)	Saint Lucie (2)			
Byron (2)	Hope Creek (1) ***	Salem (2) ***			
Calvert Cliffs (2)	La Salle (2)	Seabrook (1)			
Callaway (1)	Limerick (2)	Sequoyah (2)			
Catawba (2)	McGuire (2)	South Texas (2)			
Clinton (1)	Monticello (1)	Summer (1)			
Columbia Generating Station (1)	Nine Mile Point (2)‡‡	Surry (2)			
Comanche Peak (2)	North Anna (2)	Susquehanna (2)			
Cooper (1)	Oconee (3)	Turkey Point (2)			
Davis-Besse (1)	Palo Verde (3)	Vogtle (2)			
D.C. Cook (2)	Peach Bottom (2) ††	Waterford (1)			
Diablo Canyon (2)	Perry (1)	Watts Bar (2)			
Farley (2)	Point Beach (2)	Wolf Creek (1)			

Table 2: Spent Nuclear Fuel Inventory by Reactor Group/Subgroup (As of December 31, 2022)

CITE THE SOURCE

Table notes:

† Two B2 sites include one shutdown reactor and two operating reactors.

†† Excludes prototype, experimental, and disabled reactors (Fermi-1, Peach Bottom-1, and Three Mile Island Unit 2). 6

‡‡ Nine Mile Point and James A. FitzPatrick are treated as a single site due to proximity and shared site boundaries.

Hope Creek and Salem are treated as a single site due to proximity and a shared ISFSI.

After this point, I'm no longer noting everywhere you need to cite your sources.

It frankly needs to be everywhere.

When you mention these sources in the text in a manner that's unclear about where the data and information came from,

where the figures and tables have been reproduced, etc.

Many more citations need to be added throughout referring to everything relevant.

Reactor Type	Dry Inventory			Pool Inventory		Total Discharged SNF	
	Assy.	Initial Uranium (MT)	SNF Casks	Assy.	Initial Uranium (MT)	Assy.	Initial Uranium (MT)
PWR	94,407	16,675	1,399	78,008	14,131	172,415	30,805
BWR	74,774	32,252	2,463	64,472	27,232	139,246	59,484
Totals	169,181	48,926	3,862	142,480	41,363	311,661	90,289

Table 3: Current Inventory at NPR site by Storage Method as of December 2022

When referring to the sites, it's more common to refer to these as NPPs (nuclear power plants). Consider this. ALSO, CITE THE SOURCE

Table 3 presents the inventory distribution between wet and dry storage across all NPR sites. This table highlights the ongoing shift from pool storage to dry cask systems, driven by pool capacity limits, plant shutdowns, and long term storage planning in the absence of a federal repository.

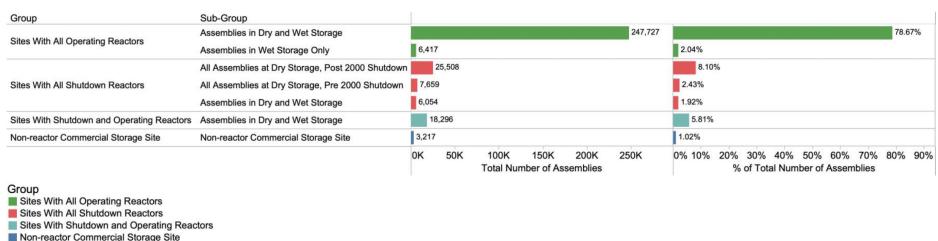


Figure 2: Nuclear Power Reactor and ISFSI Sites (non-DOE) Currently Storing SNF

CITE THE SOURCE

Figure 2 summarizes the distribution of commercial SNF assemblies across non-DOE reactor and ISFSI sites by reactor operating status and storage configuration. The majority of SNF assemblies (approximately 79%) are located at sites with all operating reactors, with most assemblies stored

in a combination of wet and dry storage. Sites with fully shutdown reactors account for a smaller but non-negligible fraction of the inventory, primarily stored in dry casks following reactor shutdown. Sites with both operating and shutdown reactors and non-reactor commercial storage facilities together represent a minor portion of the total assembly count. This breakdown highlights the strong coupling between reactor operational status and SNF storage practices and provides important context for evaluating transportation, consolidation, and fuel cycle transition scenarios.

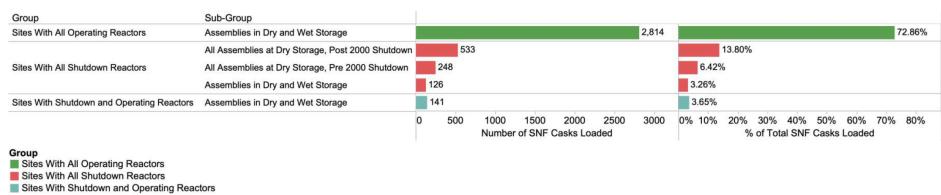


Figure 3: Dry SNF Storage Casks Loaded at Nuclear Power Reactor Sites

The cumulative number of dry storage casks loaded across the commercial reactor fleet is illustrated in Figure 3, the increasing trend reflects both ongoing reactor operations and the migration of older assemblies from pools to dry storage. The widespread use of dry casks underscores the importance of long-term interim storage in national waste management planning.

GC-859 data also provide insights into fuel characteristics at discharge. Over time, average burnup has increased from early values below 20 GWd/MT in the 1970s to approximately 50 GWd/MT today. Correspondingly, initial enrichment has risen from about 2% U-235 in early fuel designs to nearly 4.5% in modern PWR and BWR assemblies. These changes reflect improvements in core design, regulatory allowances, and utility strategies aimed at extending fuel cycle lengths and improving economic performance.

The distribution of burnup and enrichment for discharged assemblies is represented in Figure 4, demonstrating a clear shift toward higher burnup fuel across the fleet. This trend influences isotopic composition at discharge, particularly increasing plutonium and minor actinide production.

Figure 5 shows the annual average enrichment and burnup of U.S. reactor discharges from 1968 to 2022. The steady upward trend in both pa-

The writing checklist is clear, this should be ^{235}U , not U-235. Please check whole document for these instances and fix them.

rameters reflects technical and regulatory evolution in fuel management, including the adoption of higher enriched fuel and increased cycle lengths.

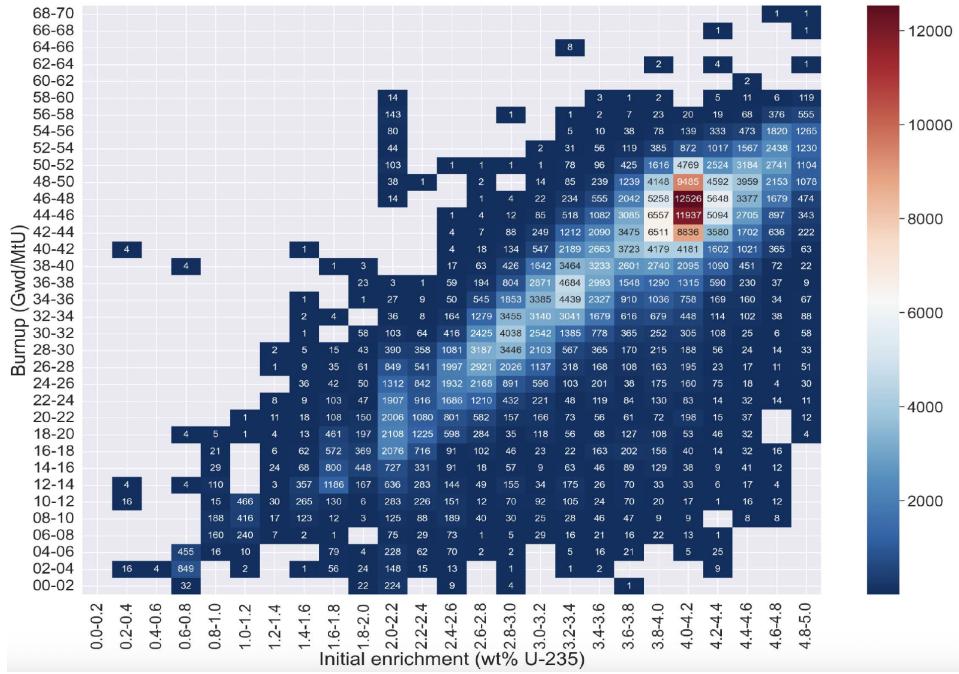


Figure 4: Burn-up (GWd/MTHM) & Initial Enrichment (% U-235) by Number of Assemblies of SNF Through December 2022

Figure captions should be complete sentences. CITE THE SOURCE

Elements	Decay Heat (Watts/MT)							
	Time (years)							
	1	10	30	50	70	100	300	500
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	4,608	1,576	824	516	323	160	1	0
Noble Metals Ag, Pd, Ru, Rh	3,447	14	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	3,843	109	17	3	1	0	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	1,515	785	613	516	449	381	199	139
Others	522	21	3	1	0	0	0	0
Totals	13,936	2,505	1,458	1,036	773	541	201	139

Table 4: PWR 60 GWd/MT Spent Nuclear Fuel Decay Heat

figure captions should be complete sentences. CITE THE SOURCE

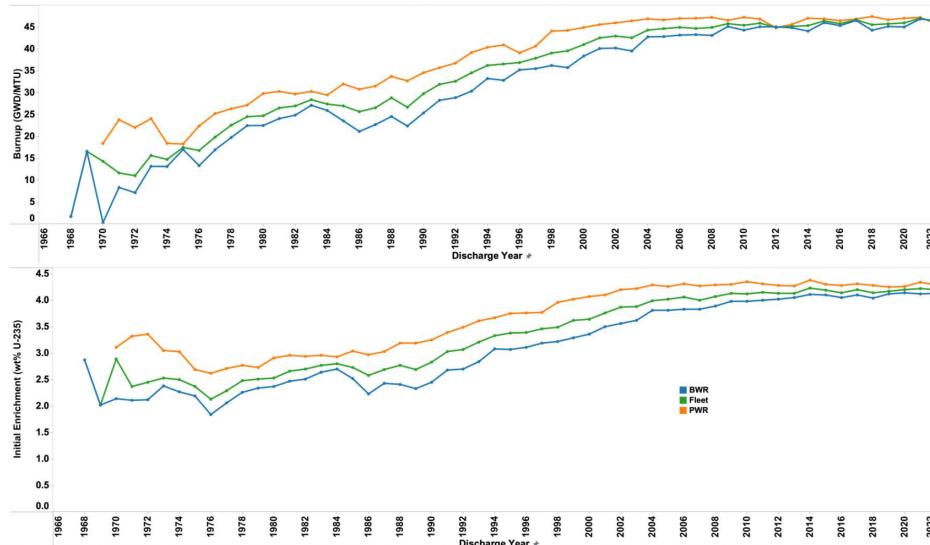


Figure 5: Average Annual Burn up (GWd/MT) and Enrichment (U-235%)

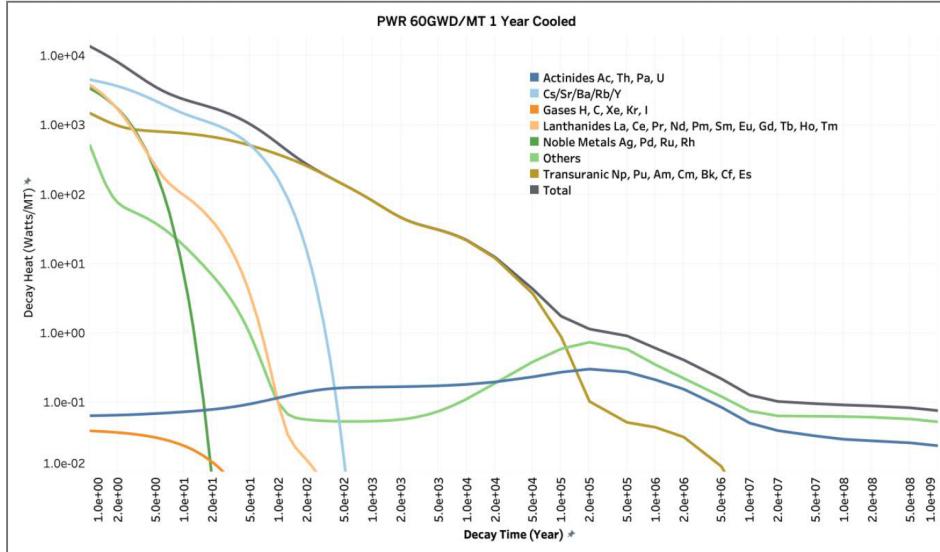


Figure 6: PWR 60 GWd/MT Spent Nuclear Fuel Decay Heat

Representative burnup cases, drawn from the UFDC [Inventory Report](#), provide insight into decay heat behavior. These cases include PWR fuel discharged at 40 and 60 GWd/MT and BWR fuel discharged at 30 and 50 GWd/MT, typical values bounding the burnup range of modern LWR fuel. These representative isotopic compositions are commonly used in fuel cycle modeling tools such as CYCLUS, ORIGEN, and UNF-ST&DARDS.

create acronym... what is UFDC? Where is the citation?

please add these acronyms to acros.tex.

As seen in Table 4 and Figure 6 the decay heat profile for PWR fuel discharged at 60 GWd/MT. At early cooling times, decay heat is dominated by fission products such as Cs-137 and Sr-90. At longer cooling times, actinides, particularly Pu-238, Pu-241, and Am-241, become the primary contributors. Higher burnup fuel retains more long-term decay heat, which has implications for storage, transport, and disposal.

Elements	Decay Heat (Watts/MT)							
	Time (years)							
	1	10	30	50	70	100	300	500
Gases H, C, Xe, Kr, I	0	0	0	0	0	0	0	0
Cs/Sr/Ba/Rb/Y	3,558	1,257	662	414	259	128	1	0
Noble Metals Ag, Pd, Ru, Rh	2,669	11	0	0	0	0	0	0
Lanthanides La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Ho, Tm	2,734	92	14	3	1	0	0	0
Actinides Ac, Th, Pa, U	0	0	0	0	0	0	0	0
Transuranic Np, Pu, Am, Cm, Bk, Cf, Es	1,627	760	591	496	433	369	199	139
Others	420	17	2	1	0	0	0	0
Totals	11,008	2,137	1,271	914	693	498	200	139

Table 5: BWR 50 GWd/MT Spent Nuclear Fuel Decay Heat

Table 5 and Figure 7 present corresponding decay heat characteristics for BWR fuel discharged at 50 GWd/MT. Similar to the PWR case, short term heat generation is controlled by fission products, while long term heat output is driven by actinides. These representative datasets are essential for evaluating engineered storage systems and for bounding performance assessments in fuel cycle simulations.

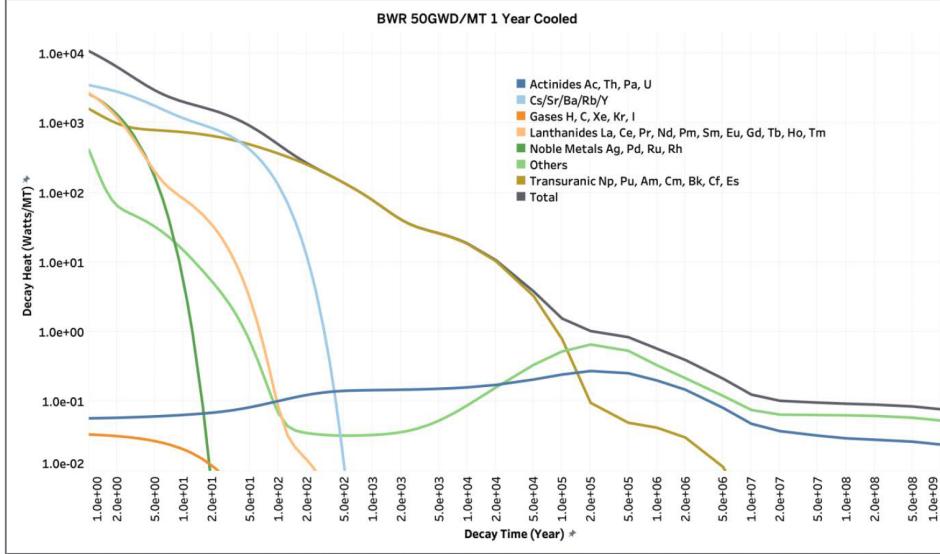


Figure 7: BWR 50 GWd/MT Spent Nuclear Fuel Decay Heat

While commercial reactors generate the vast majority of SNF in the United States, the DOE manages a separate and highly diverse inventory originating from research, defense, and demonstration reactors, which is discussed in the following section.

4 SNF at DOE Locations

The U.S. DOE is responsible for SNF that falls outside the commercial nuclear power sector. This includes fuel from defense production reactors, test and research reactors operated across national laboratories, early demonstration power reactors from the Atomic Energy Commission era, university research reactors once transferred to federal custody, and fuel used in research, examination, or fuel cycle development programs. DOE also manages SNF originating from naval nuclear propulsion, although naval fuel is tracked separately due to classification restrictions and highly specialized handling requirements.

Unlike the relatively standardized commercial LWR inventory, DOE's SNF inventory is highly heterogeneous. It includes fuel from graphite moderated reactors, sodium cooled reactors, high flux isotope production reac-

tors, heavy water reactors, TRIGA research reactors, breeder reactors, and early prototype power reactors. Fuel enrichments span a wide range from depleted uranium for production reactors to highly enriched uranium exceeding 93% U-235 for test and training reactors. Many reactors used bespoke fuel element geometries and materials, resulting in over 229,000 individual fuel elements or pieces, covering several hundred unique fuel types. This diversity is central to DOE's ongoing challenges in characterization, consolidation, and long term disposal planning.

By the end of 2022, DOE managed approximately 2,446 MTHM of SNF (excluding naval fuel), as documented in the Spent Fuel Database (SFD). To support system level evaluations, this inventory has been grouped into 34 standardized categories based on fuel matrix, cladding type, cladding condition, and enrichment. These parameters influence corrosion behavior, radionuclide release, storage system performance, and repository compatibility. Each category aggregates fuel with similar physical and chemical characteristics, enabling more tractable modeling of a highly diverse inventory.

cite the database here – also, is SFD its real name?

By you? by them? Be clear.

Radionuclide inventories for DOE-managed fuel are estimated through template depletion models that represent typical fuel behavior at different burnups and cooling times. These templates are then scaled to match the mass, enrichment, and operating history of individual SNF records. Based on these models, the total expected radioactivity of DOE-managed SNF in 2030 is approximately 96 million Ci for the nominal case. A bounding case, intended to capture the highest burnup or least well characterized assemblies, reaches approximately 195 million Ci. These values emphasize the wide variability in DOE SNF and the presence of small subsets of high activity fuel that dominate radiological behavior.

Table 6 shows the projected decay heat distribution of DOE spent nuclear fuel canisters for the year 2030. Most DOE canisters generate less than 300 W and over 60% generate less than 100 W, about 97 % of the DOE SNF canisters will be generating decay heat less than 300 watts. Nearly all the DOE SNF canisters (>99%) will be generating less than 1 kW, indicating that the majority of DOE SNF is relatively low power at long cooling times.

DOE SNF		
Decay heat per canister (watts)	Number of canisters ¹¹	Cumulative %
<50	1,411	52.1%
50 - 100	459	69.0%
100 - 220	647	92.9%
220 - 300	100	96.6%
300 - 500	77	99.4%
500 - 1000	6	99.6%
1000 - 1500	3	99.7%
1500 - 2000	-	99.7%
>2000	7	100.0%
Total	2,710	

Table 6: Projected decay heat distribution of DOE spent nuclear fuel canisters for the year 2030

Table note: ¹¹ Canister counts are derived from an SFD loading algorithm and have been rounded up to whole canisters. They provide a relative comparison across decay-heat ranges and do not represent actual as-loaded canisters. Totals may therefore differ from the SFD database, and cumulative percentages are based on the algorithm results.

In 1995, DOE made the strategic decision to consolidate SNF storage at three primary sites: the Hanford Site in Washington, Idaho National Laboratory (INL) in Idaho, and the Savannah River Site (SRS) in South Carolina. These locations now host nearly all DOE-managed SNF. Hanford contains the largest share, approximately 2,128 MTHM, primarily stored in sealed stainless steel Multi-Canister Overpacks (MCOs). INL stores approximately 270 MTHM, much of it originating from research and test reactors. Savannah River Site (SRS) holds approximately 27 MTHM, largely from isotope production reactors and research reactor returns. Although DOE has established standard disposal canister designs intended to support eventual geologic disposal, no DOE SNF has yet been packaged into these standardized canisters.

DOE also manages approximately 173.6 MTHM of spent nuclear fuel that originated from commercial nuclear power reactors, but was transferred to DOE for research, testing, and fuel cycle demonstration activities. This inventory includes core debris from Three Mile Island Unit 2, high-temperature gas-cooled reactor fuel from the Fort St. Vrain reactor, and various LWR assemblies used in post-irradiation examination, rod consolidation experiments, and vitrification studies. Much of this fuel is no longer in intact assembly form and therefore requires packaging in specialized canisters prior to storage and disposal. Table 7 summarizes the decay heat characteristics of the 950 canisters containing non-standard and research-origin spent nuclear fuel managed by DOE.

In addition to research and commercial origin fuel, DOE manages naval reactor SNF through the Naval Nuclear Propulsion Program. This fuel is discharged from nuclear powered submarines, aircraft carriers, land based prototype reactors, and moored training ships. Naval fuel is fabricated with highly enriched uranium, resulting in exceptionally low transuranic production compared to commercial LWR fuel. The current inventory is approximately 40 MTHM, with projections indicating less than 65 MTHM by 2035.

Decay heat per canister (watts)	2030	
	Number of DOE Standard Canisters ¹²	Cumulative %
<50	792	83.4%
50 - 100	54	89.0%
100 - 220	33	92.5%
220 - 300	40	96.7%
300 - 500	3	97.0%
500 - 1000	24	99.6%
1000 - 1500	0	99.6%
1500 - 2000	0	99.6%
>2000	5	100.0%
Totals	950	

Table 7: Decay heat characteristics of canisters containing SNF of commercial (NPR) origin managed by DOE

Table note: ¹² Canister counts are derived from an SFD loading algorithm and rounded up to whole canisters. They provide a relative comparison across decay-heat ranges and do not represent actual as-loaded canisters. Totals may differ from the SFD database, and cumulative percentages are based on the algorithm results.

Naval SNF is stored in specially engineered canisters, either “naval short” or “naval long” variants, designed to meet repository heat, shielding, and criticality constraints. As of 2022, 201 naval SNF canisters have been loaded and are stored at INL. Although naval fuel is highly enriched, long term decay heat is generally modest due to low transuranic buildup, as shown in Table 8, that provides the distribution of Naval SNF canisters

based on nominal decay heat.

Decay heat per canister (watts)	Number of canisters	Cumulative %
500 - 1000	13	3.3%
1000 - 2500	36	12.3%
2500 - 5000	94	35.8%
>5000	257	100.0%
Total	400	

Table 8: Decay heat characteristics of naval SNF canisters

Overall, DOE's SNF inventory is characterized by its diversity, historical complexity, and unique storage challenges. While commercial LWR fuel dominates total mass in the United States, DOE fuel dominates in terms of variety, specialization, and the need for tailored treatment and disposal strategies. This distinction is critical for national level fuel cycle assessments and informs the development of repository design criteria and waste acceptance requirements.

5 SNF at Other Sites

Beyond commercial nuclear power reactors and DOE facilities, a small amount of SNF is located at other sites throughout the United States. These holdings are comparatively minor totaling only about 1.35 metric tons of heavy metal (MTHM), yet they represent a diverse set of institutions and reactor types that contribute to the broader national fuel cycle inventory. The SNF at these locations is cataloged in the DOE Spent Fuel Database and originates primarily from university research reactors, government agency operated reactors, and commercial research and development centers.

University research reactors constitute the largest group within this category. Approximately twenty such reactors are currently operating in the United States, typically at very low power levels ranging from less than one watt to approximately 10 MW, depending on reactor design and research application. Because these reactors use fuel at much lower power densities and achieve much smaller burnups than commercial reactors, refueling events are infrequent. In many cases, entire reactor lifetimes may pass without the need for a fuel discharge. When spent fuel is eventually removed from university research reactors, it is transferred to DOE custody, most commonly to the INL or the SRS, where it becomes part of the broader DOE-managed SNF inventory discussed earlier. A small number of specialized critical facilities, such as the AGN, 201 reactors or the Rensselaer Polytechnic Institute Critical Facility, operate at such low power that they are not expected to generate any spent fuel for discharge.

Table 9 provides a listing of the university reactors and the quantities of spent nuclear fuel at those locations. The quantities reported include the in-core amounts and SNF which has not reached the end of its useful life. Although these facilities represent a wide geographic distribution, the total quantity of SNF remains very small compared to commercial or DOE sources.

In addition to university operated facilities, several research reactors are run by other government agencies. These include national defense, materials testing, and specialized experimental reactors that support federal research programs. Similar to university reactors, permanently discharged fuel from these facilities is shipped to INL or SRS, where it is incorporated into DOE's consolidated inventory. Table 10 summarizes these government operated research reactors and the corresponding SNF quantities that have been transferred to DOE management.

State	Installation	Inventory (kg)
California	University of California (Irvine)	20.34
	University of California (Davis)	80.34
Florida	University of Florida (Gainesville)	19.30
Indiana	Purdue University (West Lafayette)	12.03
Kansas	Kansas State University (Manhattan)	21.44
Maryland	University of Maryland (College Park)	19.84
Massachusetts	University of Massachusetts-Lowell	10.64
	Massachusetts Institute of Technology (Cambridge)	20.21
Missouri	University of Missouri (Columbia)	28.95
	University of Missouri (Rolla)	25.52
North Carolina	North Carolina State University (Raleigh)	484.05
Ohio	Ohio State University (Columbus)	26.15
Oregon	Oregon State University (Corvallis)	75.63
	Reed College (Portland)	18.95
Pennsylvania	Pennsylvania State University (University Park)	37.94
Texas	Texas A&M University (College Station)	68.76
	University of Texas (Austin)	42.83
Utah	University of Utah (Salt Lake City)	25.77
Washington	Washington State University (Pullman)	57.53
Wisconsin	University of Wisconsin (Madison)	58.29
Total		1,154.48

Table 9: University research reactor sites and their associated SNF inventories

State	Installation	Inventory (kg)
Colorado	U.S. Geological Survey (Denver)	65.76
Maryland	National Institute of Standards and Technology (Gaithersburg)	13.91
	Armed Forces Radiobiology Research Institute (Bethesda)	18.27
Rhode Island	Rhode Island Atomic Energy Commission, RINSC Reactor (Narragansett)	19.24
Total		177.17

Table 10: Research reactors operated by other government agencies and the associated SNF transferred to DOE custody for long term management.

A final category within this group consists of commercial research and development centers, a small number of which operate or historically operated research reactors. These facilities contribute modest quantities of SNF, and in some cases, such as the BWX Technologies site in Virginia, they support fuel-cycle research and destructive examination activities rather than power-producing reactor operations. Table 11 lists these commercial R&D centers and their corresponding SNF inventories. Although the total mass of fuel generated by these institutions is small, their presence reflects the broad technical landscape of nuclear research in the United States and the need for DOE to manage diverse and specialized fuel forms originating from non-power, non-defense applications.

State	Installation	Inventory (kg)
California	Aerotest Research Reactor (San Ramon)	17.50
	General Electric (Pleasanton)	3.98
Michigan	Dow Chemical, Research Reactor (Midland)	14.81
Virginia	BWX Technology, Fuel cycle R&D Center (Lynchburg)	43.89
Total		80.19

Table 11: Commercial research and development centers with spent nuclear fuel inventories

Overall, the SNF at these other sites represents the smallest contribution to the national fuel inventory by mass, but it remains important due to its broad diversity and the unique characteristics of the research-reactor fuels involved. When transferred to DOE custody, this fuel must be integrated into the same long-term planning, storage frameworks, and disposition pathways used for the larger DOE SNF inventory.

6 Reprocessing Waste

In addition to SNF, the United States manages a substantial inventory of HLW produced through reprocessing activities. Reprocessing refers to the chemical separation of uranium, plutonium, and fission products from irradiated nuclear fuel. Although commercial reprocessing ended decades ago in the United States, large quantities of waste were generated during both defense missions and early nuclear technology development. These materials remain an important component of the national waste inventory and are distributed across several DOE sites, as well as one former commercial facility at West Valley, New York.

The physical form of reprocessing waste varies depending on the treatment processes used. Historically, reprocessing operations produced large volumes of liquidHLW stored in underground tanks. Long term isolation of these wastes requires stabilization, and two principal methods have been used: vitrification and calcination. Vitrification involves blending liquid waste with glass-forming additives and melting the mixture into a durable borosilicate glass that is poured into stainless steel canisters. Calcination, used at INL, converts liquid waste into a granular, powder like solid through high temperature evaporation. In addition to these aqueous waste forms, INL also manages metal and ceramic waste streams produced through electrochemical treatment of sodium-bonded SNF, a specialized fuel type used in early fast reactor programs.

Among the DOE sites, SRS has made the most progress in vitrification. Since 1996, the Defense Waste Processing Facility has immobilizedHLW into standardized glass canisters, producing 4,346 canisters as of December 31, 2022. INL, by contrast, generated roughly 30,000 m³ of liquid waste during past reprocessing operations; between 1960 and 1997, this material was converted into approximately 4,400 m³ of calcine, which is currently stored in stainless steel bins housed within concrete vaults. At the Hanford Site, reprocessing during defense plutonium production generated an even larger inventory: approximately 56 million gallons of liquidHLW. About 220,000 m³ of this material remains in underground tanks, and a major vitrification facility is under construction to process the waste into glass for long term disposition.

Hanford also stores 1,936 cesium and strontium capsules produced between 1974 and 1985. Originally removed from liquid waste to support isotope applications, these capsules contain high concentrations of fission products and historically accounted for nearly 109 million curies of radioactivity. Through natural decay, the inventory has decreased to about 42 million curies, and continued decay will further reduce the heat output and radiological hazard over the coming decades. DOE is currently preparing new dry storage systems to replace the aging water filled storage basins that house these capsules.

Electrochemical treatment at INL provides a distinct pathway for stabilizing sodium-bonded fuel from early fast-reactor programs. This process separates uranium metal from fission products and residual materials, generating two waste streams: a ceramic waste form containing salts and active

fission products, and a metallic waste form containing cladding hulls and noble metals. Up to 60 MTHM of sodium bonded fuel may ultimately be treated, and about 4 MTHM has been processed to date.

The overall radionuclide inventory associated with DOE reprocessing waste corresponds to an estimated 1.3 million watts of decay heat. Most vitrified waste canisters, over 99% are projected to generate less than 1 kW of thermal power, reflecting the durability and stability of the immobilized waste forms. Although the total number of canisters may change as waste treatment continues, the radioactive content of the waste will decrease only through radioactive decay.

The only commercial reprocessing facility ever operated in the United States was located at West Valley, New York, where Nuclear Fuel Services processed approximately 640 MTHM of SNF between 1966 and 1972. This operation generated about 2,500 m³ of liquidHLW, which was vitrified between 1996 and 2001 into 278 canisters. These canisters, including two used to drain the processing melter and one nonroutineHLW canister, remain stored on site. Although the total waste mass is small compared to DOE's defense related inventory, the West Valley canisters remain an important legacy of the nation's early commercial nuclear fuel cycle.

7 Incorporating the National SNF Inventory into CYCLUS

The detailed characterization of the U.S. SNF inventory developed in this report provides a foundation for quantitative fuel cycle modeling using the CYCLUS simulation framework, shown in Figure 8. CYCLUS is an open source, agent based nuclear fuel cycle simulator that enables the construction of user defined fuel cycle systems through modular facilities ("archetypes"). Each facility implements specific behaviors such as storage, processing, transformation, or consumption of nuclear materials allowing complex fuel cycle scenarios to be assembled from flexible, interoperable components. The comprehensive summary of national SNF presented in this report directly informs the development of new CYCLUS modules and scenarios designed to evaluate XDS configurations and examine their potential impact on the U.S. waste inventory.

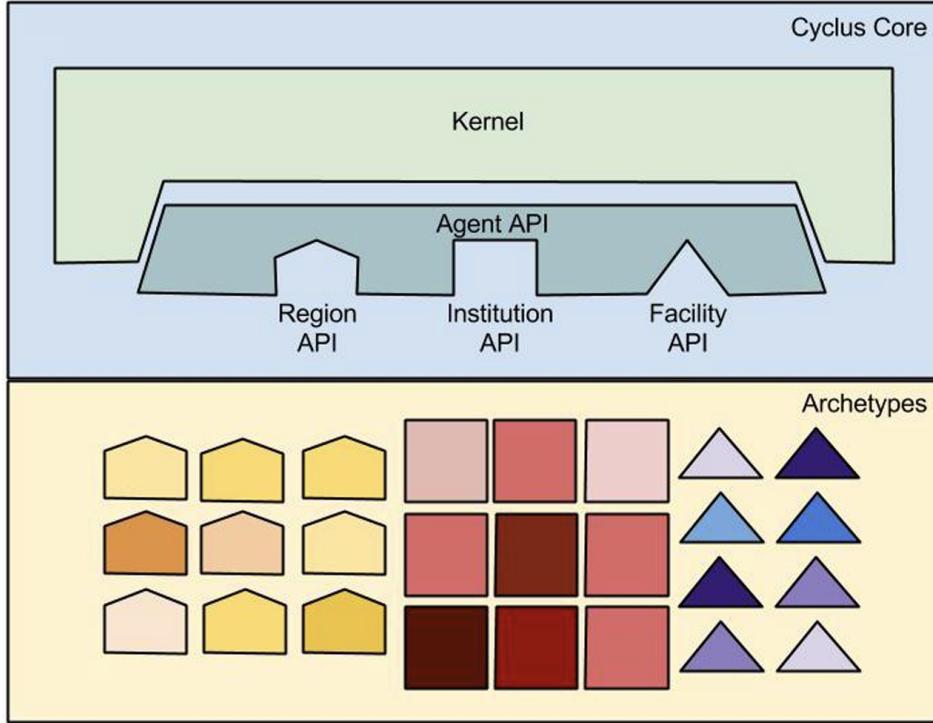


Figure 8: The CYCLUS core offers an API that simplifies kernel interactions, allowing archetypes to be loaded modularly into the simulation [2].

A central objective of this work is to quantify the fuel-cycle performance of XDS technologies at isotopic resolution. Achieving this requires realistic input streams that reflect the current and projected isotopic compositions, burnup histories, and decay corrected radionuclide inventories of spent fuel discharged from commercial reactors. Using the updated STANDARDS 5.0.1 dataset (formerly UNF-ST&DARDS), age corrected isotopic vectors are used to construct representative SNF compositions that capture the effects of burnup, initial enrichment, fuel type, and decay time. These data form the basis for establishing XDS input streams and for disaggregating the national SNF inventory into resource classes that vary in transuranic content, radiotoxicity, or suitability for transmutation. In this way, CYCLUS simulations can distinguish which portions of the national inventory hold the highest potential value for Minor Actinides (MA) burning XDS concepts.

create acronym
in
acros.tex

To support these objectives, a dedicated U.S. inventory module is being developed within CYCLUS. This module is designed to represent the national waste inventory as a dynamic storage type facility that holds SNF categorized and parameterized according to the latest STANDARDS dataset. Within the module, each fuel batch is stored as a material object with an associated mass, isotopic composition, and decay history. When combined with the other logic and facilities available in CYCLUS, the module enables external CYCLUS facilities, such as a specific ADS or FDS facility to request material based on user defined specifications. When material is supplied, the inventory is automatically updated to reflect removal of the requested mass and isotopes. This functionality allows scenario studies to explore how much of the national inventory could be processed, the rate at which materials are consumed, and how inventory composition evolves over time as different technologies are deployed.

Parallel to the inventory module, an XDS facility module is under development to generically represent accelerator driven systems capable of consuming transuranic rich SNF. This module is structured to accommodate a range of ADS design concepts, including different target materials, coolant types, and fuel compositions. The first implementation is based on the ADS configuration proposed at Argonne National Laboratory. Within CYCLUS, the ADS module receives material from the U.S. inventory module, processes it according to user specified operating parameters, and tracks the resulting mass reduction, changes in isotopic composition, and key performance metrics such as minor actinide destruction rate, energy production, and waste radiotoxicity reduction. The combination of these two modules one representing the national inventory and the other representing consumption pathways enables system level evaluation of how ADS deployment scales, how many units are needed to achieve specific waste reduction goals, and how quickly the inventory could be transmuted under different scenarios.

Should these be batches or assemblies (real question, I don't know the answer.)

I don't mind this approach to decay handling, but we could instead use the decay method
<https://fuelcycle.org/a>

I would also recommend allowing this to be loaded with an optional cyclus lat-long location so that, if we want to model all 100 different locations, we can

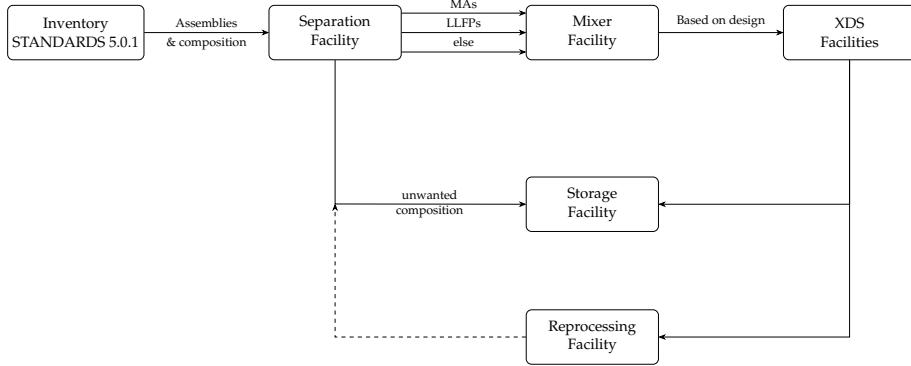


Figure 9: Conceptual flow from UNF-STANDARDS inventory to XDS, storage, and reprocessing.

Together, these modules create a quantitative framework linking the detailed SNF characterization performed in this report with forward looking fuel cycle analyses. By embedding accurate isotopic compositions derived from STANDARDS data into CYCLUS simulations, it becomes possible to evaluate XDS system designs, assess trade offs among accelerator or target configurations, compare transmutation strategies, and measure their aggregate impact on the U.S. waste inventory. This integration ensures that future scenario analyses are grounded in realistic, data driven representations of the commercial and DOE-managed SNF resources, enabling robust evaluation of advanced fuel cycle strategies.

The isotopic feed streams used for XDS transmutation in CYCLUS are derived directly from the STANDARDS 5.0.1 dataset at representative discharge burnups (40–60 GWd/MTU for PWR fuel and 30–50 GWd/MTU for BWR fuel), with decay corrections applied to match the assumed spent fuel cooling time. For scenarios focused strictly on minor actinide (MA) reduction, the feed consists of the isotopes that dominate long term radiotoxicity, decay heat, and neutron absorption in the commercial SNF inventory: uranium (U-235, U-238), plutonium (Pu-238 through Pu-242), neptunium-237, americium (Am-241, Am-242m, Am-243), and curium (Cm-244 through Cm-247). Plutonium isotopes are included to maintain the subcritical multiplication factor of the XDS, while the MA vector represents the primary target for transmutation. In some XDSs designs, technetium-99 and iodine-129 are also incorporated in the feed because of their strong spectral-shaping effects. [3]

A second, extended feed stream is used for XDS concepts that aim to simultaneously transmute long lived fission products (LLFPs) alongside actinides. In this scenario the MA composition described above is supplemented with selected LLFP isotopes that significantly influence long term radiotoxicity or neutron economy, including Tc-99, I-129, Cs-135, Se-79, Sn-126, Zr-93, Pd-107, Kr-85, and Sm-151. These LLFPs are incorporated only when the system design explicitly targets LLFP destruction; otherwise they appear solely as fission products generated during irradiation. Together, the MA-only and MA+LLFP feed definitions allow CYCLUS to represent a spectrum of XDS concepts ranging from conservative actinide burner designs to more aggressive, waste reduction strategies. For molten-salt-based XDS systems, the precise feed composition also reflects chemical compatibility requirements, including the redox potential and solubility of dissolved actinides or surrogate fluorides in the carrier salt. [4]

The output stream generated by the XDS facility in CYCLUS represents the “spent fuel” of the ADS irradiation stage and captures the isotopic changes that occur during transmutation. Following irradiation, the material contains reduced quantities of minor actinides, particularly Am-241, Am-243, Np-237, and multiple curium isotopes, which reflects the primary transmutation objective of the system. The plutonium vector evolves through a combination of fission and neutron capture reactions, typically showing reduced Pu-239 and Pu-241, and corresponding growth in Pu-240 and Pu-242. When LLFP transmutation is not activated in the scenario, long lived isotopes such as Tc-99, I-129, Sn-126, and Pd-107 remain in the output inventory. Overall, the resulting composition demonstrates substantial actinide mass reduction, increased fission product content, and a modified transuranic vector, providing a physically realistic representation of XDS discharge material for further processing, storage, or reinsertion into subsequent fuel cycle stages. [5]

8 Conclusion

The national inventory of SNF reflects more than six decades of commercial power generation, research reactor operations, defense missions, and early fuel cycle development in the United States. The vast majority of this inventory originates from commercial light water reactors, which have discharged approximately 91,000 MTU of fuel through the end of 2022. These

assemblies are stored almost entirely at reactor sites, either in spent fuel pools or in independent spent fuel storage installations. Their characteristics, particularly the steady historical increase in fuel enrichment and burnup strongly shape isotopic composition, decay heat behavior, and long term storage and disposal requirements. As burnup approaches 60 GWD/MT for typical PWR fuel, the isotopic vectors relevant to depletion modeling, repository design, and criticality evaluations continue to evolve in ways that require consistent, data driven characterization.

In parallel to the commercial sector, the DOE manages a smaller but significantly more heterogeneous SNF inventory of roughly 2,446 MTU. This category encompasses materials from defense production reactors, national laboratory test reactors, early demonstration power reactors, university and government research programs, and high enrichment research reactor fuels. These diverse fuel forms span a wide range of enrichments, cladding materials, and fabrication methods, and therefore play a distinct role in system level evaluations of storage, transportation, and disposal. Additional small quantities of SNF totaling about 1.35 MTU remain at university and commercial research facilities, but all such material ultimately transitions into DOE custody for long term management.

Reprocessing waste constitutes another significant element of the national inventory. At the Savannah River Site, 4,346 vitrified waste canisters have been produced through decades of HLW treatment, while the West Valley Demonstration Project has generated an additional 278 vitrified canisters from past commercial reprocessing operations. Together with calcined waste at the Idaho National Laboratory and liquid HLW stored at Hanford, these materials represent the legacy of earlier reprocessing activities and highlight the complexity of stabilizing chemically diverse and highly radioactive waste streams for geological disposal.

Taken together, these inventories illustrate the technical breadth and historical depth of spent fuel management in the United States. They also underscore the importance of accurate, assembly level isotopic data for fuel cycle modeling, decay heat estimation, criticality safety, and waste package design. As future analyses depend increasingly on realistic depletion behavior and burnup dependent material compositions, the systematic characterization summarized in this report provides a necessary foundation for national fuel cycle assessments and future repository planning.

References

- [1] Joe T. Carter and Kaushik Banerjee. Spent Nuclear Fuel and Reprocessing Waste Inventory. Spent Fuel and Waste Disposition FCRD-NFST-2013-000263 Rev. 9, PNNL-33938, Pacific Northwest National Laboratory, Richland, WA, May 2023.
- [2] Kathryn D. Huff, Matthew J. Gidden, Robert W. Carlsen, Robert R. Flanagan, Meghan B. McGarry, Arrielle C. Opotowsky, Erich A. Schneider, Anthony M. Scopatz, and Paul P. H. Wilson. Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework. *Advances in Engineering Software*, 94:46–59, April 2016. arXiv: 1509.03604.
- [3] Yousry Gohar, Yan Cao, and Adam R. Kraus. ADS design concept for disposing of the U.S. spent nuclear fuel inventory. *Annals of Nuclear Energy*, 160:108385, September 2021.
- [4] Adonai Herrera-Martínez, Yacine Kadi, and Geoffrey Parks. Transmutation of nuclear waste in accelerator-driven systems: Thermal spectrum. *Annals of Nuclear Energy*, 34(7):550–563, July 2007.
- [5] Proceedings of the Specialist Meeting on Accelerator Based Transmutation, Villigen 1992.