U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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Advanced Non-Light Water Reactors: Integrated Waste Management System Considerations

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Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors
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Disclaimer

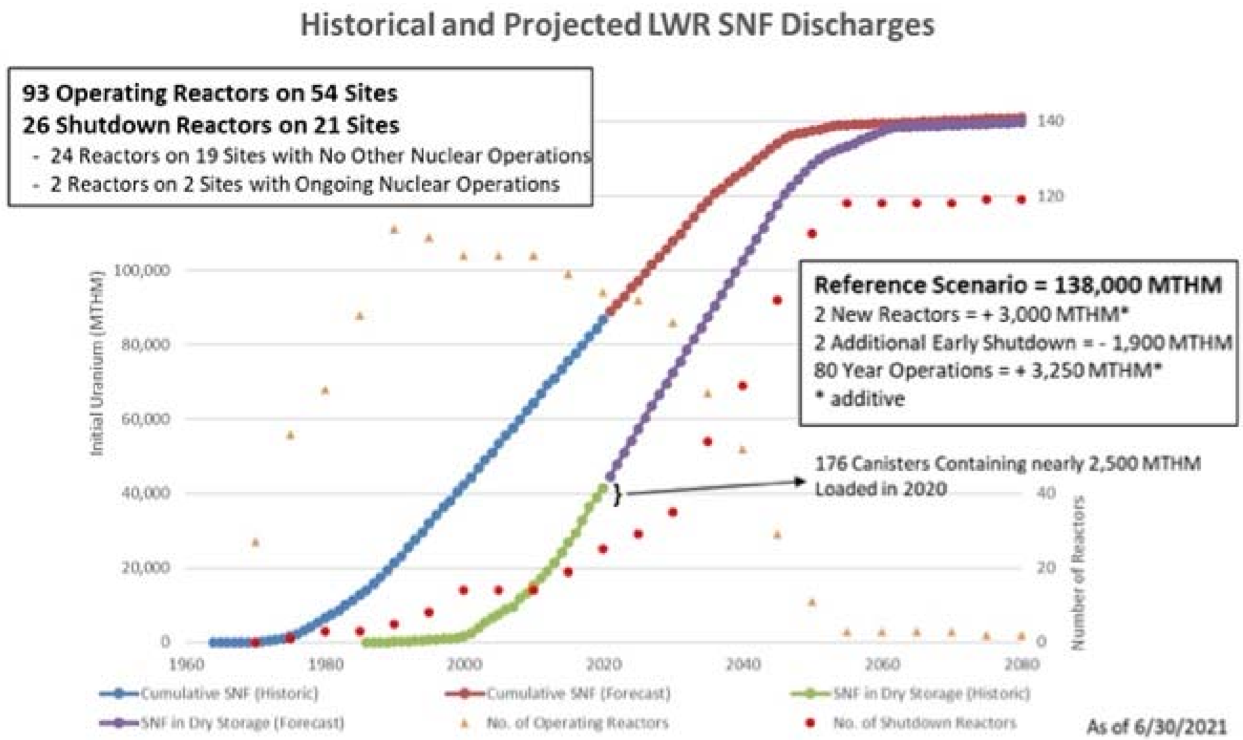
This is a technical presentation that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

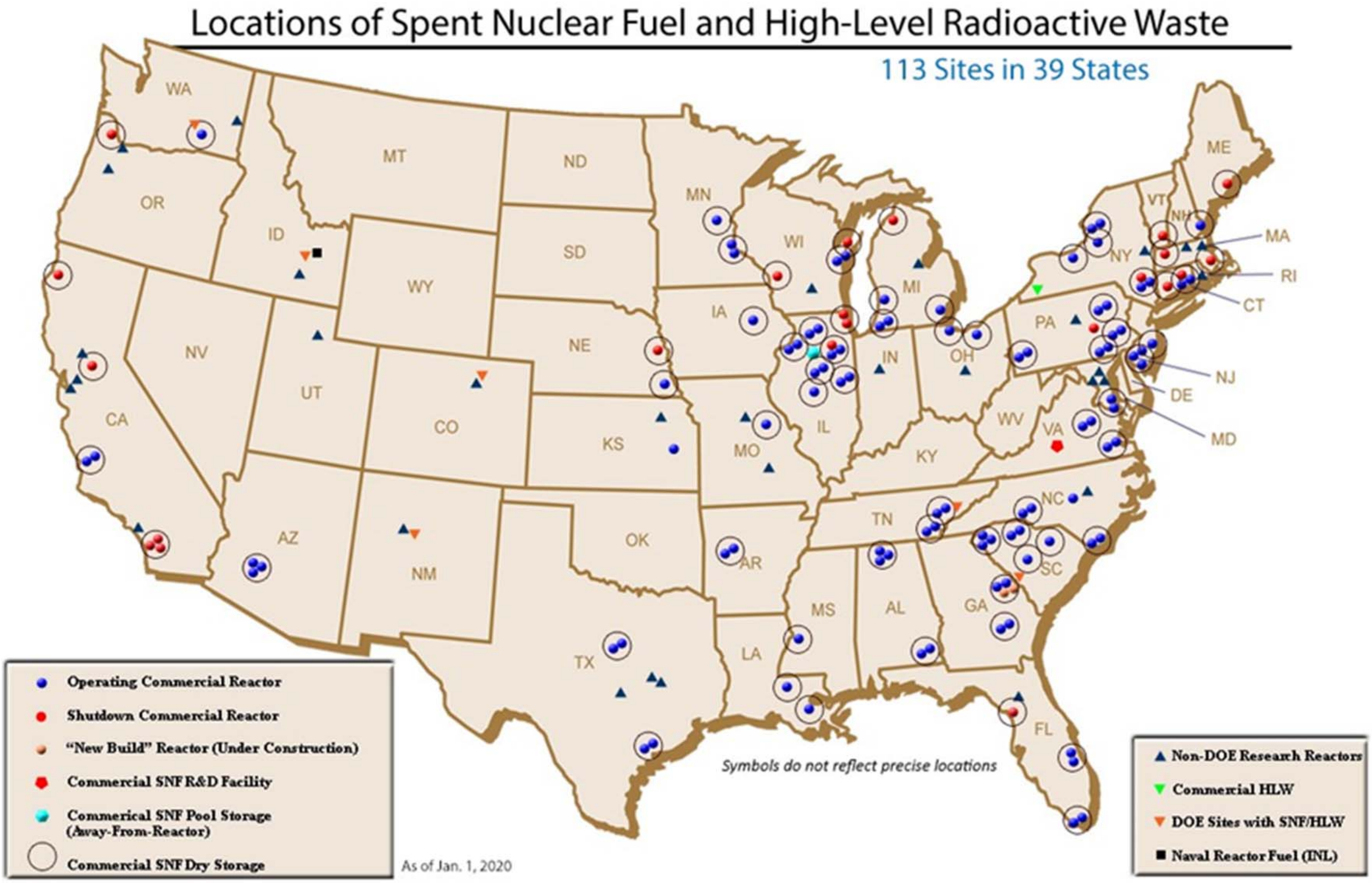
This presentation reflects technical work which could support future decision-making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

The existing U.S. LWR fleet has and continues to generate SNF that must be managed

- Over 86,000 MTHM of SNF discharged and in interim storage at reactor sites
- About 2,000 MTHM discharged per year
- Over 3,000 dry storage canisters (over 41,000 MTHM)
- About 200 dry storage canisters added per year
- Potential growth to ~145,000 MTU



Nearly all existing commercial SNF is stored at the reactor sites where the waste was generated



Of the 74 commercial reactor sites, 19 sites have ceased reactor operations

Deployment of new commercial LWRs will increase inventory of SNF that must be managed

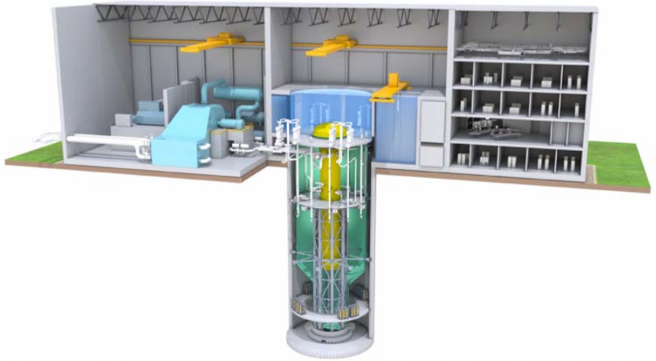
Vogtle Units 3 and 4

Source: https://www.energy.gov/lpo/vogtle

NuScale SMR

Source: https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

GE Hitachi BWRX-300 SMR



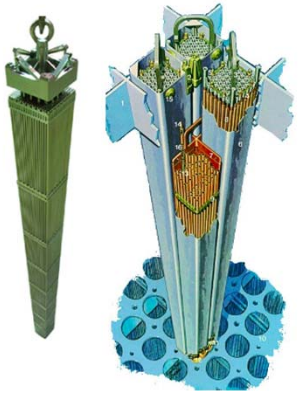
Source: https://www.energy.gov/ne/advanced-small-modular-reactors-smrs

Holtec International SMR 160

Source: https://www.energy.gov/ne/articles/infographic-advanced-reactor-development

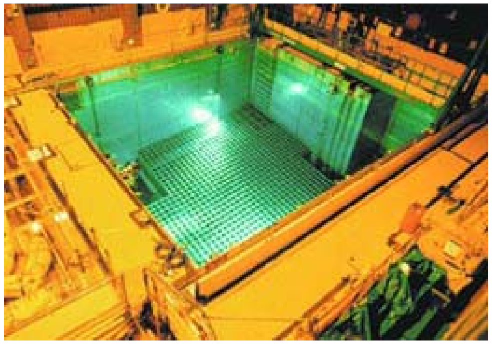
There is considerable experience and knowledge regarding the management of LWR spent nuclear fuel

LWR Fuel



Source: https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx

LWR Spent Fuel Pool



Source: https://www.nrc.gov/waste/spent-fuel-storage/pools.html

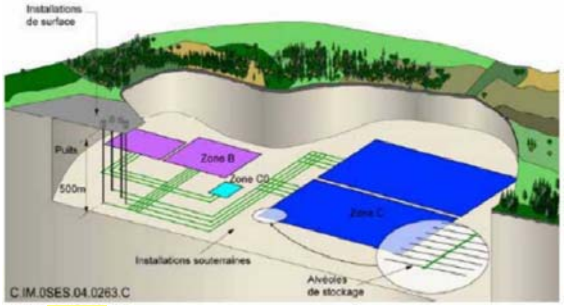
LWR Independent Spent Fuel Storage Installation

Source: https://www.energy.gov/ne/fuel-cycle-technologies/nuclear-fuels-storage-transportation-planning-project

Spent Fuel Transportation

Source: https://www.energy.gov/ne/articles/5-common-myths-about-transporting-spent-nuclear-fuel

Spent Fuel Disposal



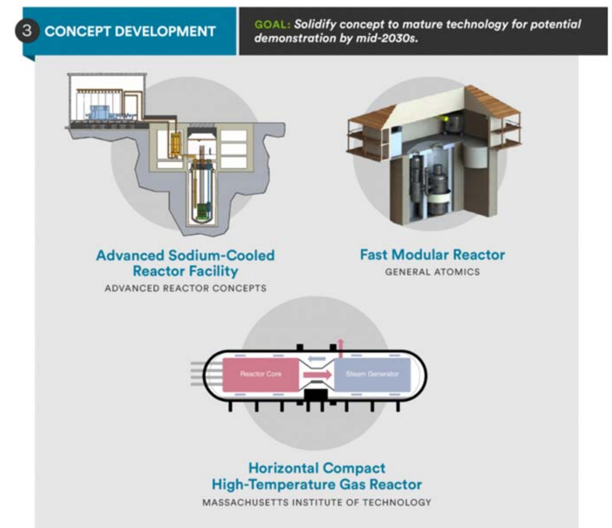
Source: https://www.osti.gov/servlets/purl/1640198

A variety of advanced reactors with a range of fuel designs are under development

SHELF	6.6	PWR in Immersed NPP	NIKIET	Russian Federation	Detailed Design
PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
StarCore	14/20/60	HTGR	StarCore Nuclear	Canada/UK/US	Pre-Conceptual Design
GTHTR300	100 - 300	HTGR	JAEA	Japan	Pre-licensing
GT-MHR	288	HTGR	JSC Afrikantov OKBM	Russian Federation	Preliminary Design
MHR-T	4 × 205.5	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	JSC Afrikantov OKBM	Russian Federation	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic Design
SC-HTGR	272	HTGR	Framatome, Inc.	United States of America	Conceptual Design
HTR-10	2.5	HTGR	INET, Tsinghua University	China	Operational
HTTR-30	30 (t)	HTGR	JAEA	Japan	Operational
RDE	3	HTGR	BATAN	Indonesia	Conceptual Design
PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
ARC-100	100	Liquid Sodium	ARC Nuclear Canada, Inc.	Canada	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
microURANUS	20	LBR	UNIST	Korea, Republic of	Pre-Conceptual Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
SVBR	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	LMFR	LeadCold	Sweden	Conceptual Design
EM^2	265	GMFR	General Atomics	United States of America	Conceptual Design
Westinghouse LFR	450	LMFR	Westinghouse Electric Company, LLC.	United States of America	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	United States of America	Conceptual Design
PART 5: MOLTEN SALT SMALL MODULAR REACTORS					
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual Design
smTMSR-400	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
CA Waste Burner 0.2.5	20 MW(t)	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	ThorCon International	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor - Wasteburner	300	MSR	Moltex Energy	United Kingdom / Canada	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	United States of America	Conceptual Design
KP-FHR	140	Pebble-bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual Design
Mk1 PB-FHR	100	FHR	University of California at Berkeley	United States of America	Pre-Conceptual Design
MCSFR	50 - 1200	MSR	Elysium Industries	USA and Canada	Conceptual Design

PART 6: MICRO MODULAR REACTORS					
Energy Well	8	FHTR	Centrum výzkumu Řež	Czech Republic	Pre-Conceptual Design
MoveluX	3~4	Heat Pipe	Toshiba Corporation	Japan	Conceptual Design
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual Design
Aurora	1.5	FR	OKLO, Inc.	United States of America	Conceptual Design
Westinghouse eVinci	2 -3.5	Heat Pipe	Westinghouse Electric Company, LLC.	United States of America	Under Development
MMR	5-10	HTGR	Ultra Safe Nuclear Corporation	United States of America	Preliminary Design

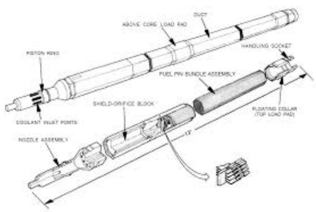
Source: IAEA, Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition



Source: https://www.energy.gov/ne/articles/infographic-advanced-reactor-development

There is less experience and knowledge in managing commercial non-LWR spent nuclear fuel

Non-LWR Fuel

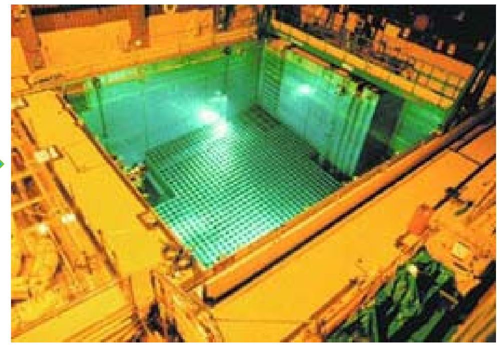


Sources:
https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth

https://www.nrc.gov/docs/ML1914/ML19149A371.pdf

https://public.ornl.gov/conferences/MSR2016/

Non-LWR At-Reactor Storage



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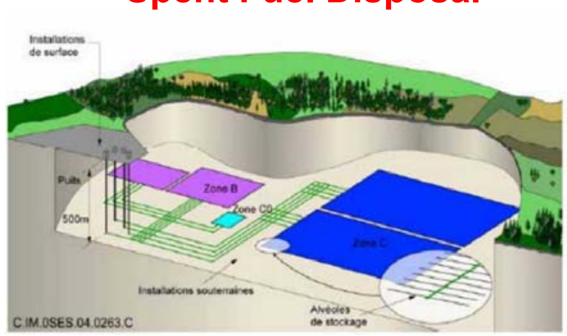


https://www.osti.gov/servlets/purl/1640198

- A strategy to complete the nuclear fuel cycle would help build local, Tribal, and State relationships and increase public trust and confidence in the ability to manage reactor discharges.
  - *Today, America's nuclear power reactor fleet provides a majority of the nation's zero-emissions electricity, and advanced reactors offer the promise of additional clean, "always on" energy production for the future. ANS professionals are working diligently to develop and deploy advanced nuclear energy systems such as small modular light water reactors and Generation IV reactors.* ***However, we are very concerned that the lack of a credible, demonstrated HLW management plan threatens these efforts, which are essential for our clean energy future****.* [American Nuclear Society testimony to the U.S. Senate Committee on Energy and Natural Resources, June 2019, emphasis added]
- Seven states have laws that aim to restrict the construction of new nuclear power facilities that are linked to the lack of a capability to dispose of spent nuclear fuel

[https://www.ncsl.org/research/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility.aspx]

The U.S. Department of Energy is moving forward

- **Jennifer Granholm, Secretary of Energy** remarks to the American Nuclear Society Annual Meeting. "[W]e want to move forward with finding a consent-based siting strategy. That's why our funding request includes 20 million dollars to support planning for the near-term consolidation and storage of nuclear waste." (https://world-nuclear-news.org/Articles/USA-needs-nuclear-to-achieve-net-zero-says-Granhol)
- **Dr. Kathryn Huff, Principal Deputy Assistant Secretary for the Office of Nuclear Energy.** The preservation of the existing fleet in the United States and the deployment of new advanced reactor types, "[I]s only possible if DOE makes progress in the context of an energy- and environmental-just consent-based siting approach process for interim and eventually permanent spent nuclear fuel storage." (https://www.energy.gov/ne/articles/qa-acting-assistant-secretary-dr-kathryn-huff-shares-her-vision-future-nuclear-energy)

Multiple agencies and organizations have responsibility for managing spent nuclear fuel

- Environmental Protection Agency (EPA) sets radiation protection standards
- The Utility/Operator sites, designs, and submits license applications including an environmental report in accordance with requirements established by the U.S Nuclear Regulatory Commission (NRC)
- The NRC prepares an Environmental Impact Statement for the proposed reactor and conducts a review of the license application including any required hearings
- The Utility/Operator constructs and operates reactors in accordance with its NRC license
  - Responsible for the management and storage of all spent fuel until accepted by DOE in accordance with the standard contract
- The DOE manages and disposes of spent fuel it accepts under the Standard Contract as required by the Nuclear Waste Policy Act of 1982, as amended (NWPA)
- The NRC regulates interim storage, permanent disposal, and certifies SNF transportation casks.

The Commission shall not issue or renew a reactor license to any person unless they have entered into a contract with the Secretary or are in good faith negotiations to enter into such a contract [NWPA, section 302(b)(1)(A)]

- The standard contract was amended for new reactors
- Appendix E, General Specifications, for acceptance of SNF and HLW has been modified
  - *DOE shall accept all HLW covered by this contract that meets DOE's general specifications. Detailed acceptance criteria and general specifications for such HLW will be issued by DOE no later than one(1) year after the Nuclear Regulatory Commission dockets the first license application for a facility to reprocess or recycle SNF*
- Provisions in the amended standard contract regarding SNF acceptance and liability for new reactors (summarized below)
  - *DOE will begin the acceptance of any SNF and/or HLW from a nuclear power reactor covered by this contract no earlier than twenty (20) years from the initial discharge date of SNF from that power reactor.* (Article II)
  - *DOE will complete acceptance of all SNF and/or HLW generated by the nuclear power reactor covered in this contract no later than the performance date absent unavoidable delays or Purchaser-caused delays* (Article II)
  - *The term performance date means the date that is ten (10) years after the expiration of the original term of the operating license, or the term of any license extension(s)….* (Article I.28)
  - *In the event circumstances beyond reasonable control of the Purchaser or DOE, such as …. acts of Government in either its sovereign or contractual capacity (including, but not limited to, acts or inaction of Congress that, outside the control of DOE or Purchaser, affect DOE's ability to accept or the Purchaser's ability to deliver, SNF in a timely manner)…..* (Article IX.A)
  - *Such damages shall be in the amount of $5 million per year (in January 1, 2008 dollars, adjusted for inflation based on the Consumer Price Index) for each year until DOE completes acceptance of all SNF and/or HLW from the nuclear power reactor covered by this contract* (Article IX.C)

For exact language see the Standard Contract for the Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste, 10 CFR 961

https://www.energy.gov/gc/downloads/standard-contract-disposal-snf-andor-hrw

https://www.energy.gov/gc/downloads/standard-contract-amendment-new-reactors

The NWPA established the Nuclear Waste Fund to cover DOE's costs in managing and disposing of spent nuclear fuel from commercial nuclear reactors [NWPA, section 302]

- Established the initial fee at 1 mil (0.1 cent) per kilowatt-hour of electricity generation
- Requires that DOE review the amount of the fee to determine if there will be sufficient funds to manage and dispose of the spent nuclear fuel -Total System Life Cycle Costs (TSLCC)
  - To date have, in general, only considered the management and disposal of uranium dioxide fuel assemblies from the existing fleet of LWRs
  - To date, no TSLCC projections have resulted in a fee adjustment
  - In 2013 a Federal Court directed DOE to set the fee to $0, which occurred in 2014
- The processes and facilities needed to manage advanced non-LWR SNF are uncertain (e.g., SNF treatment)
- In addition, some advanced reactors may not be used to produce electricity and having a waste fee based on energy generation may require further consideration

Interim storage of SNF for multiple decades will likely be required for advanced reactors either on the reactor sites, or at a consolidated interim storage facility(ies)

New technologies for the safe and secure storage of SNF from advanced non-LWRs may be needed

- Uncertainties regarding the use of existing LWR dry storage concepts as being either technically viable or providing an optimal-storage solution.
- Additional R&D and technology development may be needed to build the bases for regulatory compliance
  - And for any waste forms from SNF treatment
- It is anticipated that a CIS facility would need to operate until the fuel can be moved to final disposal, among other factors such as the need to identify, license, and construct a facility, plus the time needed to move the SNF.
- System integration focused on:
  - Material handling, integrated condition monitoring,
  - Ability to transport at some point in the future when on-site and near-site infrastructure may differ significantly from when the reactor is in operation,
  - Waste acceptance and disposability, and
  - System compatibility

Regulations for managing SNF are well established and applicable to advanced non-LWRs

Uncertain how applicants would demonstrate regulatory compliance for advanced reactor SNF (and treatment waste forms)

- How applicants address the environmental effects of continued storage of SNF (10 CFR 51.23) and of fuel cycle activities for a reactor (10 CFR 51.50(c)) in environmental reports that must be submitted with license applications
- Transportation (10 CFR 71) and storage (10 CFR 72) and the associated guidance were not developed explicitly considering advanced non-LWR spent fuel forms and types
- The state of the art in geologic repository science, engineering, and safety analysis has evolved considerably since the promulgation of the generic regulations for geologic disposal (10 CFR 60)
- How SNF treatment would be regulated (i.e., under a reactor license or as a production and utilization facility)

Research, development, and demonstration of technologies for all aspects of the back-end of the nuclear fuel cycle is needed

Both inform future decisions and to implement the spent fuel management strategies ultimately chosen

- LWR SNF management is a mature technology
  - Characteristics of LWR SNF and technologies for managing it are known from decades of research, development, and technology demonstration
  - Work underway to improve understanding and develop new technologies
- Information needs and technology gaps that can be filled in the near-term to advance non-LWR SNF management
  - Continue to make progress and build confidence that SNF from advanced non-LWRs can be managed safely and securely
  - Lessons learned and technologies developed for managing LWR SNF can help more efficiently establish the technical bases for managing advanced non-LWR SNF
  - Advanced reactor demonstrations present an excellent opportunity for development and demonstration of back end of the fuel cycle technologies

Near-Term Activities for the Management of Non-LWR Spent Nuclear Fuel

Fuels and Waste Forms	• Quantifying the SNF characteristics including the understanding of fuel forms, initial fissile material loading, anticipated discharge burn-up, decay heat, radioactive source term, and isotopic composition • Evaluating storability, transportability, and disposability of SNF forms and types
Treatment	• Identifying treatment options necessary to convert non-storable, transportable, and/or disposable SNF into a form that would meet acceptance criteria • Quantifying the characteristics of treated waste forms
Transportation	• Developing conceptual design options for transportation packaging and concepts of operations for transportation • Evaluation of transportation regulatory guidance to identify gaps and areas where efficiencies could be gained
Interim Storage	• Quantifying the performance attributes of storage forms (spent fuel or treated wastes) • Developing conceptual design options for interim storage facilities, both at- and away-from reactor • Evaluation of storage regulatory guidance to identify gaps and areas where efficiencies could be gained

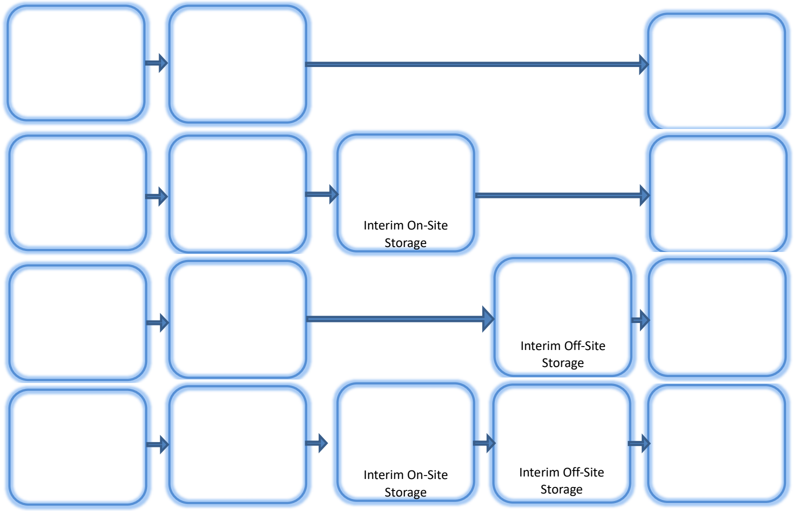
Near-Term Activities for the Management of Non-LWR Spent Nuclear Fuel

Disposal	• Quantifying the performance attributes of disposal forms (spent fuel or treated wastes) • Develop waste packaging options and conceptual design options for geologic disposal facilities for SNF and treatment waste forms • Develop generic safety cases for the geologic disposal of SNF and treatment waste forms • Evaluation of disposal regulations and regulatory guidance to identify gaps and areas where efficiencies could be gained.
Reprocessing (if desire to pursue closing the fuel cycle)	• Development and advancement of reprocessing techniques • Development of waste forms for isolating radionuclides • Development of facility concepts • Quantifying the characteristics of reprocessing waste forms
Integration	• Develop integrated waste management system-level modelling tools that include all potential aspects of an integrated waste management system for advanced reactor SNF • Continual evaluation of options for the management of advanced reactor SNF • Generically evaluate the environmental impacts of continued storage and transportation of SNF and treatment waste forms and the fuel cycle impact of advanced reactor concepts • Evaluate options for determining future disposal fees • Engagement with stakeholders at various levels • Potential amendments to disposal contracts • Possible licensing actions related to transportation, storage, and disposal

Demonstrating progress in the safe and secure management of SNF is essential for the successful deployment of advanced non-light water reactors

- Nuclear energy can play a prominent role as the U.S. moves toward deep decarbonization and a clean energy future
- Advanced nuclear reactors that are more flexible and economical than the current fleet of operating reactors are poised to be deployed over the next decade
- The SNF that will be produced by advanced reactors will differ than that being discharged today
- New processes and technologies to manage the spent nuclear fuel from reactor discharge through ultimate disposal in a repository
- A number of activities can be undertaken now to begin making progress
- Build a foundation for the establishment of an integrated waste management system

Planning for an integrated waste management system for advanced reactors is important



- Experience in managing SNF generated by the current fleet of LWRs shows that decisions made in isolation can result in sub-optimal solutions with respect to the entire waste management system
- Integrated waste management system analysis is necessary to understand all possible options, approaches, and strategies to inform all stakeholders and future decisions
  – Brings in the knowledge and experience of all stakeholders to establish a coherent and well-integrated waste management system
  – Multiple stakeholders with different goals/objectives and perspectives
  – Allows for consideration of flexibility – essential for moving forward in the face of uncertainty

Questions?

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