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

# Evaluation of Advanced Reactor Spent Fuel Management Facility Deployment


Milos I. Atz[1] and Robby A. Joseph[2]

[1]Argonne National Laboratory

[2]Idaho National Laboratory


IAEA Technical Meeting on Back End of the Fuel Cycle Considerations for Small Modular Reactors
September 20-23, 2022
Vienna, Austria

# Presentation outline

1. Introduction and background
2. Generic milestones and SNF management facilities
3. Case studies: management challenges, facilities, and milestones
    a. Example: sodium-cooled fast reactor
    b. Other advanced reactor SNF types
    c. Microreactor SNF management
    d. Overarching observations
4. Conclusions

# Acknowledgements

- Gordon Petersen and Josh Jarrell, Idaho National Laboratory
- Mark Nutt, Rob Howard, Natalia Saraeva, Pacific Northwest National Laboratory
- Roger Blomquist, Argonne National Laboratory
- Kevin Connolly, Oak Ridge National Laboratory
- Brian Gutherman, Gutherman Technical Services, LLC

This presentation has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of Nuclear Energy under contract DE-AC02-06CH11357.

# Disclaimer

This is a technical presentation that does not account for 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.

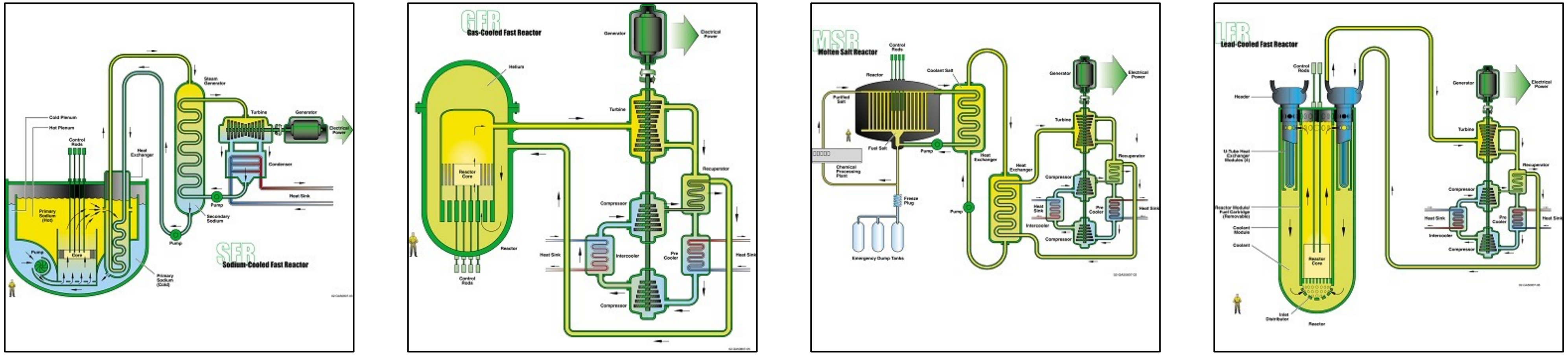
To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

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 a lack of 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.

This information was prepared as an account of work sponsored by an agency of the U.S. Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

# Introduction

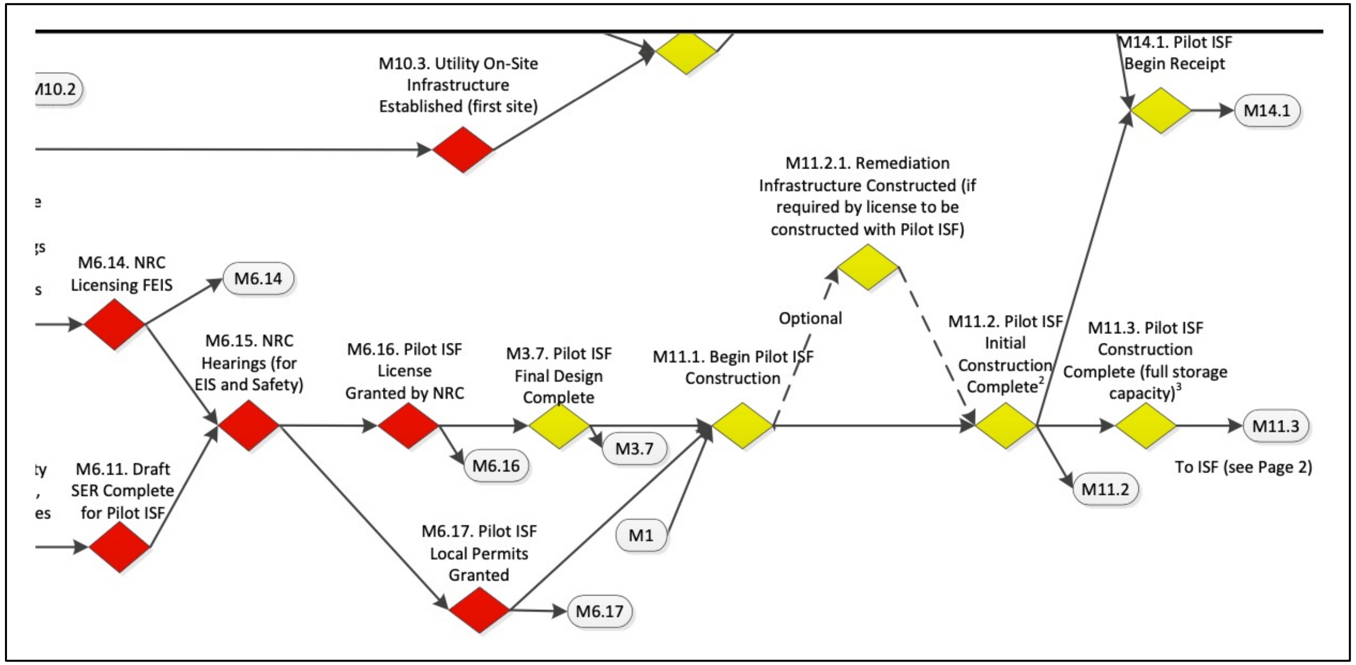
- Many proposed SMR designs are advanced non-LWRs
- Advanced reactor SNF will take many forms and have variable characteristics
- New management requirements may raise new challenges
- Planning must investigate deployment risks and uncertainties
  - Execution Strategy Analysis
  - Performance Assessment of Strategic Options




*Diagrams for various Gen-IV reactor concepts; from left to right: SFR, HTGR, MSR, LFR [2]*

# Milestones and activities

*Milestone*: achievement required to reach the final goal of SNF facility deployment
*Activity*: any R&D, design, or decision to achieve an intermediate goal




Milestone under control of implementing organization

Milestone *not fully* under control of implementing organization

Activity

*Example portion of a success precedence diagram (from Ref. [3])*

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- Siting the facility
- Establishing transportation infrastructure
- Designing the facility
- Licensing the facility
- Constructing the facility
- Testing the facility

# Generic milestones for SNF management facility deployment

- **Establishing responsibility**
- Siting the facility
- Establishing transportation infrastructure
- Designing the facility
- Licensing the facility
- Constructing the facility
- Testing the facility

**Formal authorization of an organization to site and develop the facility**

**Determination of organization management structure**

**Determine financial responsibility**

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- **Siting the facility**
- Establishing transportation infrastructure
- Designing the facility
- Licensing the facility
- Constructing the facility
- Testing the facility

**Develop siting process**

**Request and evaluate volunteer sites, identifying alternatives**

**Negotiate consent agreements with host communities**

**Designate site**

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- Siting the facility
- **Establishing transportation infrastructure**
- Designing the facility
- Licensing the facility
- Constructing the facility
- Testing the facility

**Design and test rolling stock**

**Design and obtain NRC approval of transportation packages**

**Manufacture and procure transportation fleet**

**Identify maintenance needs and design maintenance facilities**

**Plan: select routes, obtain approvals from authorities, and enter contracts**

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- Siting the facility
- Establishing transportation infrastructure
- **Designing the facility**
- Licensing the facility
- Constructing the facility
- Testing the facility

**Establish facility scope and conceptual design**

**Complete safety analysis**

**Establish acceptance criteria**

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- Siting the facility
- Establishing transportation infrastructure
- Designing the facility
- **Licensing the facility**
- Constructing the facility
- Testing the facility

**Prepare and submit license application for nuclear facility to NRC**

**NRC reviews the application, prepares EIS considering alternatives and incorporating public input**

**Obtain necessary licenses and permits from local, tribal, state, and federal authorities**

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- Siting the facility
- Establishing transportation infrastructure
- Designing the facility
- Licensing the facility
- **Constructing the facility**
- Testing the facility

**Prepare site**

**Construct facility, all ancillary facilities, and the necessary transportation infrastructure**

# Generic milestones for SNF management facility deployment

- Establishing responsibility
- Siting the facility
- Establishing transportation infrastructure
- Designing the facility
- Licensing the facility
- Constructing the facility
- **Testing the facility**

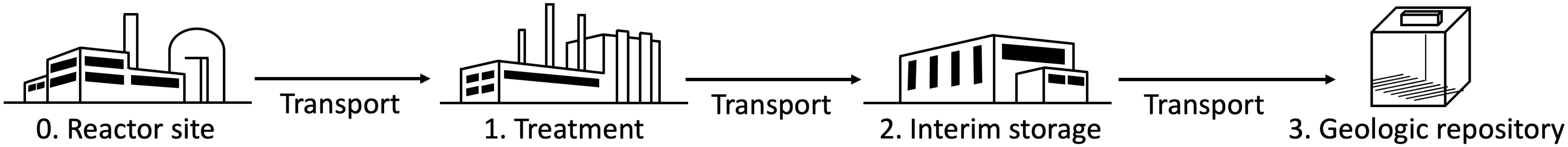
**Conduct pre-operational testing to verify facility performs as designed and licensed**

**Potentially include pilot-scale demonstration prior to full-scale operation**

# Generic advanced reactor SNF management operations and facilities

0. After discharge, SNF must be cooled and stored on-site
1. SNF may require treatment to remove unacceptable (e.g. chemically reactive or water soluble) fuel components and produce stable waste forms
2. SNF may be stored at a consolidated interim storage facility away from reactors
3. Ultimately, SNF would likely be disposed of in a geologic repository

Transportation likely required between at least some steps




*Generic SNF management flow sheet for direct disposal assuming fuel treatment step and transportation between all facilities [1]*

# Putting it together: conceptual matrix of operations/facilities and milestones

Consider advanced reactor SNF management requirements: which combinations of operations/facilities and milestones appear to pose challenges?

| Milestone / Operation/ Facility | Establishing responsibility | Siting | Transportation infrastructure | Facility design | Licensing | Construction | Testing |
|---|---|---|---|---|---|---|---|
| On-site storage | | | | | | | |
| Fuel treatment | | | | | | | |
| Off-site storage | | | | | | | |
| Transportation | | | | | | | |
| Disposal | | | | | | | |

*The following slides discuss advanced reactor SNF characteristics and management challenges in this framework*

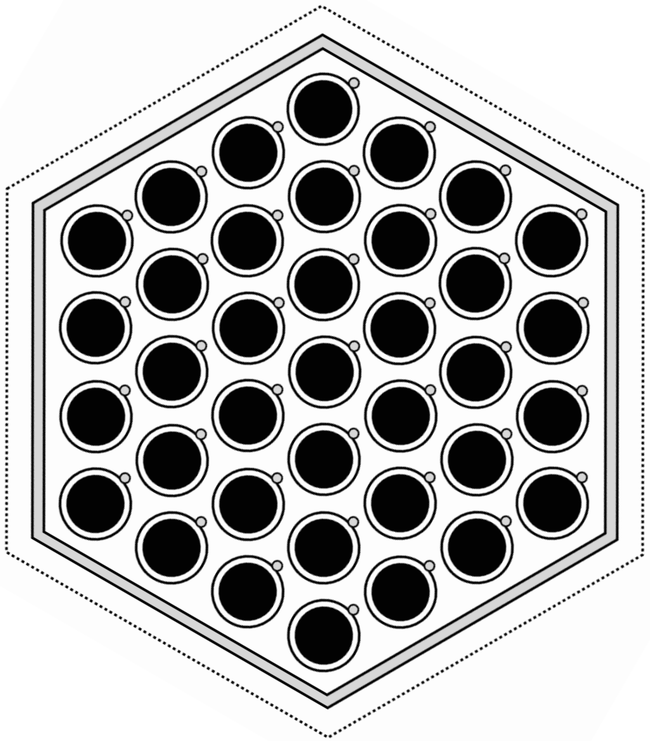
# Example: sodium-cooled fast reactor (SFR) SNF

Characteristics

- U-Zr or U-Pu-Zr metal, clad in stainless steel
- Hexagonal pin bundle in stainless steel duct
- Sodium bond to improve fuel-clad heat transfer
  - Proposed annular designs could omit bond sodium

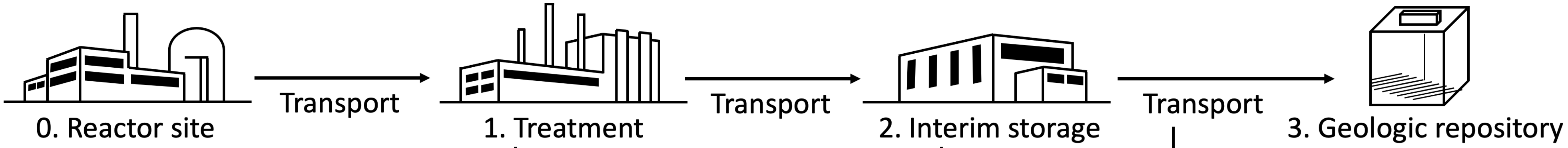
Compared to LWR SNF

- Higher burnup and higher thermal efficiency
- Lower heavy metal discharge per electricity generated (mass and volume)
- Higher decay heat and dose rate



*Cross-cut diagram of an example SFR fuel assembly*

# SFR SNF management requirements




**On-site storage**
- Keep sodium-bonded fuel away from moisture
- Decades of storage experience, including with failed fuel

**Treatment**
- Bond sodium *may* need to be removed
- Options include pyroprocessing, alcohol wash, and "MEDEC"

**Off-site storage**
- If treatment wastes are HLW: regulations preclude ISFSI storage
- Use of existing LWR packaging requires license and/or certificate revision

**Transportation**
- U.S. has experience shipping sodium-bonded SNF
- Package must be designed/certified for SNF decay heat, dose rate

**Disposal**
- Metal fuel less robust than oxide fuel in repository
- Disposal of sodium-bonded fuels requires more R&D to support evaluation
- Waste from treatment assumed disposal-ready

# SFR SNF management milestone challenges

| Challenge | Milestones | Operations and facilities | Comments |
|---|---|---|---|
| **Ownership and financial responsibility** | Establishing responsibility | Fuel treatment, disposal | Responsibility for R&D and execution must be established |
| **Designing for operations** | Facility design | All | Design must accommodate unique SNF characteristics |
| **Licensing new technologies** | Licensing | Storage, treatment, transportation | Limited experience with commercial SFR; if HLW, treatment wastes excluded from ISFSI |

# Observations for other advanced reactor SNF

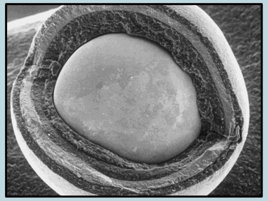
## High-temperature gas-cooled reactor SNF

Characteristics

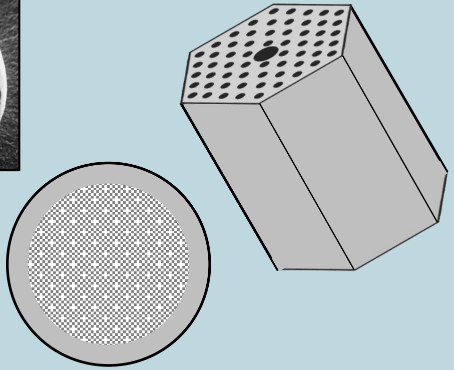
- Robust TRISO-based fuels
- High burnup, thermal efficiency
- Low fissile density

Anticipated challenges

- Material accountancy for SNF pebbles during on-site storage



From DOE [4]



# Observations for other advanced reactor SNF

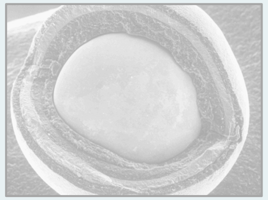
## High-temperature gas-cooled reactor SNF

<u>Characteristics</u>

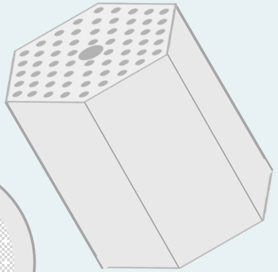
- Robust TRISO-based fuels
- High burnup, thermal efficiency
- Low fissile density

<u>Anticipated challenges</u>

- Material accountancy for SNF pebbles during on-site storage



From DOE [4]



## Liquid-fuel molten salt reactor SNF

<u>Characteristics</u>

- F and Cl salts; Pu, HALEU, or Th/U-233 fuel
- Salt discharged at shutdown
- Separate fission prod. streams

<u>Anticipated challenges</u>

- Salt instability
- Management of entire SNF inventory at EOL
- Establishing responsibility and reducing uncertainty in salt treatment and waste form prep
- Licensing new technologies and storage classifications

# Observations for other advanced reactor SNF

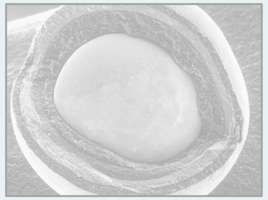
## High-temperature gas-cooled reactor SNF

Characteristics

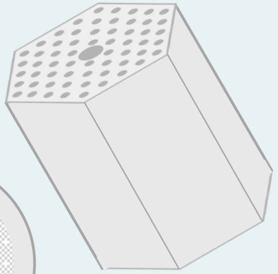
- Robust TRISO-based fuels
- High burnup, thermal efficiency
- Low fissile density

Anticipated challenges

- Material accountancy for SNF pebbles during on-site storage.



From DOE [4]



## Liquid-fuel molten salt reactor SNF

Characteristics

- F and Cl salts; Pu, HALEU, or Th/U-233 fuel
- Salt discharged at shutdown
- Separate FP streams

Anticipated challenges

- Salt instability
- Management of entire SNF inventory at EOL
- Establishing responsibility and reducing uncertainty in salt treatment and waste form prep
- Licensing new technologies and storage classifications

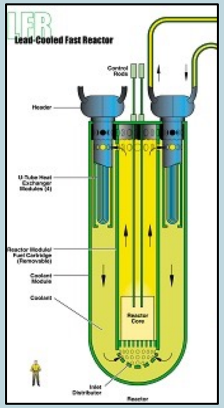
## Lead-cooled fast reactor SNF

Characteristics

- Oxide ($UO_2$ / MOX) or nitride (UN) fuel
- Helium backfill or lead bond
- High burnup, thermal efficiency

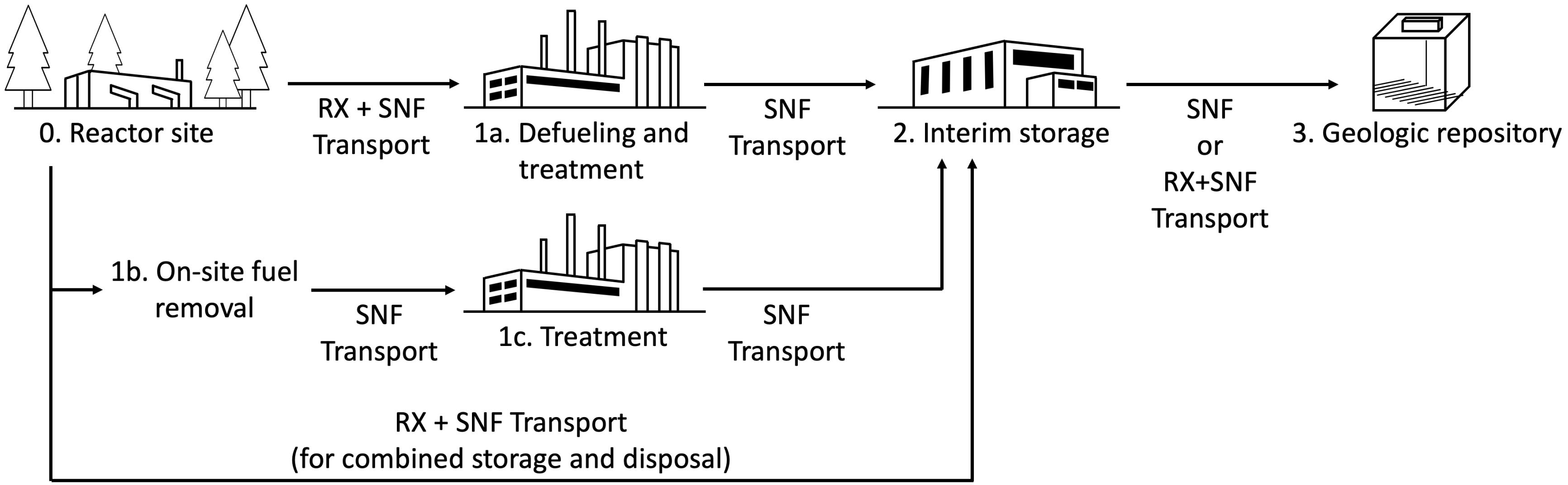
Anticipated challenges

- Acceptability of lead-bonded SNF in a repository
- UN stability as a waste form
- Licensing – lack of experience



# Microreactor SNF

- Microreactors loosely related by size, but all other features can be different
- Many concepts are non-LWR:
  - SNF will have similar challenges to that from larger reactors
- Common characteristics: long cycle length, HALEU fuel, remote siting




*Possible microreactor SNF management pathways [1]*

# Challenges for microreactor SNF management

<u>Combined reactor/SNF shipment</u>

- Size and weight limitations
  - Transportability
  - Remote deployment – limited infrastructure
  - Unclear if coolant can remain in reactor
- Criticality safety for lower-burnup, higher-enrichment SNF
  - Flooded package must be subcritical

**Simplifies on-site management, complicates transportation**

<u>Separate reactor/SNF shipment</u>

- Necessitates on-site fuel handling:
  - Build/deploy facilities to the site
  - Remote deployment – limited infrastructure
  - Need to plan for off-normal conditions, damaged fuel
- Criticality safety and physical protection
  - SNF has higher fissile content than that from larger power reactors

**Complicates on-site management, simplifies shipping**

# Overarching observations

Challenges not uniformly distributed across operations/facilities and milestones.

- More/larger challenges for operations and facilities earlier in the management process: on-site storage and spent fuel treatment
- Some milestones are largely independent of the spent fuel to be managed: siting, construction, and testing

Beyond technical design/demonstration of the necessary technologies, the challenges could require one or more of the following:

1. NRC rulemaking
2. Congressional legislation
3. Unique physical security considerations

# Conclusions

- Proposed a framework to consider how challenging aspects of advanced reactor SNF management affect potential facility deployment
  - Generic SNF management pathway for direct disposal back end
  - High-level deployment milestones applicable to any facilities
- Case studies:
  - Overview on sodium-cooled fast reactor SNF management
  - Brief discussion on additional insights from other reactor SNF types
  - Microreactors pose new SNF management challenges – potential pathways proposed and investigated
  - Overarching takeaways and observations
- Importantly, none of the identified challenges are disqualifying – all can be accommodated with R&D, planning, and regulatory reform
- For more information, details, and discussion, please see Ref. [1]

# References


1. M. Atz, “Generic Activities and Milestones for Deploying Advanced Reactor Spent Fuel Management Facilities (Rev. 3).” ANL/NSE-21/28 Rev. 3, Argonne National Laboratory (2022).

2. Gen-IV International Forum, “Technology Systems.” (2013). https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

3. R. Stoll et al, "Development of an Execution Strategy Analysis (ESA) Capability and Tool for Storage of Used Nuclear Fuel (UNF)," in *IAEA International Conference on Management of Spent Fuel From Nuclear Power Plants*, Vienna, Austria (2015).

4. US DOE NE, “TRISO Particles: The Most Robust Nuclear Fuel on Earth.” (2019). https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth