

PACKAGING SAFETY, SECURITY, AND SAFEGUARDS (3S) FOR NUCLEAR FUEL CYCLE MATERIALS IN STORAGE, TRANSPORTATION, AND DISPOSAL

Y. LIU
Argonne National Laboratory
Lemont, IL, United States
yliu@anl.gov

J. SHULER
U.S. Department of Energy
Washington, D.C., United States

Abstract

Packaging is essential and central to nuclear fuel cycle materials in transportation, storage, and disposal. Principles and practices for aging management of radioactive material packaging and dry cask storage systems for spent nuclear fuel are described, with emphasis on aging-related environmental degradation of materials, and structural health monitoring of structures, systems, and components that are important to safety. The overview is based on years of experience in conducting technical certification review of transportation packaging for the U.S. Department of Energy (USDOE) and developing guidance documents for USDOE and the International Atomic Energy Agency on aging management for dry cask storage systems for long-term storage and subsequent transportation of spent nuclear fuel. The concept of Safety, Security and Safeguards (3S) by Design for the packaging life cycle is elucidated, providing a framework that should be applicable to meeting the challenge of packaging 3S for existing and advanced nuclear fuel cycle materials in transportation, storage, and disposal.

1. INTRODUCTION

The nuclear fuel cycle has been illustrated in the open literature, as shown in Figure 1, by a cycle that has a beginning and an end, and clockwise movements of nuclear fuel cycle materials between fuel cycle facilities (e.g., conversion, enrichment, fuel fabrication, power plant, pool and dry storage, reprocessing, and disposal), where each step can vary in duration from years to decades and may last over centuries in the final disposal stage. Packaging for nuclear fuel cycle materials in various physical and chemical forms must be designed and manufactured to meet the safety requirements of containment of radioactivity, protection against radiation, and criticality control during transportation, storage, and disposal [1]. No structures, systems, and components (SSCs) of a nuclear packaging can maintain their safety functions without the management of aging-related environmental degradation of materials over time.

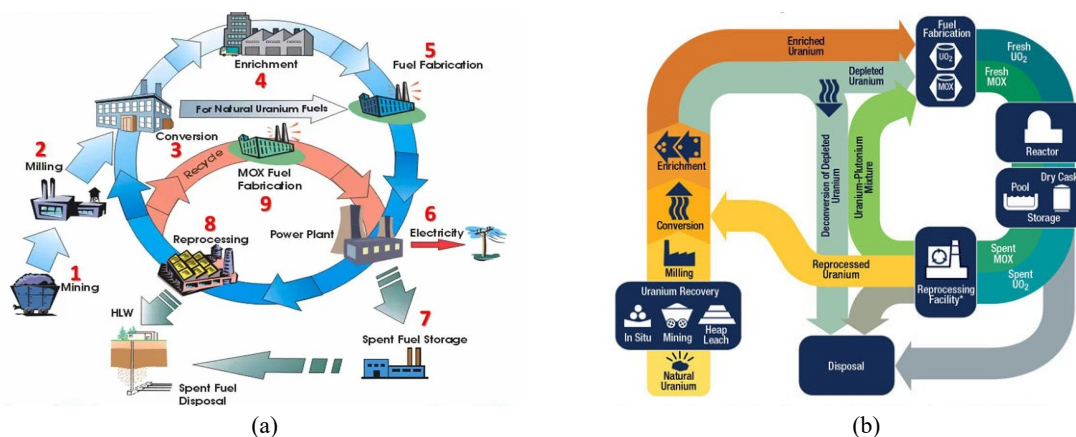


FIG 1. Illustrations of Nuclear Fuel Cycle. Sources: (a) International Atomic Energy Agency (IAEA) and (b) United States Nuclear Regulatory Commission (USNRC)

The individual objectives of nuclear packaging in operation may be stated as follows: (1) Protect people from radiation (**Safety**); (2) protect materials and facilities from malevolent people (**Security**); and (3) protect society from nuclear weapon proliferation (**Safeguards**). The common objective of nuclear packaging in operation, combining the three individual objectives of 3S, can be stated as follows: **Protect people, society, the environment, and future generations from the harmful effects of ionizing radiation.**

In recent years, there has been a recognition that efforts are needed to ensure that the safety, security, and safeguards (3S) disciplines for packaging and transportation of nuclear and other radioactive material (RAM) work together to avoid conflicts among the three disciplines [2-4]. Beginning in 2013, a series of training courses on transport security for nuclear and other RAM has been convened in the United States at Argonne National Laboratory (Argonne) under the auspices of the U.S. Department of Energy (USDOE) Packaging Certification Program, Office of Packaging and Transportation, Office of Environmental Management. The two transport security courses have focused individually on international and U.S.-domestic transport. Two new courses on transport emergency response and decommissioning of facilities and site closure have also been developed and offered by Argonne as part of the DOE Packaging University Program with the University of Nevada, Reno (UNR) since 2015, which also includes Quality Assurance for RAM packaging and application of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for nuclear transport and storage [5]. Together, these six DOE/Argonne/UNR training courses incorporated the knowledge accumulated over decades of work involving U.S. and international regulatory standards; recommendations and guidance on transportation packaging 3S; and extended storage of spent nuclear fuel (SNF) and high-level waste, as well as advanced technologies associated with the back end of the nuclear fuel cycle. Among the advanced technologies are the ARG-US remote monitoring systems technologies, which have been developed by Argonne and deployed at multiple DOE sites for monitoring nuclear fuel cycle facilities and transportation [6-9]. Remote Area Modular Monitoring (RAMM) for canister surface temperature measurement (TM), or RAMM-TM [10], is the latest derivative of RAMM; it was developed and extensively tested for canister gas leakage detection, using a 1/4.5-scale model cask, in a joint program with the Central Research Institute of Electric Power Industry, Japan, between 2019 and 2022 [11-14].

Drawing on the accumulated knowledge in packaging for transportation of nuclear and other RAM and extended long-term storage of SNF and high-level waste, including aging management [15] and the ARG-US remote monitoring systems technologies, this paper will provide a framework of **3S by Design** that should be applicable to meeting the challenge of packaging 3S for existing and advanced nuclear fuel cycle materials in the transportation, storage, and disposal phases.

2. PACKAGING LIFE CYCLE AND 3S BY DESIGN

Figure 2 is a schematic showing (a) the life cycle of a packaging for nuclear and other RAM, and (b) a Venn diagram of nuclear packaging and its three main functional objectives of ensuring 3S during the life cycle of the packaging – *from cradle to grave*.

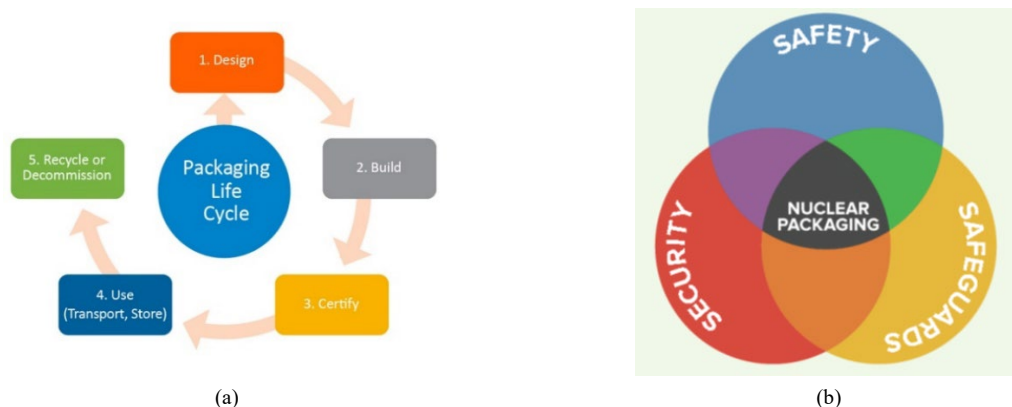


FIG. 2. Schematics showing (a) life cycle of packaging of nuclear and other radioactive material and (b) Venn diagram of a nuclear packaging and its functional objectives during its life cycle.

3. AGING MANAGEMENT AND STRUCTURAL HEALTH MONITORING

Reference [15] describes the principles and practices for aging management of RAM transportation packaging and dry cask storage systems for SNF, with emphasis on aging-related environmental degradation of materials, and structural health monitoring (SHM) of SSCs that are important to safety. The overview is based on years of experience in conducting technical certification review of transportation packaging and developing guidance documents on aging management for dry cask storage systems for long-term storage and subsequent transportation of SNF [16].

There are four types of aging management programs (AMPs) that manage aging effects on SSCs in nuclear power plants and spent fuel dry cask storage systems for license renewal applications [17–20]. These four types of AMPs are (1) **prevention programs** that preclude aging effects from occurring, (2) **mitigation programs** that slow the effects of aging, (3) **condition-monitoring programs** that inspect/examine for the presence and extent of aging, and (4) **performance-monitoring programs** that test the ability of a structure or component to perform its intended safety function for the period requested in the license renewal application. More than one type of AMP may be implemented for a component to ensure that aging effects are managed throughout the extended period of operation, which may vary from years to decades. Some aging effects may not require an AMP if the effects can be shown, by analysis, to be incapable of adversely affecting a safety function for the licensed operating period. Such analyses are referred to as time-limited aging analyses (TLAAs). Examples of TLAAs are (1) fatigue analyses of metallic structures and components to determine the number of loading cycles to failure, (2) corrosion-rate calculations to determine if the loss of material from metallic surfaces could degrade structural and shielding functions, and (3) boron depletion analysis of neutron poison plates to evaluate the potential loss of criticality control due to neutron irradiation.

For RAM transportation packaging, the IAEA Safety Standard [21] states, “*The design of the package shall take into account ageing mechanisms.*” For aerospace, civil, and mechanical engineering systems, the term structural health monitoring (SHM) [22] is often used to refer to the process of implementing a damage identification strategy, whereby damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, that adversely affect the system’s performance. SHM, therefore, is closely related to aging management, as it is almost equivalent to a combination of condition monitoring and performance monitoring of SSCs that are important to safety.

4. LEARNING AMPS

All recent aging management guidance documents emphasized the importance and need for updating AMPs during extended storage because the state of the storage system components, related technical knowledge, and related regulations may change. To ensure continued safe storage of spent fuel, operating experience on age-related degradation and aging management should be used to update AMPs. Operators should review operating experience to confirm that the AMPs remain effective at managing age-related degradation or make any necessary changes to the AMPs to ensure their continued effectiveness. In this way, the AMPs are considered learning programs that evolve in response to operating experience and aggregated knowledge. This approach, called the “Plan/Do/Check/Act” (PDCA) cycle, was first introduced for aging management of SSCs in nuclear power plants, but is also applicable to spent-fuel dry storage systems, as illustrated in Figure 3, which shows that understanding of aging of SSCs is fundamental to the development and optimization of activities for aging management during the PDCA cycle.

It is important to emphasize that the purposes of AMPs are to manage aging effects on SSCs caused by aging mechanisms and environmental degradation of materials. Chapter 2 in the USNRC *Managing Aging Processes in Storage (MAPS) Report* [20] provides definitions of materials, environments, aging mechanisms, and aging effects, whereas Chapter 3 in the MAPS report provides evaluation of aging mechanisms for cask and internals, neutron shielding materials, neutron poison materials, concrete overpacks, and spent fuel assemblies. Similar classification and evaluation of materials, environment, aging mechanisms, and aging effects can be found in the USDOE aging management report by Chopra et al. [23] and a forthcoming IAEA TECDOC report [24].

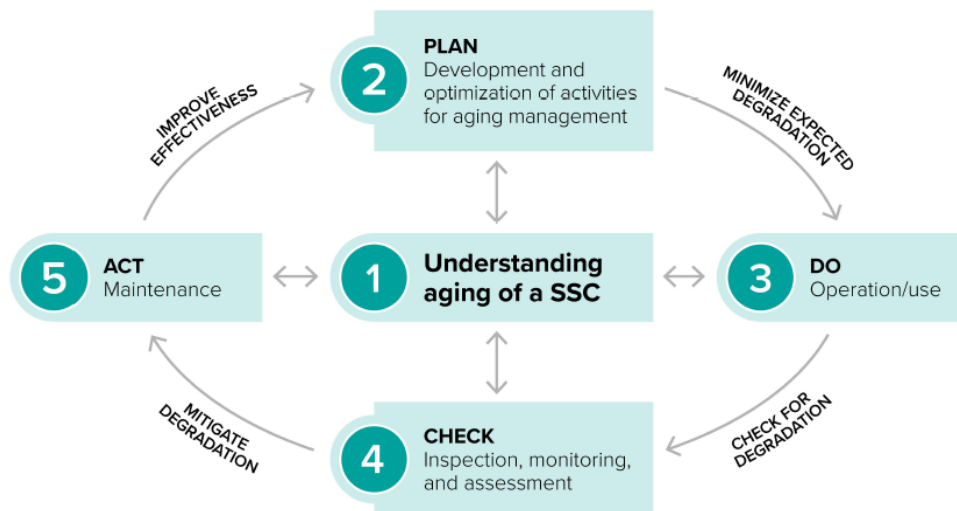


FIG. 3. Update of Aging Management Programs – Plan/Do/Check/Act (PDCA)

5. INSPECTION, MONITORING, MITIGATION AND REPAIR

Chapter 7 of the IAEA TECDOC report [24] provides descriptions of the state-of-the-art technologies for inspection, monitoring, mitigation, and repair in AMPs that include subsections on bolted-cask systems and welded-canister systems, and each subsection contains three additional sub-subsections on aging-related effects, inspection challenges, and non-destructive examination operational experience. Other subsections cover (1) concrete inspection and (2) monitoring systems that are, or could be, employed to help augment inspections or potentially reduce the frequency of (or eliminate) inspections. Continuous and periodic condition and/or performance monitoring would enable timely detection of aging effects, such as pressure drop and/or leakage from the confinement boundary of bolted casks or welded canisters, thus enabling mitigation and repair (M/R) to allow SNF dry storage to continue while reducing risk, ensuring public safety and health, and protecting the environment. Various monitoring technologies are at different stages of development and implementation. The primary monitoring systems that are in common usage today are pressure-monitoring systems for bolted-cask systems and temperature-monitoring systems for both bolted-cask and welded-canister systems. Other monitoring systems under development include acoustic emission, helium, radiation, and concrete degradation.

Figure 4 shows a contrast of periodic inspection and continuous monitoring of a welded SNF canister for indications of chloride-induced stress corrosion cracking (CISCC), followed by M/R for continuing storage, transportation, and disposal. Both condition monitoring by periodic inspection and leakage performance monitoring may be necessary, as they are complementary tools for aging management.

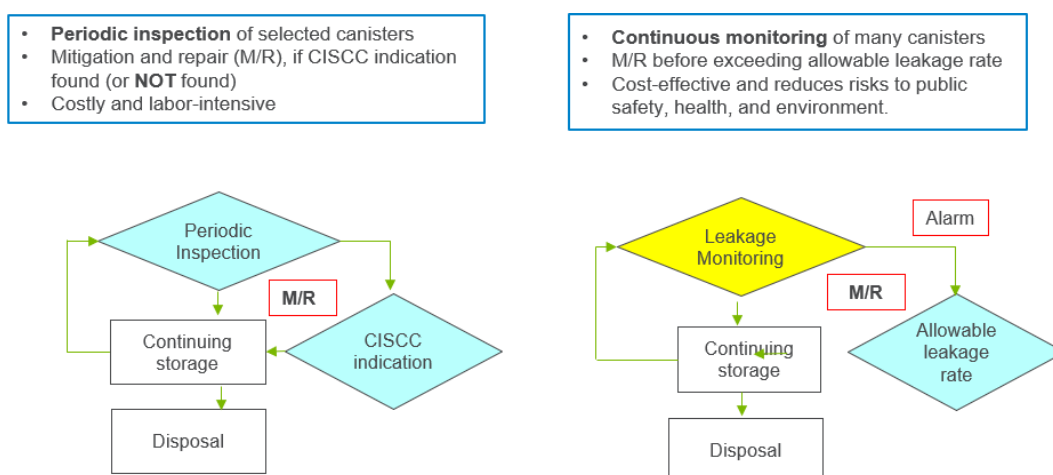


FIG. 4. Periodic Inspection and Continuous Monitoring of Welded Canister of Spent Fuel.

6. PRESSURE AND TEMPERATURE MONITORING

The pressure-monitoring system for bolted casks is a surveillance measure to identify a hypothetical metal seal failure of either the inner primary-lid system or the outer secondary-lid system. The double-barrier design allows one to monitor the pressure level in the intermediate cavity and send a signal if critical pressure loss occurs, followed by inspection routines to identify which seal (or the monitoring device itself) has failed. Subsequent repair routines consider replacement of the pressure monitoring device or a metal seal of the secondary-lid system. If a seal replacement cannot be performed without moving the cask to a hot cell or a nuclear power plant pool (both of which are usually not available in an interim storage facility), a third repair lid can be assembled on top of the secondary lid to re-establish a two-barrier-lid system.

As mentioned earlier, a RAMM system for canister surface temperature measurement (RAMM-TM) has been developed for detection of gas leakage from spent fuel canisters. The detection methodology has been demonstrated in canister gas-leakage experiments conducted by using a 1/4.5-scale model cask; both helium and air gas leakage from the model canister, caused by simulated CISCC, were detected within hours after the start of the leakage. The change in canister surface temperature between the top and bottom centers of the canister during gas leakage (depressurization) triggered automatic alarms, providing a sound basis for early detection of gas leakage from the canister. This detection methodology, when implemented for actual canisters containing spent fuel, would allow for consequences management after canister breach by CISCC through the implementation of necessary mitigation actions to continue dry storage and aging management, reduce risks to public safety and health, and protect the environment.

7. HIDDEN DAMAGE

Even with periodic inspection of canister surfaces for indication of CISCC and continuous monitoring for canister gas leakage using RAMM-TM (or other means), challenges remain in aging management and prognostic prediction of remaining life of spent fuel and SSCs in transportation packages and storage canister systems because structural failures are intrinsically an emergent phenomenon; for example, in brittle fracture, a long period of crack initiation is followed by a short period of crack propagation after a critical flaw size is reached. In the case of high-burnup spent fuel, embrittlement of the cladding owing to hydride re-orientation during vacuum drying and early storage [25] may be hidden from periodic inspection and continuous monitoring, so that the “absence of evidence” of damage is not the same as “evidence of absence” of damage. Emergent behavior is common in natural disasters triggered by giant earthquakes and avalanches.

8. 3S BY DESIGN FOR ADVANCED REACTOR NUCLEAR FUEL CYCLE

Designers and developers in the United States have identified at least eight concepts for advanced reactor technologies to pursue for operation by 2030. A wide array of fuel types and forms are associated with these reactor concepts, with high-assay low-enriched uranium (HALEU) predominating. These advanced reactors and fuels would be part of an advanced-reactor nuclear fuel cycle, including transportation and packaging, that links each step in the fuel cycle. Furthermore, transportation has been recognized as the most vulnerable of all steps in a nuclear fuel cycle. 3S by Design is both an economic opportunity and a technological challenge in the early stages of design and development of these advanced reactors, as well as for the entire advanced-reactor nuclear fuel cycle, including transportation. Based on previous work at Argonne on identifying conflicts and synergies among 3S, opportunities for 3S by Design can be identified for transportation and packaging—by applying the basic principle and methodology for determining synergies and conflicts that are applicable to each of the 3S disciplines from design to operation throughout the advanced-reactor nuclear fuel cycle. The methodology underlying the basic principle addresses the degree of access to nuclear material and to nuclear information that is either required or prohibited by national and international requirements. 3S by Design based on the basic principle and methodology, therefore, can help to significantly reduce design and operating costs and to avoid costly retrofitting, in the United States and elsewhere, where vendors and transporters may not be familiar with international safeguards under the States/IAEA Voluntary Safeguards Offer Agreement.

9. DISCUSSION

The following quotes are taken from the Background section in the announcement of this International Conference on the Management of Spent Fuel from Nuclear Power Reactors: Meeting the Moment:

“The safe, secure, and sustainable management of spent fuel from nuclear power reactors is key to the future of nuclear energy.”

“The implementation of SNF management strategies can take decades, and national strategies must be flexible enough to accommodate potential future options and new technologies that will enhance the safety and sustainability of nuclear power.” ... “There is a lack of clarity regarding spent fuel storage durations, due in part to the long lead time to develop, and obtain societal support and license for, deep geological repositories. This subsequently impacts the handling and transportation of spent fuel, as well as downstream steps, in the long term.”

“The needed knowledge management and knowledge transfer over multiple generations of experts is a particular challenge. This will be important to ensure that the service life of storage systems can continue to be extended to cover the necessary timeframes until SNF final disposition is implemented.”

These quotes are selected to echo the main points of this paper, which are that packaging is essential and central to nuclear fuel cycle materials in existing and advanced reactor nuclear fuel cycles that share the same objectives of ensuring 3S during packaging’s life cycle in transportation, storage, and disposal. Advanced technologies and knowledge management and transfer are themes affecting multiple generations in the future.

Advanced technologies associated with the backend of nuclear fuel cycles were described in two recent joint papers by researchers at Argonne and Bundesanstalt für Materialforschung und-prüfung (BAM), Germany [26, 27]. The paper “Cooperation in Advanced Technologies Associated with the Back End of Nuclear Fuel Cycle” presented in the Special Session: Performance assessment of spent fuel in storage and transportation, SMiRT-26 [26] describes the Argonne/BAM collaboration research activities in seven topical areas in the last decade: (1) Guidance documents on aging management programs, (2) mechanical properties of high-burnup fuel claddings, (3) long-term performance of metallic and elastomeric O-ring seals, (4) polymeric neutron shielding materials, (5) modelling and simulations of structural and thermal performance of spent fuel and dry cask storage systems during storage and post-storage transportation, (6) advanced surveillance technologies for the monitoring and inspection of dry cask storage systems during storage and subsequent transportation, and (7) geological repository engineering technology (e.g., disposable containers), which was the latest topical area included in the renewed Memorandum of Understanding between Argonne and BAM (2020–2025). The other paper by Liu and Völzke presented in Session 4.5 Aging management of spent nuclear fuel in extended storage and transportation, WM 2024 [27] provided updates of Argonne/BAM collaborative activities after SMiRT-26, focusing on aging management guidance, and selected advanced technologies for pressure and temperature monitoring during extended storage, with a brief discussion of joint conference activities, training and knowledge transfer, and advanced nuclear reactor fuel cycles.

Other advanced technologies such as digital twins are already widely used in Industry 4.0 applications that focus on interconnectivity, automation, machine learning, and real-time data for manufacturing and supply chain management. A digital twin replicates a physical entity by bridging the physical and virtual worlds, with real-time transmission of data, thus allowing the virtual entity to exist simultaneously with the physical entity. The digital twin provides both the elements and the dynamics of how a device operates and lives throughout its life cycle. The connection between the physical object and the corresponding digital twin is established by generating real-time data using sensors. RAMM-TM for real-time, remote spent-fuel-canister gas leakage detection due to CISC is a good example of a digital twin application, as described in more detail in Reference [28].

Block-chain or digital-ledger technology (DLT) is another advanced technology that is being evaluated for nonproliferation and export controls [29], maritime shipping and port management [30], nuclear waste handling [31], and transport security, specifically for the ARG-US TRAVELER using the Hyperledger Fabric platform, which is scalable and supports both private transactions and confidential contracts [32]. A prototype block chain for ARG-US TRAVELER is being developed for testing and demonstration applications in 2024.

As mentioned earlier, Argonne has conducted six week-long training courses as part of the USDOE Packaging University program since 2015. These courses were convened annually at Argonne, except in 2020 and 2021 because of COVID-19. While COVID-19 prevented travel, it also provided opportunities to explore

electronic delivery platforms using advanced learning tools, including web-based apps for categorization of materials and transport security plans; geofencing and extended-reality scenarios for transport security and emergency response exercises; and interactive audience survey systems [33]. These new tools have greatly enhanced the training's effectiveness, particularly for transport security and emergency response, for which extended-reality (or metaverse) methodology allows classroom exercises involving scenarios that cannot be achieved in the physical world. With increasing access to e-Learning via Internet, these new tools should find even broader applications in meeting workforce and educational demands and help attain the goals of packaging 3S for nuclear fuel cycle materials in transportation, storage, and disposal.

10. SUMMARY AND CONCLUSION

Packaging is essential and central to nuclear fuel cycle materials in transportation, storage, and disposal. Principles and practices for aging management of radioactive material packaging and dry cask storage systems for spent nuclear fuel are described, with emphasis on aging-related environmental degradation of materials, and structural health monitoring of structures, systems, and components that are important to safety. The overview is based on years of experience in conducting technical certification review of transportation packaging and developing guidance documents on aging management for dry cask storage systems for long-term storage and subsequent transportation of spent nuclear fuel. The concept of Safety, Security, and Safeguards (3S) by Design for advanced-reactor nuclear fuel cycles during the packaging life cycle has been elucidated, providing a framework that should be applicable to meeting the challenge of packaging 3S for existing and advanced nuclear fuel cycle materials in transportation, storage, and disposal.

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