

Challenges and Opportunities for 3S by Design for Transportation and Packaging for the Advanced Reactor Nuclear Fuel Cycle

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ABSTRACT

The Nuclear Energy Agency tracks 42 small modular reactors (SMRs) in 13 countries and has assessed their progress toward commercialization and deployment. Safe, secure, and safeguarded SMRs and fuels are essential for international commercialization. SMRs and advanced reactors that currently use lower levels of technology and have licensing readiness could be deployed at scale by the 2030s. Some of these technologies aim to close the back end of the fuel cycle by reprocessing and recycling spent nuclear fuel. These technologies span an enormous range of reactor concepts (e.g., water-cooled, gas-cooled, fast spectrum, micro, and molten salt) and configurations (e.g., land-based, multi-module, marine-based, and mobile) and the entire fuel cycle. This range creates a multitude of challenges and opportunities for safety, security, and safeguards (3S) by design in the life cycle for the transportation and packaging of unirradiated and irradiated fuel—in particular, throughout the entire nuclear fuel cycle, in which transportation is widely recognized as the most vulnerable link.

Safety routinely has been the first of the 3S disciplines to be considered for nuclear transportation and packaging. However, the International Atomic Energy Agency (IAEA) Incident and Trafficking Database shows that thefts during transportation of nuclear material in the last decade reached 14% of all reported incidents, highlighting the added importance of strengthening transport security measures. In comparison, safeguards awareness is a relatively new priority; nuclear facilities in States under international agreements must meet international legal obligations. The U.S. Nuclear Regulatory Commission 3S Virtual Workshop held in December 2023 broadly noted that consideration of 3S at the early stage of design was important for identifying synergies and conflicts, but U.S. vendors are often unaware of safeguards requirements. Nonetheless, obligations for 3S need to be met worldwide.

This paper, which is based on our previous work on conflicts and synergies with international packaging and transport 3S and culture analysis for international nuclear transport, describes the basic principle useful for determining synergies and conflicts that is applicable to each of the 3S disciplines from design to operation throughout the nuclear fuel cycle. The methodology underlying this principle addresses the degree of access to nuclear material and access to nuclear material information that is either required or prohibited by national and international requirements. On the basis of this principle and methodology, this paper identifies challenges and recommends opportunities for identifying 3S synergies and conflicts for nuclear transport and packaging to help reduce design and operating costs and to avoid costly retrofitting, particularly in the United States, where vendors and transporters may be less familiar with international safeguards under the U.S./IAEA Voluntary Safeguards Offer Agreement.

NATIONAL & INTERNATIONAL TRANSPORTATION 3S

International commercialization of advanced nuclear reactor technologies and nuclear materials, including transportation of exports and imports, must meet national as well as international requirements. U.S. national requirements include U.S. Nuclear Regulatory Commission (NRC) regulations for the safety, security, and safeguards (3S) for transportation and packaging, in particular 10CFR37¹, 10CFR70², 10CFR71³, 10CFR73⁴, and 10CFR75⁵. The NRC has recognized the significant interest in (3S) during design and operation throughout the nuclear industry to meet regulatory requirements.⁶

Worldwide, nations have similar national requirements for nuclear technology imports and exports that may involve U.S. technologies. In addition, international requirements apply to nuclear 3S for international commercialization of advanced nuclear reactor technologies and nuclear materials, including transportation. It is a generally accepted principle that nuclear material is more vulnerable to diversion while it is being transported between sites or facilities because such transfers occur outside facility safety and security boundaries.⁷

As of 2023, 94 countries were party to the Convention on Nuclear Safety.⁸ This Convention establishes a legal obligation to apply certain general safety principles to the construction, operation, and regulation of land-based civilian nuclear power plants.

As of 2021, 164 countries were party to the Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment.⁹ The CPPNM establishes legal obligations regarding the physical protection of nuclear material used for peaceful purposes during international transport.

As of 2023, the International Atomic Energy Agency (IAEA) has concluded comprehensive safeguards agreements with 182 countries. IAEA safeguards are embedded in legally binding agreements concluded between a nation and the IAEA.^{10, 11} Through a set of technical measures, or safeguards, the IAEA verifies that countries honor their international legal obligations to use nuclear material and technology only for peaceful purposes.

ADVANCED REACTORS & FUEL CONCEPTS BEING DESIGNED & DEVELOPED

Two recent U.S. National Academies reports note there are 17 different advanced reactor designs for as many as 17 nuclear fuels, most of which are HALEU.^{12, 13} (See Table 1.) These two reports address 3S for packaging, transportation, and storage for advanced reactor technologies and nuclear materials for the front end and back end of the nuclear fuel cycle. Ten developers have submitted 11 designs for license applications or preapplications to the NRC. 3S for nuclear packaging and transportation will be required for the reactor and fuel concepts shown in Table 1.

Worldwide, the Nuclear Energy Agency (NEA) has recently reported 21 Small Modular Reactors (SMRs) with at least six different nuclear fuels are being designed and developed. Some of these technologies are available in the market now, with many others following in the next 5 to 10 years.^{14, 15}

Regulatory and licensing systems vary from nation to nation. Steven Burns, former Chairman of the NRC, has been active in harmonizing international regulatory and licensing frameworks. Harmonization for 3S would support international commercialization of nuclear reactors and nuclear materials.¹⁶

Table 1. Technologies being Considered That Are Relevant for Nuclear Transportation 3S

REACTOR CONCEPTS

Small Modular Reactor (LWR)
High Temperature Gas Cooled Reactor
Molten Salt Fast Reactor
Liquid Metal Fast Reactor
Pebble Bed Reactor
Micro Reactor

FUEL CONCEPTS

HALEU
TRISO
Uranium Metals
Uranium Compounds
Graphite
Uranium-233
Thorium
Plutonium

3S INTERFACES AND INTERACTIONS

The 3S disciplines interact during each operational stage throughout the entire nuclear fuel cycle, including transportation and packaging. (See Figure 1.) To increase design and operation effectiveness and to avoid costly backfitting during operation and schedule delays, the most effective time to address 3S interactions and interfaces is during the design and planning phases.

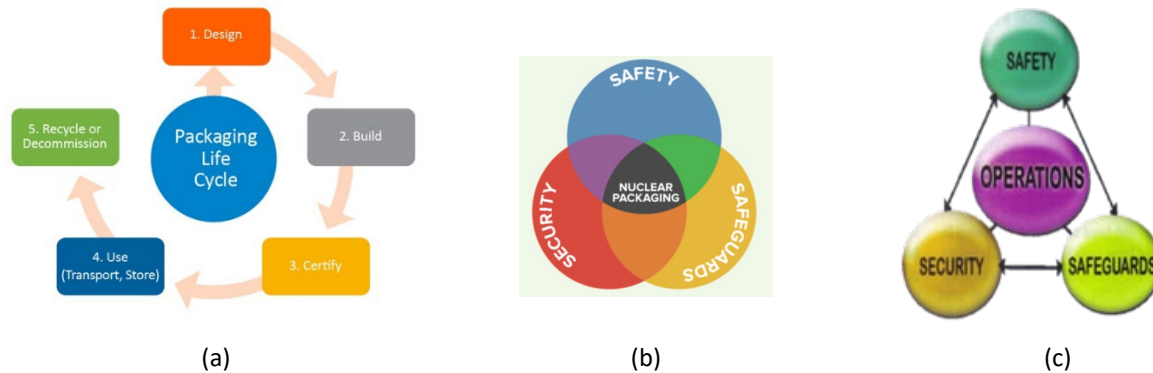


Figure 1. (a) Packaging life cycle, (b) Nuclear packaging 3S and 2S Interactions, and (c) packaging operations.

CHALLENGES & OPPORTUNITIES: TRANSPORTATION & PACKAGING 3S BY DESIGN

This section addresses challenges and opportunities in terms of 3S synergies and conflicts for packaging and transportation of advanced nuclear reactor technologies and nuclear materials. For exports and imports, international commercialization will require application of legally binding IAEA requirements, recommendations, and guidance. This paper extends a comprehensive assessment previously performed¹⁷ that considered a suite of relevant international regulatory documents relating to transport 3S for identifying synergies and conflicts. Using these documents, 25 key topics were identified, categorized, and evaluated. The discussion below identifies synergies and conflicts in the context of operational challenges and opportunities for stakeholders, in particular, designers, vendors, operators, and regulators.

3S Nuclear Disciplines Culture

Challenges: Why is nuclear culture important for international nuclear transport? 15 million packages of radioactive material are transported annually around the world, involving numerous international cultural interactions. Numerous international designs for advanced reactors for international commercialization involves international nuclear exports and imports. The timing is opportune for incorporating 3S cultures into new designs for international nuclear transportation and packaging.

Edgar H. Shein, well-known organizational culture expert, notes: “Culture pervades everything.”¹⁸ Schein’s organizational culture concept, and how it applies to international nuclear transport across national borders where international regulatory and technical interactions interface extensively, have recently been explored.¹⁹ Unlike safety culture, which is strongly supported throughout the nuclear industry, international safeguards is a little-known subject for many designers. To facilitate the safeguards by design (SBD) process and directly address the perceived “weakness in the design community’s safeguards culture,” guidance is needed to address the cultural aspects of SBD.²⁰

The IAEA has issued guidance for nuclear safety culture and for nuclear security culture. However, the IAEA has not issued guidance for nuclear safeguards culture or international nuclear transportation culture. There is increasing importance and need to understand 3S culture bias as interest in international commercialization of advanced nuclear technologies increases.¹⁷

Opportunities: Transport of nuclear material is increasing worldwide across national borders under various nuclear 3S regulatory cultures. International safeguards are based on the existence of a system for national safeguards that are in turn based on a system of operator safeguards (i.e., MC&A), which brings international safeguards into parity with international safety and international security re 3S culture.

Synergies: Where there is an integrated safety/security/safeguards culture, it is likely that interfaces and interactions will reveal synergies early in the planning and design process. The result of a greater mutual understanding can lead to greater cost effectiveness and operational efficiency without costly retrofitting.

Conflicts: One obstacle for developing a 3S culture is that IAEA safeguards documents are silent on nuclear safeguards culture, including lack of definition; but the IAEA has placed significant emphasis on nuclear safety culture and nuclear security culture, both of which are defined²¹ and have been addressed in IAEA guidance. Although IAEA definition and guidance for safeguards culture is lacking, 3S interactions and interfaces can still be identified on the basis of 3S objectives.

Regulatory Infrastructure

Challenges: The U.S. DOE has challenged U.S. vendors to undertake design and development of advanced reactor technologies for the nuclear fuel cycle. This effort involves applying the 3S disciplines for these nuclear technologies, including packaging and transportation for exports and imports.

Opportunities: The U.S. DOE promotes and supports infrastructure for the design and development of advanced reactor technologies for the nuclear fuel cycle. The U.S. NRC has begun recognizing and addressing the necessary regulatory infrastructure for licensing these advanced reactor technologies. U.S. nuclear vendors are undertaking design and development of these nuclear technologies and fuels.

Synergies: U.S. agencies, DOE and NRC in particular, are cooperating and coordinating development of a regulatory infrastructure for international commercialization of advanced reactor technologies. The IAEA has issued international requirements, recommendations, and guidance related to packaging and transportation for the export and import of nuclear technologies.

Conflicts: U.S. vendors, including providers of packaging and transportation, are subject to U.S. regulatory requirements, including 10CFR37, 10CFR70, 10CFR71, 10CFR73, and 10CFR75. In addition, national requirements of importing nations must be considered and whether the importing nations have legally binding arrangements for 3S, including IAEA requirements, recommendations, and guidance. U.S. exports are subject to legally binding cooperation agreements. In particular, the U.S. has 23 international agreements for peaceful nuclear cooperation that contain legally binding conditions for undertaking significant nuclear cooperation with other countries pursuant to Section 123 of the U.S. Atomic Energy Act.²² U.S. nuclear technology exports to other countries must be covered by legally binding requirements for imports in other countries. Those requirements address the 3S disciplines and are typically met with IAEA SSR-6 for safety, the CPPNM for security, and an IAEA Comprehensive Safeguards Agreement for international safeguards.

Graded Approach and Defense in Depth

Challenges: Each 3S discipline has a unique graded approach and a corresponding defense in depth.

Opportunities: There is regulatory variation for each graded approach, which typically depends on the type and amount of nuclear material involved in the design for packages and transportation. Consequently, there can be various options for defense in depth, depending on the graded-approach level. The IAEA has defined “graded approach” to help understand and apply a graded approach and has

extensively described “defense in depth” as a hierarchical deployment of different levels of diverse equipment and procedures for application to safety and security.²¹

In the U.S., the graded approach for safety is based on potential accident sequences identified and levels of consequences for an Integrated Safety Analysis. (See 10CFR70.²) The graded approach for domestic MC&A is based on detecting theft, loss, and diversion for Special Nuclear Material Categories I–III. (See 10CFR70.²) MCA and physical protection make up the primary elements of a domestic safeguards program.²³ The NRC lists its export licensing authority for a range of nuclear technologies and materials. (See 10CFR110.²⁴) The graded approach for international safeguards is based on the IAEA technical objective: timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.¹⁰

Synergies: The synergistic consistency among the 3S disciplines for a graded approach and for defense in depth provides opportunities for cost-effective design and planning. A graded approach for the range of nuclear materials goes hand-in-hand with defense in depth provided by the range of technologies available to ensure that 3S by design (3SBD) is proportional to potential consequences.

For example, design may start with a graded approach where 3SBD varies with the level of enrichment (for example, LEU versus HALEU) followed by applying defense in depth where 3SBD varies with type and level of technology needed for safety, security, and safeguards such as visual monitoring or remote electronic monitoring with variable frequency and intensity.

Conflicts: Objectives, graded approaches, and defense in depth may be addressed differently in design. If conflicts are apparent they should be addressed early in design and planning for cost-effectiveness.

Applications for Licenses

Challenges: Every nuclear nation has its own nuclear regulations and licensing process, which in most cases is a lengthy, complex process and consumes a large amount of resources. Licensing harmonization seeks functional equivalence in regulations promulgated by each sovereign nation.^{16, 25}

Opportunities: Early global harmonization in the regulations and licensing process is important to the vision of global export of new nuclear technologies. Synergistic benefits can be achieved by harmonizing licensing practices for international transport and packaging of advanced nuclear technologies.

Synergies: Harmonization and standardization bring synergies to the regulatory and licensing process for packaging and transportation 3S design. Harmonization should be a joint priority of national regulators and the nuclear industry, starting with establishing consistent definitions and regulatory frameworks.

Conflicts: Each 3S discipline requires submittal of information to regulatory authorities for licensing. Conflicting information and duplication of submitted information can result. Without harmonization, there may be conflicts. Sharing 3S information helps avoid duplication and conflicts that delay licensing.

Definitions

Challenges: Several key terms are used for the 3S disciplines. Definitions of these key terms may vary for each 3S discipline. In some cases, key terms may not be defined. The terms include: competent authority, regulatory State authority, regional authority, carrier, consignee, shipper, receiver, transport, and operator.

Opportunities: While definitions used in the 3S disciplines may not be the same or may not exist, synergies arise where definitions are the same; but care is needed where definitions differ.

Synergies: Note that definitions of Categories I–III are the same for “special nuclear material” in 10CFR73⁴ and for “nuclear material” in IAEA Nuclear Safety and Security Glossary²¹ and in IAEA Nuclear Security Series No. 13.²⁶

Conflicts: Note that IAEA safeguards do not use “Categories of Nuclear Material” as the basis for IAEA safeguards. IAEA safeguards use “significant quantity” of “direct use nuclear material” and “indirect use nuclear material” as the basis for inspections and safeguards conclusions.

Information Availability

Challenges: Access to certain nuclear information related to design and operation may be restricted for any one of the 3S disciplines. In particular, access to information for purposes of IAEA safeguards may be required; whereas, access to the same information for purposes of safety or security may be restricted.

Opportunities: The 3S opportunity is based on determining what nuclear information has restricted access and then determining the conditions under which that information can be made available in order to satisfy all 3S requirements. Typical nuclear information that may be sensitive includes transportation plans and schedules, advance information, records and reports, package design information, Certificate of Compliance, Design Information Questionnaire (DIQ), package labels, and vehicle placards, or other proprietary, commercially sensitive, or classified nuclear information.

Synergies: Much of the same nuclear information that is sensitive is needed for all 3S disciplines in order for the 3S disciplines to be effectively carried out. Mutual agreement among 3S experts for sharing the same 3S information with regulators is more efficient than each discipline having individual restrictions.

Conflicts: Conflicts may arise when access to nuclear information is restricted for purposes of safety or security, but the same information is needed for application of safeguards by IAEA international inspectors. Conflicts can be resolved by several methods: (1) sensitive information may be viewed only onsite when needed, or (2) sensitive information may be transmitted to the appropriate regulatory authority where it is then protected by limited-access rules. Agreement on availability of needed information must be reached among the respective 3S experts as well as by the regulator and operator.

Package and Transport Conveyance Design

Challenges: Regulating safety is a national responsibility. The IAEA’s safety services encompass design, where the design description may include specifications, engineering drawings, and reports demonstrating compliance with regulatory requirements. IAEA SSR-6 applies to safety design for packages and conveyances for radioactive material, including nuclear material.²⁷ Safety measures, security measures, and safeguards measures must be designed and implemented in an integrated manner so that measures for one 3S discipline do not compromise measures for one of the other 3S disciplines.

The CPPNM includes application to physical protection of nuclear material during international transport as well as domestic use, storage, and transport. IAEA safeguards include operator’s provision of design information to the IAEA to identify features of facilities and nuclear material relevant to enabling application of IAEA safeguards to nuclear material in sufficient detail to demonstrate verification.

Opportunities: Best 3SBD opportunities for packages and conveyances exist during planning and design.

Synergies: Package and conveyance design information is relevant to each 3S discipline. Robust design, testing, and manufacture are primarily governed by transport safety and regulatory requirements. Synergies can be gained by actively sharing design information among all 3S disciplines rather than parallel duplication of effort by each of the 3S disciplines individually. IAEA safeguards require access

before shipment and after receipt of shipment, but not during shipment. Typically, IAEA uses optical or electronic seals on packages and remote electronic monitoring of shipments. Transport monitoring and tracking can be synergistically achieved for all 3S disciplines, for example, by using Argonne ARG-US remote monitoring systems technology.^{28, 29, 30}

Conflicts: Potential conflicts with safeguards is low if 3SBD of packages and conveyances is considered early in design and planning stages. Conflicts can arise if design does not provide for use of IAEA seals on packages and remote monitoring during shipment. Retrofitted design after operation is expensive.

Inspections

Challenges: All 3S disciplines require or recommend inspections. Regulators, operators, and the IAEA have primary roles in compliance with these requirements.

The regulatory body shall carry out safety inspections to verify compliance with requirements.^{31, 32, 33} Before shipment of a package, the shipper of the package shall ensure, by inspection, that regulations and certifications have been complied with. For shipments across international borders, packages may be opened for inspection during custom operations.²⁷

Under Fundamental Principle C, Legislative and Regulatory Framework, of the CPPNM, the national authority is responsible for establishing and maintaining a regulatory framework of physical protection requirements that include a system for licensing and inspection of nuclear facilities and transport to verify compliance with applicable requirements.⁹ The operator must ensure that any missing or stolen nuclear material is detected in a timely manner by means such as the system for nuclear material accountancy and control and the physical protection system (e.g., inspections).²⁶ NRC national requirements regarding regulatory inspections for nuclear transportation are found in 10CFR37 and 10CFR73.

For IAEA safeguards inspections, INFCIRC/153 and INFCIRC/540 apply. U.S. and IAEA have signed a Voluntary Offer Safeguards Agreement. NRC 10CFR75 applies to IAEA safeguards in the U.S.

Opportunities: Under multiple 3S regulations, some inspection activities for 3S are the same.

Synergies: Joint inspections are recognized by the IAEA. Some 3S inspection activities can be shared to reduce duplication, financial expenses, and intrusiveness. For example, inspector access, nuclear material measurements, design information, records, and reports may be shared. MC&A information may be shared for security inspections and safeguards inspections. It may be acceptable to share technologies and related information such as for containment (e.g., seals) and for surveillance (e.g., cameras).

Conflicts: IAEA safeguards inspectors are required to respect safety and security regulations. When sharing activities and information, there may be limits to physical access to material or information. For example, design information may be considered proprietary, commercially sensitive, or classified.

Seals and Unattended Monitoring

Challenges: Two key advanced technologies used by the IAEA for maintaining continuity of knowledge for transporting packaged nuclear material are the use of tamper-indicating devices, such as optical or electronic seals, and the use of unattended remote monitoring, such as with electronic or film cameras. These technologies apply to both domestic and international shipments. Agreement for use and for transnational data transmission is required by host nations.

Opportunities: A 3S design team (including safety, security, and safeguards experts) facilitates communication and cost-effective implementation of 3SBD. Design optimization addresses planning

transport routes so that containment/surveillance or flow monitoring systems clearly distinguish between routine and non-routine nuclear material transfers, as well as between nuclear and non-nuclear items.³⁴ Seals and remote monitoring have been applied to nuclear material packages by shippers, receivers, and the IAEA for multiple 3S purposes. Where nuclear material packages are effectively designed for one joint seal and monitoring system, the 3S experts may agree to share the seal and the monitoring system.

Synergies: Where there is early 3SBD to accommodate seals and remote monitoring, and with mutual agreement of the parties involved, a single seal and status monitoring system could be shared synergistically for 3S.

Conflicts: As long as a single seal and monitoring system is mutually accepted and shared, there could be minimal potential for conflict for the three disciplines while achieving the objective for each. This outcome would also require agreement of the parties regarding trans-national data transmittal.

Transport Incident/Emergency Response

Challenges: Planning and response to incidents or emergency during transportation and in-transit storage is an essential requirement for shipping nuclear material, particularly in view of future international commerce for advanced reactor and nuclear fuels technologies. In the event of an accident or incident during transport, all 3S disciplines come into play for the emergency response teams.

Opportunities: Given the 5- to 10-year time frame expected for international commerce in advanced nuclear technology, early response planning and preparation by operators and regulators can be timely for all 3S disciplines. Nuclear operators and regulators worldwide must be prepared for emergency responses to transportation incidents.

Synergies: Licensed operators in the U.S. are required to have transportation plans, including information management, operational control and transportation security, and emergency response. The NRC has an incident response program to provide expert consultation, support, and assistance with respect to events. The IAEA's role in the event of a nuclear or radiological incident or emergency includes notification and exchange of information, assessing consequences, providing public information, providing assistance, and coordinating inter-agency response. With so many agencies and responders involved, there are opportunities for synergies among the necessary cooperation, coordination, and communication efforts by operators and regulators for all 3S disciplines.

A safe, secure package and conveyance design synergistically helps reduce potential damage to the package and theft of the contents. It also helps preserve the integrity of the nuclear material and related data for safeguards requirements. Sharing physical access control and information can be 3S-synergistic before and during an emergency.

Conflicts: Conflicts can arise where planning is insufficient and responsibilities are not clear; in particular, where organizational interfaces/interactions and information-sharing are not defined.

Training

Challenges: Training, including cross-training, is essential for each of the 3S disciplines.

Opportunities: On-the-job cross-training is an opportunity to bring together vendors' experts who are skilled in their respective 3S disciplines to share their expertise and jointly identify 3S interfaces and interactions. This experience can then be passed on to other experts through training programs.

Synergies: Synergies and their benefits may go unrecognized. Benefits are realized when safety, security, and safeguards are addressed jointly by experts early in the planning and design stages rather than in

isolation. Some IAEA Members have begun incorporating 3S considerations into training and into their regulations. For example, recognizing the need for a better understanding of interactions and interfaces among safety, security, and safeguards, Argonne National Laboratory has developed a series of transportation security courses that include a module on 3S discipline requirements.^{17, 35}

Conflicts: There are no apparent conflicts in jointly training experts on interfaces and interactions among the 3S disciplines. The potential penalty of not cross-training 3S experts and not jointly considering the 3S disciplines is costly retrofitting after operation has begun.

SUMMARY AND CONCLUSIONS

1. There is increasing interest in implementing 3SBD throughout the nuclear industry.
2. The 3SBD approach is valuable for meeting 3S objectives.
3. The most cost-effective phases that address synergies and conflicts are planning and design.
4. Benefits of the 3SBD approach apply to all stakeholders, in particular, designers, manufacturers, carriers, consignors, vendors, and regulators.
5. Costly retrofitting and delays in operation can be avoided by 3S experts who jointly and systematically address the 3S disciplines.
6. Certain functions must remain independent and non-conflicting, but where possible, benefits from synergies can be gained and conflicts can be avoided by jointly considering 3S interactions.
7. Training and demonstration of 3SBD, such as in the Argonne National Laboratory Transport Security Training Courses, can help develop approaches for 3S synergies and avoid conflicts.

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