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Safeguards Considerations for Coated Particle Fuel Fabrication Facilities

Strategic Security Sciences Division

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Executive Summary

As coated particle fuels are developed to support advanced reactor designs, it is important to identify any steps or processes required for coated particle fuel fabrication that may involve safeguards approaches distinct from those used for traditional oxide fuel fabrication techniques. There are currently several countries, namely China, Germany, South Africa, Japan, and the United States, pursuing coated particle fuels with plans for near-term commercial deployment of tri-structural isotropic (TRISO) fuel. China continues to develop a high-temperature gas-cooled reactor, the HTR-PM, while South Africa's Eskom may restart development of their PBMR concept, both of which require coated particle fuels (World Nuclear News, 2020). X-Energy in the U.S. has partnered with Japan's Nuclear Fuel Industries (NFI) to supply coated particle fuels for Japan's High-temperature Test Reactor (HTTR). X-energy is developing its own pebble-bed concept called Xe-100 and associated pebble fuel, while other major U.S. fuel suppliers could also enter the marketplace (World Nuclear News, 2020). Additionally, the demand is only expected to increase, as new advanced reactor concepts are commercialized. As a result, it is important to ensure that there are no knowledge gaps when it comes to safeguarding future facilities.

This study compared current international safeguards approaches for a reference oxide fuel fabrication facility with two types of TRISO fuel fabrication facilities to identify the potential technology considerations and/or gaps. The following reflects the major findings of this analysis:

- Nuclear material accountancy (NMA) will be a challenge for TRISO fuel fabrication facilities, particularly on preventing protracted diversion of individual fuel elements with or without substitutions of the material.
- Further development into nondestructive analysis (NDA) techniques specific for TRISO fuel is necessary for verifying the fissile material content, particularly due to the nuclear materials being coated by multiple specialty layers.
- A TRISO cylindrical fuel compact fabrication facility (for insertion into prismatic graphite blocks) is more likely to use similar NDA methods and NMA standards as a uranium oxide fuel fabrication facility.
- NMA standards specific to TRISO spherical fuel pebble fabrication facility do not exist, but traditional NMA methods may be applied with additional inventory counting.
- Material unaccounted for (MUF) calculations in TRISO facilities are not dependent on holdup or other traditional fuel balancing factors observed in oxide fuel fabrication facilities; therefore, accounting methods for spherical TRISO fuel pebbles in canisters, individual TRISO spherical pebbles or cylindrical compacts, and prismatic blocks containing cylindrical TRISO fuel compacts must emphasize weight and inventory to meet timeliness goals. For example, spherical fuel pebbles are likely to be considered bulk material, necessitating the development of uncertainty quantification. On the other hand, fuel canisters containing pebbles may be considered under item accountancy. Similarly, fuel compacts are likely to be treated as bulk, while prismatic block fuel elements would be considered as items.
- Due to a lack of detailed information on the uranium-containing waste streams for TRISO fuel fabrication facilities, this report is unable to determine if there would be any major impact to the safeguards approaches to the waste measurements identified. Further evaluation is recommended.

- There is the potential for many alternative options of TRISO fuel kernel materials (ex. UO_2, UCO, MOX, UN), termed variants throughout the report. The application of safeguards equipment and techniques, including gamma spectroscopy and neutron counting, will need to be assessed and optimized for the specific variant in question.
- IAEA safeguards equipment has been tested extensively for traditional fuel forms (e.g., oxides, metals, solutions, and other light water reactor fuels) but may only have had limited testing for coated particle fuels. There is a necessity to determine international target values and radiation detection limits throughout the process of fuel fabrication.

Acknowledgements

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1. Introduction

This study aims to identify where existing fuel fabrication safeguards are limited in application to coated particle fuel fabrication facilities; perform a review of techniques that may be appropriate to address these limitations; and identify where further study is required. The purpose is to ensure the necessary technology and safeguards developments are established to facilitate safeguards-by-design for coated particle fuel fabrication facilities, analogous to the research and development (R&D) efforts in the advanced reactor space, including those requiring coated particle fuels and progress to higher technology readiness levels. Finally, this study will also help meet high priority objectives set forth by the IAEA in establishing safeguards R&D precedence and measurement/procedural standards at emerging fuel fabrication facilities.

To achieve these objectives, the report is formatted to (1) distill relevant background information on fuel fabrication of oxide and coated particle fuels; (2) provide an overview of the fuel fabrication techniques for a reference oxide fuel fabrication facility and two selected TRISO fuel fabrication facilities; (3) develop facility models of safeguards approaches for the reference facility and the two TRISO facilities; and (4) identify any observed technology needs or gaps from this analysis. The specific facilities outlined in the report include the following:

- Reference facility: Oxide Fuel Fabrication
  - Fuel assemblies, containing fuel rods, which in turn contain UO_2 fuel pellets.
  - Fuel Fabrication process includes uranium dioxide (UO_2) pellet fabrication, fuel rod fabrication and loading, and fuel assembly fabrication and loading.
- Facility A: TRISO Fuel Pebble Fabrication
  - Spherical fuel pebbles of TRISO coated particles with kernels composed of uranium oxycarbide (UCO).
  - Fuel fabrication process includes kernel fabrication, coated particle fabrication, and spherical fuel pebble fabrication.
- Facility B: TRISO Fuel Compact Fabrication
  - Cylindrical fuel compacts of TRISO coated particles with kernels composed of UO_2
  - Fuel fabrication process includes kernel fabrication, coated particle fabrication, fuel compact fabrication, and fuel element block fabrication and loading.

Additional information on each facility is provided in Sections 4 and 5 of this report. Further details on oxide, TRISO fuel pebble, and TRISO fuel compact fuel fabrication may be found in Appendices B, C, and D, respectively.

2. Background

2.1. History of Nuclear Fuel Fabrication

Fuel fabrication is a major step in the nuclear fuel cycle, directly following enrichment. The predominant enrichment method is through gaseous centrifugation. Therefore, material leaving enrichment facilities will commonly be in the chemical form of uranium hexafluoride (UF_6) in large cylindrical transportation casks, although some fuel fabrication facilities may receive the material directly as uranium dioxide (UO_2). These facilities subsequently convert the material into solid fuel. There are fuel fabrication facilities in many States, including the United States, Russia, and Japan. As of 2009, it was reported there were 94 total fuel fabrication facilities in operation, of which 73 were commercial facilities (IAEA, 2009). In 2009, the fabrication capacity was just under 16,000 t HM/year, which consists of light water reactors (LWR), heavy water reactors (HWR), and mixed oxide (MOX) fuel fabrication facilities.

The most common form of nuclear fuel today comes in pellets of UO_2, termed oxide fuel, which are typically 1 cm in diameter and 1 cm in height. These pellets are stacked in tubes of cladding material to form fuel rods. The rods themselves are then inserted into an assembly skeleton to make fuel assemblies. This type of fuel is used primarily in LWRs, specifically pressurized and boiling water reactors (PWRs and BWRs, respectively), which are the most prevalent power reactors around the world. New nuclear fuel forms are being designed and produced with the advent of advanced reactor designs. While the coated-particle design is not an innovation, it has recently become a keystone for advanced reactors, such as pebble-bed (PBR) and high-temperature gas reactors (HTGR) (Price, 2012). Currently, no commercial reactors use coated-particle fuels while several experimental reactors do.

2.2. History of Tri-structural ISOtropic (TRISO) Fuel Development

With the rise in advanced reactor R&D being pursued globally, several States are pursuing TRISO fuel technology. Demkowicz *et al.* have published a highly detailed report on the history of TRISO fuel and the nations interested in it (Demkowicz, et al., 2019). This report focuses on the Tri-structural ISOtropic (TRISO) fuel design, though there are many other coated particle designs. The TRISO fuel concept was at the heart of several high-temperature gas reactors (HTGR) designs starting in the late 1950s. The first concept of microspheres of fissile material was developed as part the British Dragon Project in 1959, also supported by the United States and Germany. The Dragon reactor was the first HTGR to achieve criticality in 1964 but was terminated in 1975 (Demkowicz, et al., 2019). The Dragon Project first demonstrated the feasibility of coated fuel kernels, though the initial kernels were coated with a single pyrolytic carbon layer contained in a carbonaceous matrix that formed the fuel compacts. The purpose of the layer was more so to protect the kernel than for neutron moderation or fission product retention. More complex fuel schemes were later introduced, such as Bi-structural ISOtropic (BISO) and eventually TRISO, which would become the dominant coated particle fuel type.

The first HTGR in the United States to produce electricity was the Peach Bottom Unit 1 nuclear reactor, which operated from 1966 to 1974. The reactor used a prismatic-core design. The reactor's first core was fueled by particles composed of single-layer U-Th carbide kernels coated in pyrocarbon. Unfortunately, the single-coated fuel particles did not perform as well as planned, due to the coating cracking and breaking. For the second core, BISO particles were implemented as fuel, and TRISO particles with various kernel types were irradiated in fuel test elements (Demkowicz, et al., 2019).

In 1967, Germany began operating the Arbeitsgemeinschaft Versuchsreaktor (AVR) which was the first PBR. The initial core loading consisted of thorium-uranium carbide kernel fuel formed into BISO particles. At first, the pebble fuel elements were injection molded and then machined into shape. Fuel prepared in this fashion continued until 1969 when the production process was changed to isostatic molding. TRISO particle fuel spheres were eventually included in core reloads in the 1970s until the reactor was shut down in the late 1980s (Demkowicz, et al., 2019).

Several variations in reactor design followed in the decades after the initial three designs, such as the Fort Saint Vrain reactor in the U.S. and the Thorium High Temperature Reactor in Germany. Other countries including Japan and China were concurrently researching coated particle fuel technology. In 1991, Japan began operating its High Temperature Test Reactor (HTTR), which employs a prismatic core with low enriched (LEU) UO_2 TRISO fuel particles. China researched both BISO and TRISO fuel technology in the 1970s and 1980s and eventually used TRISO particle fuel spheres for its first PBR, the HTR-10, which achieved first criticality in 2000 (Demkowicz, et al., 2019).

2.3. Countries Currently Pursuing TRISO Technology

2.3.1. China

Following the deployment of the HTR-10 reactor at Tsinghua University's Institute of Nuclear and New Energy Technology (INET), a consortium consisting of China Huaneng, the China National Nuclear Corporation, and Tsinghua University designed and constructed the high-temperature gas-cooled reactor pebble-bed module (HTR-PM) as a demonstration plant. The design consists of two 250 MW(t) pebble-bed SMRs, which are both connected to a single steam turbine to generate electric power. The core is expected to house 420,000 pebble fuel elements and, to supply the reactor, INET will fabricate 300,000 pebble fuel elements annually (Zhang, et al., 2009). Construction began in 2012 and key components of both reactors, such as the reactor pressure vessel and steam generator, were successfully paired and connected in 2020 (World Nuclear News, 2020). In 2020, the cores were loaded, and on September 12, 2021, the first unit achieved criticality (World Nuclear News, 2021). The plant is expected to be at full power operation by 2022, aligning with INET's schedule (Fu, 2020). Construction of 18 more HTR-PM units have been proposed, along with a scaled-up version consisting of a 600 MW steam turbine driven by 6 HTR-PM units, known as the HTR-PM600 (Polaris Power Network News Center, 2021). Additional schematics and technical details can be found in *Advances in Small Modular Reactor Technology Developments* from the IAEA (World Nuclear News, 2021). In 2017, China and Suadi Arabia signed a cooperative agreement for a joint feasibility study on the construction of HTGR reactors. (WNN, 2017)

2.3.2. Japan

Japan continued TRISO research following the startup of the HTTR. However, nuclear research and power faced severe setbacks following the events at the Fukushima Daiichi Nuclear Power Plant in 2011. After March 2011, the HTTR was shut down as all nuclear reactors in Japan were required to meet new regulatory standards (IAEA Country Nuclear Power Profiles, 2020). In 2020, the Japanese Atomic Energy Agency (JAEA) announced that the Nuclear Regulatory Agency authorized the restart of the HTTR. This marks the first restart authorization granted for a gas-cooled reactor in the Country (JAEA, 2020).

Japan is also pursuing SMR technology that will employ TRISO fuel. The 300 MW(e) Gas Turbine High Temperature Reactor (GTHTR-300) is a helium-cooled, graphite-moderated reactor with a hexagonal prismatic core composed of cylindrical TRISO fuel compacts stacked into fuel rods. The JAEA intends the technology to be ready for commercialization in the 2030s (World Nuclear News, 2021).

2.3.3. United Kingdom

The United Kingdom (UK) was a pioneer in developing coated particles and TRISO technology. A conceptual design gaining ground more recently is the U-Battery, an advanced/small modular High Temperature Reactor (HTR) from Urenco in the UK. The reactor core will be prismatic with TRISO particles in fuel rod compacts. Urenco plans to begin construction of the U-Battery in 2025 and operation in 2028 (World Nuclear News, 2021).

2.3.4. United States

U.S. TRISO fuel R&D carried on from the 1980s into the 1990s, where most of the efforts concentrated on UCO fuel kernels. However, all R&D ceased in 1993 following unsatisfactory results (Demkowicz, et al., 2019). In 2002, the U.S. Department of Energy (DOE) initiated a program to develop LEU UCO TRISO particles modeled after Germany's historic fuel developments. This program included the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program, which began at Idaho National Laboratory (INL) in 2002 (Demkowicz, et al., 2019). The AGR program involved five major program elements (EPRI, 2019):

1. Fuel Fabrication,
2. Fuel and Material Irradiation,
3. Fuel Post-Irradiation Examination (PIE) and Safety Testing,
4. Fuel Performance Modeling, and
5. Fission Product Transport and Source Term.

The fuel fabrication phase is complete, and irradiation and post irradiation examination (PIE) continues at INL (Demkowicz, 2017).

There are also currently several commercial projects of varying technology readiness levels that plan to use TRISO fuels in the United States. Many of these next generation reactor designs are small modular reactor (SMR) or microreactor designs, including the Xe-100 (X-energy), SC-HTGR (Framatome, Inc.), KP-FHR (Kairos Power), and the Westinghouse eVinci Micro Reactor (Westinghouse Electric Company LLC). These reactor designs will use TRISO coated particle fuels consisting of UCO or UO_2 kernels and will have either pebble-bed or prismatic cores, except for eVinci which will have a monolith or solid core. Note that monolith or solid cores are not covered further in this report. Another special variant is the micro modular reactor (MMR) from Ultra Safe, which will have a prismatic graphite block with fuel channels that can be filled with standard TRISO fuel compacts or TRISO Fully Ceramic Micro-encapsulated (FCM) fuel pellets in a silicon carbide (SiC) matrix. The MMR will be a once-through microreactor that will not be refueled, and plant operation is slated for 2026 (World Nuclear News, 2021).

Oak Ridge National Laboratory (ORNL) partnered with X-energy in 2016 to support X-energy's Pebble Bed Advanced Reactor project, which preceded the Xe-100 design (Helmreich, et al., 2017). The study was divided into four working groups: kernel fabrication, TRISO coating, pebble fabrication, and characterization. This led to X-energy developing its proprietary fuel, TRISO-X, for commercial sale. The expertise and knowledge gained by X-energy through ORNL was instrumental to the development of their own pebble-bed SMR, the Xe-100 (Helmreich, et al., 2017). Currently, X-energy also operates a TRISO-X fuel fabrication pilot line at ORNL and reported full production sized fabrication equipment (Patel, 2021).

2.3.5. Other Countries

Other countries that are pursuing coated particle-based designs include but are not limited to South Africa (PBMR-400, HTMR100), France, Canada (STARCORE), Russia (GT-MHR), Republic of Korea, Indonesia (RDE-Micro Pebble), and Czech Republic (Energy WellTM) (World Nuclear News, 2021).

2.4. TRISO Fuel

TRISO spherical fuel pebbles consist of nuclear fuel kernels surrounded by four isotropic layers of materials to form the "coated particles". The primary purpose of the layers is to maintain fission product isolation and provide structural integrity under extreme heat (Koster, 2003). The coated particles are then embedded in a graphite matrix to form the fuel spheres or fuel "pebbles". A diagram of the kernel, coated particle, and spherical pebbles is shown in Figure 1. The coated fuel design is the technological basis for HTGRs, such as the PBR and the Advanced Gas-cooled Reactor (AGR). In these reactor concepts, the spherical "pebbles" are fed into the reactor vessel in a geometry to reach criticality. The fuel circulates continuously during reactor operation, and fresh fuel pebbles can be loaded into the containment vessel's top, while used fuel pebbles are removed from the bottom once they achieve the desired burnup. Depending on the particular concept, a pebble may be recirculated up to ten times, but must pass inspection prior to each reuse. X-energy, for example, states the Xe-100 will recirculate the pebbles up to six times (DOE, 2021). The reuse of pebbles is why PBRs do not require long reactor shutdown for refueling and may operate continuously (Koster, 2003). Note that online refueling does introduce safeguards concerns that are not present in current LWR designs, though some reactors such as the Canadian CANDU and the Russian RBMK have demonstrated online refueling capabilities.

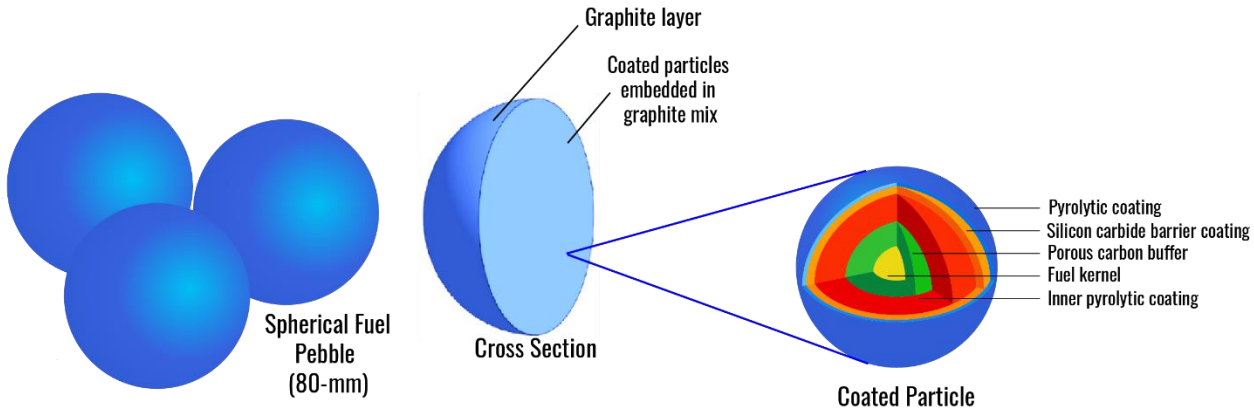

Figure 1. Spherical fuel pebble and cross-section (left), coated particle showing kernel and layers (middle), and fuel kernel (right).

In contrast to the TRISO pebbles, the AGR utilizes a prismatic-core design, in which the TRISO coated particles are embedded in a graphite matrix and formed into cylindrical compacts; these compacts are then inserted into fuel channels of prismatic hexagonal graphite block fuel elements, which are, in turn, stacked in the reactor pressure vessel. In addition to the prismatic-core design, it is worth noting that cylindrical TRISO fuel compacts can theoretically be used to fuel traditional LWRs as well. In this scenario, they are dimensionally equivalent to traditional oxide fuel pellets and would be inserted into fuel rods.

Note that for either TRISO pebbles or compacts, the kernels may contain fissile material, such as LEU, or fertile material, such as thorium or uranium-238. Kernels comprised of fertile materials may also be used for breeding blankets. The various types of TRISO fuel materials researched to date include:

- Fissile: UC_2, PuO_2, $(Th,U)C_2$, $(Th,U)O_2UO_2$, UCO,
- Fertile: ThC_2, ThO_2, UO_2, UCO

These nuclear materials may also be combined to create mixed-oxide (MOX) fuel, such as a homogenous mixture of plutonium dioxide and depleted uranium dioxide (PuO_2 + $^{238}UO_2$), plutonium dioxide and thorium dioxide (PuO_2 + ThO_2), or a mix thereof (PuO_2 + $^{238}UO_2$ + ThO_2). This study focuses on the UCO and UO_2 fuel kernel types, one for a model fuel pebble fabrication facility (herein referred to as Facility A) and another for a model fuel compact fabrication facility (herein referred to as Facility B), respectively. Special variants of other kernel types under development are noted in Appendices C and D.

3. International Safeguards Approaches

The following section provides an overview of the current international safeguards regime and relevant practices for safeguarding nuclear fuel fabrication facilities. Given the current techniques have largely been applied to and implemented in LWR oxide fuel fabrication facilities, this study draws conclusions on the applicability of these techniques to TRISO fuel fabrication and provides recommendations therein.

The purpose of international safeguards is to ensure the peaceful application of nuclear materials and activities. For non-nuclear weapon states party to the Nonproliferation Treaty (NPT), a Comprehensive Safeguards Agreement (CSA) enables a State to verifiably demonstrate proper declaration of all nuclear material and activities and that such activities are peaceful in nature. The IAEA's safeguards goals under a CSA are to be able to 1) detect diversion of declared nuclear material, 2) detect undeclared production or processing of nuclear material at declared facilities, and 3) detect undeclared nuclear material or activities in the State. At the facility level, comprehensive safeguards include the following elements:

- Nuclear material accountancy (NMA) and verification – State reports information on nuclear material inventories and movements, and the verification of that information through facility inspections conducted by the IAEA;
- Design information verification – the reporting of information on the facility's design and characteristics, and verification of that information by IAEA inspectors; and
- Containment, surveillance, and monitoring – nuclear material control (NMC) measures to maintain a continuity of knowledge (CoK) on nuclear material and activities to facilitate verification efforts.

Application of these measures is determined by subsidiary arrangements between the State and the IAEA. The frequency and intensity of safeguards measures are determined by various factors such as the quantity, throughput, type, and form of material present in the facility. For example, bulk material that may be found at fuel fabrication facilities generally requires more intensive verification measures, including taking samples for destructive analysis, as compared to item-type facilities where discrete items can be counted and measured without sampling for destructive analysis. NMA is accomplished by dividing a facility into one or more material balance areas (MBA), where the quantity of material transferred in and out, as well as the overall physical inventory, can be determined. Key measurement points (KMPs) are established where either the flow or inventory of material can be readily measured; these may be at transfer points in between MBAs or within an MBA. Measurements taken by inspectors are designed to accomplish three detection goals: gross defect detection (diversion of whole items or batches), partial defect detection (diversion of a substantial fraction of an item or batch), or bias defect detection (diversion of a small portion of material in a flow stream, over a protracted timeframe). For large bulk facilities, bias defect detection is particularly challenging because it can be difficult to distinguish from other sources of material unaccounted for (MUF), such as measurement uncertainty or holdup.

TRISO fuel presents a more complex safeguards challenge than LWR oxide fuel. While containing only small amounts of nuclear fuel in individual pebbles, TRISO fuel is more portable and concealable than an LWR fuel rod or assembly. In accordance with IAEA guidance, each piece or container of nuclear material is an item of discrete quantity, separate and individually distinct, the presence and integrity of which must be verified for NMA purposes. Nuclear material control and accountancy (MC&A) practices aim to ensure the timely detection of material diversion. Facilities employ a robust MC&A system to assist in detecting misuse of facility equipment or processes and as a deterrent against diversion activities. Preventing

protracted diversion with or without non-fuel substitutions over an extended timeframe is one of the main safeguards challenges for fuel fabrication facilities where fuel elements may be loose, pocket-sized items. In the instance of TRISO fuel kernels, compacts, or pebbles, it must be noted that multiple attempts would likely be necessary to obtain what is considered a significant quantity of nuclear material by current domestic and international definitions (Kovacic, et al., 2020). Nevertheless, significant quantities are taken into consideration for timeliness goals, because any quantity of diverted nuclear material is considered unacceptable. This aspect shall be further discussed Sections 4 and 5 of this report.

3.1. Material Balance Areas and Material Accountancy

The IAEA defines an MBA as an area where (a) the quantity of nuclear material in each transfer into or out of the MBA can be determined and (b) the physical inventory of nuclear material can be determined (IAEA, 2001). In fuel fabrication facilities, MBAs can be differentiated by the chemical form of the material. The drawing and assignment of MBAs vary by facility and may differ by number and/or layout to accommodate facility operations, material flow, and storage (in bulk or item form); this provides facilities flexibility in meeting IAEA material accountancy goals. In general, a fuel fabrication plant with a single process line may employ three or more MBAs (Pillay, et al., 1987). A single MBA for the entire facility may also be used in conjunction with sufficient KMPs for flow and inventory (IAEA, 2017). As material is transferred into and out of MBAs, the facility can define locations for the KMPs where material flow measurements can be taken, using equipment such as pellet counters. They may also define KMPs where inventory measurements can be taken, using equipment such as load cells for gravimetric measurements.

3.2. Key Measurement Points

KMPs are locations where nuclear material is measured to determine material flow or inventory. KMPs are vital to safeguarding facilities and allow for NMA without disrupting facility operations (IAEA, 2001) (IAEA, 2008). The placement of KMPs (and, in essence, MBA definitions) also relies on the accuracy of chosen measurement systems to ensure minimal uncertainty in the material quantification measurements (as defined by IAEA's International Target Values). In fuel fabrication facilities, KMPs must be placed in between MBAs, which are referred to as flow KMPs and contribute to reducing overall uncertainty. Inventory measurements, taken where material is not in movement, such as in material storage locations, are known as inventory KMPs.

3.3. Containment and Surveillance

As part of an effective NMC approach (which complements NMA techniques), containment and surveillance (C/S) measures are crucial when defining MBAs and KMPs. C/S supports CoK as material moves through a facility and prevents undetected access to nuclear material or undeclared facility operations. Facilities are responsible for the material in their possession, but the IAEA must independently ensure that CoK is maintained. The major restriction applied to C/S measures is that they cannot interfere with or disrupt a facility's normal operation and material flow (IAEA, 2001).

Containment can be accomplished with locks and seals. Locks prevent unauthorized access, while seals indicate unauthorized access or entry. Locks and seals can be found on IAEA monitoring equipment, stored nuclear material, or even specific facility equipment. Seals, such as a tamper-indicating devices (TID), do not provide the same security as locks, but they are designed to indicate if an item or material has been accessed. Thus, a system of locks and seals deny and deter malicious access, respectively. TIDs come in two varieties: passive and active. Passive TIDs require no source of power but cannot indicate the exact time of access. They can, however, provide a window of time corresponding to an inspection schedule.

Passive TIDs may include adhesives, cap seals, pull-tight seals, etc. A comprehensive list of relevant C/S equipment can be found in the IAEA Safeguards Techniques and Equipment handbook (IAEA, 2011). Conversely, active TIDs require a form of power, either external or internal. Active TIDs may be limited in deployment by distance from a power source or battery lifetime. However, active TIDs may precisely detect time of access and could be connected to an alert or alarm system. Regardless of the seal type, they must all be regularly inspected and evaluated for integrity and be uniquely identifiable. These measures may also be applied to prevent tampering of safeguards equipment used for MC&A purposes, such as load cells for monitoring material quantities, video surveillance equipment, and other measurement devices.

3.4. Non-Destructive Analysis and Destructive Analysis

Material content of the fuel may be verified by the facility operators at any time by sampling the fissile content of the container or taking a sample from a container prior to sealing and shipment. The goal is to ensure special fissionable material quantities align with facility declarations and that diversions with or without substitutions did not occur. Random sampling of material informs the detection bias, which may occur if small amounts of material were diverted over time. Thus, applying physical and chemical analysis techniques ensures the best possible accuracy.

Techniques used for non-destructive analysis (NDA) by IAEA inspectors include a wide range of gamma spectrometers, and passive and active neutron counters. Specific equipment is dictated by the fuel characteristics, such as size, geometry, and radionuclide content; the allotted space capacity within the facility; and the available power source (IAEA, 2011). NDA equipment may have large geometries and be capable of running continuously for active monitoring or smaller for on-site verification. Samples of fuel may also be retained from a container by inspectors for destructive analysis (DA) in a laboratory setting. These samples can be measured for elemental and isotopic composition. Although DA provides a more accurate report, it requires extensive time and resources while NDA may be conducted in-situ at the facility. Detailed descriptions of NDA and DA equipment and techniques may be found in the IAEA Safeguards Techniques and Equipment guidance (IAEA, 2011).

3.5. IAEA Timeliness Detection Goals

One of the goals of the IAEA and international safeguards is the timely detection of material diversion and/or facility misuse. The techniques and tools described in this section contribute to high detection probabilities. The IAEA has targeted detection times for detecting material diversion based on material categories (IAEA, 2001):

- One month for unirradiated direct use material,
- Three months for irradiated direct use material,
- One year for indirect use material.

Direct use material is defined as, “nuclear material that can be used for the manufacture of nuclear explosive devices without transmutation or further enrichment.” Indirect use material is all material except direct use material (IAEA, 2001). The detection goals are used for establishing the frequency of inspections and safeguards activities at facilities. For the reference oxide facility outlined in Section 4 of this report, the nuclear material present – LEU UO_2 – is considered indirect use material because of its low enrichment level (up to 5% for LWR fuel). Therefore, the IAEA would develop a safeguards approach to detect the diversion of one significant quantity or more of material within a calendar year.

4. Model Fuel Fabrication Facilities and Safeguards Approaches

This section examines a safeguards approach for a traditional oxide fuel fabrication facility, termed the "reference" facility, as a point of comparison for the anticipated safeguards needs of two hypothetical TRISO fuel fabrication facilities, which are described in Section 5 of this report. The first model TRISO fuel fabrication facility, termed Facility A, produces pebble fuel from UCO kernels, while the second model facility, termed Facility B, produces compact fuel from UO_2 kernels.

4.1. Reference Facility: Oxide Fuel Fabrication

Uranium oxide (UO_2) fuel fabrication for traditional LWR fuel is composed of the following steps: pellet fabrication, fuel rod fabrication and pellet insertion, and fuel assembly skeleton fabrication and fuel rod insertion. The initial conversion of uranium powder into fuel involves several pretreatment steps, including hammer milling, blending, and bulk rolling. The resulting powder is then cold pressed into pellets, sintered, ground to finished dimensions, and washed and dried (optional), before undergoing final inspection (Nuclear Regulatory Commission, n.d.). The pellets are then loaded in fuel rods, and the rods are sealed, welded, and inspected. Finally, the fuel rods are inserted into the fuel assembly skeleton, and the assemblies undergo inspection. Further details on the full fabrication process and a material flow diagram may be found in Appendix B.

4.2. Safeguards in the Reference Facility

This section outlines a traditional safeguards approach for the reference oxide fuel fabrication facility in a State under a comprehensive safeguards agreement (CSA) in place. As the current techniques were developed to safeguard oxide fuel fabrication, the reference facility illustrates the techniques in practice and will give context to the discussion on safeguarding the model TRISO fuel fabrication facilities in Section 5. An illustration of the reference facility floor can be seen in Figure 2.

4.2.1 Material Balance Areas

The floor plan is drawn for the purposes of this study only and shows a simplified MBA diagram. The dashed boxes indicate MBAs, and the diamonds indicate KMPs. The arrows show the flow of material through the facility. For the reference facility, one MBA was drawn for each of the following processes:

1. Storage areas
2. Processing area including conversion and pellet fabrication
3. Processing area for fuel rod and fuel assembly fabrication
4. Storage for fuel pellets and/or fully fabricated fuel assemblies

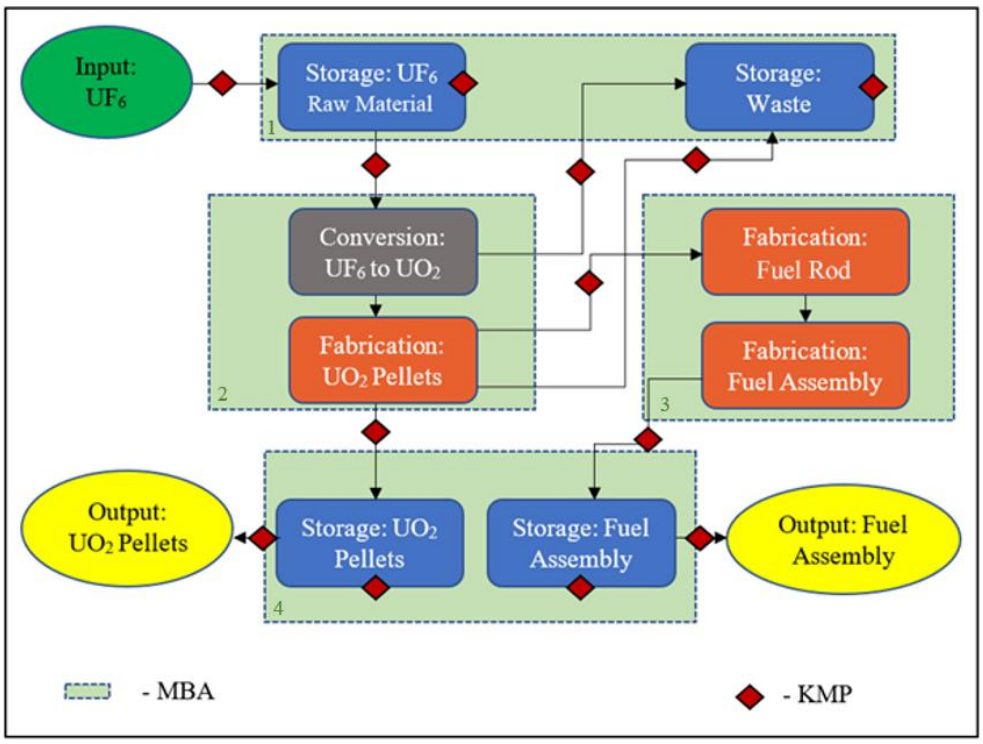

Figure 2. Sample diagram of MBA distribution for a Reference Fuel Fabrication Facility.

The division of MBAs into separate "processing", "insertion", and "storage" areas are designated such that appropriate C/S measures may be implemented to track the nuclear materials in various forms where they may be distributed and/or stored (Pillay, et al., 1987). UF_6 is typically received in large 48Y cylinders that can hold over 10,000 kg of material each (USEC, 1995). The raw material is stored in MBA 1 until it is transferred to MBA 2 for conversion. NMA measures applicable to the reference facility include weight and volume determinations of bulk nuclear material. All measurements involve uncertainties, thus calculations for MUF may be conducted in MBA 2 to ensure any material lost during processing is statistically within the limits of the facility and in accordance with safeguards requirements. Factors that contribute to the error may include scrap, waste, and material deposited within equipment during processing, known as hold-up. These contribute to a non-zero MUF value (where a zero value indicates the material measurements at the beginning and end of processing are equal). Magnitude and variability of MUF depends on uncertainty of the measurement systems, and the amount of material lost to the process or waste (IAEA, 2017). Statistically unacceptable MUF values in the reference facility and other fuel fabrication facilities may indicate material diversion.

Waste material from the conversion and pellet fabrication processes are sent back and stored in MBA 1. Following the fabrication of the UO_2 pellets, they may be placed in trays or cans for quality control inspection and/or subsequent insertion into fuel rods, depending on the layout and process of a particular facility. For the Reference facility, it is assumed the trays/ cans of whole pellets are transferred to MBA 3, where they are stacked and inserted into zirconium alloy cladding tubes. These tubes are pressurized with inert helium gas and sealed to create the final fuel rods. The fuel rods are then inserted in a specialized assembly skeleton to create the final fuel assemblies. Afterwards, the fuel assemblies are sent to MBA 4 for storage until they are ready to be shipped to reactor sites. Pellets not designated for insertion in fuel

rods may also be transferred into MBA 4, where they are weighed and collected for direct shipment to customers.

4.2.2. Key Measurement Points

For the reference facility, there are nine flow KMPs placed where material enters or leaves MBAs and 4 inventory KMPs where material is counted, for a total of 13 KMPs as seen in Figure 2 and Figure 3. KMPs can employ NDA, such as gamma and neutron spectrometry, or gravimetric measurements.

4.2.3. Containment and Surveillance

With its four MBAs and multiple KMPs, the reference facility has many locations where C/S equipment and techniques can be used. Surveillance systems (i.e., cameras) are placed between MBAs to facilitate CoK by providing additional means to detect undeclared access to, or movement of, nuclear material across the reference facility floor.

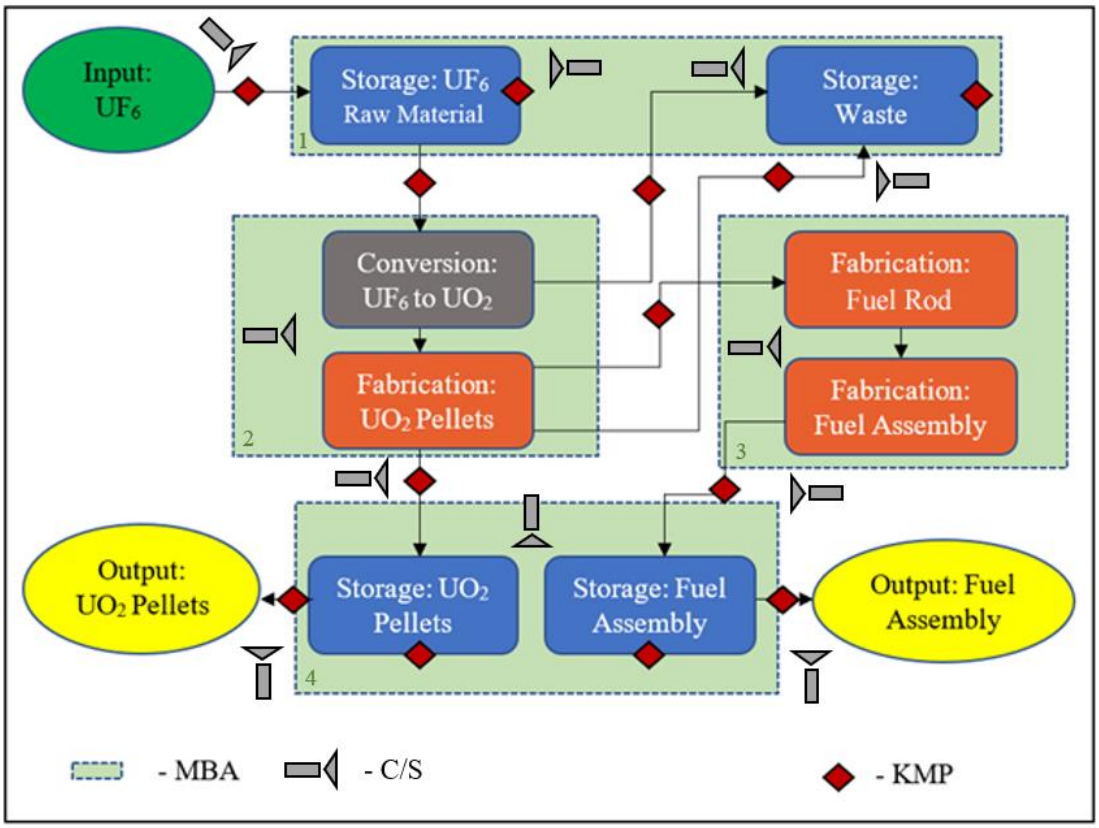

Figure 3. Reference Fuel Fabrication Facility layout with some C/S measures (surveillance).

Other equipment including radiation monitors, sensors, remote and unattended monitoring systems can be employed as well (as described in Table 1 below). Placement of surveillance and monitoring equipment depends on the layout of the facility. Surveillance equipment can be set up to transmit data in real time back to IAEA headquarters or a regional office, allowing for remote monitoring. Alternately, data may be stored onsite in equipment that can only be retrieved by IAEA inspectors. Ideally, surveillance and unattended monitoring systems can be used to detect and track material movement while also recording access to material and/or equipment for CoK. Figure 3 shows potential locations of surveillance equipment at the reference facility, in addition to the MBA layout. Note that the other C/S measures

mentioned are not depicted in Figure 3. An additional C/S measure that a facility will likely need to deploy, is sealing the final product with a TID, such as an adhesive seal, to ensure CoK is maintained until receipt by the customer.

Table 1 compiles a list of possible specialized equipment that may be utilized by the IAEA in such a facility. Further equipment lists and details regarding usage can be found in the IAEA Safeguards Techniques and Equipment handbook (IAEA, 2011).

Table 1. Safeguards Equipment for Reference Fuel Fabrication Facility

Equipment Name (Code)	Description/Application
Load cell-based weighing system (LCBS)	Measures weights of bulky objects like UF_6 shipping cylinders
3-D laser range finder (3DLR)	For design information verification (DIV) activities, to confirming no structural changes have occurred since the previous scanning, verifying the facility is constructed as declared and remains unchanged.
Portable pressure measurement Device (PMMD)	Measures volumes of solutions in storage and process tanks
Digital Multi-camera Optical Surveillance System (DMOS)	Multiple camera surveillance system for up to 16 cameras with remote monitoring capability
All in one surveillance system (ALIS)	Mains powered, single camera for installation in easy to access locations
Uranium neutron coincidence collar (UNCL)	Active neutron coincidence counter in collar configuration for verification of ^{235}U in fuel assemblies.
Waste crate assay system (WCAS)	Verification of waste materials
Improved adhesive seal (VOID)	Commercial sealing tape that cannot be removed without destroying the seal
Glass Seal (N/A)	Single use TID
Fiber optic general-purpose seal (FBOS)	In situ verifiable fiber optic seal

5. Model TRISO Fuel Fabrication Facilities

As discussed previously, there are many fuel variations for HTGRs. To illustrate the applicable safeguards approaches for TRISO fuel fabrication, two model facilities are discussed as representative of most fuel fabrication processes and methods being used or considered to be deployed globally. Facility A is a model pebble fuel fabrication facility where the TRISO particles are composed of UCO and shaped into spherical pebble fuels. Facility B is a model compact fuel fabricator that shapes UO_2 kernels into cylindrical compacts that may then be inserted in graphite element blocks.

5.1 Facility A: Pebble Fuel Fabrication

Facility A is modeled after BWXT's fabrication process for the UCO TRISO fuel employed for the AGR-2 fuel performance irradiation campaign of the U.S. DOE AGR Fuel Development and Qualification Program (EPRI, 2019). There are three main steps to the fabrication process: kernel fabrication, coating deposition to create TRISO particles, and spherical fuel pebble fabrication. A more comprehensive description of the fabrication process can be found in Appendix C. The kernels of each TRISO fuel element are composed of a mixture of UO_2 and UC to create UCO (approximately 90% U by weight). Through a process known as spherification, UCO kernels are formed then sintered to increase the density. The diameter of each kernel varies from 300 µm to 500 µm depending on the process/facility. As most kernel fabrication facilities have been laboratory-scale, this process has typically been performed via batch processing and for relatively low throughputs. States, such as China, are now moving to commercialize this technology, which includes continuous processing capabilities. Note that the waste streams for kernel fabrication are not well understood at this stage; as a result, discussion of waste streams is not included further in this report but should be evaluated once information is more readily available.

Following calcination, the kernels are enclosed in four layers of ceramics through chemical vapor deposition (CVD) to ensure each layer is consistently applied. These layers typically include the buffer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC) layers. The layers of the coated fuel kernel and respective thicknesses can be seen in Figure 4. Note that although this reflects the more commonly used layers for TRISO fuel, there is also work underway on other outer layers, such as ZrC, to better withstand higher burnup conditions.

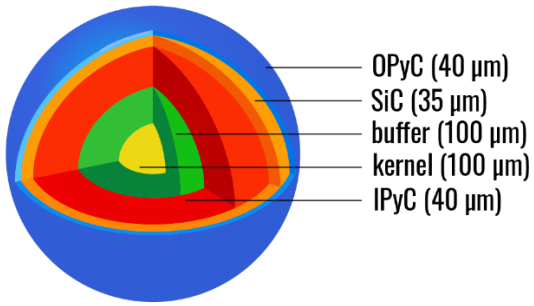

Figure 4. Cross section of a TRISO particle showing kernel and thickness of the layers (not drawn to scale).

To form the pebbles, the TRISO particles are overcoated with resinated graphite. The overcoated particles are then poured into spherical pebble molds to form an internal fueled zone. Additional matrix material is added to form a fuel-free outer shell around the fueled zone using a final high pressure molding process. The small fuel-free zone of approximately 5 mm acts as an extra barrier for possible fission product release

and protection during transportation. Figure 5 shows a cross sectional slice of a fuel pebble, including both the coated particle, graphite matrix, and fuel-free graphite outer shell.

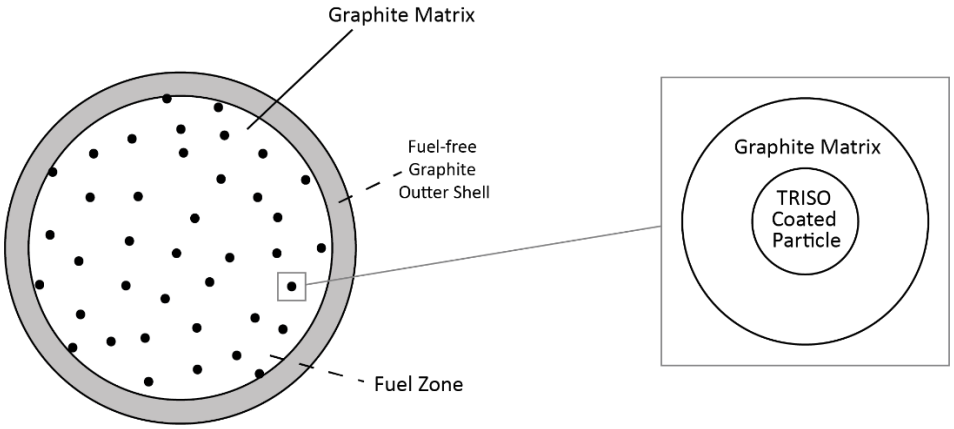

Figure 5. Cross section of a pebble fuel sphere showing fuel-free zone and embedded TRISO particles.

Along with developments in the latest Generation IV reactor technologies, continuous R&D in the TRISO fuel space has led to the development of special variants to the kernel design. These variants focus on kernels composed of UN, which have higher theoretical densities than UO_2 and UC/UCO kernels. Fabrication processes of these fuel variants are similar to the UO_2 and UC/UCO kernel process, and further discussion of fuel variants can be found in Appendix C.

5.2. Safeguards in Facility A

Much like traditional oxide fuel fabrication facilities, TRISO facilities will require a heavy focus on MC&A, but coated particle fuels will also require other unique safeguards methods, as they are not serialized items that are subject to visual inventory accountancy methods. Key differences between Facility A and the reference facility rely on the unique MC&A measures that are necessary to deter and detect unauthorized removal of TRISO fuel.

5.2.1. Facility A: Suggested Material Balance Areas

Figure 6 illustrates the Facility A floor plan and conveys proposed MBAs. The MBA layout is nearly identical to the layout of the reference facility, with the major difference being the consolidation of the reference facility MBA 2 and MBA 3 into a single Facility A MBA 2, resulting in a total of three MBAs. Since the TRISO pebble fabrication is one continuous process, all the fabrication steps are represented in one MBA. An excessive number of MBAs, including the necessary KMPs or C/S to support MC&A would interrupt the process and prove difficult to implement due to the nature of the fabrication process. MBA 1 contains raw UF_6 material that is received by the facility, as well as any waste generated in the fabrication process. MBA 2 starts with the raw material, which is converted to kernels. The kernels are then coated to form the TRISO particles. These particles are, in turn, coated and formed into the spherical pebble forms. Unlike the reference facility, Facility A does not involve grinding of fuel material that generates scrap and holdup.[1] Therefore, reliance on MUF calculations for verification may not be as significant. Dedicated instruments and unattended monitoring may be more effective instead (IAEA, 2017). However, note that

[1]Fuel material holdup is still a possibility in the fabrication facility (in stages such as the extrusion process in nozzles or other equipment) but details regarding the waste stream are unclear and the exact impacts on safeguards techniques cannot be determined at this time.

the detailed waste streams from kernel fabrication are not fully understood at this stage and may warrant future evaluation.

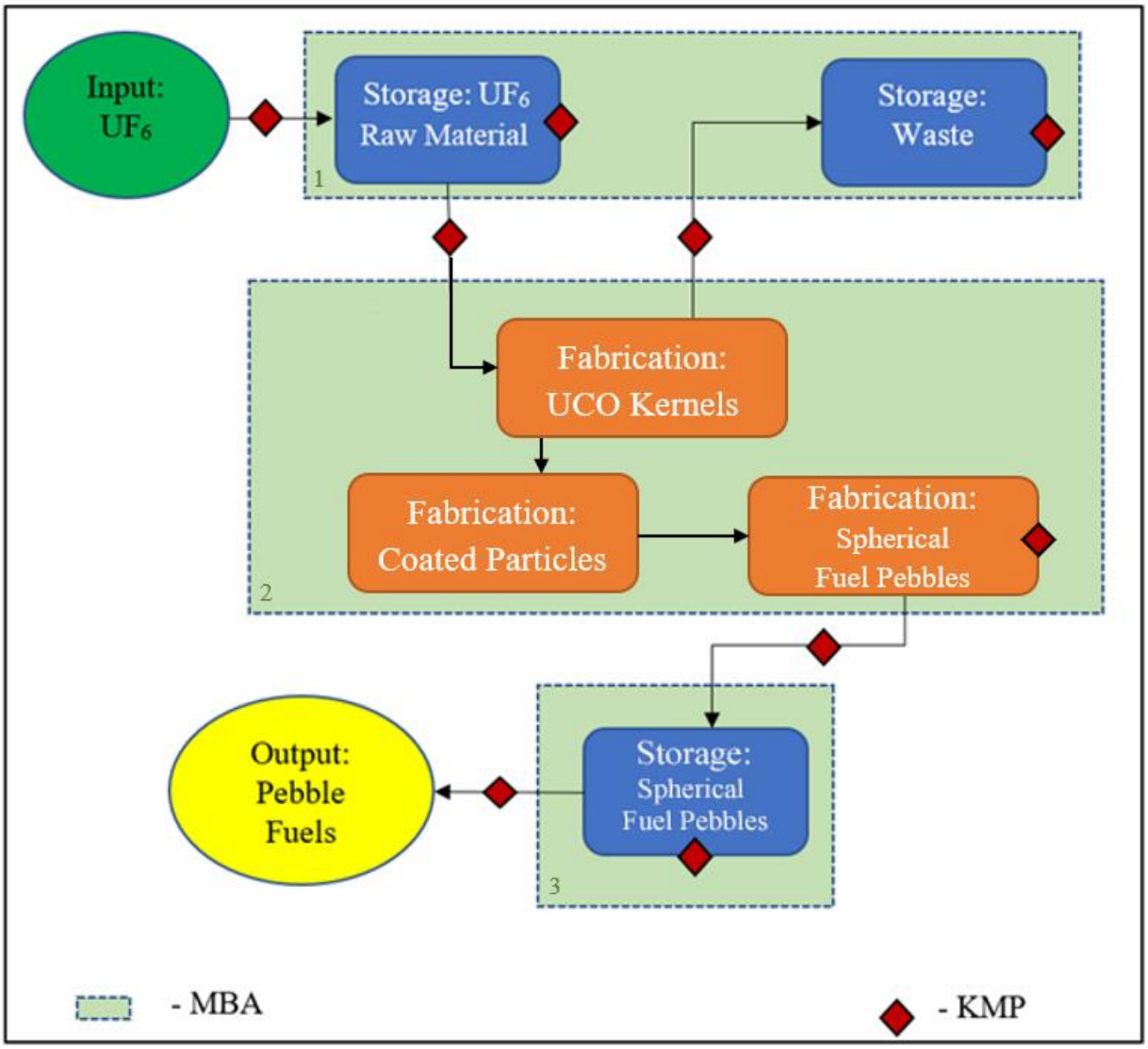

Figure 6. Sample diagram of MBA distribution for a TRISO Fuel Fabrication Facility A.

The final spherical pebbles are packaged and sent to MBA 3 prior to shipment. Contrary to the reference facility where the final product may contain customer-requested fuel assemblies comprised of fuel rods with varying enrichments and/or additives (e.g., gadolinia), Facility A's only stored product would be fuel pebbles, thus potentially simplifying material accountancy therein.

5.2.2. Facility A: Suggested Key Measurement Points

Placement of KMPs in Facility A follows the same guidelines as those proposed for the reference facility, namely pathways between MBAs and material storage locations. As there are fewer MBAs for this facility, there are also fewer KMPs, compared to the reference facility, for a total of nine. However, each KMP may also include pebble fuel inventory counting combined with weight measurements at KMPs, rather than relying on weight measurements alone. Whether fuel pebbles are considered individual items or bulk

items (by drum) has still yet to be established by the IAEA and further discussion is necessary. At this time, fabrication facilities declare fuel inventories by drum which can be verified by IAEA inspectors at the shipping facility and at the receiving facility (i.e., the pebble bed reactors or the customer) by weighing selected drums to confirm bulk pebble weight (Durst, et al., 2009). For Facility A, raw material moving into and from MBA 1 may be considered bulk material that is weighed (individually per container), while fuel material already integrated into the final spherical fuel pebbles may be considered singular items that are identified and counted in MBA 2. Final storage in MBA 3 would have a known quantity of material and a specific number of fuel pebbles that would be declared before shipment. As such, an emphasis on inventory KMPs is necessary for Facility A. Visual inspection of the TRISO pebbles is crucial to detect tampering or diversion. It is noted that visual inventory of TRISO pebbles may lead to counting errors that are likely to include measurement mistakes, recording errors, and other factors that would impact the uncertainty of inventory accounting.

5.2.3. Facility A: Suggested Containment and Surveillance Measures

C/S measures for Facility A, shown in Figure 7, should be selected following the guidelines stated in the IAEA Safeguards and Techniques handbook (IAEA, 2011). Similar to the materials of the reference facility, all product leaving Facility A would be sealed within containers with a TID to ensure CoK is maintained until receipt by the customer. TIDs could also be applied to measurement devices to prevent tampering. Some equipment that may be used for KMPs and C/S in Facility A are comparable to what was presented for the reference facility in Table 1. Further actions for CoK may include reviewing MC&A records of inventory detailing the number of TRISO pebbles and weight measurements, as well as C/S measures applied to inventory equipment to prevent tampering.

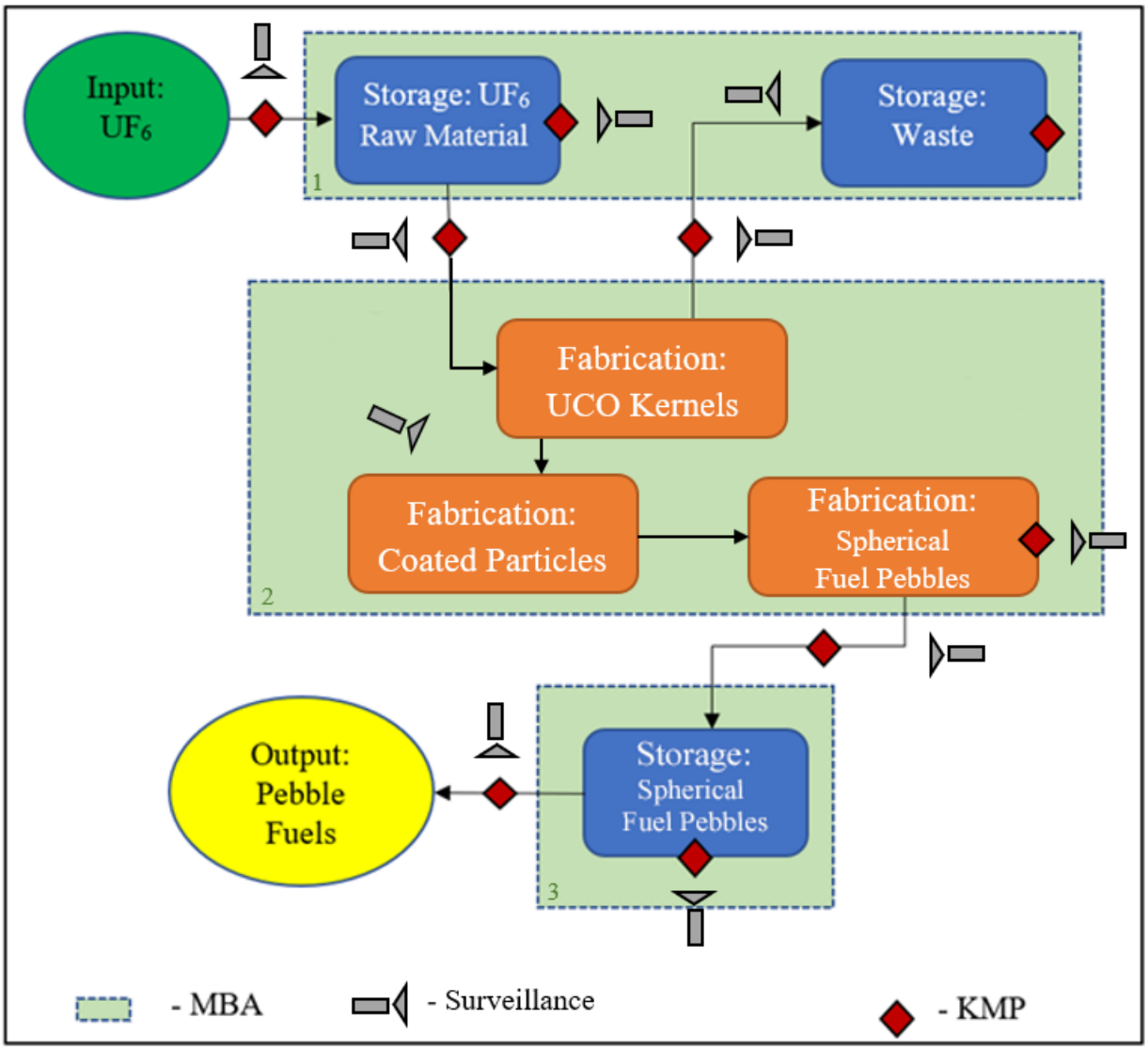

Figure 7. TRISO Fuel Fabrication Facility A layout with some C/S measures (surveillance).

5.2.4. Facility A: Suggested Non-Destructive Analysis and Destructive Analysis Methods

The most significant challenge to safeguarding Facility A is that the coated particles and final spherical pebbles may produce different radiological signals than traditional fuels depending on composition and the ceramic layers. The TRISO fuel pebbles of Facility A differ from the traditional pellets of the reference facility such that the overall composition is non-homogenous (layers of ceramic surrounding the fuel kernel and the inclusion of a graphite matrix).

For TRISO pebble fuel fabrication, the traditional NMA approaches are theoretically applicable but have not been tested at this time and will require verification. Fresh fuel pebbles are each designed to have specific quantities of fissionable material, and any uncertainties are meant to be identified and addressed by product inspection (Kovacic, et al., 2020). A sample from the container may be subjected to NDA measurements to verify the fissile content. Any measurements that exceed the declared uncertainty may indicate protracted diversion with or without substitutions with non-nuclear material. Frequent and

random sampling is key to developing an accurate and informed measurement uncertainty value, in order to not further contribute to the facility's MUF. However, NDA and DA are resource intensive efforts that require time and inspectors. The need for accuracy in verification to prevent protracted diversions throughout the fuel fabrication process is balanced against efficiency and timeliness.

5.2.5. IAEA Timeliness Detection Goals

The timely detection goal for TRISO Facility A would be one year, as the material present would be considered indirect use (IAEA, 2001).[2]

5.2.6. Facility A: Conclusions

Safeguards techniques traditionally applied to LWR oxide fuels may also be applicable to certain aspects of Facility A. Of the existing safeguards techniques, this study found that material accountancy is most applicable to pebble fuels as the size of TRISO pebbles is suitable for physical counting. Limited material holdup throughout the facility and the lack of information regarding fabrication waste treatment indicate that MUF verification may be less effective for Facility A. Lastly, NDA and DA techniques are theoretically applicable to TRISO pebble safeguards but require verification through testing. Considerations for special fuel variants, and the fact that NDA and DA are both resource intensive processes must be considered prior to drawing conclusions on the techniques' efficacy for Facility A.

5.3. Facility B: TRISO Fuel Compact Fabrication

Facility B is modeled after BWXT's fabrication process for the UO_2 TRISO fuel employed for the AGR-2 fuel performance irradiation campaign of the U.S. DOE AGR Fuel Development and Qualification Program (EPRI, 2019). The three main steps to the fabrication process are nearly identical to those described for Facility A, but the final form is that of a cylindrical compact for insertion into graphite blocks, rather than a spherical fuel pebble. The steps include kernel fabrication, coated particle fabrication, fuel compact fabrication, and fuel element block fabrication and are displayed in Figure 8.

Figure 8. TRISO fuel kernels (Left), cylindrical fuel compacts (Center), fuel element blocks that will hold fuel compacts (Right) (General Atomics, n.d.)

The UO_2 kernels are formed and coated through the same process as described previously for UCO kernels, with composition differences during spherification and calcination (UO_2 does not require carbon black prior to spherification). The UO_2 kernel will be approximately 88% uranium by weight and vary in

[2] If Facility A were to include plutonium-based MOX fuel fabrication in its repertoire, that detection goal would be reduced to one month.

final diameter depending on the enrichment content and facility. Detailed description of the fabrication process can be found in Appendix D.

Rather than spherical molds, Facility B employs cylindrical dies to form compacts. Fuel-free resinated carbon is poured into the mold first, followed by UO_2 kernels, then another layer of resinated carbon. These fuel free regions act as end caps for the compacts, which are then formed into the desired shape depending on the prismatic fuel block requirements. The TRISO fuel compacts are similar in shape to LWR oxide pellets and can be placed into traditional fuel rods and used in existing LWRs or used to fuel future advanced reactors. Final oxide pellets are approximately 1 cm in height while TRISO fuel compacts are approximately 2 cm in height. Note that Facility B focuses on fuel compacts for insertion into graphite element blocks for prismatic-core reactors.

The prismatic fuel element block includes channels for fuel compacts to be loaded, a process which is similar to the UO_2 fuel rod loading for LWR assemblies. For General Atomics' Prismatic Modular HTGR design, prismatic hex-blocks measuring 360 mm from face-to-face and 793 mm in height were used. Each fuel element/block held 210 fuel compacts. In total, the core had a fuel region consisting of 66 columns, 10 blocks high arranged in an annulus configuration that equated to over 4000 kg of uranium in the initial core loading (General Atomics, n.d.). Note that this report does not provide details on the processes for fabricating the graphite element blocks but does include this process at a very high-level for the benefit of discussing the overall safeguards approach.

The emergence of TRISO fuel technology has also prompted much R&D activity in the fuel compact space. This has quickly led to the development of special fuel variants such as zirconium carbide (ZrC) kernels or silicon carbide (SiC) in fully ceramic microencapsulated (FCM) fuel. The fabrication process for these special variants differ from what was described for UO_2 fuel compacts in Facility B. While this study continues to focus on UO_2 fuel compacts, future safeguards studies may be necessary to encompass these alternative variants.

5.4. Safeguards in Facility B

The TRISO fuel compacts produced in Facility B are similar shape and size to the oxide pellets of the reference facility; therefore this study found a combined safeguards approach from the reference facility and Facility A to be most applicable to Facility B. Emphasis on MC&A procedure is still important to prevent protracted diversion of fuel, but the size of the fuel compacts presents concerns similar to those in both Facility A and the reference facility, in terms of inventory and visual inspections. As a result, Facility B may rely on a safeguards approach akin to those of the reference facility and apply methods of bulk counting prior to forming fuel compacts or loading of the fuel element blocks.

5.4.1. Facility B: Suggested Material Balance Areas

The MBA layout for TRISO Facility B, as shown in Figure 9, is similar to the reference facility. MBA 1 contains raw UF_6 material that is received by the facility, as well as any waste generated in the fabrication process. MBA 2 starts with the UF_6 feed material which is converted to the UO_2 kernels.

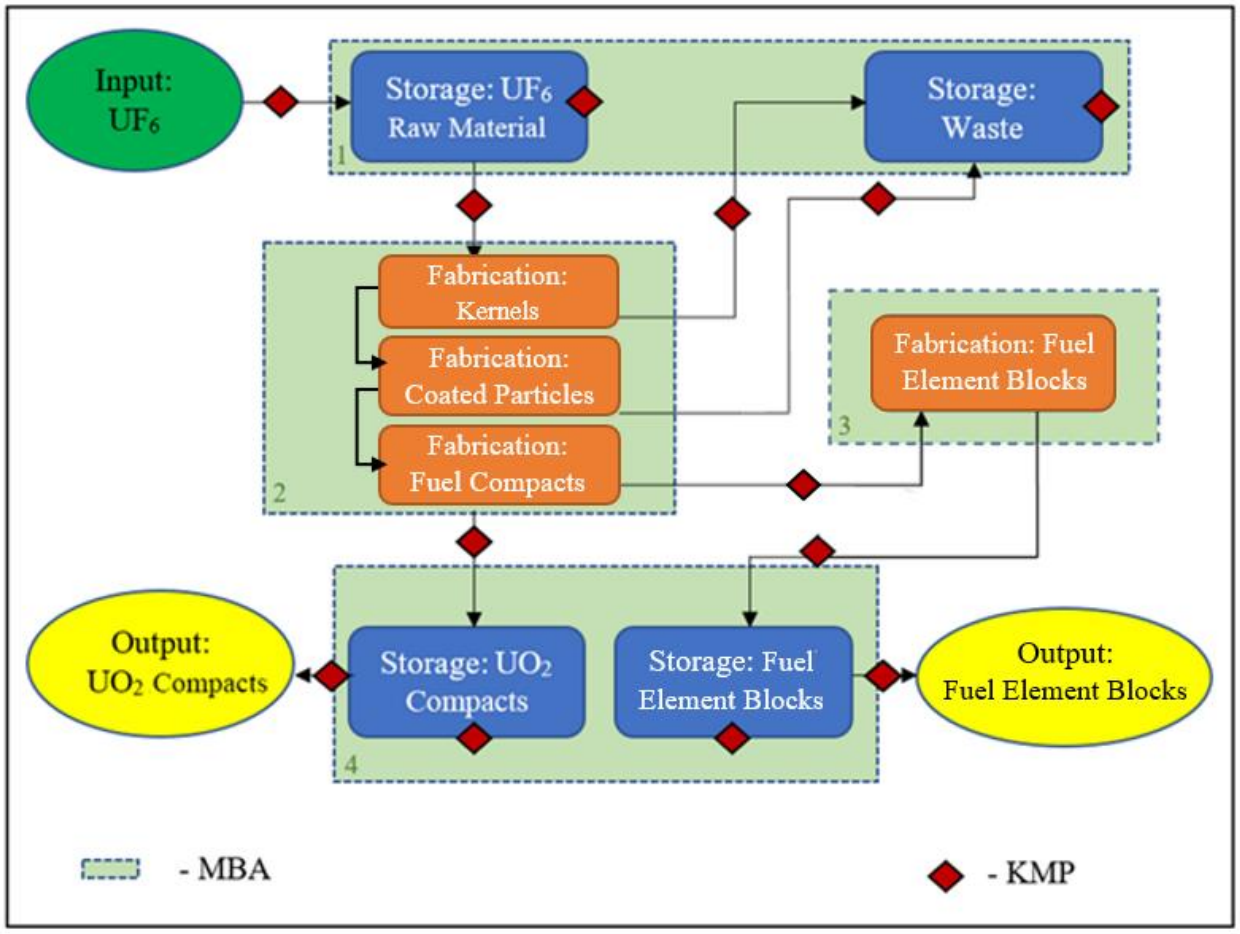

Figure 9. Sample diagram of MBA distribution for a TRISO Fuel Fabrication Facility B.

The kernels are then coated to form TRISO coated particles, which are then pressed with graphite into cylindrical fuel compacts. The fuel compacts are transferred to MBA 3 or MBA 4, depending on whether the customer only requires the compacts or the complete fuel element block. For the former, the fuel compacts are placed in storage. For the latter, the compacts are stacked end-to-end in the fuel element block in MBA 3. Each MBA will accrue MUF, akin to the MBAs of the reference facility. Once the blocks are loaded, the inventory of the fuel compacts may not be taken visually, as in Facility A; however, fuel compact counting may be performed as part of the loading process. The completed fuel element blocks are transferred to MBA 4 for storage prior to shipment. Fuel element blocks may be counted as items similar to item accountancy of fuel assemblies in the reference facility.

5.4.2. Facility B: Suggested Key Measurement Points

Placement of KMPs in Facility B follows the same guidelines as those proposed for the reference facility, for a total of 13 KMPs. Weight measurements of loose compacts in containers and loaded fuel assemblies are important in lieu of a visual inventory.

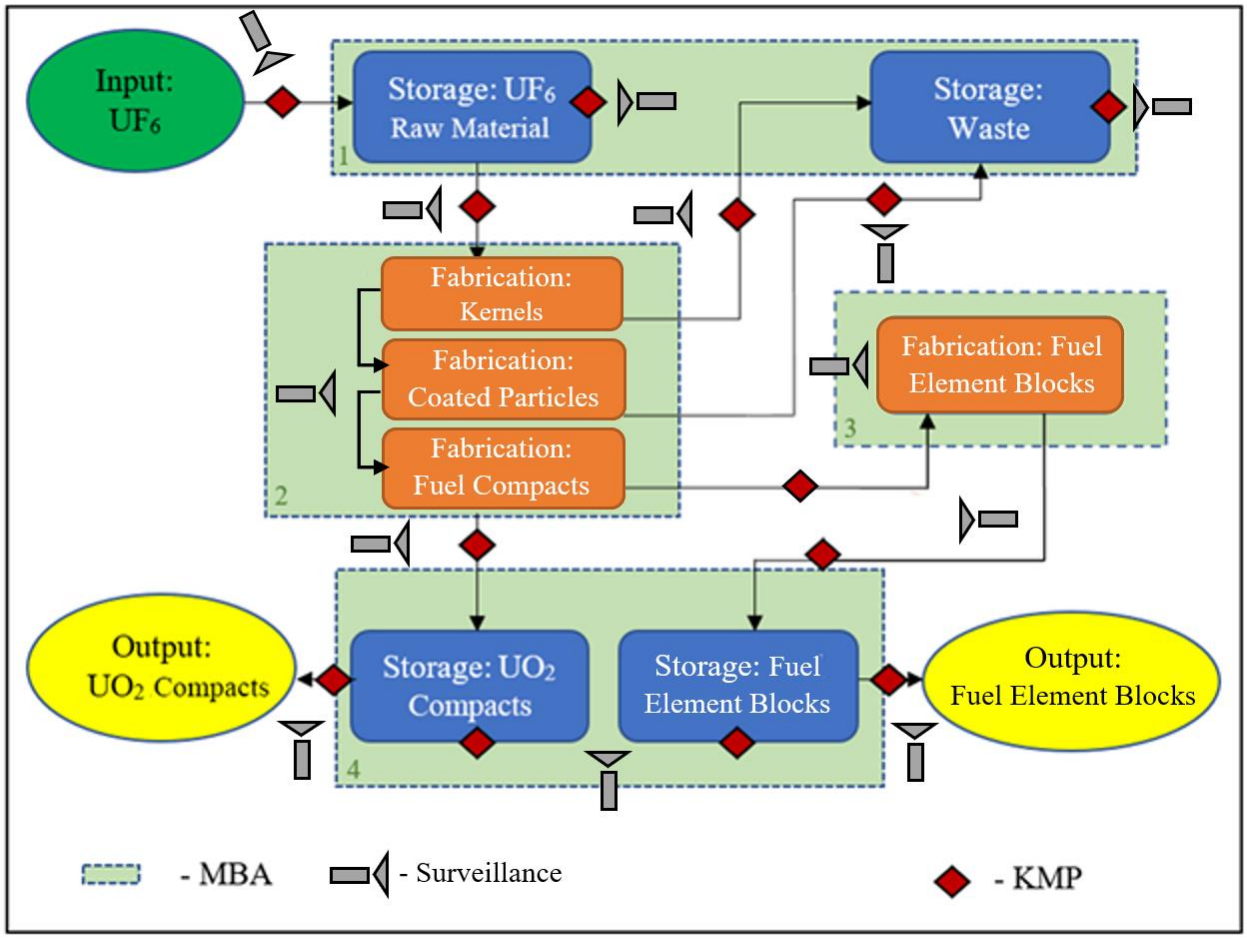

Figure 10. TRISO Fuel Fabrication Facility B layout with some C/S measures (surveillance).

5.4.3. Facility B: Suggested Containment and Surveillance

C/S measures for Facility B, shown in Figure 10, would be selected using the same guidelines as those proposed for the reference facility. Furthermore, all product leaving the facility would be sealed with a TID to ensure CoK is maintained until receipt by the customer. Equipment that may be used for CoK is similar to the equipment discussed for the reference facility and Facility A, also described in Table 1.

5.4.4. Facility B: Suggested Non-Destructive Analysis and Destructive Analysis

Techniques for NDA and DA in Facility B are likely to have challenges similar to those posed for Facility A, as both contain coated particles in a graphite matrix. As such, the coated particles and final fuel compacts or fuel element blocks in Facility B may produce different radiological signals than the traditional fuels outlined in the reference facility. These differences in composition will necessitate further NDA testing for efficacy of fissile material content measurements for both coated particles and for fuel compacts. The insertion of the fuel compacts into graphite element blocks will further complicate the analysis. Additionally, as in Facility A, the traditional NMA approaches are theoretically applicable to Facility B, but they have yet to be tested and would require verification.

5.4.5. IAEA Timeliness Detection Goals

The timely detection goal for TRISO Facility B would be one year, as the material present would be considered indirect use (IAEA, 2001).

5.4.6. Facility B: Conclusions

Current safeguards techniques for the reference facility are, in some ways, applicable to Facility B. TRISO fuel compacts undergo a shaping process and do resemble UO_2 fuel pellets in final appearance; therefore, weighted measurements and MUF calculations are reasonable techniques for verification. On the other hand, NDA and DA methods and techniques will need to be evaluated for efficacy with the TRISO ceramic coatings and graphite matrix. Additionally, after insertion into the prismatic blocks, traditional methods will not be applicable. Further refining of NDA and DA techniques to accommodate TRISO fuel's unique composition and structural characteristics may be required.

6. Other Considerations for TRISO Fuel Safeguards

6.1. Material Quantification through NDA/DA

Theoretically, NDA and DA methods may be applicable to safeguarding TRISO fuel fabrication; however, key factors, such as fuel composition and layers/coatings, must be considered, and the methods must be tested. Standard NDA equipment and techniques may not directly apply to coated particles suspended in a graphite matrix, which could present a considerable challenge for verification. Given the fuel kernel size prior to the ceramic coatings being added, the fuel material may be most vulnerable to diversion at this stage. Material quantification techniques more tailored to TRISO fabrication should be explored to verify fuel content more accurately in compacts and prismatic block fuel elements. Additionally, a complete understanding of the waste streams during TRISO processing and the requisite safeguards techniques for effective MC&A needs to be further evaluated.

TRISO fuel kernel types vary in material content and there are a variety of unique compositions. Further, signals from gamma spectroscopy, neutron counting, etc., are expected to differ depending on the kernel type (i.e., UO_2-, UCO-, MOX-, or UN-type kernels). Therefore, the IAEA must consider optimizing equipment to accommodate expanding varieties of fuels and fabrication techniques. Where resource allocation may be sparse, additional equipment or protocols should be examined, such as complementary NMC measures for classifying and tracking types of pebbles in PBRs (Gariazzo, et al., 2021).

6.2. MOX Kernels

Developments into new TRISO kernel compositions continue and may present unique safeguards challenges. For example, the presence of MOX kernels will alter the significant quantity of the material (which would alter the IAEA inspection goal) as well as shorten the timeliness detection goal to 1 month due to MOX fuel being unirradiated, direct use material. For LEU, one SQ is 75 kg of ^{235}U, while one SQ of Pu is 8 kg. If Pu is included in a fabrication stream, inspection of fuel material must be done using glove boxes due to dose rate concerns. Furthermore, different safeguards equipment must be used, which would include passive neutron detectors, glove box detectors, and other specialized equipment.

6.3. Other Technology Needs

Compared to traditional oxide fuel fabrication, TRISO fuels present distinctive challenges for NMA of numerous loose fuel items throughout the facility and taking accurate radiation detection measurements. Current IAEA safeguards equipment has been tested for traditional fuel types but not for coated particle fuel. Major challenges to the current international safeguards regime as applied to coated particle fuel are meeting international target values (ITV) for NMA measurement uncertainties and radiation detection limits. The amount of nuclear material contained within individual coated fuel is small in quantity and NDA measurements for verification may require higher precision to account for decreased source emission rate through the layers of coatings. As variations in fuel and core designs continue to develop (such as MOX fuel and eVinci's monolith or solid core), changes to the fuel fabrication process may arise.

While outside the scope of this study, a similar NMA issue is present for PBR facilities. PBRs are designed for online refueling, which presents its own safeguards challenges because material is recycled or ejected during the life cycle of the facility. Such challenges have been addressed in CANDU-type reactors and may be adapted to PBRs. Research has been conducted to detect fresh fuel entering the reactor vessel and irradiated fuel leaving the vessel. Technology that can be used for pebble movement in a closed environment (such as the PBRs' reactor containment) may be a beneficial monitoring tool if modified

specifically for use in a pebble fuel fabrication facility, given that fuel pebbles have a larger geometry than the fuel kernel and are more easily tracked (see discussion on combination of MBAs for Facility A in Section 5.2).

7. Conclusion and Recommendations

In this study, model facilities and their respective NMA approaches were presented for a TRISO pebble fuel fabrication facility (Facility A) and a cylindrical compact fuel fabrication facility (Facility B). A reference facility that fabricates standard LWR oxide fuel was used as a point of comparison for NMA in these facilities. The similarities and differences between MBAs, KMPs, and C/S, as well as equipment needs, in each scenario were discussed with an emphasis on the importance of a robust MC&A program. Finally, knowledge gaps and technology development areas specific to TRISO fuel fabrication that might be of interest to the international safeguards community were introduced for further discussion. The following reflects the recommendations drawn from these identified technology considerations and gaps:

Near-Term (6 months – 2 Years)

- Recommend the IAEA research and develop new ITV's, uncertainty values, and other criteria for safeguarding fuel composed of TRISO particles.
- Coordinate with affiliated laboratories and institutions to determine the viability and efficacy of current safeguards approaches pertaining to TRISO Fuel Fabrication Facilities.
- Due to a lack of detailed information on the uranium-containing waste streams for coated particle fuel fabrication facilities, this report is unable to determine if there would be any major impact to the safeguards approaches identified and recommend further evaluation.

Mid-Term (2 – 5 years)

- Begin/ continue development of radiation detectors optimized for material composed of coated TRISO particles.
- Evaluate NMA of TRISO facilities and develop specific C/S measures.
- Develop algorithms for random sampling of coated particle fuels and TRISO material storage containers.

Long-Term (5 – 10 years)

- Implement optimized radiation detection equipment into future pilot fabrication facilities.
- Implement new design information examination (DIE) and DIV for future pilot fabrication facilities.
- Evaluate performance of radiation detectors and update designs, if needed.

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Appendix A: List of Abbreviations and Acronyms

ADU	Ammonium Di-Uranate $(NH_4)_2U_2O_2$
BWR	Boiling Water Reactor
C/S	Containment and Surveillance
CoK	Continuity of Knowledge
CSA	Comprehensive Safeguards Agreement
CVD	Chemical Vapor Deposition
DIE	Design Information Evaluation
DIV	Design Information Verification
FB-CVD	Fluidized Bed – Chemical Vapor Deposition
FCM	Fully Ceramic Micro-encapsulated
HEU	Highly Enriched Uranium
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
IIV	Interim Inventory Verification
ITV	International Target Values
IPyC	Inner-Pyrolytic Carbon
KMP	Key Measurement Point
LEU	Low Enriched Uranium
LWR	Light Water Reactor
MBA	Material Balance Area
MC&A	Material Control and Accounting
MOX	Mixed-Oxide
MUF	Material Unaccounted For
NDA	Non-destructive Assay
NMA	Nuclear Material Accounting
NMC	Nuclear Material Control
OPyC	Outer-Pyrolytic Carbon
PBR	Pebble Bed Reactor
PIV	Physical Inventory Verification
PWR	Pressured Water Reactor
SiC	Silicon Carbide
SMR	Small Modular Reactor
TID	Tamper-Indicating Device
TRISO	Tri-structural-isotropic
ZrC	Zirconium Carbide

Appendix B: UO_2 Fuel Rod Fabrication Process

B.1. UO_2 Pellet Fabrication

The oxide fuel fabrication process, shown in Figure 11, begins with the receipt of enriched uranium hexafluoride (UF_6) from enrichment facilities. The material arrives in large, pressurized cylinders that are stored until processed. UF_6 is a solid at room temperature and atmospheric pressure. To extract the material from the cylinders, heat is applied causing the material to sublimate from the solid phase to the gas phase which is then piped and bubbled through water. The material dissolves into the water forming uranyl fluoride (UO_2F_2). A base, such as ammonium hydroxide (NH_4OH), is added to the solution to precipitate the uranium out of solution in the form of Ammonium Di-Uranate (ADU). The precipitate is then dried in an oven, and the material is calcined above 600°C in the presence of hydrogen (H_2) gas to produce UO_2 powder.

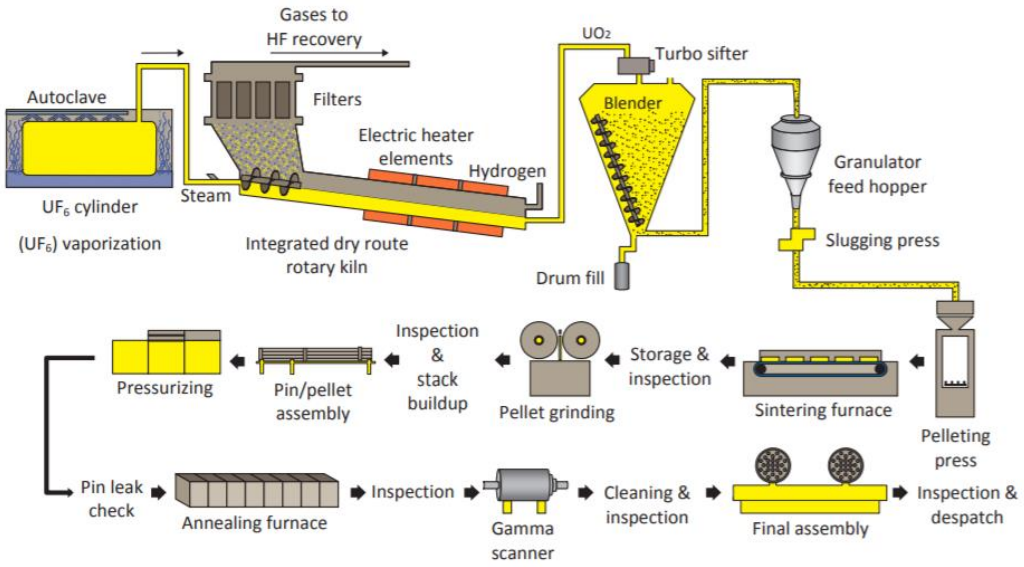

Figure 11. Sample material flow diagram (IAEA, 2017). Copyright IAEA, reproduced with permission.

The UO_2 powder is subjected to hammer milling to pulverize the powder into a uniform consistency and mixed with an adhesive to form the final material for the pellets. The material is pressed into individual pellets via pressing. To increase stability and density, the pellets are then sintered at 1700°C under H_2. During sintering, the pellets are intentionally formed larger than the final fuel assembly size. Therefore, grinding (either dry or in a slurry) post-sintering ensures a precise and uniform diameter across all pellets.

B.2. Fuel Rod and Assembly Fabrication and Loading

The pellets may be washed or blown with air to remove excess scrap material then loaded onto trays for final drying to remove excess moisture before loading into fuel cladding tubes and weld-sealed to form the final fuel rods (referred to as pin in Figure 11). The final fabrication step is to place the fuel rods in the assembly skeleton to form the final fuel assemblies. Completed fuel assemblies are then cleaned and stored until they are ready to be shipped to customers (Nuclear Regulatory Commission, n.d.).

Appendix C: The TRISO Pebble Fuel Fabrication Process

C.1. Kernel Fabrication

Kernel fabrication begins with a high pH solution and an acid-deficient uranyl nitrate (ADUN) solution. Uranyl nitrate is prepared by dissolving uranium oxide compounds in nitric acid. BWXT employed an emulsification/ internal gelation method to form the kernels in solution, as opposed to an extrusion/ external gelation process.[3] The uranyl nitrate reacts with the high pH environment and forms uranyl hydroxide gel droplets. To form a carbide, carbon black must be added to the solution before gelation occurs. After the gel spheres are formed, they are aged which makes them firmer, then subsequently washed of residual material and reactants. Next, the gel spheres are air-dried then placed in a high-temperature furnace and calcined in a helium gas environment to form UCO spheres. After calcination, the spheres are sintered to shrink their volume, increasing their density to approximately 11.0 g/cm^3. Kernel diameters will vary from 300 µm to 500 µm depending on process/ facility (Demkowicz, et al., 2019).

C.2. Particle Fabrication

Once the kernels are fabricated, four coatings are added in layers to create the TRISO coated particles. CVD is used to coat the kernels accurately and consistently. The first and innermost coating is the buffer layer, which is applied by CVD using acetylene in argon (Ar) diluent. The next layer is the inner-pyrolytic carbon (IPyC), which is deposited using a mixture of acetylene, propylene, and Ar diluent. The third layer is the SiC layer that is deposited using methyl trichlorosilane with hydrogen in an Ar diluent. The final layer is the outer-pyrolytic carbon (OPyC), for which the deposition process is identical to that of the IPyC layer. The thickness of each layer is shown in Figure 4. During each coating step, the fluidized-bed temperature is precisely controlled to allow the layers to properly form. Typical deposition process temperatures for the coating layers are, as follows: buffer – 1450°C, IPyC – 1265°C, SiC – 1500°C, and OPyC – 1290°C (Hunn, et al., 2008). The final density of each coated particle is approximately 1.9 g/cm^3 with a diameter that depends on the enrichment.

C.3. Spherical Fuel Pebble Fabrication

The coated particles are formed into spherical pebbles after being homogeneously distributed in a graphite matrix material. Graphite is the most common choice for matrix material due to its thermal conductivity, high-temperature strength, and ability to moderate neutrons. A phenolic resin binder is added to graphite powder to maintain the spherical pebble shape, once formed.

At this time, X-Energy is considering two pathways for pebble pressing: isostatic and quasi-isostatic (Helmreich, et al., 2017). Isostatic pressing is the more direct method of the two where a rigid mold is employed under high pressure from a hydraulic press to form the spheres. Quasi-isostatic is nearly identical to isostatic except that a hard-elastic material is used in the mold. The benefit of using an elastic material is that it reduces the required pressure, and thereby, the size and cost of the hydraulic press. The

[3] As the names suggest, the main difference between the two processes is where and how the gel droplets are formed. Emulsification combines two immiscible liquids, such as vinegar and oil, with the help of a surfactant/emulsifier, like lecithin, that acts as a stabilizer to form small droplets within a solution. Mayonnaise is an example of a culinary emulsion. Gelation occurs in solution. On the other hand, extrusion occurs outside of a solution, where droplets are formed from an extruder or nozzle, and once the droplets are large enough, they fall into the solution below. The droplets do not dissolve in the solution but remain as droplets and eventually form stable gels.

temperature can be increased during compression to pyrolyze or carbonize the resin to form a stronger pebble. Following the carbonization stage, the pebbles are placed in a lathe to remove rough surfaces. The final step consists of the removal of any unreacted volatiles under vacuum at 1950°C for one hour. The final diameter of each pebble is approximately 6 cm or roughly the size of a conventional tennis ball (Zhao, et al., 2006).

C.4. Special Fuel Variant: UN Fuel Kernel

A special variant to the UO_2 and UC/UCO kernels is uranyl nitride (UN). A major advantage of UN kernels over the other kernel types is the higher theoretical density. Compared to the theoretical densities of the UO_2 and UCO kernels produced in the AGR study of approximately 10.9-11 g/cm^3, the UN kernels can achieve theoretical densities of approximately 14.3g/cm^3.

UN kernels are prepared in much the same way as UCO; however, the starting materials vary slightly. To begin, uranyl nitrate is mixed with an aqueous hexamethylenetetramine (HMTA) solution. Using a similar internal gelation process from the UCO line, microdroplets are made. Carbon black is then added to the droplets. The droplets are calcined in an Ar-H_2-N_2 environment to produce $UC_{1-x}N_x$. The ratio between carbon and nitrogen may vary based on the initial carbon black content and the calcination gas mixture. After the UCN/UN kernels are produced, they can be coated exactly as described for UCO TRISO particles (Ledergerber, et al., 1992). A newer synthesis route follows similar steps but does not require H_2 gas for calcination; instead, ultra-high purity (UHP) Ar and UHP N_2 gases are used. The calcination process consists of four steps: (1) eight hours under UHP Ar gas as temperature ramps up to 1400°C; (2) slower eight-hour ramp up to 1900°C, still under UHP Ar; (3) 10 hours at 1900°C under UHP N_2; and (4) cool down at a max rate of 20°C/min under UHP Ar (McMurray, et al., 2016).

Appendix D: The TRISO Fuel Compact Fabrication Process

D.1. Kernel Fabrication

The fabrication process for UO_2 kernels is nearly identical to that of UCO kernels as described in Appendix C for TRISO pebble fabrication, except there is no carbon black introduced into the uranium emulsion before gelation. During calcination, the ADUN gel droplets are converted into UO_2. Following the sintering process, a kernel of 9.6% enrichment will have a final diameter of approximately 508 µm and a density of approximately 10.9 g/cm^3. Kernels of this process will be approximately 88% uranium by weight. As is the case with kernels fabricated in TRISO Facility A, the kernel diameter for a specific facility will vary and may depend on the uranium enrichment.

D.2. Coated Particle Fabrication

Coated particles are fabricated via a deposition process that is identical to that described in the TRISO spherical pebble fuel fabrication in Appendix C.

D.3. Cylindrical Fuel Compact Fabrication

The basic process to fabricate a cylindrical fuel compact is similar to that described for TRISO Facility A. However, rather than spherical molds, cylindrical dies are used to form the compacts. Fuel-free resinated graphite is first poured into the die bodies before the overcoated TRISO particles are added and finally another fuel-free layer of resinated graphite is added to the top. The fuel-free regions act as end caps to the compacts. The compacts are then compressed and heated to form the final shape. The diameter of the fuel compacts can be around 10-15 mm, depending on the prismatic graphite blocks they will be inserted into. The fuel compacts may be fully cylindrical or annular, depending on the reactor design. Figure 8 shows images of the kernels, fuel compacts, and the final fuel element blocks. (General Atomics, n.d.).

D.4. Fuel Element Block Fabrication

The final prismatic fuel element is a graphite block with channels for fuel compact loading. The compacts are loaded end-to-end in these blocks. For General Atomics' Prismatic Modular HTGR design, prismatic hex-blocks measuring 360 mm from face-to-face and 793 mm in height were used. Each fuel element/block held 210 fuel compacts. In total, the core had a fuel region consisting of 66 columns, 10 blocks high arranged in an annulus configuration that equated to over 4000 kg of uranium in the initial core loading (General Atomics, n.d.).

D.5. Special Fuel Variant: ZrC Coating

The most common ceramic TRISO coating is SiC, followed by zirconium carbide (ZrC). The purpose of the ceramic layer is to act as the structural frame of the kernel and retain fission products and gasses. Ceramic layers can commonly fail via over pressurization, fission product interactions, and kernel migration, also called the Amoeba effect (Gulol, et al., 2008). The Amoeba effect can occur with a spherical kernel when carbon monoxide (CO) gas is formed below the ceramic layer which migrates to the cooler side of the kernel. As time goes on, the solid phase carbon forms and subsequently pushes the kernel towards the hotter side (Powers & Wirth, 2010). The probability of kernel migration can be reduced by preventing CO gas from forming. One method to accomplish this is to use ZrC for the ceramic layer. Thermodynamically, it is more favorable to form zirconium dioxide (ZrO_2) than CO or SiO_2 at temperatures up to 1600^{o}C (Porter, et al., 2013).

ZrC coating can be formed in a similar method to SiC through fluidized bed CVD. To form the chemical gas that will coat the particles, chlorine gas reactions occur with zirconium metal at 600°C to form zirconium chloride ($ZrCl_4$). The new gas compound is then introduced into the coating vessel where it reacts with acetylene gas at temperatures between 1350°C and 1450°C to form ZrC, which then coats the fluidized particles.

D.6. Special Fuel Variant: Fully Ceramic Microencapsulated Fuel

An alternative to TRISO particles embedded in a graphite matrix is fully ceramic microencapsulated (FCM) fuel. The ceramic matrix for this variant is SiC, the same material applied as a coating to TRISO kernels. FCM fuel can be formed into pellets, compacts, or pebbles. Fuel material prepared in this way exhibits the following properties (Snead, et al., 2011):

- High burnup tolerance;
- Thermal conductivity ~10x greater than UO_2;
- Fission gasses fully retained; and
- High structural stability

FCM fuel is used in HTGR and fluoride-salt cooled reactors. It can also replace conventional UO_2 fuel in LWRs, when prepared as pellets using legacy dimensions. FCM fuel may use TRISO particles with kernels of UO_2, UC, UCO, UN, or MOX. It is fabricated through a liquid phase sintering process called Nano-Infiltration and Transient Eutectic-phase (NITE) process (Katoh, et al., 2002). The process combines SiC nanopowder with TRISO particles and oxide additives. The mixture is then formed into the desired shape through hot pressing and sintering. FCM fuel pellets can be produced with very low porosity, achieving near-theoretical density (Snead, et al., 2011). FCM fuel of any TRISO particle kernel type (UO_2, UC, UCO, UN, or MOX) is a recent development that warrants research for safeguards implications. IAEA equipment may be sufficient for LEU and natural uranium FCM fuel but fine tuning may be required.

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