Safeguards by Design Considerations for Modular Molten Salt Reactors

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Abstract

Current international safeguards approaches for power reactors were developed and optimized for standard light water reactors and are not directly applicable to molten salt reactors. This paper presents specific novel safeguards measures that might be considered by the International Atomic Energy Agency and design considerations that might be incorporated by advanced reactor designers to improve the future effectiveness and efficiency of safeguards implementation into a modular molten salt-fueled reactor design (e.g., ThorCon's molten salt reactor). Novel safeguards measures may take advantage of the homogeneous nature of the fuel salt in liquid salt-fueled molten salt reactors, which allows for remotely-obtained samples that are representative of the isotopic concentration of all fuel salt in the loop at the time of sampling. Additionally, intrinsic characteristics of the reactor system (e.g., the frequency response to intentional perturbations) could be leveraged to provide a unique and real-time indication of diversion of nuclear material from the fuel salt. Effectively inventorying nuclear material during maintenance periods, when components will be changed out, will be a unique challenge for the IAEA. This paper presents suggested design considerations that designers might consider to reduce the burden of independently verifying quantities of nuclear material.

1 Introduction

1.1 Safeguards by Design

Safeguards are a set of technical measures to ensure that nuclear facilities are not misused and that nuclear material is not diverted from peaceful uses. Safeguards by design is a concept wherein these technical measures are integrated into the design process of a new nuclear facility. This can cover the initial planning, design, construction, operation, and even decommissioning of the facility. Safeguards, both domestic and international, are an important legal requirements. Safeguards by design can help avoid costly and time consuming modifications while also making the safeguards more effective and efficient. [4] SBD built into the design of a reactor also help scale up the production of that reactor type as it lowers the overall cost and man-hours necessary to preserve continuity of knowledge on all nuclear material at the site. Current safeguards are designed for light water reactors and exclusively rely on item accountancy techniques. Safeguards for advanced reactors have not yet been developed, but are necessary to facilitate the operation of these reactors. [5]

1.2 Molten Salt Reactor Specification

Molten salt reactors (MSRs) use molten halide salts as the primary coolant. If the fuel is solid and fixed, it is not too dissimilar from a standard light water reactor. However, the type of MSR discussed in this paper has the in liquid solution with the molten salt and flowing throughout the primary loop. This is an important distinction as it will characterize the safeguard techniques used for the reactor core. Other general qualities of the MSRs discussed in this paper is that it is graphite moderated, modular, and relies on thermal neutrons. For the sake of discussion, we will take a specific look at ThorCon's TMSR-500 reactor design as an example of how safeguards for a modular MSR could operate. ThorCon's design was chosen due to the wealth of documentation publicly available and its similarity to ORNL's molten salt reactor experiment. The ThorCon inspired power plant design used in this paper features a pair of MSR modules that contains two Cans, shown in Figure 1. Each Can contains a reactor core, primary system piping, pump, primary heat exchangers, and off-gas tanks. Only one Can in each module is operating at a time. The lifetime of a Can is four years of operation due to the degradation of the graphite moderators in the core. The fuel salt is then transferred to the partnered Can which begins operation. The Can that had been operating is then switched into cooling mode for the next four years. After which, the Can that has been cooling is shipped off to be refurbished and is replaced with a new or refurbished Can. The nuclear material is found in four places: the fuel salt in the primary loop of the operating Can, the spent fuel salt cooling in the partnered Can, the makeup fuel salt, and a small amount in the used flush salt.[6]

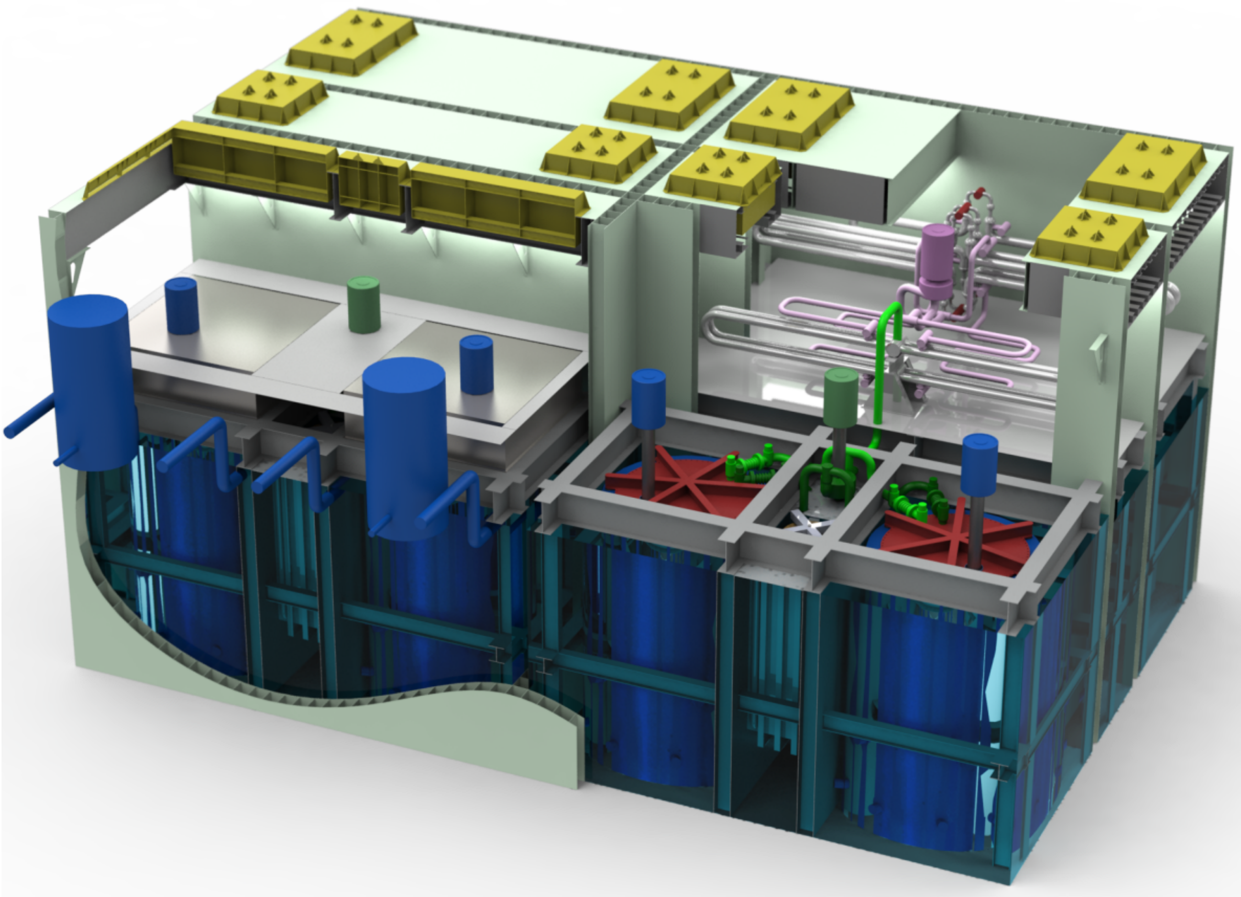

Figure 1: A pair of ThorCon TMSR-500 modules. [6]

1.3 Challenges with MSR Safeguards

Safeguards are traditionally done through the precise accounting of nuclear material at material balance areas (MBAs). Item accountancy increases the precision by parceling out the material to be separately measured and identified with serial numbers. Unlike standard light water reactors (LWRs), the fuel in a molten salt reactor is mixed within the liquid carrier salt, forming a homogeneous substance known as the fuel salt. For light water reactors the fresh fuel arrives in fuel assemblies, consisting of fuel rods that contain thousands of fuel pellets. The fuel stays in those assemblies throughout its time at the plant which allows for item accountancy, where individual fuel assemblies are considered individual items with unique serial numbers. Within a molten salt reactor, the fuel salt is liquid and being continuously pumped throughout the primary loop. This means that item accounting cannot always be used, and that the plant must at least somewhat be considered a bulk accounting facility. This necessitates the development of bulk accountancy techniques that may need to be uniquely adapted to MSRs. Bulk accounting is traditionally thought to be more difficult. [1] This is because bulk MBAs are usually large and unwieldy for the precise measurements required of international safeguards. A large challenge to MSR safeguards is the inapplicability of many current IAEA standards and procedures, which are designed for light water reactors and various non-nuclear power plant facilities. Material accountability is currently done based on physical units, but MSRs require the development of new methods. The fuel salt in an MSR is a homogeneous mixture of carrier salt elements, fission products, uranium, and transuranium actinides. If thorium is a part of the fuel, thorium and protactinium isotopes are present as well. Though homogeneous, the variation of isotope concentrations in the fuel salt changes continuously, which allows for the use of isotopic analysis and radiometric dating of samples to calculate the isotopic composition of the fuel in the reactor when the sample was taken. MSRs also have the unique option of on-line reprocessing and various refueling schemes. [3]

2 Safeguards Plan

Similar to most other nuclear power plants, an MSR power plant will have three material balance areas: fresh fuel storage, the reactor Can, and spent fuel storage. As discussed, bulk accounting techniques must be used. This is particularly true for the reactor Can where the fuel salt is liquid. At this location, there are qualities which can be possibly used as safeguard mechanisms. Firstly, the homogeneous nature of the fuel salt allows for the use of samples to be representative of all the fuel salt. Secondly, the fact that the fuel flows throughout the primary loop means that fission products flow with it. Some of these fission products are short lived and an expected fraction of them would decay before reentering the core. Spectral analysis can observe these short lived fission products. Finally, any fuel composition bearing ^{238}U, such as low enriched uranium (LEU), will accumulate plutonium as it undergoes burnup. Plutonium accumulation has noticeable effects on the reactor dynamics. This allows for the detection of a diversion of plutonium from the fuel salt by analyzing frequency response of the reactor system. Plutonium is a direct use nuclear material and must be rigorously safeguarded. The frequency analysis can likely be extended to other fuel options, as long as there is noticeable change in delayed neutron precursors during the fuel cycle. Prior work on this concept has been investigated by Dr. Chvala, Alex Wheeler, and others at the University of Tennessee, Knoxville. [7] Further details and discussion on these techniques is included in Section 4.

2.1 Plan Overview

As discussed, the reactor Can must use bulk accounting techniques. However, the fresh fuel and spent fuel MBAs are not necessarily excluded from using item accounting techniques. In this manner, the use of bulk accounting can be minimized to the reactor Can and item accounting can be used wherever possible. The fresh fuel and spent fuel MBAs therefore become item accountancy access points to the wider world. This transition between item and bulk accountancy is one of the key innovations for MSR safeguards. Other key innovations are the bulk accounting techniques: the use of archival sampling, isotope monitoring, and frequency analysis for safeguards.

The three material balance areas are shown in Figure 2 along with the transitions between them. Different techniques are used at each node to take advantage of the unique condition and destination of the material at that location. Standard item accountancy techniques such as discrete packaging, serial numbers, and individual weighting are used at the fuel MBAs. When departed from these MBAs, automation is exclusively used to provide a degree of separation between the operators and the bulk material. Seals and one way channels are used in loading zones to aid in a smooth transition. Flow rate monitors and scales should be used to confirm that all of the material that entered the channel was deposited to the other side. Once in the reactor Can itself, innovative bulk accounting techniques are interwoven for redundancy, reliability, and precision. These techniques rely on the unique qualities of a molten salt reactor such as the homogeneity and evolving isotopic concentration of the fuel salt.

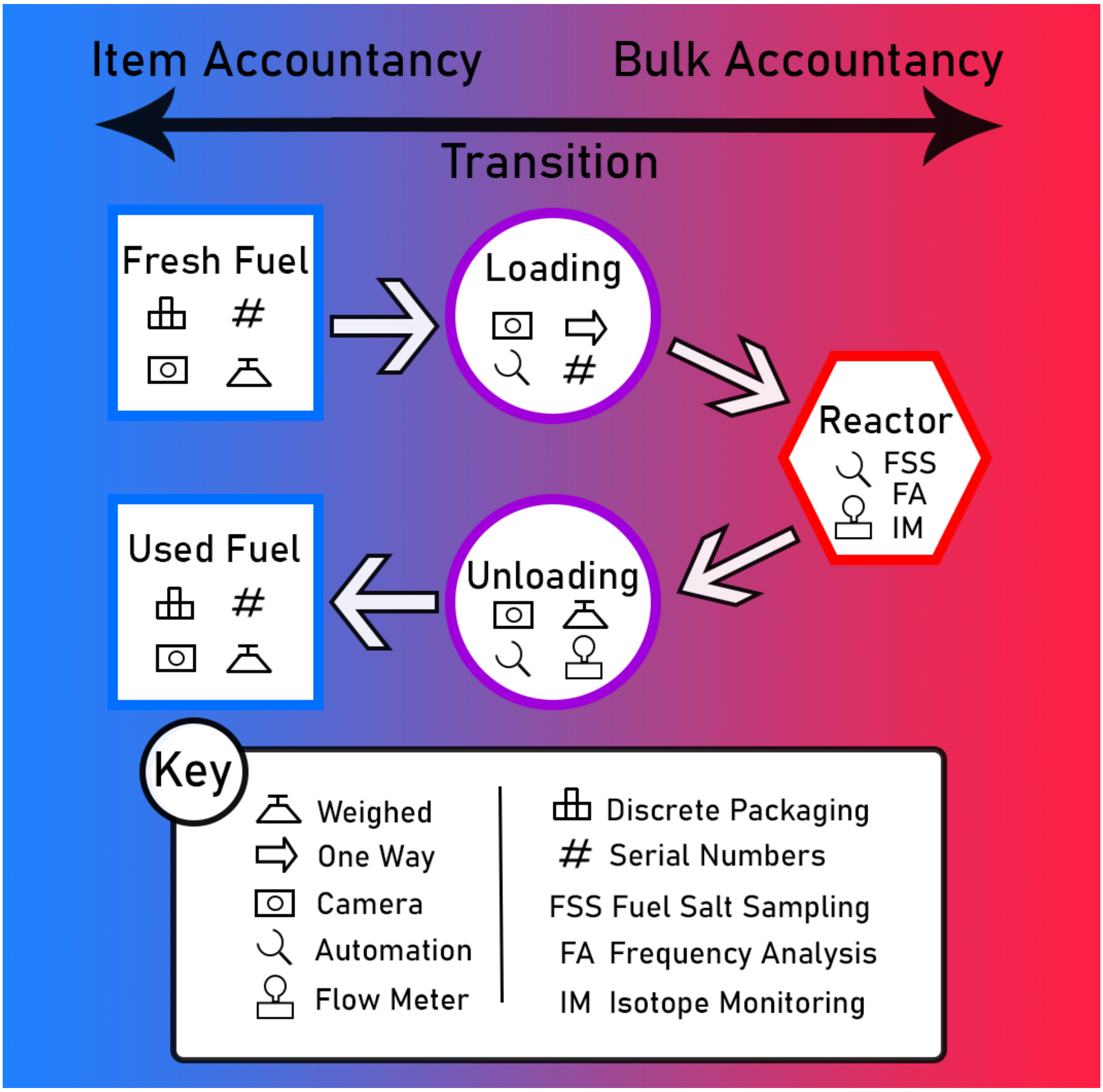

Figure 2: Safeguard plan overview

2.2 Accountancy Transitions

2.2.1 Fuel Loading

Refueling a LWR involves the extensive process of shutting down the reactor, removing the spent fuel assemblies, and inserting the fresh ones. Refueling an MSR is considerably easier and can be done with the reactor on-power during normal operation. To refuel an MSR, small amounts of refuel salt are added to the fuel salt over the course of its operating lifetime. The approximate amount of added refuel salt should be in the tens of grams per day, but the exact number is dependent on the specific reactor design and fuel type. No draining of the fuel salt from the primary loop takes place during the operational lifetime of the Can, which reduces the risk of diversion. Whenever the fresh refuel is removed from storage, it is imperative that the amount removed equals the amount added to ensure no diversion. This is the step where the transition between the item and the bulk accountancy takes place and it is important to be accurate. The exclusive use of automation when departed from item accountancy is recommended to add a degree of separation between the operators and the nuclear material. The fuel loading process should be exclusively one-way with the use of single entrance doors, which are already in use by the IAEA. The fuel salt containers can be brought in, have their serial numbers scanned, and have the fuel salt moved from the container to the reactor can under camera observation. The cameras should be broadcast via a live satellite feed to be observed and recorded by the IAEA. The fuel unloading process should similarly be automated and under camera observation.

2.2.2 Fuel Unloading

The spent fuel salt, which still has a large amount of fissile material still in it, will first cool down, then be removed from the site and sent to a handling facility. There are two Cans per module at the site, with one in operation and one cooling. The transfer of fuel salt from the Can beginning cooling to the fresh Can will occur within the sealed module. The removal of the cooled can and the insertion of the fresh can provides a different, more vulnerable, situation than regular refueling. Following ThorCon's model, new or refurbished Cans will be brought to the site every four years. The old Can, which has been cooling for the past four years, will then be emptied into its accompanying Can, flushed, and sent away to be refurbished.

When the Can is flushed, residual nuclear material will invariably be left on the inner walls. The IAEA only allows for a very limited amount of material unaccounted for (MUF). Facilities with too high of a MUF are in violation of their obligations. It is therefore important to keep the MUF as low as reasonably possible. To prevent this material from being unaccounted for, a method for verifying the amount inside. Volume measurements based on flow rates can lead to an estimate for the maximum amount, but a more rigorous method is necessary to satisfy IAEA requirements. It may be possible to determine the amount of nuclear material through measurement of the radiation in the Can. If unfeasible, the best course of action may be to quantify the amount of nuclear material residue once the Can has been sent back to be refurbished. This could be something as thorough as scraping or otherwise removing the material off of the inner walls, or an approximation based on the known surface area of the inside of the Can and the average residue thickness. However, there may be safeguard issues with transporting the Can while it still contains nuclear material. At the very least, it would require the transport ship to be under the same rules other forms of nuclear material transport follow.

To confirm that all of the fuel is successfully transferred over with no diversions, the volume of the fuel salt in the Cans should be measured before and after the transfer. However, malicious state actors could possibly spoof the volume measurements by siphoning fuel salt while adding salt without fuel of equal volume or otherwise falsifying the results. To prevent this, the design information verification for the reactor needs to ensure the channels between the Cans are well known and only as numerous as necessary. The channel between the Cans would be an important part of the design to examine during any design information verification or otherwise whenever possible. Ideally, the fuel transfer mechanism should be a pipe in a shielded conduit with separate IAEA seals that only the IAEA personnel can open. Therefore, IAEA inspectors would need to be present for the fuel transfer to unlock the seals and watch over the process to ensure no diversion takes place. As this is the most sensitive part of the fuel cycle at the plant, which only occurs once every four years, it should not pose an overly significant burden on the IAEA.

Tangential to the Can switching process is the fact that, in the ThorCon design, the cylindrical drain tanks are not replaced when the Can is. This presents a unique risk during the transfer process when those tanks would be exposed. If the drain tanks have been used during operation, the fuel inside of them needs to be accounted for. The large exit channel from the Can is a unique issue. For the design to remain as it currently is, a method must be developed to verify the quantity of the nuclear material in the drain tank and preserve the continuity of knowledge there. The connection to the drain tanks would need to be included in the design information verification too.

The simplest solution, which would bolster the safeguards during this stage, is to have the drain tank be a part of the Can itself, shown in Figure 3, and have the drain tanks be replaced with the rest of the Can. It is the recommendation of this team to incorporate the drain tanks within the Can.

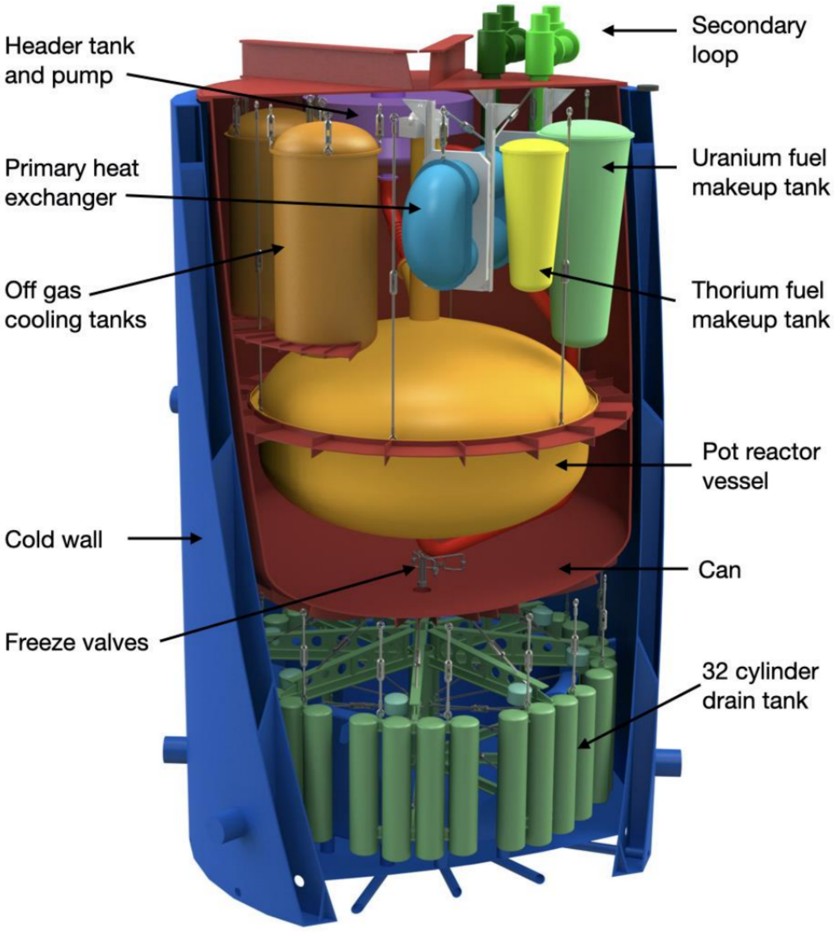

Figure 3: The ThorCon MSR Can, cold wall, and drain tanks. The Can includes all components encased in the red section. [6]

3 Material Balance Areas (MBA)

3.1 Fresh Fuel MBA

Fresh fuel will be brought every other time fresh Cans are brought to the site. During the reception of the fresh fuel salt at the site, the fuel salt will not need to be liquid yet. The fuel salt is solid at room temperature. Solid fuel salt can be sealed in specially made containers and regarded with standard item accounting techniques. The containers should be marked with unique serial numbers for proper item accounting and of a size preferable to the IAEA and facility operators for weighing and storage. Whether that size should be large enough to necessitate a crane, like fuel assemblies in an LWR, or small enough to be carried and inspected by a single person has yet to be determined. Input from people familiar and experienced with IAEA procedures is requested. There is also the possibility of making the container out of a single material with no opening. Such a container would act analogous to an old-fashioned wax seal, where any damage to the seal indicated a possible breach of the container. If this design possibility is pursued, the material selection method would need to be employed to determine the best materials to use. It could be possible to choose a material with a far lower melting temperature than the fuel salt to melt it away in preparation for fuel loading. Conversely, the container could have a much higher melting point to allow for the fuel salt to be heated and drained out of the container as a liquid. Regardless, the container must not be cost prohibitive and must be durable and within certain size and weight parameters. The specific shape is unimportant, but it should be stackable for transport and storage. There is also value in having the containers be reusable to lower the cost, simplify the overall system, and have well known weights. It is also possible for these containers to be dual designed to also be used for the reception of spent fuel. A safeguards approach for fresh fuel is crucial to the detection of a possible diversion, as the reception of nuclear material is a vulnerable time in the fuel cycle. Continuity of knowledge must be preserved during transport, reception, and storage to ensure that all of the material sent is received properly at the site. This is therefore an important location for a material balance area for accurate accounting of nuclear material in storage. This is the MBA where the material is stored after being received at the facility and an accurate register must be kept.

3.2 Spent Fuel MBA

Similar to the fresh fuel MBA, the fuel salt in the spent fuel MBA does not necessarily have to liquid still. When unloaded from the reactor Can, it can be loaded into distinct containers which are marked with unique serial numbers and weighed. It could be advantageous to have the containers be the same ones used in the fresh fuel storage. However, due to the increased isotopic complexity and decay heat of the spent fuel, it may be necessary to have uniquely designed containers. Once the spent fuel salt is allowed to solidify, it loses its homogeneity. Various decay products build up as defects in the solid lattice in possibly underexplored ways. Some of these products are artificial or otherwise rare, and can be useful in other industries. Much of the fissile material is still present in the spent fuel. After the spent fuel has adequately cooled, it is therefore advantageous to send it away from the power plant to a reprocessing facility to be separated and recycled. This allows for both the use of the rarer isotopes and the closing of the fuel cycle for greater fuel efficiency.

3.3 Reactor Can MBA

The reactor Cans are sealed within their module during operation and only dealt with via automation. During operation, there is an intense heat and radiation. The fuel salt is well mixed, flowing, and its isotopic concentration evolves with burnup and online refueling. These unique qualities allow for the use of innovative bulk accounting techniques. The techniques are archival sampling, isotope monitoring, and frequency analysis. These three techniques are each discussed in detail in the next section. The techniques gleam information about the material in the primary loop through different means to offer greater precision and redundancy. Archival sampling offers the greatest precision and can flexibly be used for either nondestructive or destructive assay. However, it is the most intensive and would require a laboratory setting to be tested. For this reason, the fuel salt sampling system (FSSS) should be set to take samples via automation at determined intervals. The samples should then be stored in the sealed power module in their own sealed safe. This safe would only be opened if other techniques have warranted it or when the Can is sent for refurbishment. In this way, the contents are examined when needed or at four year intervals, which greatly lowers the burden on the IAEA. Isotope monitoring and frequency analysis can both be performed with greater ease and regularity. Isotope monitoring can be done passively and frequency analysis should be routinely done once per operator shift. These three techniques operate on different time scales to allow for a greater range of data collection and improved data resolution.

4 MSR Unique Safeguards Techniques

4.1 Archival Sampling

A clever technique that can turn the seemingly negative aspect of bulk accountancy of fuel salt into a uniquely positive one is archival sampling. A pea sized drop of fuel salt can be siphoned, scooped, or otherwise removed from the primary circuit by a fuel salt sampling system (FSSS) can be used as nearly unfalsifiable proof of the state of the fuel salt at the time of its removal. The removal mechanism would be robotic due to the intense heat and radiation, and also to limit the access to the mechanism. Once the pea of molten fuel salt is removed, it will freeze without external heating. With a recording of the exact time the siphoning occurred and an accurate reading of the isotopic concentration of the pea at the time of assay, calculations can determine the isotope concentration of the fuel salt at the time of siphoning. Due to the homogeneity of the fuel salt, the isotopic concentration determined this way is representative of all the material in the primary loop at the time of sampling. This could potentially be compared to the expected fuel isotopic concentration at that time due to its burnup which is known from the reactor's power history. Fuel burnup codes would need to be developed for MSRs and be verified and validated to the IAEA's standard. If any fuel salt had been diverted, then the fission happening in the core would result in a change in the isotopic concentration from what was to be expected. This is because the fuel salt is homogeneous and any removal lowers the amount of fissile material in an equal ratio, but ongoing fission changes the isotopic ratio itself. Selectively removing a particular element, such as plutonium, would be even easier to detect in the fuel salt's isotopic vector. Consideration should be taken to have the shape of the pea be suitable for analysis, but that is dependent on the type of isotope detection method used. Pea shape could possibly be irrelevant if the pea is going to be crushed, for example. Ultimately, it would depend on the detection technique and assay preferred by the IAEA.

The exact mechanical system needed to create the fuel salt pea is unnecessary to design at this stage of the project, but it is important to recognize that every access channel to the reactor adds more security and safety risks. Therefore, for an access channel to be added to the design, it must be a worthwhile net positive towards ensuring no fuel diversion takes place, comparing the advantages and disadvantages of such a system. The IAEA requires that only its own equipment is used for any official measurements and that their safeguards systems are kept under seals to prevent tampering. For the sampling system to be useful to facility operators for reactor performance and optimization tests, samples and measurements would need to be taken when they require. The possibility of requesting the presence of IAEA officials to open the seals is unlikely and could be prohibitive. Due to these conflicting interests, the possible advantages of the FSSS are dependent on its general design, where there are three viable options: 1) sampling only for archival purposes and have the FSSS locked away behind IAEA seals; 2) sampling with the option of performing regular measurements on site, where only the measuring equipment needs to be removed in case of failure; 3) regular removal of the samples from the site for offsite measurements. For the purpose of safeguards alone, the first option is superior. However, there could be room for a compromise similar to the second option, where samples taken for archival purposes are sealed in a vault openable only by the IAEA if any inconsistencies in the operational history of the power plant appear, but the option for samples to be taken and used by the facility operators. In this way, the remote handling and piping system of the fuel sampling system could be used to take samples for both the IAEA and reactor operators, assuming they would need separate samples.

The advantages of a fuel salt sampling system would be quite large. It would be a method for the routine archival of the status of the fuel salt within the reactor for safeguard purposes and a useful metric towards the analysis of the reactor's performance. Other drivers for the ability to analyze the isotopic composition include design and operation optimization, the validation of operational burnup codes, and other computational reasons. The isotopic results could thus benefit both the IAEA and the facility operators. The disadvantages of the FSSS are that it opens up a possible avenue for diversion and also that, if the system were tampered with, it could help hide that a diversion took place. If the sampling mechanism is designed to be small enough to have a low maximum removal rate, then diversion through that channel would be a lengthy and difficult process. Assuming the volume of a pea is $0.1\,\mathrm{cm}^3$, the amount of plutonium in the fuel being 2% of the uranium concentration, and the density of the fuel salt is $3.5\,\mathrm{g/cm}^3$, the amount of peas needed to comprise a SQ of plutonium is well over 500,000 which would take a lengthy amount of time and be highly likely detected. Therefore, the risk of tampering with the fuel salt peas or the FSSS is far greater than the risk of theft. To prevent tampering, the FSSS and peas could be built into the containment structure of the reactor, with the peas locked in a briefcase sized vault, and the only access to the FSSS under seals. The seals could be models already proven and in use by the IAEA.

4.2 Passive Gamma Signatures

It is valuable to have multiple measuring points and techniques to have redundancy and greater precision. Sampling and destructive assays can yield the desired precision but will often bring added burden to the IAEA. Large bulk accounting facilities, such as the Rokkasho Reprocessing Plant in Japan, have previously required an onsite IAEA laboratory. [2] Though that is an extreme example considering the drastic size difference between the type of modular MSR facility discussed in this paper and a massive reprocessing plant. The burden on the IAEA can be reduced by having passive unattended measurements. These measurements can help warrant the use of destructive assay outside of scheduled times. One form of this unique to MSRs is short-lived isotope monitoring (SLIM). This SLIM technique would operate by having a scintillator placed near the outlet channel of the core and another near the inlet channel. Short-lived fission products will flow out of the core, through the primary heat exchanger, and back into the core. During this travel time an expected percentage of them will decay. The two scintillators could therefore passively observe the spectral emissions of these isotopes at the two points. If a diversion takes place, this would decrease the observed emissions at the core inlet. If so, a further investigation can begin. This monitoring can be done passively during operation. Similar techniques that are already in use are K-edge densitometry and X-ray fluorescence. These x-ray measurements are commonly used at PUREX reprocessing facilities to aid in material accounting.

4.3 Frequency Response Analysis

Frequency response analysis is a technique common in system dynamics where an oscillating input into a system creates an oscillating output which has a gain and phase shift associated with each distinct frequency of the input. The graphical depiction of the gain and phase shift across a range of frequencies is a Bode plot. A convenient physical interpretation of the gain and phase change is that of a gas powered car. A certain amount of stepping on the gas pedal will have a certain level of acceleration; the gain. Likewise, there will be a time delay between the depression of the pedal and the acceleration; the phase shift. Using this analogy, the use of gasoline fuel with a percentage of ethanol in it will yield a different gain and phase shift than fuel without ethanol or even a different amount of ethanol. This is where frequency response analysis can become an innovative tool towards safeguards. As the reactor operates, some neutrons will be absorbed by ^{238}U in the fuel and subsequently transmute into ^{239}Pu. As the reactor goes through burnup, plutonium will therefore buildup. ^{239}Pu is fissile and will experience some burnup as well. The increasing fraction of fission reactions involving plutonium causes changes in the kinetic parameters, mean neutron generation time, and delayed neutron fraction of the chain reaction. Therefore frequency response analysis will yield different Bode plots across the life cycle of the reactor. As shown in prior work, these Bode plots can be predicted through simulations. [7] If plutonium has been removed from the reactor then there would be a noticeable divergence from the simulations. A major advantage of this technique is that it is a relatively easy to perform mode of nondestructive assay. The way it would be performed at a power plant is by moving a control rod very slightly up and down at various frequencies to input an oscillating reactivity change. This results in an oscillating power output which can be measured through standard means. An alternative way is by adding a small oblong control surface in the core which can be spun at different frequencies. This would result in a known oscillating reactivity wave. With either method, this test could be performed quickly and regularly. Similar tests often take approximately fifteen minutes. This analysis can be done as a standard part of each shift to increase precision.

5 Conclusion

Molten salt reactors have various unique safeguard considerations that require innovative thinking and techniques but reap unique rewards. Various forms of physical protection can make diversion from a MSR unpreferred and difficult. However, physical protection is distinct from safeguards and efforts beyond physical protection must be made to preserve the continuity of knowledge for the nuclear material at the site. The nature of use of fuel in a reactor means that normal operation has a lower safeguard risk due to the high temperature and radiation; thus, it is necessary to focus efforts to specific vulnerable time frames. The material at the facility must be rigorously accounted for at each location, shown in Figure 2. For a ThorCon-like MSR, these locations are the fresh fuel storage, reactor modules, and spent fuel storage. The two fuel storage MBAs should operate with item accounting techniques with well designed transitions to and from the reactor Can, which is in bulk accountancy. Multiple unique bulk accounting techniques are used in the Can to ensure that no diversions have taken place and independently preserve the continuity of knowledge. Even small diversions over regular intervals could lead to a loss of a significant quantity of nuclear material. The homogeneous nature of the fuel salt, combined with the continually changing isotopic concentrations, allows for the use of calculations and mathematical modeling to guarantee the nuclear material is being used for its intended purposes. Such a tool will be critical at providing a thorough continuity of knowledge at the plant.

6 Acknowledgments

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