Advanced Reactor Safeguards and Material Accountancy Challenges
Dr. Ben Cipiti, Sandia National Laboratories, USA

Berta
Doing today's introduction is Dr. Patricia Paviet. Patricia is the Group Leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She's also the National Technical Director of the Molten Salt Reactor Program on behalf of the US Department of Energy. She's also the Chair of the GEN-IV International Forum Education and Training Working Group. Patricia?

Dr. Patricia Paviet
Thank you very much, Berta. Good morning, everyone or good evening. It's a pleasure to have with us Dr. Ben Cipiti. He's a Distinguished Member of the Technical Staff in the Nuclear Energy Fuel Cycle program area at Sandia National Laboratories with over 18 years of experience in safeguards and security analysis for advanced nuclear reactors and fuel cycle facilities.

He's the National Technical Director for the Advanced Reactor Safeguards program in the Office of Nuclear Energy within DOE. This program works to help advanced reactor, small reactor vendors solve material control and accounting and physical protection challenges for the US deployment.

Dr. Cipiti has a deep technical background in safeguards and developed the Separation and Safeguards Performance Model for analysis and design of materials accountancy systems for nuclear facilities. Safeguards, Security, including cyber, and Safety by Design is a core principle in Dr. Cipiti's work, promoting the need for consideration of the 3S's early in the design process to help the nuclear industry develop robust yet cost effective system design.

Dr. Cipiti earned a Ph.D. in nuclear engineering from the University of Wisconsin, Madison and a Bachelor of Science in Mechanical Engineering from Ohio University, Athens.

Without any delay, first of all, thank you so much, Ben, for volunteering to give this webinar, and I give you the floor. Thank you again, Ben.

Dr. Ben Cipiti
Okay. Thank you, Patricia. I appreciate it and good to be here. So, one of my other roles is I'm also one of three co-chairs of the

Generation IV International Forum, Proliferation Resistance and Physical Protection Working Group. So, to get into this topic, I'm going to start off by talking about some of the work of the PR&PP working group, which naturally has a lot of overlap with this particular area.

One of the goals of the PR&PP Working Group is we want to ensure that nuclear reactor vendors are facilitating introduction of PR&PP features into the design process at the earliest possible stages of concept development. We call this PR&PP by design, but it does have a lot of overlap with probably what you've heard in the past, which is safeguards and security by design.

We want to make sure that PR&PP results are an aid to informing decisions by policymakers in areas involving safety, economic sustainability, and other related institutional and legal issues. Our group is not overly large, but we do have a number of representatives from different countries and entities around the world, and I think this is really important because it provides a lot of different perspectives on proliferation resistance, safeguards and security depending on the region of the world that you live in.

I do want to point you to if you're interested in learning more about the GEN-IV International Forum goals, the website is shown at the bottom, the web link. The goal that we most resonate with in the PR&PP working group is that generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons usable materials, as well as to provide increased physical protection against acts of terrorism.

So a few key points of the working group. The PR&PP methodology considers both intrinsic features and extrinsic measures. Intrinsic features are typically more associated with the fuel design and the unique performance of the particular reactor system, whereas extrinsic measures include technologies for materials accountancy and international safeguards, and that can include monitoring, surveillance, and measurements. So when we talk about materials accountancy or international safeguards, those aspects are really more part of the extrinsic measures, and so only one part of proliferation resistance, but the measures are driven by the intrinsic features, and I'll talk a little bit more about that.

I do want to talk a little bit about terminology before I get into the meat of this discussion. I'm going to be going back and forth a little bit between domestic MC&A, Domestic Material Control and Accounting versus international safeguards. And so, I want to distinguish here the difference between them. When we talk about domestic material control and accounting and physical protection systems, these systems are addressing the risk that non-state actors could perpetrate malicious acts involving nuclear material. So we're trying to prevent unauthorized removal, so theft of nuclear material or sabotage of nuclear facilities. And the threat here, the adversary in this particular case is an individual, a small group, a subnational group, and it may include collusion with an insider. So the state authority prescribes standards for protection, control and accounting of nuclear materials, including cybersecurity.

In contrast, international safeguards are designed to confirm that countries as a whole do not use nuclear activities to illicitly divert or produce nuclear materials for nuclear weapons activities. So for international safeguards, the country is the adversary. Because the country is the potential adversary, verification is performed by the IAEA or other international regulatory body. And so, one of the things that I think is important is that there is a lot of overlap between domestic MC&A and international safeguards, but there are also places where they diverge. And so, I will try to be a little bit more clear about that as I go into the presentation.

Nuclear material accounting data declared by the state generally originates from the domestic MC&A system. So, there's a basic linkage between the state and then the international safeguards.

Security isn't really the topic of this talk, but I will just say that like domestic MC&A and physical protection, international security focuses on preventing the theft of material and mitigating sabotage risks at nuclear sites. But each country is individually responsible for establishing their own regulatory body and requirements.

The PR&PP Working Group, some of the early work in the group was to develop the PR&PP methodology. I mentioned that this considers intrinsic features as well as extrinsic measures, and these intrinsic features can apply both to proliferation resistance and physical protection.

PR&PP by design is mainly about understanding where the advanced nuclear energy systems have advantages or maybe challenges that will affect how the extrinsic measures need to be used. So a key point that I want to make here is that the PR&PP Working Group is not performing evaluations to pick winners, but rather we're trying to just better inform designers and regulators on the threats and ways to mitigate those threats.

Finally, before I jump into the meat of the discussion, I do want to just point you to the GEN-IV PR&PP website. This does contain a number of open source resources that are available if you're interested in learning more about these topics. One of the most recent activities of the PR&PP Working Group has been to complete these PR&PP white papers on the six different classes of Gen-IV reactor systems. So, we currently have five of the six white papers available publicly. This includes the sodium cooled fast reactor, lead cooled, supercritical water cooled, gas cooled, and very high temperature reactor.

We're still working on the molten salt reactor and hope to have that one completed sometime this year.

We also have a companion crosscut document that actually was just finalized and is now available on the website that discusses PR&PP considerations which crosscut all reactor designs. The methodology has been developed through a succession of revisions. It's currently in revision 6, and that's also available online, and we've applied the methodology in the past using a case study approach. There's an example sodium cooled modular fast reactor system report that's available as well.

The PR&PP Working Group also maintains a bibliography. We try to just keep track of the work that's done specifically in this area, but it also includes relevant references on work that's done in safeguards and security, so that can be a good source of information as well.

With that, let me jump into the main topic, which is safeguards and MC&A challenges for advanced reactors. I'm going to start off focusing a little bit more on the domestic side. So I want to talk about domestic MC&A challenges.

From a domestic MC&A perspective, when we think about what is needed to meet the regulations in a particular country, advanced reactors that utilize traditional fuel assemblies, so fixed fuel assemblies like light water reactor type of designs, sodium or lead fast reactors, microreactors that have solid or fixed fuel or prismatic cores, they're all mainly going to follow MC&A approaches that are well defined. The way we do MC&A for these types of reactors is we do item accounting for all fuel elements on site, and we use burn up codes to estimate fissile content.

Where we really start to see some challenges come up more is as we go to the more exotic fuels. So pebble bed reactors that utilize solid TRISO fuel pebbles flowing through the core, as well as liquid-fueled molten salt reactors are going to require different MC&A approaches.

And so, the MC&A regulatory approach for both are going to pull from requirements that were built up around large light water reactors as well as bulk handling facilities.

Particularly in the US, but I think this is probably going to be the case around most of the world, the regulatory space was built up around large light water reactors. There's also some regulatory space that covers fuel cycle facilities. And so, the regulations for these types of reactors may pull from both, but understanding that, in many cases, they weren't really designed for these types of systems.

When it comes to international safeguards for existing reactors, there's a number of references that are available provided by the IAEA. The figure I'm showing here on the right, this comes out of one of the IAEA Nuclear Energy Series reports. Generally speaking, for existing reactors, international safeguards is composed of surveillance cameras on the reactor, spent fuel pool, and fuel transfer areas. There are seals on containment penetrations and fuel transfer channels. NDA measurements may be used on fresh and irradiated fuel. Item accounting and verification of assemblies in storage areas. And then finally, potentially, power monitoring, spent fuel discharge monitors, and fuel bundle counters protect against misuse scenarios.

So if I were to generalize it, what I would generally say is that international safeguards is mainly trying to protect against diversion or misuse of the reactors. And so, there's a lot of focus on surveillance and seals to ensure that operations are occurring the way they're supposed to at an existing reactor. So we have a wealth of knowledge internationally in how we do safeguards for reactors that have solid fixed assemblies.

I'm going to go through the different classes of the Gen-IV systems. I'll start off with the sodium fast reactor, and to kind of introduce each one, I'm going to start off by talking about some of the key points that were raised in the PR&PP white papers.

The sodium fast reactor PR&PP white paper looked at five reference designs to cover a different range of reactor sizes and types that have been looked at across the world. This covers compact loop versus pool configurations, as well as small modular types of designs. Generally, we found that, but little variation in PR&PP was found between the different systems, and many PR&PP considerations were similar to any fast system.

Some of the characteristics. Fast systems generally have higher actinide content than large light water reactors in terms of per assembly, but the assemblies tend to be smaller. They're just a little bit smaller. Item accounting assemblies can easily be applied, and there's experience out there in doing that. These reactor assemblies usually have higher radiation doses. For a sodium fast reactor, you have operations under sodium, which requires specialized equipment, and that can provide some PR&PP advantages just because of the difficulty of accessing the material.

The white paper also looks at the use of blankets. The use of blankets to breed material can present a proliferation resistance challenge. But we do have experience on using extrinsic measures to detect blanket misuse or diversion scenarios that are fairly mature. And so, I want to just point you to, if you wanted to get into this in more detail, specifically for this type of design, we do have this example, sodium fast reactor PR&PP case study that went through this in a lot of detail in 2009.

The lead cooled fast reactor is very similar to the sodium fast reactor in terms of the reactor characteristics, the main difference just being the different coolant. There were three reference designs looked at for the white paper. Again, a closed fuel cycle was assumed. Plutonium fuel containing minor actinides is contained in the fuel assemblies. The designs are set up to avoid the presence of pure plutonium streams. And some of these, many times in fast reactor systems, they look for a fuel cycle, or the goal is to have a fuel cycle where eventually you don't need any enrichment. But that's balanced by the fact that you do have some sort of a reprocessing capability needed.

This white paper talked a little bit about pin removal. All of the reference designs assume that pin removal of assemblies was not possible. And then the SSTAR design, which is more of a modular design, uses a lifetime sealed core. So the difficult to access cores and high amount of automation required in these reactors do provide some PR&PP advantages. But I think the sort of general theme here is that when you have a reactor with solid fuel and fixed assemblies, we're following MC&A and international safeguards approaches that have already been established by the existing light water reactors.

The supercritical water reactor is probably the most similar to existing light water reactors. This white paper looked at eight different design tracks. The reference systems cover a combination of both pressure vessel and pressure tube type designs, and they all utilize battery fueling. So generally speaking, these designs can utilize well-established safeguards and security approaches that are similar to light water reactors. One slight difference is that the newer fuels may utilize high assay LEU, and so that has slightly higher material attractiveness.

And then, the last one I'll talk about, at least for the time being, is the gas cooled fast reactor. This white paper looked at one design track, which is a 2400-megawatt reference design. Other designs like ALLEGRO and EM2 concepts are discussed. Generally, the system assumes a closed fuel cycle. Again, the fuel contains plutonium with minor actinides. Again, fuel pins are not separated from fuel assemblies on site, and higher radiation levels for both fresh and spent fuel help to hinder theft.

But the key theme with these first four classes of reactors that I'm talking about again is that we've got solid fuel assemblies, solid fixed assemblies. You're mainly in the mode of item accounting of the assemblies and then reliance on burn up codes to declare the inventories in the reactor.

So where we start to see some challenges and some differences is when we move into the pebble bed reactors. Pebble bed reactors utilize hundreds of thousands of pebbles containing nuclear fuel, which circulate through a fluidized bed. There's a few key considerations I want you to kind of keep in your mind as we go through this discussion for this type of reactor. First off, one pebble contains only a very small amount of nuclear material, so it takes literally thousands of pebbles to acquire a significant quantity. The pebbles also leave the core at a rate of once every 30 to 60 seconds, and they have to be checked for integrity and burnup. Those that haven't reached the burnup limit will be circulated back into the core.

It's important to note that one spent pebble may represent a significant source of radioactive material, and then finally, the input fresh fuel and spent fuel will be stored in canisters.

There's been some very recent work looking at some preliminary material balance area structure for a pebble bed reactor. Now, this work has kind of looked at this design from the considerations both for domestic MC&A as well as international safeguards. There’s a little bit of overlap here, but I am going to focus a little bit more initially on domestic MC&A. And so this work is referenced here at the top, if you'd like more information. This work has been done at Oak Ridge National Laboratory.

The basic setup for a pebble bed reactor for the material balance area structure is to potentially break it up into three sub-MBAs. Now, this isn't set in stone. The general thinking when this figure was put together is that most existing reactors are set up with just one MBA for the whole reactor. From a domestic MC&A perspective, we may look at breaking it up into individual item control areas or sub-MBAs, but from an international safeguards perspective, you could also consider breaking this up into three separate MBAs as well.

Sub-MBA 1 includes the fuel receipt and storage and then transfer into the reactor. Sub-MBA 2 would be the reactor core itself and the pebble handling system. So that's going to be the more complex area of the plant. And then finally, sub-MBA 3 includes spent fuel storage and any damaged fuel pebbles which may come out of the reactor as well.

The flow key measurement points are shown here as the blue arrows. Those are the main fuel transfer areas between MBAs or into the facility or out of the facility. And then there's also a number of inventory key measurement points shown here as well, the key places where we have to determine or estimate or measure the inventory in process in the system. I'll go through these all in a little bit more detail.

For sub-MBA 1, this includes fresh fuel receipt and storage. Sub-MBA 1 is going to be an item control area mainly, since the fresh pebbles will be shipped and stored in canisters.

I'm going to talk a little bit about the US perspective here. In the US, we're looking at the Versa-Pac VP55 as a potential candidate for transportation and storage of fresh fuel pebbles. And this container can hold on the order of about 350 pebbles. Part of the reason that this might make sense to be a good size to use for transportation and storage is that from a US perspective, we have NRC category II MC&A detection thresholds, which are set to about 300 grams of U-235. This is about equal to 300 to 350 pebbles or essentially an entire container. So, it kind of makes sense to set your container size somewhat equal to what the detection threshold would be for loss.

I do want to note that an IAEA significant quantity is much, much larger. So again, this is really just focusing more on what might be done from a domestic MC&A perspective. If there's a high confidence in the fuel fabrication and fuel transfer process, an acceptable approach will be to confirm the canister ID as it comes in and inspect the seal for tampering. Pebble counting and sampling is unlikely to be needed again from a domestic MC&A perspective. I'll talk a little bit more about that later. But pebble accounting will also be occurring when transferring the pebbles to the reactor.

Sub-MBA II is the reactor and pebble handling system. And as I mentioned, this is the more complex area of the plant. The pebble handling system has to have an area for pebble cooling. You're going to have pebble counting in multiple locations. There's going to need to be some sort of an imaging type of measurement for pebble integrity to look for damaged or broken pebbles. There's a potential to do a batch identification measurement. There will need to be a burnup measurement on every pebble, and there has to be a system for rejection of damaged pebbles and pebbles that are at the burnup limit.

So there's a few accounting drivers for the pebbles that I want to talk about. And before I talk about this, we kind of mentioned at the beginning of this presentation that one of my focus areas is on 3S by design. I'm a huge proponent of consideration of safeguard, security, and safety when designing advanced nuclear energy systems. Especially for advanced reactors, I think this is kind of an example of why I think this is important. From an MC&A perspective, for both domestic and international safeguards purposes, pebbles really only need to be accounted for on the canister level. We've already sort of established this in the sense that because the fissile material content in each pebble is so small, from a theft or diversion standpoint, we have to acquire a very large number of pebbles. But from a process control perspective, the operator needs a burnup measurement on every pebble exiting the reactor to determine which pebbles can be recirculated versus which have reached the burnup limit. And this is really just for economics. I mean, the pebble operator wants to recirculate the fuel as much as they possibly can. So the better that burnup measurement is going to be, the better fuel utilization they'll get.

Then finally, from the standpoint of protection of rad materials, from a physical protection standpoint, an operator would not want to lose even one spent pebble because it could represent a source for an RDD type of device. So we have three different perspectives here. MC&A, process control, and protection of rad materials. And I think they all have to be considered when you're designing your overall safeguards and security system for these reactors.

Couple of other comments. A pebble integrity measurement is required to check for damaged pebbles. There have been lessons learned from past demonstrations that, you know, have been used to help reduce the number of damaged pebbles through better designs. But we do still need operational experience to determine the damaged fuel rates for the current and existing class of pebble bed reactors.

Operators may also consider additional measurements to track fuel batches that may not strictly be needed from an accountancy standpoint, but it's something that could just help the operator, help them to optimize their overall system.

I do want to note that the pebble path through the reactor can vary widely, and so it's very difficult to estimate just from computer modeling what the burnup is going to be of the pebbles. This is really the main reason that we need a burnup measurement on every pebble.

I'm pointing to some work here. More details can be shown in the reference below. This work at Oak Ridge looked at the variation of pebble burnup as a function of pass through the reactor. What you can see here is that there's quite a large range in the air bars, depending on the path the pebble takes. So, for example, if your burnup limit for your reactor was 100 gigawatt days per metric ton, you could have some pebbles that reach that burnup limit after just four passes, whereas you could have some pebbles that maybe have gone through seven or eight passes before reaching it.

The operators will likely utilize sampling and destructive analysis, especially mainly at startup, because they're probably going to – and especially for the first generation of pebble bed reactors of these new reactors coming out, they're probably going to want to verify the burnup measurements and help to validate depletion calculations. But the hope is that eventually they gain more experience. They won't have to do as much DA in the future.

The range and number of pebble passes, though, can vary considerably. And so again, this is really why we have to focus on that burnup measurement for each pebble.

I do want to just note a little bit more about that burnup measurement. Likely gamma spectroscopy will be used for the burnup measurement. It does face a number of challenges. The first one is that I mentioned before that the pebbles are coming out every 30 to 60 seconds, so you do have a short measurement time. The pebbles are short-cooled. There's only hours of cooling after they come out of the reactor. So the spectra can be quite a bit different than what we're normally used to seeing with long-cooled spent light water reactor assemblies. And the measurement system's got to operate 24 hours a day, seven days a week. These are all pretty stringent requirements for a gamma spec type of measurement used for burnup.

There's some interesting work that's being done at Brookhaven National Laboratory on the use of machine learning to improve burnup measurements that I'd like to follow a little bit more. What this work is doing is looking at a comparison of applying traditional linear regression predictions for burnup to a machine learning approach. The main difference here is that rather than just using linear regression on certain fission product peaks or ratios of peaks, it's using machine learning to learn off the entire spectra to tighten up the prediction on the burnup. I think what's been interesting about this work, too, is that it seems to provide a better result as you go toward a shorter cooling time. And that's exactly the regime we're going to be in with a pebble bed reactor. So hopefully, this will provide a way to just improve that burnup measurement a little bit for the vendors.

The last area in the pebble bed reactor is sub-MBA 3, which is where we're storing spent and damaged fuel. This is again an item control area. Since the spent or damaged pebbles will be stored in canisters, each canister will be characterized through summing of the burnup measurement estimates and likely weighing of the canisters. One particular challenge may be burnup measurements on damaged fuel. It's not really clear to me yet that that's been looked at in a lot of detail, and then the canisters will be sealed and accounted for in storage. But mainly, this is an item accounting area.

A lot of what I just presented in the past several slides was really more from the standpoint of domestic MC&A. I do want to kind of cross over into international safeguards a little bit more now. The Gen-IV PR&PP Working Group does have a PR&PP white paper on a very high temperature reactor. This does cover both prismatic and pebble bed reactor designs that use TRISO fuel. The white paper talks about the high dilution factor of the fuel, along with the lack of maturity for industrial reprocessing of TRISO fuel, which does provide a proliferation resistance advantage. And then the prismatic designs benefit, as I've talked about earlier, from item accounting of fuel assemblies, whereas the pebble bed designs have the additional safeguards considerations requiring more monitoring and measurements.

One of the main advantages here is that it does take on the order of 50,000 to 100,000 pebbles to acquire an IAEA significant quantity. So you're talking about having to divert just a huge amount of material, physical volume and mass and then you have to process it in order to do something with that material.

There is certainly a body of work in the past that's looked at international safeguards approaches for pebble bed reactors. The reference shown here at the bottom was work done about a decade ago based out of Idaho National Laboratory. I'm not going to go through this in detail, but it went through some of the key measurement points within a basic pebble bed reactor. The key equipment that was looked at included surveillance cameras, seals, pebble counters, and non-destructive assay. I think as we learn more about how vendors plan to meet the domestic MC&A requirements, we want to look at how some of those technologies may transfer over to international as well. For example, would we want to consider a burnup measurement as a joint use piece of equipment that might be used both for domestic and international? And I think there's a lot of questions there, a lot of questions about the maintenance of those, how reliable they are ultimately, if IAEA has control over that, if that's going to be a problem or not. I think there's still a lot of things that need to be looked at as we think a little bit more about the transfer to international safeguards.

There's also some much more recent experience. The IAEA does have some very recent safeguards experience with the HTR-PM reactor in China. The reference that I pulled this from is shown here at the bottom. This was presented four or five years ago at the IAEA Safeguards Symposium.

The main technical objectives of IAEA safeguards in this case were to detect diversion of fresh fuel, detect diversion of core fuels or irradiated target materials, and detect diversion of spent fuel pebbles within a pebble bed reactor. If I follow the same sort of breakdown that I showed previously with the three sub-MBAs, the focus of this work for sub-MBA 1 was to do accountability of all canisters, to select some canisters randomly selected for pebble counting, and to take one pebble for an NDA measurement. They also were looking at doing surveillance on the loading area to keep track of the nuclear material and what was going in and out of the system.

Sub-MBA 2, which, as I mentioned, is the more complex area of the plant from a domestic MC&A perspective, this area focused on surveillance and radiation detectors applied to key penetrations.

And then for sub-MBA 3, it was recognized that remeasurement was not going to be possible. So they were looking at a dual containment surveillance strategy. NDA measurements would be taken of the pebbles during packaging and then surveillance and NDA to track material movements.

One interesting thing that came out of this study was that the design used storage or stacked storage silos, which stacked the spent material on top of itself underground. And so, IAEA had talked that it might be nice to have a vertical pipe next to each silo for a gamma detector to be able to run it up and down to detect that material. There also would be seals on the silo plug.

So I think when you kind of look at what was looked at in this paper, you can see some of the differences between domestic and international safeguards. From an international perspective, there was less focus on being invasive to the reactor itself and more about just making sure that you're detecting that there's not unauthorized material going in or leaving the reactor. Whereas from a domestic MC&A perspective, we may have a little bit more focus and more measurements and technology on the reactor sub-MBA itself.

Okay, so let me then switch gears to the last class of reactors, which I haven't talked about yet, which is the liquid fueled molten salt reactors. So MSRs see considerable design variations. But I'm going to break up the liquid fueled reactors into two general categories. The first is going to be MSRs that have limited onsite salt processing, and then the second is going to be MSRs with fission product processing on site. So any liquid fueled MSR, at the very minimum, is going to need some level of processing of the salt. You have to pull out noble metals, and you have to pull out off gases at a minimum. But some designs don't plan to remove fission products or do anything to the actinides and instead replace the salt or the entire reactor vessel every seven to eight years. So these reactors are going to have periodic, very large inventories of fresh salt and spent salt that will need to be handled. They may also have some periodic small amounts of makeup salt that might need to be added to the reactor as well.

The other class of reactors, if you do full fission product processing on site, they can be designed to continuously process the salt for a 60-year plus design life. So you're going to have less makeup salt and recovered waste that are going to be needed or produced at any one time. But this is going to be occurring continuously over the life of the reactor, and the amount of processing equipment for the salt is going to be higher in these types of systems.

From a domestic MC&A perspective, there was some recent work done. Reference is shown again at the bottom on an MC&A approach for liquid fueled MSRs. This particular approach looked at breaking up the overall MSR into five key areas. The first was item control area one, which just simply included receipt and storage of fresh salt or makeup salt. MBA 1 then included the transfer of that salt into the process. So opening up those containers and putting them into the process. MBA 2, again, was the more complex area of the plant, because this includes the reactor core, the operations, and any separations that have to occur. MBA 3 receives the irradiated fuel salt and packages it into a waste form. And then finally, item control area 2 would be the storage of that package waste.

So, let's talk a little bit about some challenges. Domestic MC&A is likely going to require – I'm focusing more on MBA 2 here. Domestic

MC&A will likely require a process monitoring approach for MSRs, and what I mean by that is that periodic salt measurements are going to be required. So we're probably going to need to, in some way or other, account for the actinide content in the salt. In order to do that, you'd have to have both an actinide concentration measurement as well as a total salt volume measurement. You need both to determine the total fissile inventory.

For the actinide concentration measurement, sampling and destructive analysis is possible, but the operator would prefer an online measurement. A couple of technologies that are being looked at right now, these aren't the only ones, there's others that could be applied, but just a couple of examples include online spectroscopy as well as voltammetry measurements. Both these technologies should be able to determine actinide quantification to sub 1% types of levels of uncertainty. And because it's online, it just provides a lot of value, not only for just tracking the actinides, but also for other operational data for the operator.

Now, the salt volume is challenging due to the complex geometry of the reactor and the salt processing loops. So we have to kind of remember here that this is not an accountability tank at a reprocessing facility with a really well-defined geometry that can be really easily calibrated. This is a nuclear reactor. You've got a loop that goes to heat transfer. That's a very complex geometry. You're also going to have salt processing steps which further add complexity to it. So you can kind of imagine that estimating or measuring the salt volume is going to be difficult, and it's going to be very hard to get down into the sub 1% uncertainties for this type of a measurement. So, I think this is an area that really could be more of the limiting factor in that total fissile content measurement for a molten salt reactor.

I do want to note that there's some university work, and I'm sorry I didn't reference it here, looking at an isotope dilution technique. I think that's something that will be interesting to follow. It might lead to some new approaches for doing a volume measurement, but that is going to be an aspect that we'll have to do some more work on.

Another challenge with molten salt reactors is that recent work has shown that there's going to be a high error for actinide measurements due to the buildup of actinides in the salt over time. Now, it's important to point out here that if you look at an MSR, the actinide content is really no larger than an equivalent-sized LWR, at least from a power output perspective. But what's unique is that we're trying to measure the entire content, and we just don't do that with a light water reactor. We don't ever try to just measure all the actinides in a light water reactor, because they're all in fixed assemblies. So we have this huge actinide content that we're trying to measure with one measurement.

And so what happens is that especially in a uranium plutonium system, the plutonium is building up over time from the startup of the reactor. And so your measurement uncertainty is building up over time. That's what's kind of shown here in this figure. The line in the middle represents the MUF, the material unaccounted for. Or if you were in other spaces, you might call this an inventory difference measurement. Whereas the blue envelope is the plus or minus two standard deviations on the measurement error. Because the plutonium is building up in your reactor, you're getting to a point where well before a year of operation, your MUF value, your one standard deviation, is well above a one significant quantity of plutonium. So you can kind of see that there's, when you get to that point, there's really almost no way that you're going to detect a loss of material that's equal to one significant quantity.

So these limitations and measurement uncertainty, and these results were assuming you had a 1% uncertainty on the measurement, so this isn't something that's just going to be solved by going to lower and lower measurement uncertainty.

From a domestic standpoint, we're probably going to have to have more reliance on containment and surveillance and physical protection to help ensure that material is not removed. And one thing that's important to point out is that the fissile content in the salt is very dilute. You've got a very high radioactive field. It's not like you just bring a briefcase in and take material. I mean, this is a molten salt. It's difficult to handle. So again, from a domestic standpoint, we can kind of take advantage of all that and rely more on physical protection to protect these reactors from material diversion.

This is really a big diversion point with international safeguards. So international safeguards, you can't rely on physical protection. This is a place where we may have to require more on monitoring of reactor conditions. For example, if a salt is removed from the system, it's going to have a pretty dramatic effect on the power levels. I think that's an area where we need to do a little bit more work to understand what are some of these additional measures that could be applied from an international safeguards perspective for molten salt systems.

The PR&PP Working Group does have a molten salt reactor white paper. I mentioned that that's not publicly available yet, but we hope to get that out this year. This white paper does look at three design classes. It looks at the two classes I talked about with the liquid fueled. And then the third one is molten salt reactors, where they have a solid fuel, but only use salt as a coolant, similar to the Kairos Power design. That particular design really would have pure MPP features that are more similar to a pebble bed reactor. So really, I think a lot of the focus was more on the liquid fuel designs.

Some of the comments which are sort of obvious by this point is that the designs with on site fission product removal will have slightly more PR challenges in that they resemble bulk handling facilities, so more extrinsic measures will be needed. But the liquid fueled reactors without fission product removal, they're designed to replace the core, the salt every seven to eight years. But then that salt does have to be processed. So you're adding more complexity to the fuel cycle itself since there's going to be an additional facility that's going to have to process that material.

The high radiation field, the rather dilute actinide content and remote handling are a barrier to theft. I talked about that a little bit already. So those are some things that can be taken advantage of, especially from a domestic perspective.

Okay, so I've talked about the six different classes of Gen-IV reactors. I hope that that was kind of a good overview of kind of where we see more of the safeguards and MC&A challenges. I think generally it's an exciting time to be in the nuclear industry. I'm really enjoying seeing all the advanced reactor vendors out there and seeing these designs move from paper studies to deployment.

I think the Gen-IV International Forum is also transitioning. Whereas the last 20 years, I think, were more of a period of R&D and supporting the designs. We're in a period now of trying to transition to help the nuclear industry more as the vendors move toward deployment.

So generally, just key takeaways are while there are domestic MC&A and international safeguards challenges with advanced reactors, we do have a lot of experience with safeguarding designs that utilize solid fixed fuel assemblies. The pebble bed reactors and the liquid fueled molten salt reactors do have some more R&D needs. But I think there's already been a great deal of progress in recent years to establish the technologies and approaches that may be used to safeguard these systems. So hopefully we'll continue to move forward, and we'll find additional ways and additional R&D which will help out these systems.

I thank you for your attention, and I'm happy to take any questions.

Berta
Great. Thanks, Ben. As questions are coming in, as always that we do, we'll take a look at the quick look at the upcoming webinar presentations. Early in April, we have a presentation on the overview of nuclear graphite R&D in support of advanced reactors. In May, graphite molten salt interactions, and in June presentation, there'll be a panel discussion on international knowledge management and preservation of SFR.

The first question, Ben, is monitoring of subatomic particles like neutrino play any role for unauthorized removal of plutonium?

Dr. Ben Cipiti
There has been a large body of work on antineutrino detectors for the reactor itself. For example, breeding plutonium or using a different material than it was designed or declared for. So, it does have value in that particular area. But from a MC&A perspective, it's a slightly different type of measurement because it's not providing that detailed accounting of nuclear material. It's more from a larger perspective of is it being used as declared or not?

Berta
Thank you. And then we've received questions in advance regarding physical security of nuclear facilities. I know that you've talked quite a bit about that during your presentation, but do you have any additional thoughts on ways that we can ensure the physical structure in adverse conditions, such as maybe in Ukraine?

Dr. Ben Cipiti
Yeah, so this topic has come up recently. The war in Ukraine, I think, is causing a little bit of a questioning of physical protection design for nuclear energy. I think one thing that I – this again is really just kind of my personal opinion that I want to caution on with these types of questions is that nuclear energy already is subject to the most stringent requirements for security compared to any other power source. The advanced reactors are already currently struggling with the physical protection requirements. The main point of this is just that whereas a very large reactor at 1000 megawatts can support having tens of guards on site protecting the reactor, as you go towards smaller and smaller reactor designs, it becomes increasingly uneconomic to have a large number of physical protection staff on site.

On the physical protection side, one of the things that we're trying to do is really optimize it and develop new designs that reduce the number of onsite staffing. When we talk about the threat of a country coming in and attacking and taking over, I think it's worth thinking about. And we hope that we have designs that can be pretty shut down, safe, and be good in those kind of situations, or mostly good. But in a way, it's really kind of an unfair thing to put on nuclear as compared to any other power source. We establish a design basis threat because we have to establish some kind of a reasonable threat to protect against. If you add a full military coming in, there's no way we can make a nuclear reactor robust to something like that. And we really shouldn't even talk about putting on some kind of a requirement like that.

So, I think that these discussions are good to think about, but my caution is just that it shouldn't be something that leads to new security regulations for nuclear energy systems.

Berta
Thanks, Dr. Cipiti. I think that was a great answer to a difficult question. I apologize. Let me catch up here, folks. This is the one that you've already answered. Has PR&PP considered PR of related fuel cycle facilities enrichment for HALEU or reprocessing, particularly an NWS?

Dr. Ben Cipiti
Oh, a nuclear weapon state. Okay, so the PR&PP Working Group focuses really just on the Gen-IV reactor system. So we mainly just focus on the six classes of advanced reactors. Now, that being said, we do sometimes touch on the fuel cycle just in the sense that we do sometimes have to talk about open and closed fuel cycle. This was also touched on in the crosscut report. We do talk about the fuel cycles and some of the differences from a PR&PP perspective, but it generally hasn't really been our focus in the working group. I think that's something that increasingly we may need to think about or address, especially if some of the advanced reactors do take off, and we start seeing a lot of deployment.

Right now, there's a big focus really just on getting the fuel for those reactors. I think there's a little bit more of a focus on the front end. I think that's part of the question was alluding to. We do need to make sure that we understand safeguards and security requirements also for the frontend facilities like HALEU enrichment facilities, as well as fuel fabrication facilities using HALEU, because that's not something that we have. I mean, we don't have these, like, large plants out there right now. In the future, we'll probably be thinking a little bit more about reprocessing. But I think right now we really just have to focus on the frontend activities and making sure that we have the resources in place to adequately meet the regulations and meet the safeguards and security regulations for them.

Berta
Thank you. In the past, there was a study based on the German AVR experience trying to perform item counting with barcodes on fuel pebbles. I haven't heard anything about that recently. Do you know how that turned out?

Dr. Ben Cipiti
I know that there's some challenges with that, and there's differences depending on the type of pebble bed system. The gas cooled pebble bed systems do see a little bit more kind of erosion and abrasion to the pebbles than, for example, the pebble bed design that would be molten salt cooled. My understanding about some of the recent thoughts on that is I don't think that there's necessarily a desire to do a bar code on each pebble, but they may look at doing some kind of a larger marking on the pebbles just to indicate a batch number. Now, the reason for this, and this is kind of my perspective from an MC&A standpoint, is that we don't need to track pebbles individually. From an MC&A perspective, we need to do it at, like, a canister level, and the burnup measurements are going to allow us to do that, and we can sum up what's coming out of the reactor.

There may be interest in doing a batch identification. And what I mean by that is you're going to constantly be having new batches of fuel coming into the reactor, as you're pulling out some of your spent pebbles. If you can identify what batch that pebble is, you might know, oh, hey, that was only put in six months ago, so we probably don't have to do a burnup measurement on it. So it could potentially be a way to optimize the burnup measurement system and just be a way for the reactor vendor to kind of better track what's happening with the pebbles and how many times are they being circulated through the system. But generally speaking, doing a barcode or an identification every pebble just isn't going to be needed.

Berta
Thank you. Can you please indicate the most advanced research going on with online reprocessing? I mean, how fast MSRs can be deployed?

Dr. Ben Cipiti
I'm not sure I completely follow that question. Let me try to answer it from a couple perspectives. So, in terms of the online salt processing, some of the molten salt reactor designs that are out there, there's not a lot of vendors that are looking at full on site processing of the salt. If they do full on site reprocessing, that is additional unit operations. It's additional measurements that may be needed from an MC&A perspective. I think generally the technology for that is, I

wouldn't say it's at the industrial level, but I think much of it has been demonstrated. So I think it's at sort of a semi mature point, but I think that there's a lot more that would need to be looked at from an international safeguards perspective with those types of facilities.

I hope I answered that question. I'm not sure if it was getting more into reprocessing of other fuels.

Berta
Thanks. For long life SMRs for like 10 years, supposing the non-access to core is monitored by IAEA, what would be needed as a complementary safeguards measure? Would that imply a new consideration of the timeline for safeguards activities?

Dr. Ben Cipiti
Yeah, that's a good question. I think it touches on something that maybe I wasn't, like, overly clear of in the presentation. A lot of my comments about having solid fixed assemblies or sealed cores, it's not that there's no challenges there, but it's more just that we have a lot of technologies in place that we can pull from. And so, I see them as areas that probably require less R&D than some of the other reactors.

So sealed cores are kind of an interesting concept, because potentially we could simplify things quite a bit, in the sense that means that you put a seal on it and you don't have to do any verification as long as that seal is intact for the life of that reactor. So I think that that has a potential to really optimize international safeguards. Now, that's kind of balanced by the fact that if we get to a point where we have a very large number of small modular reactors or microreactors out there, that could just be a lot of different assets that IAEA would have to keep track of.

So, I think that there's pluses and minuses to it. The complementary measures part of the question – I think that's a good question. That's not an area that I focus on quite as much specifically myself. So I don't know that I can give a real great answer to that. But I think the question there might be more of a challenge of what kind of a seal do we use that has a very long life, really, mainly just to optimize how often IAEA would have to go in and do maintenance or check on things, can we develop a seal, for example, that's going to be good for 10 years?

Berta
Thank you. This is just a comment that asks for your opinion. It appears pebble bed core reactors are desirable from a material

safeguard perspective since a bad actor, but after still a lot of spent fuel in order to obtain enough plutonium through reprocessing, it seems this type of reactor design is desirable from a physical protection perspective. Would you agree?

Dr. Ben Cipiti
I think there's two questions there. There's the sort of PR side, and there's the PP side. The entire, I think, development of TRISO fuel was really done, at least partly, from a PR perspective.

Now there's another side of that, too. It was really designed more from the safety perspective first. But I think it was also recognized that this is a proliferation resistance advantage because the fuel is very dilute, and it's difficult to process. So, yeah, I think that kind of gets to that intrinsic proliferation resistance feature. And, yeah, so there are advantages there for sure when you go to TRISO fuel.

Now, physical protection is, I think, a different topic. Again, from a physical protection standpoint, we have to think about theft as well as sabotage. And so from a theft standpoint, yeah, if I were an adversary, I wouldn't steal pebble bed fuel. I think that's kind of ridiculous. I think I could figure out much better ways to get nuclear material. But from a sabotage perspective, pebble bed fuel is just as much of a target as any other spent fuel.

So, from a physical protection perspective, we still have to adequately protect the reactor. We have to protect any of the spent fuel on site because any sort of access to that and ability to either steal it and use it in an RDD type of device or a sabotage act at the facility can release a significant amount of radioactivity.

Berta
Thank you. Current proliferation resistance assumes IAEA safeguards, but should we consider beyond safeguards, that is IAEA monitoring might be rejected by the country?

Dr. Ben Cipiti
Well, that is taken into account in the methodology. The PRPP methodology does take into account both the extrinsic measures as well as what are the agreements that are in place? So, yeah, if a host country is not accepting IAEA safeguards, that's sort of a different story. My perspective all along in proliferation risk type of studies or PR&PP methodologies is that, any system has some sort of risk associated with it, and some have more PR risks, maybe some have more PP risks, and we do have to apply extrinsic measures to adequately protect those facilities. My view has been one more of

that any facility can be protected. It's more a matter of how much is it going to cost, how much measurement do we have to do, how many tags and seals, how many additional measures do we have to add to it to really be comfortable with IAEA safeguards verification.

So I think that's like the main thing that we're looking at is what sort of level of and what sort of cost ultimately is it going to take to protect these systems? When we talk about a situation like that where a country is not going to be accepting of it, that's really kind of a very different policy type of question that isn't really addressed here.

Berta
Thank you. What is the typical fissile content of in a prism HTGR? Less than an SQ?

Dr. Ben Cipiti
So any reactor, if it's going to be a reactor, is going to have more than one SQ. So it doesn't really matter what the size is. Even the smallest microreactor is going to have to have enough material to be critical. So any reactor is going to have more than one SQ at the very least.

Berta
Thank you. Can we use the Internet of things for safeguarding or material accountancy in Gen-IV reactors?

Dr. Ben Cipiti
I'm sorry, was the question do we or can we?

Berta
It says can we?

Dr. Ben Cipiti
Okay, let's see. I'm not entirely sure what that question is getting at. Let me try to answer it this way. I think that there's still kind of ripe a lot of R&D spaces in the areas like machine learning, artificial intelligence, concepts like state level safeguards approach. I think there's still probably a lot more that we could do in those areas. So, like, just as an example, when I talked about the molten salt reactor and I talked about how from a domestic standpoint, we may be able to rely more on physical protection, but we can't do that from an international safeguards perspective. That may be an area where we do need to explore a little bit more, what are some other newer techniques or out-of-the-box thinking ways that we can safeguard these facilities? So, for example, for a molten salt reactor, we may want to apply some kind of a machine learning approach that looks at all the reactor parameters to determine if there's some kind of a

misuse scenario happening. So it might be a combination of the measurements, your sampling, your bulk mass. It might be your power level indicators. You might even be just do things with temperature or the frequency of fuels and waste salt leaving the system. So I think that there is a lot more that probably could be looked at there. But I also will say that I think those areas are a little bit more challenging because it sometimes takes a lot of R&D to prove that those concepts could work. And then you have to start looking at a lot of different scenarios to see if you can kind of break it.

I hope that answered the question. I'm not sure if I answered that really well.

Berta
Thank you. Ben, how are we doing for your time? It looks like there are still questions coming in.

Dr. Ben Cipiti
I'm fine.

Berta
More questions. Do we have time to keep going for a few more of these?

Dr. Ben Cipiti
Yeah.

Berta
Okay, great. For some technologies, is it possible that the challenges related to safeguards, monitoring and protection rule out a reactor technology over time? For example, the cost of implementing safeguards for a molten salt versus pebble reactor.

Dr. Ben Cipiti
As I mentioned in one of the slides, our goal in Gen-IV is not to pick winners or losers. We're really just trying to look at where the challenges are and where you may have to apply additional measures.

I do think that it's certainly possible that I think the market could lead to designs that are just going to be not as attractive economically because of the additional requirements. And some of that could be inherent to the system. Some of it could just be through maybe a company that's just not dealing with safeguards and security well.

So one of our big messages, I think, in our community that we try to push over and over again is safeguards and security by design. And this is from both the domestic and the international standpoint. We want vendors to consider these requirements, these regulations very early in the design process so that you're not creating expensive retrofits, you're not completely designing the system and then realizing, oh, this wasn't designed very optimally for safeguards or wasn't designed optimally for security.

My opinion is that the vendors that do that early are going to have a competitive advantage, and the ones that do not could be the ones that fold. I'm going to be a little bit on my soapbox here, but I think one of the things that's a little frustrating to me right now is that many times with the advanced reactor vendors, I think that there's individual people who are in safeguards or security or in licensing that understand this, and they do want to push it, but sometimes they're not being heard by their bosses, by the CEOs of the company. Oftentimes it's the CEOs that they like this idea of this little compact microreactor that they just kind of drop off somewhere. They like the idea of their pretty pictures of their SMR that they can deploy all around the world. And the individual staff are trying to tell them, well, no, we need to put a fence around this. We need to do some basic level of security. We need to think about international safeguards if we're going to put it all around the world. So that message is something that I think continues to need to be pounded, and it really comes down to whether or not these vendors are going to be successful or not.

Berta
Thank you. I'm interested in the AI-based burnup calculation done by the us colleagues, not only for that, but also for many advanced SG techniques for the quasi bulk fuel type reactors. Are there any large-scale experiments planned in the US?

Dr. Ben Cipiti
Yeah, that's a good question. I think one of the things we're trying to do, and this is specifically on the pebble beds, we do hope to get into some short-cooled measurements of pebble fuel next year. That's something that's going to take a little bit more planning because it's going to be something we'd have to do jointly with the high temperature gas reactor working group, at least in the US, along with the safeguards work that we're doing in the advanced reactor safeguards program. But, yeah, we'd like to do some short-cooled pebble measurements and use that to get actual data and then try to apply the machine learning approaches to that to determine if it's effective as shown. So the work that was shown there, that at this point is still just modeling work. So, yeah, we definitely need to get to a point where we have some more experimental data to back that up.

Berta
Thank you. A similar question is what we've already talked about on PR. Current fiscal protection assumes design basis threats, but should we consider beyond design basis threats? Since we adopted beyond design basis accident for reactor safety, which is severe accident, should we also adopt that same concept for physical protection?

Dr. Ben Cipiti
I might answer that question a little bit differently. I think I already kind of talked earlier about how – I have a lot of concerns and I think we have to be careful in anything that's going to add additional regulations to the vendors. I think there needs to be a really strong justification for that just because of the effect of the cost on the reactors.

The one thing I will say, though, is that I do think that as part of safeguards and security by design, we do need to think about what are potential future threats. There's things coming out there on the horizon that we are aware of and may not necessarily be in a design basis threat right now, but it might be prudent for a vendor to consider working that into their physical protection system.

I don't want to go into a lot of detail on that, but it's really just a way of recognizing the fact that we site a reactor right now, and it may still be operating in 40 years or 60 years. So what is the threat landscape going to look like at that point in time? It's not necessarily to say that we can predict everything that's going to happen, but we may be able to do some things with designs that protect against some of those future threats. So, for example, underground siting does help to kind of mitigate some of those potential future threats that may be out there. So, yeah, I think that's something that at least we're looking at on the US side in terms of physical protection systems. It's not perfect. We're never going to predict it exactly right. But I think it is something to focus on.

Berta
Thank you. Would you agree that the item counting reactor types you described would rely mostly on the same methods, technology, and devices to be safeguards at the same level as today's PWR? However, they could represent progress and require less intensive or time-consuming safeguards, efforts in particular, perhaps taking into consideration reliance on the process monitoring and a higher burnup.

Dr. Ben Cipiti
That's a good question. You're kind of touching on a couple things there. Well, there's advantages and disadvantages in moving

towards advanced systems. There's a lot of movement today around the world and moving towards the small modular deployment concepts or microreactors. And so, the disadvantage is that if IAEA, for example, has to safeguard hundreds or even thousands of new reactors, it's really questionable where they're going to get the resources for that. So I think we're going to naturally be pushing more towards remote monitoring just simply so IAEA can keep up with all that.

The advantage is that each individual system in many ways should be simpler. A large reactor is a very large site with a spread out kind of large number of vital areas. It may be that as we move towards small modular reactors and especially towards microreactors, that they just become a lot simpler from an IAEA safeguards perspective. What I mean by that is you may have less penetrations that you have to seal, you may only need one or two surveillance cameras if the reactor is small enough, it's basically just one location, or maybe you just have the reactor and the spent fuel and that's it.

So, I think that there's probably a lot of activity we could look at to try to really optimize that, try to do as much remote monitoring as we can. And frankly, I think we're going to have to because there could potentially be so many systems out there.

Berta
Thank you. Let me remind everyone again that the handouts from today's slide deck – the slide deck is available on the handouts pane. You can download that right to where your laptop or where you're viewing from. They'll also be posted with the recording of today's presentation on the GEN-IV website. So we do appreciate your attention. And what a great engaging live Q&A! It's always the most interesting to see the level of interest and the number and the range of questions that we get. And I really appreciate your expertise, Ben. Thanks for sharing your thoughts and perspectives today to answer all of those questions.

Dr. Ben Cipiti
Thank you. I appreciate the questions. They're great questions and definitely some of them make me think. So, I appreciate the thought.

Berta
Patricia, do you have any closing thoughts? She's self-muted, so I'm not sure. But Ben, thank you again for your time and your expertise. Thanks everyone for attending. Our next presentation, we usually spread these out, but they're almost back to back this month. So 5th of April. Let me remind your calendars that that'll be our next GIF

presentation. And I think with that, we'll go ahead and end today's discussion. Thanks, everyone.

Dr. Ben Cipiti
Thank you, Berta. Appreciate it.

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