Proliferation Resistance and Physical Protection of Gen IV Reactor Systems
Dr. Robert Bari, Brookhaven National Laboratory, USA

Berta Oates
Welcome everyone to the next Gen IV International Forum Webinar Presentation. Before we get started, I do want to do a few housekeeping sorts of topics. The first of which is in the 'Download PowerPoint Pod.' If you click that, the slide deck is available to download directly to your computer station, and you are welcome to do that. Today's presentation is being recorded and that archive will be posted on the Gen IV website and that link will be available when the thank you notes go out today.

Last but not least, there is a link to a survey. We do appreciate your feedback and we take your comments very seriously. If you have comments on the presentation today, ideas for upcoming presentations, anything of that nature, we appreciate that very much. The questions, we will take at the end of the presentation, and you can type those into the Q&A pod. We will take as many questions as we have time for.

With that, with no further ado, we'll get started with today's presentation. Doing today's introduction is Dr. Patricia Paviet. She is the Director of the Office of Materials and Chemical Technologies within the Department of Energy, Office of Nuclear Energy. And she is also the Chairperson for the GIF Education and Training Task Force. Patricia?

Patricia Paviet
Thank you very much, Berta. Good morning, everyone. It's my pleasure to have Dr. Robert Bari with us today. He received his doctorate from Brandeis University. He is currently a Scientific Advisor at the Brookhaven National Laboratory. He has over 40 years of experience in nuclear energy research. He has performed studies on safety, security, nonproliferation of advanced nuclear concepts.

For 15 years, Dr. Bari was co-chairman of the working group on proliferation resistance and physical protection of the Generation IV International Forum. He has served on the Board of Directors of the American Nuclear Society and as President of the International Association for Probabilistic Safety Assessment and Management. Dr. Bari was awarded the Theo J. 'Tommy' Thompson Award in 2003 by the American Nuclear Society. In 2004, he received the Brookhaven National Laboratory Award for Outstanding Achievement in Science and Technology. He is a fellow of the American Nuclear Society and of the American Physical Society. He has participated in risk-based standards development for nuclear technologies for more than two decades.

Without any delay, I am going to give you the floor, Bob. I wanted really to thank you for giving this webinar. Bob retired just a few months ago but still very active and willing to present this webinar. Thank you, again, Bob.

Dr. Robert Bari

Thank you, Patricia, for a very kind introduction. Thank you to all the participants in this presentation. For some of you, it's very early in the morning, and for some of you it's very late. Thank you all for your willingness to come and listen to this presentation. As an introduction, I want to note that, as we embark on a path towards a growing number of nuclear power plants worldwide, it's important to consider the goals of Generation IV, the four top-level goals. And, they are, ‘sustainable nuclear energy,’ ‘economically competitive nuclear energy,’ ‘safe and reliable systems,’ and the focus of this presentation is the fourth goal, ‘proliferation resistance and physical protection,’ which I’ll be referring to sometimes as ‘PRPP’ or ‘PR&PP’ because it's certainly a mouthful to say all of that.

As we think about moving forward in these four areas with the designs of the new Generation IV systems, let's look at sustainability and getting that right. What's important there, of course, is a ‘reliable fuel supply’ and the ‘waste issues.’ And that's independent of whether we have an open fuel cycle or the closed fuel cycle where we reprocess and recycle. It's very important to assure that we have fuel and can dispose of the waste at the same time or in the course of the nuclear enterprise I should say.

Economics is another very important aspect for nuclear power and we need to get that right of course. We have an economics modeling group of the Gen IV organization and they are working very hard to assure that there are methods for getting to an economically robust and competitive nuclear power situation worldwide. But, of course, we see that to be cost-effective we’ve got to be mindful of the fact that we have seen cost overruns with nuclear power, we have seen bankruptcy recently with nuclear power, particularly in the United States, and that was a rather hard blow. And third, we need to assure that nuclear power is competitive relative to other sources of generating electricity.

Third, we need to think and assure that we get the safety picture right. And, fortunately again, we have a working group within Gen IV, the risk and safety group who is working on that, developing an approach to assuring safety and building safety into the design process for Gen IV systems. As we proceed with that and as they’ve been developing their methodology, they have been very mindful of gathering the lessons learned from the Three Mile Island accident, the Unit 2 in Pennsylvania in

1979. The Chernobyl accident in the former Soviet Union in 1986. And the Fukushima accident in Japan in 2011. So, they are working to assure not only safety but reliability as well.

Our mission is getting PR&PP right. The story there is very simple. It's one picture is worth more than a thousand words. We just must prevent what we see in this picture.

What I'm going to talk about today in this webinar are four things connected with the working group. One is what are we? The PRPP group, Gen IV have already hinted it to it a little bit. A little bit about our methodology, what we came up with. And then thirdly I'll talk about the case study that we did to help illustrate the methodology. And it was very important, as we developed the methodology, to have that case study working hand-in-hand with methodology development. And fourth, I'll say something about our interactions with the Gen IV designers, the six Gen 4 design concepts that have been proposed a decade and a half ago and have been worked on very diligently by many, many people over the course of the time.

The reason why we need to talk about that of course is that they are the ultimate owners of our methodology. The use of this approach, the Gen IV approach, is key towards assuring PR&PP for the future designs.

At the outset, I should note that we've taken on two missions within the PR&PP activity. One is assuring 'proliferation resistance' or at least assuring that we have a methodology for it. And second is 'physical protection.' And these are distinct activities. In fact, if we had been assigned from the get-go to take on one or the other, either one would have been enough of a job for us. They are both very important topics. But they are distinct topics, and it's important to recognize that distinction.

'Proliferation resistance' refers to the situation in which the host state is the adversary, a host state of a Gen IV system. Then it goes forward to do malevolent things with the Gen IV system. And that is indicated here as connected with diversion or undeclared production of nuclear material or misuse of the technology leading to weapons or other nuclear explosive devices.

On the other hand, 'physical protection' is a case where the host state is now the defender and there is a subnational entity or a non-host state actor, a terrorists perhaps who is trying to either steal material or sabotage it for the purpose of gaining nuclear explosives or radiation dispersal devices.

So there are these two and they are distinct, so we'd have more of a challenge in developing the methodology from that point of view. But there are some synergies between the two and we tried in our overall approach to exploit those similarities, trying not to overplay them, and on the other hand not to underplay the similarities. And it's very important in the broader context of understanding these distinctions and not to conflate ‘proliferation resistance’ and ‘physical production’ as some people do, particularly folks who are detractors of the nuclear energy, trying to use events or circumstances connected with one, to say, ‘Aha, we’ve got a problem in the other area.’ They are distinct and it's important to realize the distinction here and as we have defined it. And as we’ve defined it, we’ve accordingly developed our methodology.

We have a charter. A charter was given to us. Back around 2003 when we started the activity, we formed a group, appointed by the participants in the Gen IV International Forum. The basic idea is to demonstrate a methodology, develop it and demonstrate it so that one could be able to do assessments of PR&PP with three major tasks. One is to characterize in and of itself what the relevant proliferation and security threats are that we are concerned with for future nuclear energy systems.

Secondly, to specify measures for expressing the system’s proliferation resistance and physical protection. How good are we doing, what are the things we are measuring it against. And thirdly, to develop the methodology to assess the measures and quantify them. But very important in all of this is to work it in a consensus type of approach where all of the international participants are in agreement that yes, this is the approach that makes sense to all of us and that is what we strove to do and we worked to develop a coherent approach to our methodology.

The major products of the group, and I’ll reiterate this again at the end, is we’ve developed the methodology and it's a document that's available on our website shown at the lower portion of this slide, easily available to everyone. It’s an open website. The methodology is there. Easy to find and click on. The second major piece is the example case study that we did and I’ll say more about that in a few minutes. And the third is what we call a ‘comparison study.’ It’s really comparing our methodology to where we stand with the six Gen IV designs with regard to PR&PP.

Those are three major documents easily obtainable from our website. For those who would like to see more information, I strongly encourage you to go to that website and see these documents and hopefully read them and use them as you move forward. Along the way, we developed some supporting products, a bibliography, and I’ll say more about that later, detailed references for researchers, and practitioners, and designers in particular. We also developed a shorter document which frequently asked questions about PR&PP and people who just wonder about what is the subject probably, the least familiar of the four goals of Gen IV and how we approach it. So this gives you a good idea in a nutshell of how you do it and what the further references are. So again, that's available on the website. The other major product, the key product really in all of this is our ongoing interactions with the Gen IV designers, like ‘This is why we are doing this. This is why we did it,’ and I’ll say more about how we’ve interacted with the Gen IV designers every step of the way in this activity.

And in terms of the value of PR&PP to future designs, there are three aspects of that. The first is, I am a firm believer that you should use this methodology, whether the Gen IV designers or other advanced nuclear concept designers, use this methodology very early on in the design. Right as the design concept is being formulated, start to bring in PR&PP so that it’s built-in, it’s not something that’s retrofitted at the end of the design when one is going to a regulator or an international body for approval for the design. So it's important to work it into the design very early on. And the way to really approach that is to interact with the designers. The methodologists should interact with the designers every step of the way. As the design matures, the PRPP model would mature along with it. We call that ‘progressive refinement.’ It’s a bootstrap type of thing. As the methodology gets better, some insights come from the methodology. It goes into the design, the design is then advanced, and then the methodological model is advanced as well. So, it moves along with the design right through full operation and it’s continued to be used throughout that entire process, and in fact right ultimately into decommissioning over the long, long term.

And thirdly, the PRPP results could be useful to policymakers at the get-go in terms of informing choices about the designs and how one interfaces with the regulators and other institutional bodies in terms of what's important for the design early on. So, this is an opportunity to get these ideas at the forefront very early on.

In terms of an actual evaluation, what is needed, what should be considered? One, what are the policy directions and how do you formulate the questions in terms of PR&PP? What are you asking about the systems in terms of their robustness for PR&PP? In any scientific enterprise, asking the right questions is key. So that's the first very important step. Specific to PR&PP, it's the adversary context for threat definitions. What are the objectives of the adversary or actor? What are the capabilities of that actor in terms of economics, the technology? And third, what are the strategies that the actor adversary might put in place to carry out the malevolent act.

Important is understanding the designs in the evaluation. The people who participate in the evaluation have to include the people who know the system best, namely the designers. So, that design, as it relates to PR&PP, is key to doing the evaluation. The overall fuel cycle architecture is going to be important in all of this, whether it’s a once-through or a closed cycle or even something more global in terms of sharing, providing fuel and taking it back between various organizations. All of that has to be brought into account. The safeguards and security contexts are key here as well. You need to know what safeguards and security systems are being put into place in the design and how those mitigating features help in terms of understanding how to forward the objectives of the malevolent actor.

It's good to have some reference case baseline to compare and see how good one is doing in terms of – this always true of course, how good am I doing? Is there some reference? Is it a baseline? Is it a set of goals that have been put forth? So, that is important overall in an evaluation.

Our methodology, and here it is at a very high level, basically it's a scientific approach. We consider our system, the PRPP system, and we ping it with challenges just as one does in a scientific experiment. You want to understand some system and you typically ping it in some way, probe it, and look for the outcomes, what you measure, what comes out of it, whether you are scattering particles or you are measuring temperatures here. Here we're pinging it with treats and we are looking at how our PRPP system responds, and we calculate and assess the outcomes. In terms of system response, we have to consider two very broadly different aspects. One is the 'intrinsic' design itself in terms of the physical features of the Gen IV system, its technical design features. All of that taken together, we consider the 'intrinsic protection' within the Gen IV system. And then we have another piece and we call that the 'extrinsic.' Those are the institutional arrangements that are brought to bear. If it's PP, it's typically the state regulator who would say, 'Well, this is what you've got to do in terms of physical protection, you've got to assure the following.' Or, if it's a PR, Proliferation Resistance, it's typically at least the IAEA, the International Atomic Energy Agency, who provides the guidelines. So, that's another aspect for the 'extrinsic' part.

And these two, it's not additive, it's more interactive between the two, because the 'extrinsic' will say something about what you should be doing in the intrinsic part and vice versa. The intrinsic, you'll see how well you're doing in terms of the requirements put upon the designer by the various organizations that come into play. And what one should be mindful of in all of this is that it's a very difficult area. Proliferation theft and sabotage involve an intelligent adversary who could react even during the course of a scenario in terms of adjusting. So, the human interplay is very important here. So, it was really competing adversary and defending forces and that needs to be recognized in the assessment, and so that makes it a very hard thing to do but not impossible but also very necessary.

This just turns that viewgraph over, going vertically now. We have the ‘challenges’ ‘system response’ and ‘outcome,’ and blowing up the ‘system response’ a little bit more. One needs to define what the elements of the system are that are of interest for PR&PP, for the full nuclear system that's being considered. The ‘target identification and categorization,’ these are targets of opportunity for the malevolent actor.

Then, thirdly, it's getting an assessment of what actually happens in the system when it's being threatened. Our methodology has a pathway approach that we’ve taken. It's an inductive approach where one works one’s way through the various possible evolving states of an attack and how it evolves. And then one estimates the so-called ‘measures’ which I’ll talk about in a minute, what are the outcomes. And these various pathways can be compared in terms of their importance. And one then assesses and presents the final results for consideration.

This is just a quick look at how one would actually step through in a nine-step process. This is in our methodology report. I won’t read all the details here. You could see them as well in terms of the exact points that occur in each of these boxes. Basically you need to frame the evaluation, form a study team, and I should mention that the study team has to be interdisciplinary as we are looking at many aspects of a difficult problem. Decompose the evaluation and develop a plan for how folks are going to do the analysis. Collect and validate data and then do the big thing. Step 6 is ‘perform the analysis’ and 7 is ‘to integrate and present the results.’ And these results get presented in various ways depending upon the audience involved in the information gathering. It could be at a high level, it could be at the level of designers who have to modify results. Reports have to be written. And finally and very importantly, the key to all this is to have adequate peer review, people who could validate what's been done, and give guidance on how to improve the study where it might have shortcomings. And itself is an interactive process and brings one back to probably step 5 again until one really converges on a robust assessment.

Let me say something about the PR&PP measures that I’ve hinted at. The group early on in its activity came up with its PR measures and the PP measures. We came up with six measures for PR&PP. Well, six for PR and three for PP. For PR, one is the technical difficulty of carrying out the proliferation activity. The timeframe for doing that which includes the time in which one initially starts to plan or the adversary starts to plan for a proliferation activity. And it could be a very long time. The cost to the proliferator, the probability of detection by typically the IAEA. Very important is number 5, the ‘fissile material type.’ What type of uranium? Is it enrichment? Is it plutonium? What is mixed in with it? The typical materials that in our report we talk about at length. And ‘detection resources efficiency.’ That’s basically the cost of putting safeguards in place. Well, that should be in there as well in terms of understanding the robustness of a system with regard to PR.

PP is very similar but we are managed because typically PP is mandated by the state and individually and separately by each country. We've characterized it in terms of 'probability of adversary success' the 'consequences' of that success, and 'resources' that the protector/defender would have to put in place to protect against the malevolent act.

These are then mapped into specific metrics and you'll have to go to our report to see it. Time does not permit me to go through all of that. But you can go to our report, it's shown at that link at the bottom, to see in each case what are the recommended metrics, suggested metrics in some cases that that we propose. Of course, the designers come up with their own or fashion it to their own stylized needs for their particular assessment. Those are the measures. And now the threats on the frontend of all of this. We've built what we call 'threat matrix.' I'll, in the interest of time, just look at one piece of it. The 'proliferation resistance' part, you could read on your own. The 'physical protection' part, and of course, this is all, again, discussed in our report.

We are looking at four broad features, namely the 'actor type,' the 'actor's capabilities,' the 'objectives' of the actor, and the 'strategies.' You could see here, without me going into lots of detail – obviously, the actor is the 'host state.' The resources are economic, technical skill, the possible nuclear materials, basic industrial capabilities, nuclear capabilities. Then, in terms of weapons, it's a question of 'how many.' Is it just one weapon or ten weapons? What is the reliability of these weapons that are being fashioned? What is the desired stockpiling of weapons by the adversary? How would they be delivered and the production rate of the weapon? So, those are mixed into the overall understanding, the objectives, and how to proceed in the analysis given whatever is specified in this. You might say, 'Well, just one weapon, and we want to have a high reliability. It's not being stockpiled of course.' Then there is a question of, 'How it would be delivered?'

So, those things would be specified and it would be part of the analysis. And then the strategies are important. Is the adversary interested in the concealed diversion as opposed to overt diversion where everyone knows that something is going on but not taking very specific actions yet for that? Is it concealed facility misuse, overt facility misuse? And then lastly, independent clandestine manufacturing facilities based on Gen IV systems. So, that's a replication type of scenario. And then the similar things with 'physical protection' which you could read in our methodology report in more detail.

In terms of system response, as I indicated, we advocate a pathway approach, and an inductive one, where one starts with assumptions about how the attack is going to be carried out. And what one does and here is just a notional look at what a pathway scenario might look like, the key thing here is that it's being decomposed into pieces and then reaggregated at the end to some finished result or a collection of results. Ultimately, depending upon what the outcomes are, there may be various branches here.

And ultimately the pathways are a basically a potential sequence of events followed by the proliferator or adversary to achieve the objectives. And there may be obstacles along the way and that would be a good thing. And what's important as well here is the time-dependent aspect of the problem and making assessments of the uncertainties. There are going to be lots of uncertainties in the analysis because right from the get-go the design is in its early stage. And also what the adversary might do is not precisely known. So one needs to recognize these things and quantify those uncertainties, or even at a qualitative level, getting a sense of these uncertainties.

And again, this is discussed in our report in how one would reflect this in the analysis. So, it's not a final point number answer that one gets but a range ultimately.

As I've indicated, between PR and PP, there are similarities, and differences and these are just quickly summarized here. I think I've said some of these things already. For the threats, we have diversion, misuse, and breakout scenario for PR. Similarly for 'physical protection' we have material theft, information theft, and sabotage. 'International safeguard' is a key for the 'proliferation resistance.' And domestic safeguards. And physical security systems for 'physical protection' are key. And the PR tends to be slower moving events. They are planned. It might be a protracted diversion of materials. Whereas the 'physical protection' event tends to be fast, and it's an attack, but it's not always the case in each and so one needs to be aware of that in terms of the analysis. And PR will definitely have international implications, violation. And PP will certainly have a minimum regional implication, certainly within the states in which the attack has occurred.

What we recognized early on in our methodology design development is that the probability of detection for a new system particularly as one is introducing new safeguard systems because the safeguard systems that we know at IAEA are largely defined in terms of generation to nuclear reactor systems. Here we are looking at newer systems and some of them not tried in any real sense. And how does one develop a safeguardability and how does one even calculate the probability of detection of a malevolent act?

We thought it would be useful early on to introduce a notion of safeguardability which is defined by us as the ease with which a system can effectively and efficiently be put under international safeguards. So, this gives us a figure of merit for the probability of detection. And it's the property of the whole nuclear system. It's not one system at a time but overall it needs to be applied across the board to the entire nuclear system under consideration.

In terms of safeguards, this is now in the world of 'intrinsic' aspects. Here is why you need to consider safeguardability because there are differences. The accountancy tools and measures that we know for the Gen II systems may need to be modified for non-conventional fuel types. New fuel loading schemes may present novel accountancy challenges. And the accessibility of nuclear material could be different. You could have facilities that are operated continuously in terms of refueling or you might have to just consider how is the facility refueled. What is the location and possible mobility of a facility? Could it even be, let's say, a floating nuclear power plant? And the existence and location of other nuclear facilities nearby or in coexistence with the new facility.

So these things need to be considered in future reactor safeguards. I should say, IAEA is giving a lot of thought to this and has produced various documents which can be found in our bibliography which I'll indicate a little bit later on.

Just continuing, fuel leasing and supply arrangements that avoid on-site storage of fresh fuel and/or used fuel need to be considered in the future reactors. Access issues for both the inspectorate and the adversary is important. And communication for remote monitoring by communication with the operator, state, and the IAEA, all of that will be new, and is being considered by IAEA and others, but this has to be part of the extrinsic aspect of the assessment problem.

For the 'physical protection' side of the house, one has to consider, 'Will this be different and how might it be different and how would it affect the safeguards, the international safeguards? What are the push-pulls between international and domestic safeguards in terms of, well, say, material accountancy, for one?'

'Will the site or nearby sites have more or less ancillary equipment like hot cells, pin replacement capabilities, fuel storage, and research reactors activities?' 'Will the containment be shared with multiple units; will there be underground containment?' All of this is very important for future safeguards.

In terms of developing our methodology, from the beginning we recognized that we are starting anew. There had been of course some work done in previous decades but not a lot, not at least as far as we wanted to go. We thought that to carry out a methodology, to develop it and present it, we needed some reference guide for ourselves. We decided within the first year or so of our activity that we needed to develop an example model, not one of the Gen IV systems but an advanced system that some of us in the group were at least familiar with, and somehow that came out to be a sodium fast reactor. Several of us had had a previous experience one way or another with a sodium fast reactor. One of the fortuitous things is that there was a design from the early 90s, maybe late 80s, that was put forth in the US by Argonne National Laboratory called the 'integral fast reactor,' which no longer is being pursued as it was back then. But we had the good fortune of group members from Argonne participating with us.

They developed a genericized version of the IFR that we could then call the 'ESFR' and use that as a test case for our methodology development. So, we took training on this design with the help of several people at Argonne in terms of what that design is, what we should be looking at. And that was very, very helpful.

We were able to use the entire system as kind of indicated here. It's a 4-unit system for 300-megawatt electric reactors with a fuel cycle capability within – I'll show a little blown up version of this in a second. But basically we wanted to confirm the applicability at different levels of design detail, provide examples of how our methodology would be useful for the future systems, and also to help us guide us in terms of where we should be shoring up the methodology itself. And we did some of that.

Here is the ESFR in a little bit more detail in terms of the flow chart. You could see four 300 megawatt electric reactors. Here is a fuel cycle facility. Some of the others, I won't go into in detail. But again, you could look at, and I strongly encourage you to look at our case study report on our website. It will give you a lot of detail on how we carried it out, carry out the study. The scope of it was, we considered – and this is the entire group and there are probably about 15 or 20 people in the group attacking different parts of the problem from a point of view of concealed diversion of material, concealed misuse of the facility, breakout scenarios and overt diversion and misuse occurring. And for the PP side of it, we looked at the theft of weapons-usable material, and also sabotage of the facility system elements. We looked at all of that and, again, there is a lot of detail in the report.

Now, I'll just tell you what our lessons learned were broadly from this. First and foremost is that the methodology can be applied during the conceptual stage of system development. Secondly, completeness in identifying attractive targets and pathways is important. They can be identified as one progresses with the analysis. Very important is the third bullet item here, the third major bullet item is that of course when you start looking at a new system, there are going to be uncertainties, or you are going to have to make some assumptions about how something behaves or how something is protected. The way we regarded that is that when you make those assumptions in the analysis, and if it's a major thing, we then think of that as a functional requirement for the design basis. And you need to document that. And then that becomes a requirement. In other words, if you want your assessment to come true, you have to make sure that you've met that functional requirement, which was a basic assumption. Now, of course, you could change that assumption if you can get a better answer, or you could relax it, if you think it was not strongly relevant, or you have some other way of achieving your goal. But that was a very key thing there that these assumptions need to be documented and recorded. The assessment requires considerable technical expertise broadly and we recognize it. Unfortunately, in our group, we had some broad expertise across the various countries and the organizations that participated. We also recognize that some standardization would be needed in the future as the methodology progresses with further case studies or actual studies that we envision being done by the system designers of Gen IV.

Lastly, what's very important is that we obtained insights along the way in doing the analysis. One does not have to get all the way to the bottom-line results to say 'Aha, I now know how this thing is operating,' or 'how it could be protected.' But early on, one could even find aspects of the design or insights about it that can then be implemented to improve it. So that's a very valuable part of the activity and we found this to be the case.

Let me turn now to the workshops that we carried out with the Gen IV designers and with others. We opened our workshops to all who were interested in the various countries, the Gen IV countries. We were not exclusive in this. But ultimately, the objective here was to inform the designers of what we are doing and to hear from them – more importantly, to hear from them what their needs are in terms of our design activity. So it's a dynamic activity between us. The near-term objective is to focus the methodology towards the system development needs, generate insights concerning design and operation, to enhance the performance with regard to PRPP longer-term, establish beneficial PRPP-related design and operation principles and practices. And then supporting all of this is to establish a good working relationship between the experts in the PRPP working group and the designers. That's something we continually work on. As you could see at the bottom of this slide, we've had 11 workshops in various locations, and we intend to have more as time goes on to get people involved with what we are doing and get that dynamic interaction.

It's getting the designers to become familiar with the capabilities and limitations of the methodology and identify techniques and procedures to enhance the application of the methodology effectively.

Gen IV, of course many of you have seen this. Gen IV sits here on the right. The beginning of it all was with Gen I back in the 50s, through 60s, through 70s. And then we have the big growth of nuclear power worldwide where we now stand with 440 or so nuclear power plants. And now we've already embarked, we have some Generation III and Generation III Plus plants that are actually operating some, and are being built, and some are yet being designed. But our focus is on the six Gen IV designs which are indicated here. The sodium fast cooled reactor, the very high temperature reactor, gas-cooled fast reactor, supercritical water, lead-cooled fast, and molten salt reactor. They all share one basic thing in common, and that's their architecture.

On the left-hand side of each diagram there you see where the nuclear energy is being generated, typically in a reactor core, and a fluid is heated. It's transported by a plumbing system. Ultimately, typically, to a turbine, which then cranks the generator and out comes is the electricity. So, the basic idea is the same in all of these but the working fluid is different, the way the neutronics works its way out in the reactor is different in each case.

As summarized here, now looking vertically downward, we see the neutron spectrum. Very quickly, the coolant, the working fluid for heat transfer. And the range of possible fuels. This is from a 2009 Annual Report of Gen IV and so some of these might have changed a little bit. Refueling modes. Whether it's online/offline. And fuel cycle open and closed or open or closed. And then the power of the reactor, the range of powers. PRPP is mostly concerned with the possible fuels, refueling modes, and the fuel cycle. Those are the three real focus elements for PRPP in terms of where the analysis will vary. Of course, the different fluids will impact the analysis as well, and the spectrum of the neutrons. But the fuel's refueling and fuel cycle are key to the analysis.

As a result of workshops that we held with the system steering committee that managed the six Gen IV design. That's the acronym SSC here which I haven't spelled out, I don't think. We worked with them back starting around 2007, 2008, 2009, in a series of workshops, three or four workshops that we had. We were working with them on trying to develop whitepapers with each of them jointly co-authored by the PRPP working group, and each of the individual system designer groups for each of the six designs. And the basic idea of the whitepaper indicated on the right-hand side of the viewgraph is what is that technology, what is its fuel cycle, what are the PR&PP targets and adversary opportunities, what are the scenarios of concern, how one might protect against PR&PP. And then finally, what are the open issues, what are the needed R&D elements for PR&PP for each of the specific designs.

And the report was published again on our open website. You are all encouraged to read it at that link. It's got two parts each. Six whitepaper jointly written and approved by EG and PG of Gen IV and each of the design groups. The first part of the report is actually shown on the left-hand side of the viewgraph where we basically set up what our objectives were, how the workshops were conducted, and some of the cross-cutting issues amongst the various designs. Fuel type, coolant, moderator, refueling modes, are just the things I mentioned earlier, safeguards topics. Again, I encourage you to read it. I should also tell you that we are in the process of updating all of this with the system designers. We've embarked on, I would maybe call a 'phase 2' of that overall activity. We are looking afresh at where we are today with the Gen IV designs, where the methodology is today, how do we talk with each other. We've already had a major workshop on this just about a year ago in Paris. We are embarking on updating the whitepapers, trying to figure out how we might start to take a deeper dive with a few of the Gen IV designs in terms of implementing key aspects of the methodology. So, this is happening. It's good that it's happening because people change in the PRPP working group over the course of the years. People change in the designer groups. In both cases, some of what we've done back 6 or 8 years ago, 10 years ago, is new people are involved and they need to come up to speed and understand what we did and help to carry it forward as we move on.

In all of this, what will designers and analysts actually do? At the outset, I should say it's a team effort, a multidisciplinary team. Key to all of it is the designers who have to really take ownership of this activity using the PRPP tools to improve their design, bring it early on in the analysis. Safety analysts would be helpful here too because there is a safety, safeguards interface. We didn't invent it; it's been there long before we came on the scene. It's always been an issue or a topic of interest in any nuclear concept. Safeguards, security, people need to be involved as well. IAEA needs to participate in some way in this, or people trained with safeguards need to be involved. Security analysts need to be involved. And analysts, more generally, in terms of folks who can carry out the pathway analysis and get to the quantification, some of it involves expert elicitation because we are going to encounter here new areas where expert opinion needs to be brought to bear and put into the assessment. So, human factors analysis analysts are going to be needed here as well. So, it's a big team that needs to be involved. So, early on, one starts with the plant models at a block diagram level, and similarly one would have PRPP models at a block diagram level. And as I indicated earlier, progressive refinement would occur and we would bring the models up-to-date as the designs mature. And, very important to all of this would be interactions in the sense of the broader team, with the regulators, with the IAEA, as appropriate to the design. In each country it's different and the IAEA has its own views to the extent that it would be involved in such studies. As I understand it, they are very interested in it.

And, to the point on that, IAEA has been promoting what they call 'safeguards by design,' 'international safeguards by design,' which is really a subset of 'PRPP by design.' And they've developed documents which are indicated in our bibliography for that very aspect of it. They are strong advocates of getting involved early with designs, getting involved with regulators early on, and the designers, and it all moving forward in a cost-effective and efficient way.

I mentioned that we have frequently asked questions documented. It's actually a small trifold, folded up. It's one page but folded in three as the trifold is. What we did was we came up with, as indicated here, 17 questions, like 'What is PR&PP? 'What is the form of the result?' I am just picking some of these off here, not read them all. 'At what stage of evaluation should PRPP evaluation be performed?' For each of these questions, there is a short paragraph type answer with as appropriate references to where to get further information. If you are not familiar at all with what we're doing, maybe this is the first step in terms of getting a better idea of what PR&PP is all about. And there is the easy web link to that. But again, you go to the major website of Gen IV and all of this will come out. In fact, I think it's highlighted on Gen IV's open cover page.

The bibliography that I mentioned. Here, this is a little bit more lengthy document, but it's essentially a collection of references broken up into essentially five sections. One is our official reports that we've written and our deliverables. Some of them have been translated, by the way, into non-English language. I know for a fact that the Japanese have translated these PRPP reports into Japanese for use by their designers. And there may be others. But, in any case, we have a section on PRPP articles in papers that have been collected over time, and applications be interesting to people to see these and get a sense of how you might do some of these analysis. And then we have papers in articles by members and non-members but using the PRPP methodology. It's an interesting thing that we found that not only has PRPP been looked at within Gen IV but folks outside of Gen IV have seen our open literature papers that have been in the conference presentation, and said, 'Yeah, this is very interesting, let me try it.' And they have. It is gratification, and validation I should add, from that, that people have been able to pick up our methodology, methodology report, read it, and then apparently understand it, and use it, and get results. So without coming back to us and saying 'Could you explain what this uncertain thing that you've written here?' They've been able to carry it out. We've seen the results of their activities and are pleased to know that people can take this work and actually use it. So, it's been valued outside of Gen IV as well.

And then just a broad collection of papers on the subject matter in Section 4 and then Appendix A has IAEA papers and documents that are related to PRPP, and an aspect in their INPRO activity, their advanced reactor activity that they have been carrying out for several years.

Important to all of this – key to all of this in fact is the folks who've made PR&PP happen. I just have the honor and pleasure to tell you this story but it came about because a lot of people worked very hard over a decade and a half. I don't have a picture large enough to show all of them over that 15 year period. I wish I did. But here, some of them are indicated in this workshop that we had. But everyone deserves the acknowledgment for this truly international effort which really – a lot of collegiality. You see the countries and organizations that participated. I am just very thankful to everyone who participated over these last 15 years in effectivity.

Major accomplishments: I've already said this a few times. It's the methodology report, the case study report, and the joint efforts with the six system designer groups. And again, they are available at that website shown here one more time.

And just as final notes, in all of this, it's not just the bottom-line results that you get out of a PRPP assessment that's important. It is important to get those bottom-line results but it's the insights that you get along the way from doing the assessment. It's a discipline process, it gets you to look at every stage of what you're doing. And sometimes early on, and I have been involved in various studies in safety and nonproliferation over the years, and it's typically the case that you find out early on that 'Aha, here is something that's very interesting and it informs our design, so it's very helpful.'

Secondly, as I've been saying, do these studies, start them now, early in the design process for the full nuclear energy system, and you are definitely going to benefit from it. You don't want to wait until everything is built and then say 'Gee-whiz! I've got to go ahead now and do a PRPP analysis,' and then the regulatory body or the IAEA comes back and says as well, 'You know, you've got to change your system.' And then you find that 'Well, I'm going to have to move a wall, or I'm going to have to do something else, change out something,' and that comes very costly, and incurs time delays.

So, doing it early is a good thing. And finally, don't do just one report and say ‘Aha, I’ve done it. I have done my PRPP analysis. I’ve met my checklist requirements. I am done.’ It’s not. It’s a journey. You’ve got to keep doing it. It’s a living study, a living document, throughout the full lifecycle of the facility. I encourage all of this. Thank you for your attention. I am happy to receive questions now.

Berta Oates
Thank you, Dr. Bari. If you have questions for the presenter today, go ahead and please those into the Q&A pod, and we will come back and get as many of those as we have time for. While those questions are coming in, let's just take a quick peek at the upcoming webinars planned in the Gen IV series.

In June, a presentation from Dr. Ignatiev on ‘Molten salt actinide recycle and transforming system with and without thorium-uranium support,’ otherwise known as ‘MOSART.’ In July, a presentation on ‘Astrid: The lessons learned,’ by Dr. Varaine with France. In August, a presentation on BREST-300 Lead Cooled Fast Reactor by Dr. Rachkov with the Institute of Power and Engineering with Russia.

Dr. Bari, are you able to see that there is the first question.

Dr. Robert Bari
No. I see something called ‘presenter chat’ down on the right-hand corner. Do I have to click on something?

Berta Oates
In the Q&A pod, there are the…

Dr. Robert Bari
Oh, I have to find – oh – no, I don’t see anything in the Q&A pod. Oh, let’s see. Let me – okay. What do I see…?

Berta Oates
So the presenter view if you scroll over to….

Dr. Robert Bari
Right. Yes, I do have that now.

Berta Oates
The first question is ‘How is the blanket perceived…?’

Dr. Robert Bari
Okay. ‘How is the use of blankets perceived in the PRPP space?’ Okay. I am trying to guess that – I am going to assume that we are talking about blankets in a breeder reactor, is that what the questionnaire is asking

about, when he said ‘blankets.’ I would just say that it has to be part of the integral analysis if you do have blankets in your reactor which have material that you are going to breed or fuel from. In fact, in our case study you can go back and look at that and you could see that we’ve looked at some alternatives. If not write in the case study report, we certainly have some follow on documents that are in our bibliography.

So, ‘perceived’ is yes, it has to be analyzed to get a full picture of what's going on because obviously there are going to be materials of interest that are going to be in those blankets as time goes on. Okay. Next question. ‘Thank you, Dr. Bari, for a very interesting and significant presentation.’ I don't think there is a question there, it’s just a thank you. I accept that. Next question from Dr. Khassenov, ‘Which of the Gen IV reactor design is the most promising in terms of PRPP aspect?’ I would say that they all are. No winners and losers here. I think they all show features that are certainly promising. We are basically encouraging analysts and the designers to continue on with their efforts. I think we have six good designs there from a PRPP point of view, and we need to just make them better, and make sure that the PRPP goals of Gen IV come true when the analysis is completed.

Okay. The next one is a good question. It's coming from Dr. Cojazzi who is one of the co-chairs of the PRPP group and a long-term contributor to what we have today in terms of PRPP. And he’s asking, ‘How long will a PRPP evaluation take?’ He asked me a few questions. ‘What effort is needed?’ Three questions. ‘Can the methodology be simplified?’ Okay. Good questions from Giacomo.

The evaluation should progress in stages. I would guess that within a year some good results should be coming out of the PRPP analysis. Again, it depends upon how much time. It's not just time, it's how many people are crunching on it at a given time, and how many people are on the design side and on the analytical side from PRPP point of view. You can get some quick results early on, several weeks to months. You can get some very preliminary information. But as we did indicate to this time parameter in our frequently asked questions, so more detail there. But I would say that start now, do these things, and it should be a living document. And you’ll start seeing the value in it fairly early on, within months, maybe sometimes in weeks. When we started our case study, we found value almost right at the beginning. It's kind of interesting, we looked at ‘Well, how can we divert fuel?’ We saw that LWR fuel assemblies were coming into the plant and we said ‘Wow! Why don't we just divert those fuel assemblies before they get to the plant or as they being received in some way.’ That was eye-opening to some people that that would be an avenue of opportunity. And then it suggested, ‘Well, we need to be mindful of the fact that that needs to be protected.’

The second part of that, 'What is the effort needed?' Again, it needs, as my viewgraph on the team that has to be put together. And I guess this ties in with the first question. You need at least three or four people who've got this activity on their mind for at least a quarter-time or half-time, ideally full-time. So, it could be a few staff years measured, at least in staff months to start moving it forward. You need a critical mass of people and you need at least one design person, one or two PRPP people, someone who knows about safeguards. You need them regularly available to do things, ask questions, provide answers.

'Can the methodology be simplified?' That's a very good point too made by Giacomo. We thought about how to simplify it and I think the key is in the progressive refinement approach. That if one is indeed starting with the designs in their early stage, which all of them really are, if you start developing block diagrams of the systems and maybe take our case study as a cue here, start developing block diagrams for PRPP, I think that can be helpful in terms of at least understanding how much depth one should be going into.

And this can come from actually doing the analysis. The more people we have doing these analyses and reporting on them jointly in, let's say, an expert group's meeting of Gen IV, giving other people insights as we develop a cadre of people who are working collegially in this area, I think it will help, people will learn about the shortcuts in the methodology, what pieces of it can be done more efficiently or effectively.

Let's see. Next one is Alice Caponiti. 'Thank you. You mentioned interest in 'safeguards by design.' A newer concept being discussed at least in the US is 'security by design.'' That's a very good point. Thank you for that, Alice. 'Can you share your thoughts on 'security by design' in approaches that states might wish to follow to develop standards?'

Yeah. There is an interest in the US on 'security by design.' There have been efforts – the regulator have been interested, the NEI in the US has been interested to a certain degree in this area. At least almost a decade now there have been a series of workshops on how we can bring to bear analytical methods, something akin to what's called probabilistic risk assessments, to the security area. Of course, the security area is more challenging, as indicated in my talk, than the safety area, where it's an episodic event. There is no malevolent actor there, hopefully not. Some progress has been made in the US, but we are not there yet. But I am certainly an advocate of moving that forward. Hopefully, I believe there are – in the US there are a few or at least one or two plants that are piloting some efforts. I haven't been close to it lately. The other trick in all of this is when you are doing a security analysis of the plant by design, and in fact if you're doing it when the plant is fully operating, you are dealing with a lot of sensitive information and that's always a challenge here in terms of getting things standardized, getting it discussed openly and broadly. In fact, that applies to all of the PR and PP. Ultimately, we are budding up against the area of sensitivity.

And we talk about that a little bit in our report. There is no easy solution to it. So, international standards would be great in this area. I think to the extent that it can be done, it would be definitely helpful.

Next question. 'Do you think PRA can be applied to PR&PP evaluation? Yeah. That's a good point. I have to reveal a secret. I spent more of my life doing PRA for accidents than PRPP. But I've been thinking about PRPP for the last decade and a half a lot more so than I've been talking about accidents, thinking about accidents. The PRA, you can't just translate the whole PRA machinery into PRPP but there are elements of it that are very good for PR&PP, for both sides PR and PP. The PR side of it, there is certainly scenario development. In fact what we did was early on when we did the case study we looked at what type of approaches could be used. Can we use event trees, accident progression trees, or variations of it, accident delineation models? We looked at a host of them. Some folks looked at success trees. We tried a bunch of things. If you look in our reports, what we say about pathway analysis, we leave it to the designer to choose that. We are not being prescriptive about what you ought to do. We were saying, 'Here are a few ways to do it, and we talk about them.' In fact, in my own work with the colleagues here at Brookhaven, we've used Markov models to look at both PR and PP. You'll find those in that bibliography that is on our website.

Next question is, 'Is it expectable to see PR&PP imposed by regulators to NPP in operation?' No. I don't expect the regulators to impose it. In the US we don't even impose it for the PRA. Except of course for new plants, we do say that you should do a level 2 PRA for the new plants in design. PRPP, I guess for the PP part I guess this follows on to whatever I already said in answer to Alice Caponiti's question and that applies here, to the PP side. For the PR side, I don't see the IAEA, at least in my vision, which is not 2020 necessarily, and I don't have a perfect vision into what IAEA is thinking of as a full organization; they have to speak for themselves of course. But I don't know that they would then say you've got to use the PRPP for moving forward. But they are saying, they are encouraging 'safeguards by design,' 'international safeguards by design,' which is – and again, look into our bibliography, you'll see some of our documents on that, on 'safeguards by design.' Or even more easily, just Google 'safeguards by design' and you'll get some sense of where IAEA is right now on that topic. Okay? So, I think that covers the questions. I am happy to receive more or have a second round from the people who've asked if I haven't answered questions adequately. All good questions by the way.

Berta Oates
I don't see additional questions coming in. Thank you, Dr. Bari, again, for your presentation. Very informative. Thanks, everyone for attending. Your participation is greatly appreciated.

Patricia Paviet
Thank you so much, Bob.

Dr. Robert Bari
There is one more question. Let's see. Okay, he’s just thanking me. Okay. Fine. Always nice to be thanked. Can’t argue with that. Well, thank you. Thank you for allowing me to do this. Well, it’s an important thing and I am very glad that I have the opportunity to do this.

END