A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications

Dr. Junghyun Bae, Purdue University, USA (Winner of the 2021 ANS Pitch your PhD Competition)

Berta Oates
Welcome everyone to the next Gen IV International Forum Webinar Presentation. Today's presentation on A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications will be presented by Dr. Bae. He is a distinguished staff fellow at Oak Ridge National Laboratory. Doing the introduction today is Dr. Patricia Paviet. Patricia is the Group Leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She is also the Chair of the Gen IV International Forum Education and Training Working Group. Patricia?

Patricia Paviet
Good morning, everyone. Thank you so much, Berta, for the introduction. I am very happy to have Dr. Junghyun Bae with us today. He is the winner of the Pitch Your Ph.D. competition during the 2021 American Nuclear Society Winter Meeting.

Dr. Bae recently completed his Ph.D. at the School of Nuclear Engineering at Purdue University. Congratulations, Dr. Bae. He will join now the Oak Ridge National Laboratory as a Eugene Wigner Distinguished Staff Fellow.

His research focuses on the development of the high-resolution fieldable muon spectrometer using multi-layer pressurized gas Cherenkov radiators and its applications, such as muon tomography, nuclear security, spent nuclear fuel casks imaging. He earned his Master of Science degree in Nuclear Engineering from the University of California, Berkeley, and his Bachelor of Science degree in Nuclear and Quantum Engineering from the Korea Advanced Institute of Science and Technology. He has also been nominated, awarded the Roy Post Foundation Scholarship, American Nuclear Society, and the KSEA Graduate Scholarships for his contribution to the safe management of nuclear materials.

Without any delay, Dr. Bae, I am going to give you the floor. Again, congratulations on receiving your Ph.D., being the winner of the American Nuclear Society, Pitch Your Ph.D. competition. Thank you for volunteering to give this webinar.

Junghyun Bae

All right. Thank you, Patricia, for your nice introduction for me, and then Berta for coordinating this awesome webinar. Thank you all.

Good morning, good afternoon, and good evening, everyone. My name is, again, Junghyun Bae, a Eugene Wigner, Distinguished Staff Fellow at Oak Ridge National Lab. First of all, it is my great pleasure to introduce my thesis work through Gen IV International Forum webinar. This thesis work had been done when I was in School of Nuclear Engineering at Purdue University. I really appreciate you all to attend my presentation.

Now, let's move on to my presentation. Again, the title of my presentation today is A Gas Cherenkov Muon Spectrometer for Nuclear Security Applications.

Here are the items we will discuss today.

First, we will briefly introduce research motivation, and problem statement, and research objectives. In this chapter, we will get some idea why we jumped into this work and what we expect through this research.

In chapter two, we will discuss about the concept of operational principle of our proposed muon spectrometer using gas Cherenkov radiators.

After that, I will introduce our developed muon imaging algorithm, which includes muon momentum information beside muon scattering angle information.

In Chapter IV, the implementation and research of spent nuclear fuel monitoring using momentum integrated muon tomography will be presented.

After that, I will wrap up my presentation.

Let's move on to the introduction.

Here is our motivation to our research. Muon tomography has emerged as one of promising non-invasive monitoring and imaging techniques, especially for large and dense materials. It is very possible because cosmic ray muons have very high energy than the traditional induced radiation sources such as X-rays and neutrons. It is about 10 to the 9 to 12 electron volt versus 10 to the 3 to 6 electron volt.

Muon tomography already widely has been used for spent nuclear fuel cask imaging, nuclear reactor, especially monitoring damaged reactor core in Fukushima nuclear site, and nuclear material inspection in a cargo container, and even archeology to find a hidden chamber in the Great Pyramid of Giza, or geotomography to investigate magma chamber underneath volcano to predict upcoming eruption.

As we have seen, muon tomography looks very promising. However, as you know, muon tomography is not yet the major imaging technique in nuclear industry. This is mainly because of naturally low cosmic ray muon flux, which is approximately 10,000 muons per square meter per minute. To maximize the utilizability of cosmic ray muons in muon tomography application, we need to measure muon momentum. So far, since we have no capability to measure muon momentum in the field, we used to use the average cosmic ray muon momentum for calculation which is about three to four giga electron volt per c. Even cosmic ray muon momentum has a wide energy spectrum, as you can see in figure 1.1.

Then, let me show you why measuring the momentum is so important using one example of nuclear material monitoring application.

When a muon interacts with matter, it is deflected due to multiple Coulomb interaction with electrons or nuclides. Figure 1.2 shows the scattering angle distribution of muons for steel, lead, and uranium. The width of its angular distribution can be approximated using equation 1. The equation is shown in here. As you can expect, the width of multiple Coulomb scattering angle distribution depends on material density, size, and muon momentum.

The upper figure shows the muon scattering angle distribution for steel, lead, and uranium again when muon energy is 3 GeV, giga electron volt. As expected, steel has the thinnest distribution, and uranium has the widest distribution. However, I intentionally changed the muon energy for steel and uranium. The lower plot shows the muon scattering angle distribution when muon energy is 1 giga electron volt for steel, and 10 GeV for uranium. As you can see, the results are totally flipped. Uranium has the thinnest distribution, and steel has the widest distribution. The point of this example, figure 1.2, is without measuring muon momentum, the results can mislead us in identifying materials.

In the previous slide, we have discussed the importance of measuring muon momentum in the muon applications. I briefly show you three existing techniques to measure muon momentum or muon spectrometers. First, we can use a magnetic to measure muon momentum, or it is so called magnetic muon spectrometer. It is the most accurate technique to measure muon momentum or measure particles momentum. In terms of measurement resolution, it is the best. However, it not only requires a large magnet to bend muons, but also it changes the initial muon trajectories. It is not ideal in the purpose of muon tomography because the initial and final muon trajectory before and after the scattering within the material, is very important in the muon scattering tomography especially.

Secondly, we have a time-of-flight technique. It is very simple and very straightforward, and easy to couple with existing muon applications. However, it requires very sensitive timers and long distance to maximize the measurement resolution.

The third example is Cherenkov Ring Imager. We can measure muon momentum by measuring the radius of Cherenkov Ring. Its measurement resolution is pretty good. However, generally, ultraviolet [ph] Cherenkov radiator is used to induce Cherenkov radiation. It is also a very long distance to improve the resolution, and it needs a vast array of optical sensor to accurately reconstruct Cherenkov rings.

Here is a very brief summary of our research objectives.

First one is a development of fieldable muon spectrometer. There are some requirements in our design, which are: It must be easily coupled with the existing muon tomography system. It must be compact, portable, and light. Also, it must have a compatible momentum measurement resolution and high accuracy. It also has to preserve the incoming and outgoing muon trajectories.

The second research objective of ours is to develop a momentum integrity imaging algorithm without increasing or without significantly increasing computational costs.

The third objective is to improve muon tomography imaging resolution, of course, and reduce monitoring time in muon applications.

Now, let's move on to the development of our Cherenkov muon spectrometer. To develop our fieldable Cherenkov muon spectrometer, we use two fundamental physics to develop our Cherenkov muon spectrometer. First one is Cherenkov effect. The second one is the Lorentz-Lorenz Equation. As you all know, Cherenkov of radiation is only observed when a particle moves faster than the light in a given medium. In other words, there is a threshold condition to induce Cherenkov radiation in a given medium. It depends on particles' velocity or momentum, and refractive index of that medium.

Here is the relationship between the muon threshold momentum and refractive index of the medium. The refractive index of a gas medium can be changed by pressurizing and changing temperature according to the Lorentz-Lorenz Equation, which is shown in the third equation. The formula between pressure and refractive index is shown in this equation.

We summarize these two equations to show the relationship between the gas pressure and threshold momentum for muons in the last equation.

As you can see, in this equation, we are able to choose the proper threshold momentum levels for muons by pressurizing the gas medium.

Now, please see the figure on your right, figure 2.1. This figure shows the operational principle of our Cherenkov muon spectrometer. In this example, we use five radiators. They have threshold momentum levels from 0.1 to 5.0 GeV per C, respectively.

We simulated a single muon momentum of 3.1 GeV per C, which is slightly greater than 3.0 GeV per C. This muon passes all the radiator. In this example, only the first four radiators emit the Cherenkov radiation because the actual muon momentum 3.1 is slightly greater than 3.0, and the result, the expected number of Cherenkov photon is shown in the bar graph below. Obviously, the last two radiators will not emit Cherenkov radiation and zero Cherenkov photon will be observed.

After that, we recorded a presence of Cherenkov radiation using photon detector. If these detectors are triggered, or Cherenkov photons are detected, it will record one, otherwise zero. After the final signal processing, our Cherenkov muon spectrometer correctly indicates the actual muon momentum range which is greater than 3.0 but smaller than 4.0 GeV per C.

Based on two physics I introduced in the previous slide, we designed our Cherenkov muon spectrometer prototype. In this model, we used one solid radiator because it was not able to reach threshold level 0.1 GeV per C using pressurized gas without condensation. In this model, the right figure shows the visualized Geant4 simulation when a muon momentum is 3.1 GeV per C.

As you have seen in the previous slide, only the first four radiators emit the Cherenkov radiation which are shown in green in the right figure, which is figure 2.3. Obviously, the last two radiators do not emit the Cherenkov radiation.

Also, it is noted the size is only 0.2 times 0.2 times 0.5 cubic meter, as you can see on your left, which is figure 2.2; and its weight is less than 10 kilograms because it's mainly made of gases.

However, you may see some outlier data in the figure on your right, which is figure 2.3. This is because the Cherenkov radiation is not the only one with optical photon emission mechanism in this radiator. There are more. We studied a little bit more about the optical photon emission mechanisms.

As you have seen, because not all optical photons are emitted from Cherenkov radiation, we have investigated more about the optical photon emission in the gas medium, or radiator in our work. Obviously, first, there is a Cherenkov radiation which is our desired optical signal. The light intensity is proportional to the particle momentum, refractive index, and length of the medium. Cherenkov radiation has a directional light emission along the particles' paths, as shown in the figure on your right, which is figure 2.4.

Next, optical emission mechanism is scintillation. The photon intensity of scintillation is proportional to the energy loss of particle, or muon in our work, and length of the medium. A light Cherenkov radiation, the light emission direction of scintillation is uniform for all direction, as you can see in figure 2.4, again.

I am sorry it's a little slow, bad Internet connection.

The next optical photon emission mechanism is transition radiation. Transition radiation can be emitted when a muon enters and exits the different medium, as you can see in the figure on your left. However, the expected transition radiation photon emission is very negligible when muon momentum is low, smaller than tera electron volt level, and small number of boundaries.

The last optical photon emission mechanism is Cherenkov radiation, however by secondary electrons. Since muons can decay into electrons within the medium, electrons can be emitted in the radiator. Also, because the mass of electron is about 200 times lighter than that of muons, its Cherenkov threshold momentum level is also about 200 times lower than that of muons. Therefore, it is easier to emit Cherenkov radiation for the electrons.

In addition, a muon can be converted to electron by being captured by aluminum nucleus. The difference between muon decay from muon to electron capture, muon to electron conversion is, the neutrino will not be emitted when muon is converted to electron. It is a very rare event. This is currently actively researched at Argonne National Lab, Fermi Accelerator Lab, and Lawrence Berkeley National Lab. It is not yet included in Geant4 toolkit. In sum, except the Cherenkov radiation by muons, all other optical photons are considered as noise.

Among others, Cherenkov radiation and scintillation are two predominant optical photon emission mechanisms, as you can see in figure 2.5. Therefore, in our work, Cherenkov radiation is considered as our signal, and scintillation is considered as noise.

To analyze the expected number of optical photons by Cherenkov radiation and scintillation, we generated 1.1 and 3.1 GeV monoenergetic muons for 100 times in Geant4 simulation. Figure 2.6 shows the expected number of Cherenkov photons in all radiators. As expected, the number of recorded photons rapidly drop when actual muon momentum does not exceed the threshold level.

Now, we added the result from the scintillation. In general, the number of optical photons from scintillation roughly depends on material density and muon momentum. The point of this figure is, even with scintillation, the expected number of photons is sharply decreased when extra muon momentum does not exceed the threshold level.

From this result, we can refer that Cherenkov radiation can be utilized to measure muon momentum by measuring optical photon signals.

Next, figure 2.8 shows the expected number of optical photons as a function of muon momentum in each radiator. As you can see, the number of total optical photons rapidly increases when muon momentum exceeds the threshold momentum level. These results demonstrate the feasibility of our Cherenkov muon spectrometer.

Here, figure 2.9 shows the result of classification rate as a function of muon momentum. The classification rate is a probability that our spectrometer correctly measured the actual muon momentum. A discriminator is nothing but a logic function that uniformly deducts certain number of signals from all radiators during the signal processing in order to eliminate or cancel out the predictable noise signals. The result shows that when we use a combination of various discriminator levels for various momentum range, the achievable mean classification rate is about 87% in our prototype.

In order to demonstrate the feasibility of our Cherenkov muon spectrometer, we also tried to reconstruct the cosmic ray muon spectrum using our prototype which has six radiators.

Cosmic ray muon spectrum was successfully reconstructed using six momentum levels, except the highest level which is the rightmost bar graph. This is because all the muon momentum greater than 5 giga electron volt per C is cannibalized and accumulated in this level, because our maximum measurable momentum level is 5.0 GeV per C. However, this maximum momentum level problem can be easily resolved by increasing the number of radiators.

We have increased the number of radiators from 6 to 10, and 100. The left figure shows the reconstructed cosmic ray muon spectrum using 10 radiators. The right figure shows the result from 100 radiators. When we used 10 radiators, the absolute momentum measurement resolution is plus/minus 0.5 GeV per C, and the relative resolution was 21.33%. Also, when we used 100 radiators, the absolute momentum measurement resolution was plus/minus 0.5 GeV per C, and the relative resolution was 3.35%.

However, it must be noted that the resolution is obviously improved by increasing the number of the radiators. However, if we increase the number of radiators within the limited over a size, then the size of each radiator must be decreased. It means the signal-to-noise ratio will decrease. Therefore, the functionality of our muon spectrometer will be improved by increasing the number of radiators in terms of the resolution. However, it will negatively impact the accuracy. Therefore, we must find a balance within this trade-off in a given condition.

Now, let's move on to Chapter 3, which is an introduction of momentum integrated imaging algorithm. To explicitly compare the difference between existing imaging algorithm and ours, we use a table. Please see figure 3.1.

Our momentum integrated imaging algorithm has been developed based on PoCA algorithm, which is Point of Closest Approach algorithm. We named it as mPoCA. Basically, we use the same method to locate the muon scattering angle position as shown in 3.2. However, we record different value in each voxel instead of theta.

In PoCA algorithm, a muon scattering angle value is recorded in a voxel. The muon scattering angle is computed using twofold muon detectors, as you can see in figure 3.3.

Now, let's see the result of our example of benchmarking using PoCA algorithm. We can see the published simulation experiment results in figure 3.1. This experiment was performed by K. N. Borozdin et al in 2003. We tried to benchmark their work to demonstrate and to verify our work. Here is our result.

Now, let's move on to mPoCA algorithm, which is our imaging algorithm that includes muon momentum information. After some studies, we have developed an M value which is shown in figure 3.5. As you can see, M value can be calculated using scattering angle and momentum.

Figure 3.6 shows the reconstructed image of four different materials: Aluminum, steel, lead, and uranium using our mPoCA algorithm. For comparison, I also added the result of image reconstruction using PoCA algorithm. As you can see, mPoCA improved the imaging algorithm significantly.

Now, let's move on to the momentum integrated muon tomography. Figure 4.1 shows the overview of the implementation of our Cherenkov muon spectrometer in spent nuclear fuel monitoring application. Left figure is the visualized model in Geant4. The right figure shows the overview of the placement of muon trackers. The bluish planes are the muon trackers on top and the bottom of the target object which is the spent nuclear cask. In between the upper muon trackers and spent nuclear fuel cask, we place our Cherenkov muon spectrometer. In here, we can measure muon momentum simultaneously.

We simulated four scenarios in order to demonstrate our imaging algorithm, which is mPoCA algorithm, as shown in figure 4.1. First scenario is, of course, when all spent nuclear fuel assemblies are fully loaded, which is (a). Other scenarios are a part of spent of nuclear fuel assemblies are missing. We tried to get rid of two, one, and a half of fuel assemblies, and analyzed the result to find out and locate the missing fuel assemblies.

Figure 4.3 shows the muon scattering angle and M value distribution at the center of bundle of fuel assemblies are missing. At the center of bundle of fuel assemblies, there's no missing fuel assemblies. These figures are pretty straightforward. The more dense material exists, the scattering angle value and M value will have higher values, as you have seen in the bottom plot of figure 4.3.

Figure 4.4 shows the cross-sectional images when two fuel assemblies are missing, two of the middle fuel assemblies are missing using PoCA and mPoCA algorithm, and 10 100,000 and 1 million muons, respectively. The upper left figure shows the reconstructed image when two fuel assemblies are missing using muon scattering tomography using 100,000 muons. On the other hand, the lower left figure shows the reconstructed image using MMST, which is mPoCA algorithm, Momentum-integrated Muon Scattering Tomography, using 100,000 muons. The right figure, on the other hand, shows the reconstructed image using MST and MMST. However, we use 1 million muons.

Obviously, the imaging resolution was significantly improved when we used 10 times more number of muons, and when we used the MMST better than MST.

The right plots are the same plots that we have seen in the previous slide. However, two fuel assemblies are missing in the center. Due to the absence of fuel assemblies in the center, you can observe a big dip or a big drop in the center in both plots. However, when we use the M value plot, the drop or dip is more obviously shown in the plot, or clearly shown in the plot.

Figure 4.5 shows the same result, however when one fuel assembly is missing. We can easily locate the missing fuel assembly, either PoCA algorithm or mPoCA algorithm, when we use 1 million muons. Obviously, we can visually locate the missing fuel assembly using reconstructed imaging and the plot on your right.

Figure 4.6 shows the result when a half of fuel assembly is missing. Unlike the previous slide, now, it is very challenging to locate a missing fuel assembly using PoCA algorithm even when we use 1 million muons. On the other hand, it is pretty clearly shown on the lower right figure, which is when we use mPoCA algorithm or MMST algorithm and 1 million muons.

It is very noted to see there is the dip. In this statistical analysis, we easily can see the dip when we use the M value, which is very challenging to identify, and it is really hard to say there is a small dip where a missing fuel assembly is located.

We summarize our systemic analysis in two figures as you can see in Figure 4.7. The upper figure shows the result for muon scattering angle, which is PoCA algorithm, and the lower figure shows the result from M value from mPoCA algorithm.

The scattering data represents the scattering angle and M value when two, one, and a half fuel assembly is missing. Obviously, they are located under the area that's shaded in red, which represents values when fuel assemblies are fully loaded. Simply, the less overlapped they are, the better performance it has.

In addition, the value ranges of air gap and concrete shielding are also included in Figure 4.7. They have much lower values than fuel assembly because their density is much lower than uranium.

Unlike scattering angle plot and M value plot, concrete shielding and air gap are clearly separated. In general, overlapping of each area or dataset is represented as noise in imaging. As we have seen in the previous slide, reconstructed image resolution is improved when we use mPoCA algorithm.

Here's our summary and conclusion. We developed a novel muon spectrometer using a glass and pressurized carbon dioxide gas radiators. We met most design requirements, which were introduced in our research objective. First, it must be easily coupled with existing muon tomography. Our answer is, yes, it can be easily implemented by placing it between target objects in muon trackers.

Second, it must be compact, portable, and light. Our answer is, yes, it is approximately 1 cubic meter large and less than 10 kilograms. The next one is, it must have compatible momentum measurement resolution and a high accuracy. Our answer is again, yes, it has approximately 3.35%, and 21.33% when the number of radiators is 100 and 10, respectively. Its accuracy is about 87%.

The last question we need to address was, it must preserve incoming and outgoing muon trajectories. Our answer is again, yes, it barely interferes initial muon trajectory because it is mostly made of gas. However, it must be noted that although increasing number of the radiator improves the momentum measurement resolution, it will inevitably negatively impact the signal-to-noise ratio due to the decreased expected Cherenkov signals. Also, to measure high-energy muon momentum, in our case greater than 100 GeV per C, very low gas pressure needs are required.

Next, we developed and introduced M value which mathematically integrates muon scattering angle value and momentum. This algorithm does not increase the computational cost because it was developed based on existing imaging algorithm. The image resolution is significantly improved where we use mPoCA algorithm compared with PoCA algorithm.

We also saw the result of spent nuclear fuel cask monitoring when two, one, and a half fuel is missing. We were able to find out and locate a missing half fuel assembly using mPoCA, which was very challenging using PoCA algorithm. We significantly improved the image resolution and reduced scanning time to find the missing fuel assembly in a spent nuclear fuel dry cask application.

Here's our list of peer-reviewed publication related to our current works. Here is the list of publications or poster presentations and conference proceedings. Here's first page, and second page.

Thank you for listening and watching my presentation. If you have any question and comment, please feel free to ask any question using this discussion time. Thank you for your attention.

Berta Oates
Thank you. As questions are coming in, we'll take a quick look at the upcoming webinars that we have scheduled.

In August, China's Multi-purpose SMR-ACP100 Design and Project Progress.

In September, a presentation on the Development of In-Service Inspection Rules for Sodium-Cooled Fast Reactors Using the System Based Code Concept.

In October, Sodium Integral Effect Test Loop for Safety Simulation and Assessment, otherwise known as STELLA.

In November, Visualization Tool for Comparing Energy Generation Options.

Give me just a second and I am going to help you see the questions. Do you have some questions in?

The first one refers to slide 10. I think what might be best is to just go to slide 10 and take a look at that while we address that. On slide 10, you labeled the bottom figure being at three different GeV/C, but it appears to be only one value, like the top figure, but a different energy. Can you clarify, in which energy it aligns with?

Junghyun Bae
Sure. Thank you for your question. These figures, I intentionally changed the energy for muons for different materials. In case of the upper figure, I used the same momentum for muons to reconstruct this Gaussian distribution. It is very straightforward. In case of the upper figure, we should or simulate the 3 GeV muons towards steel. Then, obviously, the steel is lighter than uranium or less dense than uranium, then the distribution of scattering angle must be thinner

than uranium. This is the key parameter to identify material in muon application.

However, without measuring the momentum, or let's assume we have no idea how much energy a muon has, or how much energy muon has when it enters. That's why I intentionally changed the muon momentum for different materials. In this case, I used 1 GeV muon for steel. It means, because this muon has low energy or moved slowly, it's scattered with a large angle. That's why steel has the widest angle of distribution. On the other hand, I intentionally used very high muon momentum for uranium because it moves fast or it has very high energy, so it scattered with less angle. That's why uranium has the thinnest Gaussian distribution in the lower figure.

Of course, it is a very dramatic example, and it is unrealistic. However, this figure, I prepared this example in order to show the importance of measuring muon momentum. We do not have that capability in the field application. Again, we can measure muon momentum in the lab. However, my point is, so far, we have no capability to measure muon momentum in the field. This slide is just designed to explain why measuring muon momentum is important.

Berta Oates
Thank you.

Junghyun Bae
Did I answer the question?

Berta Oates
The next question refers to slides 39 through 41. There are several questions associated with that. The first is, are these actual fuel SNF assembly measurements, that is measurements of an actual loaded spent fuel cask? If not, what is actually modeled here? If so, is this a field measurement done at ISFSI or how long does it take to make this measurement?

The fourth question is, if not of actual SNF, do you think the radiation in the field from the SNF will impact the measurements other than accumulating dose to the operator generating the measurement?

Let me post that question and then let's advance up to slide 39 through 41 and give you a chance to explain. How about that? That starts with 39. You still have control. You can advance forward or back and talk to the sides. Do you see that question now?

Junghyun Bae
No.

Berta Oates
In your question?

Junghyun Bae
The question was, are these actual spent nuclear fuel assembly measurement – actual loaded spent nuclear fuel cask? My answer to this question is, this is the simulation result. I want to make sure all these examples, and the result of imaging construction was performed using Geant4 simulation and the imaging algorithm. It's all based on simulation. Actually, this is the actual model. We modelled the actual, the commercial spent nuclear fuel design in our Geant4 simulation.

Berta Oates
Are you trying to move it forward? I see it moving now. I can hear you clicking but it wasn't moving. I see it moving now.

Junghyun Bae
The answer for the last question is – the questioner asked the question, does the background radiation – when the spent nuclear fuel cask is stored in the interim storage place, then of course, there's a little higher background radiation than the ambient environment. The question is, does that a little higher radiation background impact this non-disrupt imaging technique?

My answer is of course, yes. However, it is less impacted than others because, as you have seen in my slide, the energy of muon is way larger than the traditional radiation. It's greater than 10 times or 1,000 times or 10,000 times higher than the traditional radiation sources such as X-rays or neutrons. It means we can easily cut off or we can easily set the threshold level of the radiation level because the cosmic ray muon has a way larger energy. We can easily cut off the background radiation by setting up the threshold energy level. That is my answer to your last question.

Berta Oates
Thank you. The next question is, for the missing fuel assembly measurements, how many measurements do you expect need to be taken in the field? For example, how many angle measurements with your proposed system are needed for the incoming and outgoing muons?

Junghyun Bae
This is a great question. In our application, we only measure a single angle. Of course, when we took the data from the various angles,

then the imaging resolution obviously will be improved. However, in this example, we only took one angle.

Another question is how long it will take. As you may know, the disadvantage of muon tomography is it takes very long. It will take about at least a couple of days, or it will take a week. Actually, that is the motivation of our research. By utilizing the momentum information, beside the muon scattering information, we believe we significantly reduce the scanning time.

Of course, by utilizing the muon momentum information in the muon scattering tomography application, either we can improve the image resolution or reduce the scanning time in order to attain the same level of resolution using without measuring muon momentum, but with measuring muon momentum. We expect we can reduce the scanning time from days or weeks to hours or within a day. That is our more specific research objective.

Berta Oates
Thank you. Are there any plans to take your system to perform an actual field measurement, NNIS ISFSI?

Junghyun Bae
My answer is yes. I was at Purdue University. We are building our Cherenkov muon spectrometer in our lab. However, now, I will join the Oak Ridge National Lab. Then, I propose to continue my research work at Oak Ridge National Lab. That's why I will join as a Eugene Wigner Distinguished Fellow, as a fellow because they can support my work. I propose to build the actual momentum integrated muon tomography system at the Oak Ridge National Lab. I have a three-year plan at the Oak Ridge National Lab. Obviously, it includes to do the test in the interim spent nuclear fuel storage site. You can expect some result soon in three years.

Berta Oates
Great! Thanks. Would it make sense to utilize an array of sensors to perform the measurements to speed up the measuring time?

Junghyun Bae
Should I understand your question correctly? If you are asking, can we use muon beam instead of cosmic ray muon to foster to attain the result? My answer is, muon beam is now currently proposed, and I think, trying to build at the Fermi National Lab. One of the scientists reached out to us to collaborate to build or propose the muon beam at the Fermi National Lab. My answer is, yes, there is no muon beam which can be used in the field. Of course, they can be used in the lab. Obviously, you may see in the CERN. However, my answer is,

there is no muon beam in the field. That's why we have to use cosmic ray muon in order to utilize a muon tomography – utilize muons in the muon tomography applications.

Berta Oates
Thank you. The next question is, I think you saw the muon data for Fukushima nuclear power plant. Is it possible to see more clearly the status inside Fukushima Daiichi by your technique?

Junghyun Bae
My answer is yes. I think you may know. Some scientists used muon transmission tomography in order to see inside of the Fukushima Daiichi reactor. More specifically, they used muon tomography in order to measure the amount of the molten core, not specifically for imaging. In this application, of course, measuring muon momentum is obviously very important because they did not utilize the muon momentum information in order to get an idea about the amount of the molten core in Fukushima Daiichi reactor.

Again, my answer is yes. Should we utilize our fieldable Cherenkov muon spectrometer in Fukushima Daiichi reactor application, then obviously, we can get more accurate and more feasible data. I believe we can get more feasible and reliable data.

Berta Oates
Thank you. There's a comment. I can go ahead and post it, I think. For your information, ORNL, Sandia, PNNL, and EPRI recently procured some commercial canisters for spent nuclear fuel. It may be worthwhile to set up a test on one or more of these systems with mock fuel to test your system before going into the field with an actual spent nuclear fuel system.

Junghyun Bae
That's true. Thank you for your comment. Thank you. Was it a question or a comment?

Berta Oates
That was a comment. The other question is, in your slides 39 through 41, do you assume the spent nuclear fuel? Is it a metal cask, or a metal canister in a concrete overpack?

Junghyun Bae
Let me move on to our portal.

Berta Oates
Is it moving for you?

Junghyun Bae
I don't think so. It's fine.

In our simulation, we did not model stainless steel cask. We only designed the overpack, the concrete overpack. As you can see, in between those fuel assemblies, there is nothing in between the fuel assemblies. When we elaborate our model, we need to model a more specific geometry inside of the spent nuclear fuel cask. Yes, my answer is, we only designed spent nuclear fuel assembly in the center and then concrete overpack which surrounds the spent nuclear fuel assemblies in the center.

Berta Oates
Thank you. The follow-up question is, what will be the impact of a three-eighths inch to five-eighths inch thick stainless steel on those results, the outer portion of the concrete?

Junghyun Bae
Is it a question or…?

Berta Oates
Yes, it's asking what will be the impact of three-eighths inch to five-eighths inch thick stainless steel have on the results?

Junghyun Bae
The obvious result we can obviously expect is, of course, the noise level will be increased. Because the space between spent nuclear fuel assemblies will be replaced by steel, then of course the density of steel is way larger than air gap, so the noise level will be increased. However, there is no reason we cannot identify or locate the missing fuel assembly in the simulation. That is my answer. Noise level will be increased. However, it will not be impacted much to locate or identify the missing fuel assemblies.

Berta Oates
Thank you. Did you include any metal in your model, such as the canister or cask walls, basket structure, etcetera?

Junghyun Bae
My answer is no. There are spent nuclear fuel assemblies in the center, and then the concrete overpack outside of the spent nuclear fuel cask assembly or bundles. There are only two materials or three. The air is filled in any empty space.

Berta Oates
Great! Thank you. I don't see no comments or questions coming in, so I'll take this opportunity to thank you, Junghyun, for your

presentation, and taking the time to put things together. I congratulate you on your expertise. We look forward to seeing your bright future. I know that your name will be heard again in the scientific community in the nuclear world.

Thanks everyone who joined today's presentation. Patricia, do you have any last closing thoughts?

Patricia Paviet
I am echoing you, Berta. Thank you so much, Dr. Bae, for your expertise. I think we wish you the best at Oak Ridge National Lab. We are looking forward to seeing your expertise moving up and entering as well [ph] in the nuclear energy sector. Thank you so much again, Dr. Bae.

Junghyun Bae
Thank you, Patricia and Berta. Thank you very much.

Berta Oates
Bye-bye.

Patricia Paviet
Goodbye, everyone. Bye-bye.

Junghyun Bae
Bye-bye.

END
