Passive Decay Heat Removal System
Dr. Mitchel Farmer, ANL, USA

Berta Oates
Doing today's introduction is Dr. Patricia Paviet. Patricia is the Technical Group Manager for the Radiological Materials Group in the Nuclear Sciences Division at Pacific Northwest National Laboratory. She's also the Chair of the Generation IV International Forum Education and Training Taskforce. Patricia.

Patricia Paviet
Thank you so much Berta. Good morning everybody. I would like to introduce Dr. Mitchell Farmer. I don't know why there is an echo. I hope it's going to stop. I don't know why there is an echo, Berta. I'm so sorry.

Berta Oates
Do you have two devices going? Maybe your computer speakers and your phone. One of those need to be muted.

Patricia Paviet
I am far away from the computer. I moved out, so it should be better. Is it better? Yeah, it looks like.

Berta Oates
Yeah. I don't hear the echo. I apologize for the technical difficulties.

Patricia Paviet
Yes. So sorry. Dr. Mitchell Farmer is a Senior Nuclear Engineer in the Nuclear Science and Engineering Division at Argonne National Laboratory. He has over 25 years of experience in various R&D areas related to reactor development, design, and safety. A principal career focus area has been light water reactor severe accident analysis and experiments.

More recently, he has also been involved in the analysis, design, and conduct of experiments related to operations and safety of Gen IV reactor concept including sodium fast reactor as well as high-temperature gas cooled reactors. He has over 200 publications in the above-mentioned technical areas. Dr. Farmer also manages the Light Water Reactor programs within Argonne's Nuclear Science and Engineering Division, in which these and other programs are carried out.

Dr. Farmer received his Bachelor's degree in Nuclear Engineering from Purdue University, his Master degree in Mechanical Engineering from the University of Nebraska and his Ph.D. in Nuclear Engineering from the University of Illinois.

I'm very happy to have you, Mitch, giving this webinar. Thank you again for volunteering, and I give you the floor. Thank you, Mitch.

Mitchell Farmer
Well, thank you very much Dr. Paviet and Berta for setting this up, and I have to say it's a real pleasure for me to be here to talk about this topic, and I want to say good morning, good afternoon and good evening to everyone who might be on the call depending on your location, and I am looking forward to an engaging discussion on this topic, and I hope we can motivate some discussion at the end.

If I have control here, okay. Well, I want to start the presentation by giving you a little bit of motivation. And as we all recall, the reactor accidents at Fukushima Daiichi reinforced the need of passive safety systems that will ensure safe shutdown of a nuclear reactor. There are two parts of riding out a postulated accident. The first is to get the reactor scrammed, but the second and equally daunting from a thermal hydraulics viewpoint is the long-term dissipation of decay heat.

The plants at Fukushima scrammed properly the way they were intended to do, but the ensuing tsunami that came up and engulfed basically the backup turbine generators that would provide the emergency cooling equipment and run that were rendered inoperable and that led to the sequence of events at Fukushima that were very troublesome in terms of terminating the accident.

The BWR out there had Mark I containment. These are very nice plants, but they were designed in the 1960s and they rely heavily on active cooling systems to be able to dissipate the decay heat. So that's an indication of why this work we are working on here is important and I just want to reinforce that moving forward in advanced reactor systems, we need to do the best we can with engineers and scientists to come up with systems that can ride out these types of unforeseen events.

This is just a follow up. Despite the fact that operators were there, the emergency core cooling systems were compromised. The objective of the plants moving forward would be to have fully passive systems that don't rely on active equipment to operate electrical power. Ideally, this equipment would always be on. It would require no human intervention to activate. And basically the bottom line is, if possible, come up with walkaway safety systems that regardless of what happens the reactor can safely dissipate the decay heat without experiencing fuel damage and fission product release. So that's the goal.

Before I move on any further, I want to say a few things about the overall goals of the work we have been working on and I think to motivate some of that, it would be good to reiterate some of the design and safety goals that were put forth several years ago for the Generation IV project. And the first is that the system will excel in safety and reliability and that comes back to the passive aspect and limiting the amount of equipment that needs to be activated by humans, reduced to a very low likelihood and degree of extended core damage that could occur during an accident. And finally, and this is important in reducing the overall cost and planning that is required to deploy a plant, and that's to eliminate the need for offsite emergency response. Those are the high-level goals.

In terms of meeting those goals, the reactor cavity cooling system has emerged as a leading concept to get there. This provides the ability to inherently dissipate and passively dissipate to get heat to the atmosphere. It offers a high degree of performance with a relative simplicity in the design. And most important thing, these ideas are not new, they have been under consideration for many years back when reactor designers first started working on development and concepts for plants.

And I want to stop right here and make one other statement. The presentation I am going to be making today is focused on the reactor cavity cooling system as a passive method for dissipating decay heat. I want to know that there are other systems out there. One example of that is the direct reactor auxiliary cooling system that's typically deployed in a lot of sodium fast reactor plants where you have a heat exchanger located in either the hot or cold poles of the reactor. That would be plumbed to an air dump heat exchanger at an elevation quite a bit above the reactor core itself. And in the event of an accident, there would be a magnetic lash or the damper would fall open and you would naturally dissipate the decay heat generated by the reactor by cooling to that type of a system.

However, that type of system has been heavily studied and I think the industry has a good handle on that. And from the viewpoint of the work we have been doing here at Argonne, we really don't have anything to offer there in that area. So I am just making the general statement that there are other ways to passively dissipate decay heat. But what I am going to focus on in this presentation is that the work we've been doing is related to the reactor cavity cooling system. So, I just want to make that clear to the folks that are listening.

Berta, the viewgraph, you could do that for me. I've lost control. I apologize folks.

Berta Oates
Bear with me just a minute.

Mitchell Farmer
Okay.

Berta Oates
There it goes.

Mitchell Farmer
All right. Sorry about that.

Berta Oates
There is a really long delay, Mitch. I apologize for that.

Mitchell Farmer
Okay. Alrighty. No problem. Well, in general, I'd just like to make a comment that the RCCS is our focus, but ultimately this work that we're working on I believe is valuable to the industry because it's providing a pathway for a safe and reliable deployment of nuclear power moving forward. The work we have been doing here has been carried out across a multi-institutional effort that's involved multiple national labs, industry, and very importantly the universities. They have really provided a lot in this program, and I'll make a note on that as we move forward.

I've advanced it, but it just takes a second. Before we get into the technical aspects, I just want to give you – referring back at the previous viewgraph – a little bit about the scope and reach for this project. Again, we're working on developing inherently safe reactor cooling system, a simple design. The concurrent approach we have taken is to involve a lot of universities and at different scales. What we're talking about here is a natural convection heat transfer process which involves a high degree of radiation heat transfer also. That's a very nonlinear heat transfer process and thus you need to do tests at different scales to verify that the physics that you think you're stating is actually scalable. And to do that we've had a variety of institutions involved here.

Starting down at really one-eighth scale, one-tenth scale in the scale of the tests that were done at University of Michigan and Texas A&M. The University of Wisconsin has also been involved in quarter scale test. This, where I have the pointer located, is just giving you an idea of the scale of the tests that we have been doing at Argonne. I would like to pan over here to the far left and just show you what the whole plant design looks like. And the first system we're going to look at is an air-cooled reactor cavity cooling system that's based on a general atomics, modular high-temperature gas reactor design and that concept is shown to the far left on the bottom there. Basically you have 5X25 centimeter structural steel tubing that surrounds the reactor silo itself. It plumbs exteriorly to air that's drawn into the building. At the top, the heated air is discharged into headers that take the heated air out of the plant. This gives you an idea of the whole scale design. We are doing half-scale tests and basically we've taken about a 20-degree sector out of the overall concept and we are looking at 12 of these tubes in a steel configuration.

The tests that we have been doing at Argonne are more integral effect. They have done a lot of separate [ph] effects testing at the universities with different methods and higher methods of diagnostics to be able to provide the data we are looking for that qualifies the system for reactor applications. So that's the idea that at least the air phase of this has been completed and was done across the broad spectrum of facilities and at different institutions.

Little bit of an overview. As I've noticed, then air-based system relies on natural circulation and laminar and turbulent flow regimes. It's a combination of radiation and convection heat transfer from the reactor vessel to air-cooled panels that draw air from the outside. It's heated. This is basically just a chimney, and then it's discharged here. This is a simple design. It can run all the time, and there is a parasitic heat loss while the system is running. But in any event, you do that to cool the reactor silo in just about any design because of the heating in there. So this system serves that function and then in the event of a trip in the primary pumps or any other kind of a perturbation in the operating system, this system naturally is in operation to dissipate the decay heat. This is a concept that's been pursued not only in some of the US designs but internationally and I've shown some of those. There are different scales. The reactor scales themselves range from tens of megawatts up to around 600 megawatts for the general atomic MHTGR design that we're going to be talking about a little bit more in detail today.

That's the air system and I've hit the advance button. I will just go ahead and start talking. Eventually, there would be a schematic that would come up here on the right-hand side. We've used air in some of the tests. We're now embarking on a water-based system. Water works just fine as a heat transfer medium also. In this case, the recipient would be of course the water. There would be a header tank located up high in the plant elevation. The water during normal operations would be driven by a pump rising to the reactor silo and discharging into this header tank that would dissipate decay heat to a heat exchange unit that would be the normal way of cooling the reactor silo.

However, in the event of an accident where it would be some kind of a transient, but you would envision losing the this heatsink here and the ability to pump the water within the water panel that cools the reactor silo. And in this case, the water would again rise by natural convection and continue the cooling process, and the idea is can you develop sufficient natural convection within this system coupled with the radiation and convection across the gap between the reactor vessel and the cooling panel to discharge this.

The nice thing about this system is that water has a very large heat capacity, and with a properly sized header tank, you can run this system for the design basis, 72 hours without the need to top off this tank after you get into a boiling heat transfer and boil down to this system here.

So this is another system we are moving on currently to look at right now, and I'll come back and say a little bit more about that in the presentation as we move forward.

Okay. Before we embark on the air system, the first thing is you have to pick a system that you want to look at and base the design on to the ceiling. And that was done at the onset of this project. And again, we focused on the general atomics MHTGR design for which we had access to the facility that designed itself and also some of the design base's access that they looked at as part of the work. Noting again, the scaling we used in the Argonne test is basically half scale vertically. Horizontally, working out from the reactor vessel, it's a 1:1 scaling in terms of the width of the silo and the hardware that we have placed in there as the air cooling panels. So that was also preserved. And if you go through that scaling, half scale, and you want to decide you want to preserve the inlet [Unclear] temperatures from the riser ducts during normal operations, then you come up with the fact that you need to do basically a square root of two times the expected heat flux off the reactor vessel during the transient and design your system accordingly.

And that's what has been done and we will reflect back on that. But the specific action that we have targeted a lot in our work is basically a depressurized conduction limited cooldown transient where we have some relatively smaller leaks that develop in the reactor or system pressure ductile boundary that discharges. And the heat transfer process is limited by conduction where you conduct heat from the core out to the radial reflector and then that's dissipated across the gap in the reactor cavity cooling system to these cooling jackets. So that's the basis that we are going to be looking at and some of the results I will present on this. But when the reactor designers estimated that in this type of an accidents the peak reactor pressure vessel temperature would reach about 441 degrees C after about 120 hours. So based on the scaling that we discussed here at a high level and the results are presented, we may later just try and keep this prediction in mind relative to where the accident would go. This would be the peak temperature. Then after that, the temperature would decline by gradual decay of the fission products in the core and a reduction in the overall decay heat load on the system.

I've advanced. Sorry folks. It's taking a minute here. I'll just reflect on some of the information that we'll see on the next viewgraph. But this type of work has been ongoing at Argonne for quite a few years. The first attempts at doing these types of tests in an integral fashion were actually carried out in the 1980s when we were working on supporting GE in the development of the reactor vessel auxiliary cooling system or RVACS design, which is basically based on the same physics that I described previously. But in that approach, the air would be drawn into the silo and basically just a large air draft cooling of the reactor vessel and that plant design. The original work that was done, we put together – well, I didn't personally but I knew the folks who did it – they put together about a 28-meter-tall test facility, roughly half scale of the PRISM design, and there was testing done to look at that to provide the data that was needed to move forward with that design from a licensing viewpoint.

Similar to that, we've reconstructed that facility to include modern data acquisition and put in a new set of instrumentation to be able to provide better data for the current test moving forward. The data that was produced in the previous test was exemplary, with very high quality. But I will say that the new suite of codes that are being used in the design of advanced reactor systems are much more higher fidelity, so there was a heavy focus on the redesign for this system to be able to provide higher quality data that could be used to qualify the more high-fidelity codes that are being developed today.

The other major thrust of the work that we've done is that we really wanted to focus on providing information that could be applied directly to support licensing applications. And in the US that means we have to follow NQA-1 standards, which puts a high degree of rigor in terms of the experimental methods of documentation. So that program was invoked with the primary purpose of ensuring that the results that we produced could be used by a designer in supporting their licensing process with the data already accepted by the NRC, and they have been involved in this process also to check basically that what the information we are providing, is that equipped in terms of meeting their requirements.

The top objectives of the NSTF program were basically to examine the passive safety for future nuclear reactors. And as I pointed out, provide a user facility to explore – I'll make a point on this later. But when you start testing, you are never quite sure what's going to come up and it's nice to have a facility that you can modify and to look at the alternative concepts to help to get you where you want to be. So that was a major thrust of the facility we put together to make it flexible and capable of being rearranged as needed to look at different ideas. And as I've mentioned, the third major point is that we wanted to generate a lot of high-quality data for code verification and validation.

I am not going to say a lot about that. I'm mostly an experimenter in my background, but in parallel with this program, there was an analysis project where we systematically applied codes to be able to qualify those to calculate the types of efforts. And there are other literatures out there that can be done on that. But basically we use relab [ph] and start CCMs that look at these tests in detail and qualify these codes accordingly. And these were very supportive in helping us run the test and provide indications of where we needed to put instruments to support the modelling.

And as I pointed out that this program was carried out at multiple scales at multiple universities looking at different separate effects types of work that was going on. And one of the final things that we wanted to do was to be able to develop a central data bank for the data that we've produced that folks could access in terms of qualifying their models for application to reactor design. So that's where we are at in terms of the goals for this project.

Moving forward, the next viewgraph will come up here in a second. But basically it's just reemphasizing the idea of the quality assurance that we applied in this program and the need for a high level of rigor, that's shown here in this viewgraph. But the main thing about this type of a process is that we had to come up with procedures, methodology, and documentation and it was externally audited by Idaho National Lab who has a very good NQA-1 program. DOE asked them to audit our processes here to make sure the work we were doing would meet NQA-1 requirements. And that required regular audits of our facility and the data and our methods. And I was very happy with the way that it came out and it gave the laboratories a good way to work together in meeting the quality assurance requirements for this program. So I just want to reiterate that was a good process and I really enjoyed the engagement on that. And to do that, it takes a really small and dedicated team of individuals that really focused on documentation and quality assurance and that was developed as part of the program.

So that's a little bit of the background. Now, I want to turn to what I would consider a little bit more fun portion of the presentation and talking about the facility itself, some of the results that we have obtained and some of the lessons we learned in terms of how this system might be deployed at a full scale in a plant design. And this you are looking at now is a facility overview on the left, and the right is a 3D rendering of it. There's a little person down there to give you an idea of the scale of the facility. But basically if I can use the pointer here, if you can follow me, there was an air inlet system that was drawn from the [Unclear] air where this would deployed, and inlet plenum that uniformly distributed air inlet through the tubes here that I'm showing, which replicated in cross section at full scale the design of the GA MHTGR. And vertically it was half scale.

Similar to the reactor, there was a collection plenum. There were two different flow paths that we provided for that. And these pipes basically discharged out to the atmosphere. The overall scale of this facility is about 26 meters tall. And again that's roughly about half scale, reduced types here were about half scale and the overall vertical elevation of the facility is about half scale also. So that's roughly where it's at.

Looking forward, this gives you a picture of what the facility looks like itself. That's Art Beck [ph] he is one of the test engineers. You're looking at the right side here. There was a large approximately 7-meter long heated system here that replicated the exterior of the reactor vessel. I am showing that here. On the other side, this replicates the interior wall of the reactor silo itself and that was treated as an adiabatic boundary condition in the facility. And that gave us the methodology we needed to be able to simulate quite a bit of transience in this system over the course of several years that we did the testing.

As I pointed out, we really focused a lot on putting a lot of instruments in this facility to be able to map the thermal response and detect variations in conditions that we thought were important. And one of the most important things we ended up doing in terms of running these tests that we didn't know at the onset is that we put a little weather condition station outside that measured obviously the air temperature exterior to the building, the wind direction, velocity, and relative humidity. These are the conditions we monitored outside the building. And looking back, we found that weather had quite a bit of influence on how this system operated and I'll say a little bit more about that as we move forward.

We also wanted to use carbon steel that's typical of what could be used in a lot of plants. The SAE 1020 low carbon steel we used here was I think representative of what they were using in the GE design at the time for the PRISM reactor, and we kept that as part of this work. And this shows basically the thermocouples that were used to monitor surface temperatures in the places to give you an idea of what it looked like.

With that done, we assembled the facility and started into a test matrix that was agreed upon with the sponsors before we started. Clearly, we did some shakedown and calibration testing as we started up to make sure things we were working the way we thought they would. We did some baseline testing at steady state operating conditions to verify that the system would keep the silo cool under normal conditions with forced convection flow, and also to shake down our instruments and measure losses at various points in the system, which were very important to characterize for the analysis folks.

We did the scaling verification testing looking at integral power effects and also reduced physical scale if we heated upper and lower portions of the system. And I am not really saying too much about the heating system we have, but it would bend [ph] and zone both vertically and radially so we could do a COSINE power shaping as we desire. We could add the mutual power scaling to look at differences when tubing and cooling systems were located in a corner. So, there was quite a bit of flexibility that was looked at in terms of the testing, but I don't really have time today to get into that much. I'm going to try to just stay to the higher-level topic that we are trying to cover.

Of course, we did performance testing looking at different factors and some of those included a single chimney configuration. We looked at forced convection flow as I said also to get some thermal hydraulic data. We looked at situations that designers were interested in. Blocked riser channels was one of those where we looked at blocking out half of the ducts and verifying that the system would perform correctly. We also did a lot of testing to verify repeatability and to look at weather effects, which in the Chicago area that's not hard to do because temperatures range radically depending on whether you are doing conditions in the summer or the winter. So we took a full advantage of that in doing the testing that was performed as part of this program. The other thing that wasn't noted here, which I thought was very notable is that we did a test where we looked at instantaneous ingress of a large volume of heavy gas, which in this case we used argon. And that was done to look at a situation in case you had the plant collocated with some kind of a chemical industry plant that we were supplying power to and if there was some situation where there was a discharge from that plant that was fed into the inlet of the cooling system, if that would impact the operational aspects. And we found that it did, but it was a short-term effect, and after a matter of minutes the system was able to recover and it reestablished normal flow.

So those are the kind of things that we looked at in the program in moving forward here. Okay, now I want to do a little – just to discuss some of the high-level tests that we had done and some of the results and indications that were provided. And the first objective was to do baseline testing conditions. And this is a large test facility. Upwards of 100 square meters of surface area, so you are going to have some parasitic heat losses. We had a target scaled power level that we wanted to operate at for the experiments. And the first thing we did was find out what are parasitic loss is so that after we knew that we could adjust the input power accordingly to get to the target net input power that we desired. And this is a large test facility. You can see that it is just the order of a day at the initial feeding level to come up to power. We were able to characterize our parasitic heat losses incremental and thereby incrementally increase that and get up to our target power for the transient. And again that could take up to 10 hours to stabilize at that level, and at that point you would be able to look at transient effects as we've done here simulating decay heat after scram.

So just to give you an idea, we took a lot of time to do this. Looking at repeatability, this is looking at different times of the year, a hot versus cold conditions. And you can see that depending on the weather you can get some influences, but basically the results are repeatable, so within pretty tight tolerance in terms of what you can get to depending on different tests and different weather conditions outside. So, we were happy with this that we were able to show the repeatability of the heating process and move forward with the testing.

Next thing you had to do was just find what the transient is going to look at, and this shows the scaled GA-MHTGR accident scenario that we investigated quite a bit. As I pointed out, this is a depressurized conduction limited cooldown transients where at times zero you develop a leak in the system and basically discharge your coolant, and after that limited by conduction and convection through the system that is driving the heat transfer to your reactor cavity cooling system.

And in this analysis they had done, the peak loaded on the exterior reactor vessel prediction to be reached at about 90 hours into the transient. By the time that was conducted and convected out to the boundary on the reactor, they were predicting a peak temperature in the reactor cavity or on the exterior of the reactor cavity of about 440 degrees C after about 120 hours. This is the driving function that we wanted to stimulate for the transient and the experimenters who I'll say more about at the end in terms of the acknowledgement, programmed this up in the digital control system for the facility and basically ran this transient to look at the effects.

And then the next viewgraph shows what are the results. And there are basically four viewgraphs here that I just want to say a few things about in terms of the results. The upper left viewgraph shows the collection of thermocouples located on the heater plates that simulated the exterior of the reactor vessel that I showed the viewgraph of earlier. This is basically just what we call a [Unclear] plot that shows all the data. But you will see that the peak temperature based on the scale testing that was done is actually quite close, about 420 degrees to what was predicted by the designers for this system a number of years ago, and that was actually occurring at about 120 hours as they had predicted.

Actually, it might have occurred a little earlier but you can see after about 100 hours you are basically stabilizing at about what the designers thought the system would evolve to.

This lower graph shows the inlet and exit temperatures on the air-cooling ducts that were dumping air. The upper right viewgraph shows the evolution of the flow rate in terms of – sorry, I can't read it, but I think it's kilograms per minute of the air transported through the reactor cavity cooling system here. You can see some bumps and whittles here, and these are basically due to atmospheric effects influencing. These are probably higher wind conditions here and also provided in the reports are the meteorological data that can be used to correlate this. But this basically shows how the system responds in a scale test at large scale during design basis accident for the GA-MHTGR.

The lower right viewgraph shows some of the temperature distributions on the riser ducts. And this data is important not only from the viewpoint of the thermal hydraulics design but also from predicting mechanical stressors in the system that the designers need to account for in terms of reinforcing the duct work to be able to tolerate the thermal stressors that would be placed on the system during an accident. And the one thing I will say is that this was a design basis accident, I think service level C, and it rides out the accident within the bounds for that. And if you are able to reestablish a flow within – I can't remember the time, but at a service level that this was put at, there are 1000 hours or so you have to regain and cool the reactor vessel, and on that basis you will be able to restart the reactor if it rode out one of these events.

I think this is very good data, and this is trying to provide some of the insights we got on that in terms of the operational aspects.

The next thing we looked at was weather effects. And these viewgraphs show the system response under the same type of an accident sequence, basically looking at red would be hot weather conditions and blue would be cold. The first thing you note is that the heater plate temperatures are very close for either case, but there is a difference in the mass flow rate that develops under cold versus hot conditions, and under colder conditions you find a higher mass flow rate and that's due to the behavior. After looking at the results, this was deduced to be a result of the effect of natural convection, which is better for an ideal gas at lower temperature because the derivative of the density of the coolant with respect to temperature is higher at lower temperatures. So that was eventually concluded to be why these results were a little different in one aspect.

Basically, the riser gas temperatures are offset based on what hot versus cold; and the colder temperatures kept the duct wall cooler than at hotter weather conditions as you might forget. But overall, the bottom line is that on the effect on the reactor vessel peak temperature is not that great and one of the other contributors to that is that radiation heat transfer is the dominant mode of heat transfer in this type of scenario. Roughly, two-thirds to three-quarters radiation versus one-third to one-quarter of convection. So, the effect on the surface temperature of the plate is not that pronounced in the results. So, this is giving you an idea of the weather conditions. A still favorable cooling behavior but shifts in the temperature on the system plumbing if you will.

Another thing we did was look at the effect of an adjacent chimney configuration, and in some of the design aspects, the inlet and exhaust ducts were pretty close together, so we did testing to look at that. And if you look over here at the left viewgraph, this gives you an idea of how we set the system up to do it. The blue line shows the inlet that was used to the RCCS, and basically we closed the valve here, ran some ductwork down to the inlet of the system and used that as the inlet and then we discharged through the normal pathway for the apparatus. And what we found here in this test and I'll go through that, is that we found quite a bit of effect here and this was also weather dependent. But during the startup, and starting up your plant, this is your configuration, you have to keep this in mind because we showed a difficulty establishing normal flow conditions here. And the blue at the inlet, which is drawn from the high bay. And you can see red is the exit temperature from the system. And you can see that there is interplay between these two as we start up and some oscillatory behavior where the hot exhaust gas is drawn into the inlet and that causes some rapid fluctuations and heat up transient. And as we move forward, eventually – we couldn't get our hands on this during the part of the operation, so we eventually started the cooling fans and shut the steps down because we couldn't get it started up right.

It shows the indication that in this kind of a system you have to be knowledgeable of it when you start up the reactor for the first time. But I will say that once the system was running, it was very robust with respect to inlet and exit conditions. But during startup we did have some transient there. And some further analysis and investigation indicated that this was principally due to the fact that the way this system was set up, and this right schematic showed the system we are looking here, and we found that we had quite a bit of flow loss on the inlet of this system before we got to the cooling aspects of it, heating and cooling, that could cause some instability and interplay here. Whereas when we get the condition where there was very little flow inlet loss, this system would start up a lot more stably. So just keep that in mind in terms of starting up the plant initially. That was one of our interesting findings that was revealed.

Completion of the air testing. I am trying to stay at about an hour here, so I'll move along a little quicker here, but I just want to say that we completed the air testing in July 2016. This was documented in open literature reports that anybody on the line can find and use in their work. We had formal audits that included not only DOE [Unclear] which is INL acting as the auditor. NRC was also a part of this process, so they came to our meetings and reviewed our data and gave us assurance that it was a meeting what they thought would be needed to be used in a licensing application. And also GA, the designer for the MHTGR, were involved. And also the heavy influence of the universities in the work we had done. This was all work the results were scrubbed and concluded to be meeting the program objectives that were at a high level laid out in 2005. We started on rebuilding the facility. We laid out detailed experimental objectives in 2013 and concluded testing in 2016.

The testing involved about 2300 hours of active feeding. We conducted 27 tests, 16 of which we concluded met the whole QA requirements for the experiment so that quite a large database after examining accident scenario, physical effects like block risers, different skewing in the heating patterns, adjacent chimneys, meteorological effects and other factors were looked at in terms of. So it's a lot of data there to support this design, and we were very happy with the way the program came out from a technical viewpoint.

That said, these high-level conclusions on the air test, ambient temperature, again reiterating the point that while heat removal performance remains largely unaffected, there are flow rate and absolute temperature variations can vary dramatically during the operation but you maintain robust heat removal.

Meteorological perturbations, as I said, there was sensitive to the weather, and I think putting the weather station out there was one of the best things we had done for this program. As I noted in the beginning, the idea was to provide a facility to look at design alternatives. And what you see here are some NI drop cowls that were designed based on the results that we had seen originally. We had just basically cover caps for these discharge lines. But there are some good ideas how we could redesign a passive cast that could be used to mitigate some of these weather effects, and these were designed, built, installed, put on and shown to be a valuable asset in terms of perturbing or reducing some of those effects. Power sensitivity and low power startup, I talked about that quite a bit. You saw that. But after you get the system up and running, system runs very well. Blocked risers blocking every other tube in the system was found to really have no large effect, and the system still ran fine. The reason every other tube was blocked in the design was that the inlet and exit headers were basically paired off one to the other so that if one system was blocked in the reactor, you would still have cooling so that's why that test was done in that manner and it showed that there was really no effect on the overall performance of the system. So that was a good piece of engineering information to get out of the testing.

So with that said, we completed this program. DOE put a lot of money in this to support the designing and fabrication of the facility. You never know what's going to be coming down the pipe, so there was a concerted effort to carefully take this facility apart, document it how it was done, and put it in safe storage so that if we needed to use it again in the future, we would have all the parts. So that's not so much to do with the technical results. We are just saying that you never know what's coming down the pipe in terms of reactor design and so we carefully disassembled this and stored the equipment in a safe configuration such that it could be brought out and used in the future if needed.

With that said, we were now well along in the stages of moving into the air-to-water conversion. As I noted at the beginning, you have the air-based system which we now feel like we have good data on at least for one system to validate the concept and the codes. There are also water-based systems and a particular one that we are looking at is the Framatome 625 megawatt thermal that uses the water cooling system. And basically, DOE sponsored us to look at this, to do trace studies, thermal analysis and calculations to design a system that would be used to convert from this air-based system that I am showing in a vertical or a horizontal cross section here and moving over to a water-based system, where these are basically water-cooled pipes that are stitched together by a steel plating and the reactor vessel would radiate and convex to this system here. By conduction, you would transfer heat into the water, which would rise to the system here and the reactor cavity wall exterior or the reactor silo wall behind it would be kept intact at a low temperature by virtue of this. I will say this is the system that's commonly used in high-temperature carbon plants in the US, both coal and natural gas. But the idea was here to apply in terms of a nuclear system that qualified for that type of configuration.

The water test section design is shown here. And again, I am reiterating the fact that we are using stainless steel here for the water riser tubes that are welded to carbon fins that would be the basis for receiving the radiation heat transfer and conducting it to the water. As I said, the fins are made of 1018 carbon. We used carbon steel here because it has the high emissivity, which is good for the radiation heat transfer process. However, in reactor systems you want to keep the water clean, obviously, and stainless steel used here provides the ability to keep the water clean while maintaining the good heat transfer processes that the carbon steel can provide in terms of the radiation heat transfer. This is the overall system design for the inlet instrumentation here. I'll say a little bit more on the exit. This is shown obviously laying sideways.

Might say, what does that look like in reality? Here is the water panel. This was manufactured by Chicago Bridge & Iron out in North Carolina. They have the facilities for making these types of devices here. Again, you see the stainless steel tube and the carbon panels. This was sand blasted before we put it in, so we go into the testing a well-characterized surface emissivity. Moving forward, this shows the rigging, getting ready, vertically standing. These are Tony [ph] I believe and Gary [ph]. He's the PI on the project. This shows the system that is moved as it's installed in the reactor cavity cooling system testing facility.

I am sort of making up in this viewgraph for the lack of one of these for the air system, but a very high concentration of instrumentation in this facility to not only characterize the thermal performance but also to provide high fidelity data for the analysts. And one thing I didn't really say a lot about but we are using a lot of fiberoptic temperature sensing in this facility that gives you very high density temperature measurements across the heating panels, and this is good for the analysts.

We also have focus on two phase flow in this facility. When you go into the boiling heat portion of it, there are a lot of flashing effects here. As you move up to the header tank, and this can influence some of the heat transfer processes. So we have devices in here, we are measuring two phase [Unclear] behavior during these transients, which are quite a bit more exciting than the air-based tests.

I will say the system rocks and rolls a little bit when the boiling starts. And this header tank is about a 4000-liter tank that's located up very high in the high bay so we get a lot of work to show that the scaffolding that was on it could adequately take this in terms of the vibrations in the loads during the test. A lot of engineering went into this facility that I won't have the time to talk about today.

Where are we at on that? The water-based facility has been completely installed. Everything has been put together, so the shakedown testing has been done to verify the instrumentation. Works accordingly. And we qualified the facility and done the single-phase demonstration test that would basically looking at normal operation of this facility with the pump running and the heat exchanger dumping heat from the header tank during normal operation.

First accepted matrix test at single phase was done in January 2019 to look at normal operations as I said. And by August of this year, we had completed the plant testing to look at single phase per matrix effects in the facility. So quite a bit of progress made there. And approximately a month ago now, the first two phase boiling heat transfer accident scenario test was done to show that the test worked in that regard and that test was quite successful.

Excuse me. This viewgraph is a little bit on the boring side, but it's just showing the overall planning and moving forward with this facility design here in terms of the work, the construction, fabrication, checkout. And basically we just completed the parametric single-phase studies tests. We are in a period of maintenance now, and we're engaging on the accident testing as I described earlier.

So the next couple of years will complete the test matrix and document these results as was done for the air-based testing. And with that test completed, we would have done a high quality level look at a large scale air-based system and a large-scale water-based reactor cavity cooling system to support our advanced reactor designs that we might want to employ this kind of a concept. And I am a firm believer that at the scales of these reactors that you could deploy these systems and feel confident that even under accident scenarios, they will be able to dissipate decay heat without operator intervention and get the job done and preserve the core, restart the reactor without fuel damage and preserve the investment in the facility. So, I think this has been a good series of tests and I'm really looking forward to the series of experiments moving forward.

Finally, this is possibly the most important viewgraph that I want to say that the Department of Energy has supported this work. We are very grateful to that. We are firm believers in this kind of work supporting advanced reactor concepts moving forward, and they have been very beautiful about making sure we had the resources to do this work right. As I also said, we have a lot of university engagement, and I want to thank the universities that have been involved, facilities been good in terms of allowing us to support students to work on the project and give them some experience so they will be valuable assets to the industry moving forward. I do want to give a shoutout to Darius Lisowski here. He's the principal investigator on this project. First, I want to say thank you to him for helping me out immensely on these viewgraphs because they wouldn't have been nearly as high quality without his input. But secondly, he's done a great job of taking this facility by the horns, running it, meeting all the requirements for it. And I am very grateful that the help that he has been able to provide as well as all the folks, the engineers and designers, that have worked on this program. And also I want to give a shoutout to the analysts that have done work to support with relab [Unclear] and the CFD [ph] codes, the work that's been done that they provided valuable insights and how we should run the facility and where we should put instrumentation.

I believe that ends my formal presentation unless there's anything else.

Berta Oates
Thank you, Dr. Farmer. If you have questions – I know several have come in during the presentation, but please do take a minute to type your questions into the Q&A pod and we'll take those questions in just a minute. While we are waiting for those, we'll take a quick look at the upcoming webinar presentations that we have planned. Next month, we have a presentation on the Czech Experimental Program on MSR Technology Development by Dr. Uhlir. In December, Madeline Feltus with

DOE will present on TRISO fuels. And in January of 2020, we'll have Thermal Hydraulics in Liquid Metal Fast Reactors by Dr. Gerschenfeld.

Bear with me a minute. I will open up. Mitch, you should be able to see the questions as well on your questions panel. There are several here and I'll just start. Near the top, there's a question that says can we regard the system would shape memory alloy actuator as a fully passive system? It doesn't require AC or DC power, but it has a moving part for actuation. And what I think I'll do is just answer that with a – I am going to post it so everyone can read it. Do you see it now?

Mitchell Farmer
I don't Berta but I may not be doing something right here. Could you read that question one more time please?

Berta Oates
Yeah. Can we regard the system with shape memory alloy actuator as a fully passive system? It doesn't require AC or DC power, but it has a moving part for actuation.

Mitchell Farmer
I am going to be frank. I am not familiar with that system, but it is based on the concept of thermal expansion to activate and that's a well-known system that's based on basic common sense physics, so I would think that it would be. You would have to, of course, do the testing to verify that it is repeatable and it works as planned. But I am frankly not familiar with that system.

Berta Oates
The next question. RCCS is a concept for boiling water reactors. It is not even for PWR. I would consider it in Gen 4. Should we understand it as an extra core cooling?

Mitchell Farmer
I would say definitely the system that we have looked at or based on looking at high-temperature gas reactor designs, that was a specific one we looked at in terms of the air and water based testing. The thing about these passive systems is that at least in terms of the high-temperature gas reactor, there is a scaling limitation on how big the reactor could be made because your limit basically relying on conduction heat transfer from the fuel out through the reflector and moving out that way. So that places a size limitation on how big this system would work. It would definitely work and I think we've shown that for gas reactor designs, it has also been shown in a different derivative design concept to be applicable for the sodium reactor design and that would be the GE PRISM design. There was testing done that was shown there. I think this system could also be used possibly for sodium systems, although there

would be differences on the battery conditions that would be applied, and I haven't really looked in that and that affected for the air system that we looked at. And the water system could be used for other concepts also depending on the coolant type and the compatibility with that system. So yes, I think it definitely applies to advanced reactor systems also.

And I believe the point about the natural convection concept would be for the EBWR [ph] where they use basically a pump-free circulation, boiling-driven heat transfer system also. That's used as the primary method for rejection of heat. So, I don't know if that was helpful but I tried to answer the question.

Berta Oates
Thank you. I apologize. Someone did point out that the lower portion of the slides were being cut off, and I was trying to fix that on this end while it was going on. I hope that I was able to resolve that. If not, I do apologize, and I will definitely take that feedback to make sure that the slides in future presentations do not come down that close on the margin. I apologize. On my end, they showed, so I don't know if it's my screen. I don't know. I hope it got better as we went along.

When it is run by air, how to make sure no water goes into the loop? Does that make sense?

Mitchell Farmer
Can you repeat that please, Berta?

Berta Oates
When it is run by air, how to make sure no water goes into the loop?

Mitchell Farmer
Well, that's a good question. It is basically accommodated by the chimney caps that were shown in the drawing there. Those are designed to keep air to be able to convect around and also to keep water out from weather effects. If you go into the details of the plant design, we didn't really get into any of that but they have engineering features in there, I believe, to make sure that even if there is water in there, that it's not influencing the behavior in its capture. Basically the way you do that is by carefully designing the caps on the air supply and return lines and then having engineering features in there even in the event that some water came in, that it would not be impactful. And this system is also fully welded together, so it's a robust structure. It's not a sheet metal configuration. If that makes sense.

Berta Oates
Thank you. The water cooling increased cost or reduced plant location versatility?

Mitchell Farmer
I think water cooling is attractive from the viewpoint. It has an attractive feature; in that it decouples you from the weather and it also provides a specified specific boundary condition for dissipating heat. And that's the boiling point in the water. So the attributes to that are that it fixes the – it somewhat decouples you from the weather conditions because you are relying on natural convection within the loop and boiling heat transfer versus coupling to the atmospheric conditions. The nice thing about the air system is that it's relatively simple. I think it reduces possibly the maintenance requirements that a water system carries with it. So, there are benefits to both systems, but at least from increasing the decoupling from weather locations, the water system is nice because it relies on boiling.

Berta Oates
With the passive approach to the heat removal, will there be a need for accident tolerant fuel?

Mitchell Farmer
Well, it's always better to have accident tolerant fuel under any regard. And the better robust you can make the fuel, the better, I think the TRISO fuel that is used in the HTGR design is probably the most accident tolerant fuel you will ever come up with. It depends for the other reactors. And moving forward, the question is depending on your accident scenarios and whether or not you decide to use accident tolerant fuel is up to the designers. But it's always better to make the fuel robust, more robust, under any condition relative to postulated accident sequences.

So I think for the HTGRs I think the TRISO fuel is the most accident tolerant fuel I've ever seen. And I think that's already part of the gas reactor folks moving forward on that. The idea with this system though is that it's specifically targeted to keep you away from getting to temperatures within the fuel that could damage it. So, accident tolerant fuel is always better, but the specifics of this design are to actually prevent that. I hope that answers the question.

Berta Oates
Thank you. Do you have an estimate of cost to backfit the system on existing nuclear power plants?

Mitchell Farmer
No idea. We are a research organization, and we are doing work to verify that it works according to plan and that it can be done. I don't know of any plants to backfit these types of systems into existing plants. As far as I understand it, these systems would be deployed in new plants moving forward, so put in from the ground up, so really just part of the

plant costs moving forward. I have no idea. I don't even know if it would be possible to backfit this into some plants.

Berta Oates
Thank you. Is there a reason why the water-assisted design tubes are used instead of having water directly contacting the reactor guard vessel wall?

Mitchell Farmer
Well, for high temperature gas reactor designs, I think that would probably overcool the system and the HGTRs that I know, you are trying to run the system at higher temperature to get the higher gas temperatures to get better efficiency in the system. And if you had water on the reactor vessel, that would in my opinion be too much heat sink and it would limit your peak temperatures you could achieve and it would probably also – if you tried to press the core temperatures up to higher level, it would probably place a great deal of thermal stress on the RPV itself. So I don't even know for a high-temperature system if that would be plausible from a mechanical design viewpoint based on the thermal stresses it would place on the system. That's one clear advantage point of just lining the silo with a cavity cooling system that can operate and dissipate the decay heat that you need while allowing the reactor vessel and the reactor system itself to operate the way it's intended to.

Berta Oates
You mentioned at some point that parasitic decay heat removal systems have been considered. Is this common in the design of these systems?

Mitchell Farmer
Well, it's been common in the plants that have been under consideration in the US for a long time. As I pointed out, these reactor cavity cooling systems are not new. They have been around for years, and in the GE PRISM design and the GA-MHTGR designs, these have been there from the get go on those. And then in the Framatome design, I know it's been in there for a while. These concepts are not new. The idea with the work that we were doing was to take them and perform testing on them to verify that they would operate according to plan and to provide the information needed to get them licensed with the NRC. So that was the intent of our work.

Berta Oates
How do you avoid corrosion in the water cooling tubes of RCCS?

Mitchell Farmer
Well, that's accomplished by using stainless steel tubes which is a common water plumbing material used in nuclear power plants and the heat transfer systems in general. It's accomplished by using stainless

steel to prevent corrosion. And the carbon fins that were in the design were welded to those and you can weld carbon to stainless if you know what you're doing, and they have been doing it a while at Chicago Bridge & Iron. That's how it's accomplished, by using stainless steel as the container for the water system itself. And then obviously you would have a water purification and monitoring system that would run as the plant operated, to be able to control water chemistry and prevent corrosion. I mean that would be the way to do that and I think that's wholly in the design for the conceptual design for the plant.

Berta Oates
Thank you. Did you consider emissivity of the RPV plate as a constant value, not dependent on temperature? Normally, the value is taken around 0.5 at least for sodium-cooled fast reactor vessels.

Mitchell Farmer
We did know online monitoring of the emissivity of the plate. What we did do is that we have instruments that looked at emissivity at the start of the test program and at the end of the test program and I think that data is readily available in the data reports for the program. So that was clearly one of the key things we wanted to measure, and it was done at several points during the program and that information is available in the reports. If not, you can't find it, we can get it to you but I'm sure that it's in there. Because that's a critical parameter. We did not measure it online though as that would be too difficult for us to do.

Berta Oates
Right. Is there a reason why for the water-assisted design, tubes are used instead of having water directly contacting the reactor guard vessel wall? You already answered that one. Didn't we do that one already?

Mitchell Farmer
Yeah. Yeah.

Berta Oates
Which point do you see as challenging to capture numerically and by so which justify experimental investigation rather than a numeral assessment? I am not sure I am going to understand that one.

Mitchell Farmer
It's a good point. That was one of the principle drivers for this program and it was identified early in the next generation nuclear power plant or NGNP program when that was moving forward in the early 2000s. And the idea was that you never know what people are going to bring in by way of a design if they want to get licensed, so the idea was that we would look at a couple of designs in detail. We would take the tools, the numeral tools that we had, and we would qualify those against these tests

and show that they worked and they worked repeatably. And then those tools would be available to numerally analyze and show the safety attributes of designs as they move forward. And I think we have been successful at that in terms of the air testing. We are moving forward in the water. And that's a good question. I think what we have shown at least in the air-based testing is that if you have good numerical models of the system, that those do pretty darn well in terms of being able to predict the behavior. I think in terms of the individual physics processes of natural convection and radiation heat transfer to the system, I think that has been shown to be calculatable and repeatable. Some of the things you get into though are more at the system level analysis, being able to model the whole plumbing through the system and look at weather effects. So those are some of the more numerical challenges from a plant system level approach. But the idea was generally to show that these codes work when they look at water and air-based systems and then you have some confidence that when you apply those to other systems as they are developed, you are being able to predict reality.

Berta Oates
Thank you. I am scrolling down. There is a long – is natural circulation of air only, no water, sufficient to remove decay heat of an MSR sized concept? Is there a max rated power whose decay heat can be removed with air only?

Mitchell Farmer
That's an excellent question and the answer to that is yes. And further, the answer depends on the reactor design and the cavity cooling design and I guess I am not actually able to answer that in detail, but the answer is definitely yes. There was a report done by INL in 2012 that looked at the reactor cavity cooling system design for HTGRs that you could find online if you're willing to look at that in terms of a plant response under postulated transients. So that has been done. It's been done numerically. I know there was also some work done for sodium-cooled fast reactors. And you're definitely right, this limits the plant size to several hundreds to maybe 1000 megawatts thermal. Don't take those as actual values, you have to do your homework and your analysis to show it. But you're exactly right. This system itself is limited into the size that it can be used for in terms of accident – the effects that heat up other system.

Berta Oates
Thank you. Great questions today. Very good questions. I think we have worked through the bulk of the questions that we have received. We may have time for one more if we have any other thoughts out there. But I want to take this opportunity to thank you again Dr. Farmer for your participation in putting this webinar together. It's great information and I know it does take a bit of time to do that. I appreciate it.

Mitchell Farmer
It's my pleasure. This is important information and it is important to the reactor safety community and people should be knowledgeable of it and we are here to help the process along. I mean that's what we need to do. I think these are really important systems for the next generation of plants moving forward, and they can do a lot to mitigate scenarios that you don't know about and keep the investment intact and fission products where they are supposed to be. So, I really am a firm believer of this kind of process. So, thank you.

Berta Oates
Thank you.

Patricia Paviet
Yeah. Thank you so much Mitch, again. Thank you Berta.

Mitchell Farmer
You're welcome.

Patricia Paviet
Great, great presentation and great turnaround with the questions.

Berta Oates
Okay. Thank you everyone.

Mitchell Farmer
Okay. Bye, bye.

Patricia Paviet
Bye, bye. Thank you. Bye.

END