Very High Temperature Reactors
Dr. Carl Sink, DOE, USA

Berta Oates: Welcome, everyone, to the Next Gen IV International Forum webinar. Today's presentation is on very high temperature reactors by Carl Sink. Doing today's introduction is Patricia Paviet. Dr. Paviet is the Director of the Office of Materials and Chemical Technologies at the Department of Energy, the Office of Nuclear Energy. She is also the Chair of the Generation IV International Forum Education and Training Task Force. Without any further ado, I'll let Patricia proceed with today's introduction.

Patricia Paviet: Thanks you so much, Berta. So today this is really my great pleasure to introduce Carl Sink, who has been working for the US Department of Energy for 24 years in various roles. He is currently a Program Manager for Advanced Reactor Deployment within the Office of Nuclear Energy, and he is responsible for coordinating cooperative research, development, and demonstration projects conducted by DOE national labs and US nuclear industry partners.

Since 2004, he has been closely associated with the Next Generation Nuclear Plant Project, the DOE initiative, to develop and demonstrate a high temperature gas cooled reactor. From 2006 through 2009, he was the Program Manager for the Nuclear Hydrogen Initiative, coordinating DOE efforts to develop high temperature water-splitting technologies to take advantage of HTGR outlet temperatures.

Within GIF, Mr. Sink has served on the Very High Temperature Reactor System Steering Committee since 2008, and currently chairs that group. He previously served on and chaired the GIF VHTR Hydrogen Production Project Management Board.

Mr. Sink holds a master's degree in Engineering Management from the Catholic University of America, and he is a graduate of the United States Naval Academy with a degree in Electrical Engineering. Before joining DOE in 1992, he spent nine years as a qualified Nuclear Engineering Officer in the United States Navy, with reactor operation assignments in a nuclear-powered cruiser and a nuclear-powered aircraft carrier.

So thank you so much again, Carl, for volunteering to give this webinar, and I give you the floor. And I am really eager to listen to your presentation. Thank you, Carl.

Carl Singer: Great. Thank you, Patricia, and good morning, everyone. I'm happy to be able to share again the information today, an overview of the high temperature gas reactor which within GIF we are approaching the very high temperature reactor concept to go to very high temperatures. We'll talk some more about that. I'll talk about the history, and I'll talk about our safety design approach, why we believe this design has very good inherent safety characteristics. And then finally we'll do some discussion of high temperature gas reactors for cogeneration and process heat use, the ways that these reactors have utility beyond electricity generation alone.

So again, why was the HTGR and the VHTR in particular selected for one of the six Gen IV concepts? It does have very good inherent safety characteristics. The fuel is made up of ceramic particles which will not melt at any temperature in their design basis operations or accident, design basis accidents.

It has a graphite core, which is a very stable material, as a structural material. It is a stable moderator that won't go anywhere. And it's also a thermal buffer for keeping the temperature within the reactor at a constant or slowly-changing temperature.

It has a helium coolant, which is an inert gas, which doesn't interact with the fuel or the graphite or any of the structural materials, which keeps corrosion concerns to a minimum.

In addition, it has diverse applications, in addition to electricity generation. It has a high efficiency power conversion capability, either through a modernized Rankine cycle or using advanced closed Brayton cycles using either the helium coolant directly or in a separate loop using another type of Brayton cycle gas coolant.

Additionally, the high temperature process steam or process heat that could be generated offer cogeneration opportunities, and we'll talk a whole lot more about that in the last part of the presentation. While we're working on high temperatures right now, up through 750 to 800°C, the envisioned goal is to get this reaction up to 950°C or 1000°C with advanced materials that may become available in the future. That's our primary concern there, to move forward with those high temperatures.

Finally, it has a good proliferation resistant, high burnup fuel cycle, very good fuel efficiency, and there's growth potential for additional fuels and fuel cycles, including plutonium and thorium, and also looking at deep burn cycles with even higher burnup of the fuel content using light water reactor spent fuel.

And there's been numerous studies on each of these topics and the specific technical details are much more in-depth than we can go in this overview presentation today. There's a lot of information in the literature to be gleaned on this. As I said, I will try to do enough detail today to whet your appetite to want to know more, and let's go ahead and get started.

So among the HTGR concept, there are two major design variants. The first one I'll show is the prismatic block design represented on the left there, of where the fuel is encased in blocks of graphite. We'll talk about how the fuel is manufactured in the fuel form in just a moment. The other main variant is what they call a pebble bed design, where the fuel is in what we call pebbles. They're about the size of tennis balls or billiard balls, and they are in a core barrel where they flow down, they come in at the top and they flow down through the core and are removed at the bottom. And how the fuel is handled, we'll talk a little bit more in a moment. Those are the two main variants of how this design is built. They have many things in common as we'll shortly discuss.

Other design options that can go with these basic reactor designs are what size, what power output you have, whether you use a Rankine in a steam ranking cycle or Brayton cycle for energy conversion, and whether you use direct or indirect heat transfer, whether you use the hot helium directly from the reactor or you go through an intermediate heat exchanger to get your secondary heat loop.

Briefly to compare, for those of you who are familiar with light water reactors, how the high temperature gas cooled reactor is significantly different. Probably one of the main differences is where light water reactors use water for both the moderator and the coolant, in a high temperature gas reactor, the graphite both in the fuel and in the core structure is used as the moderator and a helium gas is used as the coolant. That helium gas is at a very high temperature compared to the light water reactors. As you see here, up to 950°C in the operating experience compared to an average 310°C for water reactors.

The main structural material in a gas reactor is graphite compared to steel in a light water reactor.

The fuel cladding is another major difference, a zircaloy cladding in a light water reactors as compared to a ceramic silicon carbide and pyrolytic carbon fuel cladding in the high temperature gas reactor.

The fuel can be the same type of fuel, uranium oxide. We’re also looking at a uranium oxycarbide fuel for high temperature gas reactors. I'll talk a little more about why some researchers are seeing that as a very advantageous fuel to use.

Just again, looking at how the reactor is constructed leads to a difference in the power density. The high temperature gas reactor has a very dispersed core structure, and the power density within that core is quite a bit lower than a light water reactor where in the fuel elements the power density is very close and very high. That leads at the same time to the linear heat removal rate being much lower in a gas reactor, over the same distance in the core, you need to remove a lot more heat at any given time from a light water reactor.

So as I said, many of the components between a prismatic high temperature gas reactor and a pebble bed reactor are very similar. One of them is the graphite core structures, which are very similar between the two. They both have steel reactor pressure vessels. They have the ability to use steam generators. On top of the steam generator is what equates to a light water reactor coolant pump. That is where the helium circulator is located. The control rod drives are generally on top of the reactor pressure vessel, and some other items that are not, the use of an intermediate heat exchanger is not shown in this diagram, but that is another option, as I mentioned before. We are looking on a licensing framework and approach which will be quite similar, if not identical, for all types of high temperature gas reactors. And we're having to develop industry codes to go with the high temperature materials for nuclear use that have not been qualified for that before.

So far as operating experience with helium cooled high temperature gas reactors, there have also been high temperature gas reactors with carbon dioxide as a coolant, some of the earlier reactor designs were of that type, the earliest commercial designs.

In the area of power reactors there was the Peach Bottom Reactor at For St. Vrain in the US and the THTR in Germany. For each of these, it shows some of the operating characteristics, the coolant temperatures, the types of fuel used, and the peak temperature in the core it was operated at as compared to the coolant temperature. And then you see also how some of those used graphite compacts, which is what's used in a prismatic block reactor or if they used graphite pebbles.

In the area of research reactors, some that have gone before were the Dragon Reactor in Great Britain and the AVR in Germany. I'll talk a little bit more on the next slide about the other two reactors, the high temperature test reactor in Japan and the HTR-10 in China.

So these two research reactors are still operational. Since the Fukushima Daiichi accident, Japan has not yet restarted the HTTR, but it has been ready to restart, awaiting their regulatory authority to give the go-ahead, since very soon after the accident that occurred. This reactor reached a high temperature, outlet temperature, of 950°C at 30 MW in 2004. It was a strong achievement for that. And it was undergoing active testing and operations up through the point of when it was shut down and doing various types of thermohydraulic testing to gather data on this type of reactor.

The pebble bed version compared to the HTTR, which is a prismatic block reactor, is the HTR-10 in China. This reactor has done work for the Chinese to help them prepare and test out concepts for their design of the HTR-PM reactor, their commercial demonstration reactor being built right now in China. This reactor first reached its full power in 2003.

So moving on to fuel types. High temperature gas reactors can use many types of fuel, both fissile fuel with uranium and plutonium types, or also they have been demonstrated with fertile fuel using thorium, which could be used to breed fuel and make fuel for the reactor to operate. The most widely-used fuel type has been uranium dioxide, the UO2, it was used in Germany, in Japan, and in China, and it's currently the fuel being used for the HTR-PM. There has been extensive irradiation and heating testing done. This information is all available to designers today, and as I said before, it was the reference fuel type for the PBMR and the HTR-PM. The PBMR was a design that came to a very advanced state in South Africa, and you'll see some reference to that in today's presentation.

The other fuel type that has been getting a lot of attention is uranium oxycarbide. This is made up with a mixture of UO2 and UCO, and it has been seen to have much better control of carbon monoxide buildup in the fuel particles, and thus it has a better performance because of less internal pressure in the particles, and as we'll talk about later, one of the key safety features is for this type of reactor is keeping the fuel particle at the very smallest level to keep that particle intact.

So looking for a moment at the fuel particle construction or the manufacturing and fabrication of the fuel particle. So in a prismatic fuel type reactor and both also in the pebble fuel, they start with the basic element which is the TRISO coated particle. We'll see some more pictures of this, but in this photo you see the main construction elements. You've got a uranium oxycarbide kernel. The kernel is where the fuel resides in the center of the particle. Surrounding that is a porous carbon buffer, it's a very loose carbon. The purpose of this is to take the fission product gases that would come off of the fuel as it fissions and changes into fission products, and to be able to contain those within the other layers of the TRISO fuel particle.

The next layer outward from that is the silicon carbide layer. It is a hard ceramic layer that surrounds the buffer and actually serves in our functional containment design, this is the primary containment for the fission products generated during operation. Both on the inside of the silicon carbide, which actually is shown here as the light gray layer on the inside, and on the outside of that is a pyrolytic carbon layer, which in the construction of the particle helps the different layers to adhere together and to keep their integrity during the fuel manufacturing process.

So looking first at prismatic fuel, what we end up with, these tiny particles. They are the size of a pencil dot in size, and in the operation, in constructing an actual reactor core from this, you would have billions of those particles making up the entire fuel. As you take the particles, you take them, you combine them with a graphite matrix and press them into these compacts, a little bit larger than a pencil, similar to a fuel element or a small fuel part in a light water reactor, but much less content of the fissile material. And then those compacts are loaded into holes in a larger fuel element. These are about a half meter or slightly larger tall, as you see here in this picture, compared to the size of a chair.

I'll go forward for just a second to give you a better look at what one of these looks like up close. So here we see inside a radiograph of a compact. Here are all the particles inside the compact with the graphite matrix surrounding them and separating the particles within that compact. The way they are formed, there are the particles and the matrix are putting into an isostatic press die that compresses them. They come out as a green ceramic material, which is then baked and made into the hard compact form that eventually goes into the reactor fuel elements.

Now looking at the pebble bed fuel, here we have the same type of fuel kernel, in this case it's described as a uranium dioxide fuel, a UO2, which has primarily been used in the pebble bed designs to date, the same TRISO layers on the outside of that, three layers, the buffer layer, the inner pyrolytic carbon, this silicon carbide, the hard silicon carbide that contains everything inside, and then the outer pyrolytic carbon, which allows safe manufacture of the pebble. And the pebble, in the center of the pebble, there is the TRISO particles, and the toward the outside is what they call a rind of graphite, an unfueled layer of graphite outside. I'll close this for a moment and go forward.

And similarly, here is a radiograph of a pebble, which shows the fuel portion in the center and then the outer rind which does not contain fuel. Again they are put into a press, which presses that matrix and particles together into a solidified form which is then baked, and in this case finished and machined into the very smooth cylindrical or spherical shapes that are used in the reactor.

Obviously, this leads to different ways of managing the fuel and the fuel loading within the reactor. In a prismatic high temperature gas reactor, the fuel assemblies are fixed together and they are moved around in batches. This picture from the Fort St. Vrain reactor shows a fuel handling machine that moved and adjusted the location of the large fuel assemblies within the reactor as time went on and as fuel was used would be able to take the fuel out of the reactor and replace it with a fresh fuel assembly.

In a pebble bed reactor, this more or less of a cartoon drawing shows how the pebbles come in at the top, into the core barrel, and then over time they make their way down through the reactor. And there are two ways of managing this.

The first one is what's called the multiple pass scheme, where the pebbles come in from the top, they move downward through the reactor, and then as they are taken out at the bottom, they are examined to see that they are still intact and not damaged in any way and also to check how much fuel radioactivity or how much fuel life is left in the pebble. If it can still be used again, it can be taken back to the top and used again and used over and over until the fuel inside has been expended. In this way, it keeps a very homogeneous mixture of the fuel and a very uniform power distribution across the core height.

The other option is what they call the single pass Once-through-then Out cycle, or OTTO cycle, where the fuel comes in at the top, makes its way through, passes out, and then is stored at a spent fuel storage facility. As you can see, this does add some limitations because obviously the fresh fuel at the top will have more reactivity than the more used fuel at the bottom.

So moving from fuel to the next structural element or the next material element is the graphite, which plays a key role in high temperature gas reactors. In the area of neutronics, the graphite serves as your neutron moderator, as I mentioned before. It thermalizes the fast neutrons that come off of a uranium fission event to a lower energy that can efficiently fission with U-235, which is the primary fuel of this reactor.

It also serves as a neutron reflector to keep the neutrons in the core. It reflects them back in. The key way that that occurs is because it does not absorb neutrons but the neutrons would be reflected back because the graphite has a low neutron capture cross-section.

And as most people are familiar with, graphite has a very high temperature tolerance. It is a very strong material at very high temperatures, and that is why it was chosen as the key structural material for these reactors.

So on that case, looking at structural again, a picture here of a graphite fuel element block from a prismatic reactor. The blocks are used to retain the fuel compacts, as well as have channels in them for the reactivity control channels to insert control rods or other reactivity control materials.

In a prismatic core, which I'll show in the next slide, or in the pebble bed core, the graphite reflector structure retains the fuel pebbles as they move down through the annulus structure in the center, the core barrel. And the reflector structure also has vertical penetrations in it for reactivity control.

And that's what we're seeing here. This is the machined graphite blocks that are used in a pebble bed type reactor, which have holes both for the control rods and for a reserve shutdown system, which is an additional reactivity control system added in this particular reactor design.

And again, in both these cases, through some of these channels that are unfueled is where you coolant flows, your helium coolant flows through some of those channels. Some of the channels contain fuel, and other channels contain reactivity control elements.

And a pebble bed reactor.

And here is another picture of the structure of a pebble bed reactor. Looking here, this is from the HTR-10 in China. You can see these are the pebbles which are actually to give you an idea of the scale. These are about the size of billiard balls. This was during some of the initial loading of that reactor. And then they are surrounded by these graphite, machined graphite block structures that give the structural support as well as having the penetrations for doing the reactivity control systems for that reactor. Very good pictures here of that reactor and how it's constructed. Another picture at the top showing graphite block machined components that are used in that type of reactor, a pebble bed reactor.

Moving on to the next major topic I want to talk about is the safety philosophy and the inherent safety characteristics of a high-temperature gas reactor.

The first main thing that in all types of reactors, for safety purposes, we want to retain the radionuclides in the core, and in this case, our goal is to retain the radionuclides in the coated particles within the fuel. We do that in three ways: by removing core heat effectively; by controlling heat generation within the core; and by controlling chemical attack on the fuel and the fuel particles.

This is a very busy slide which is used to illustrate what we call the functional containment of this type of reactor. Our design and our desire is to not build these reactors with large reinforced concrete reactor containment structures but to be able to understand and show that we can rely on this functional containment to serve that same purpose through the different elements that are in it.

This picture right here could probably last an entire hour to discuss each one of these different components and each one of the functions that are shown here, but the primary thing I want to highlight is, here is the fuel particle with the fuel kernel, the UO2 or UCO fuel in the center, surrounded by this carbon buffer which will absorb and it's porous, it has room to absorb the fission product gases that come off of the kernel during operation, and then the three carbon layers on the outside, the two pyrolytic carbon layers, primarily for manufacturing and fabrication purposes but also to give stability to the particle overall, and then the main actor, the silicon carbine layer, which is the hard ceramic layer that in our experience is able to retain all the fission products within the fuel particle.

Surrounding that is the fuel compact matrix, or in a pebble, this would be the pebble matrix around the particles, and then in a prismatic fueled reactor a graphite block, which adds an extra layer of where any fission product, should they be released from the particle, the small fraction that has been shown to potentially be released, would be gathered there.

The other items on this, we'll talk briefly about this in the coming slides, but how different functions either can remove or mobilize any fission products within the reactor or things that will help to keep stabilized the fission products if they are released into the primary circuit or into the reactor building, if any of that should happen.

So the first item we'll talk about is how we remove the core heat.

During normal operation, the primary way that heat is removed from the core is through the helium coolant flowing through the core and going outside the core to be used for energy purposes that the core is operating for. That is the primary way that heat is removed. But in a situation where the core is shut down or in an emergency where heat needs to be removed without coolant flow from the normal operating system, we have a system which is called the reactor cavity cooling system. This system is actually in operation all the time while the reactor is operating, and it comprises maybe about 1% power loss to the reactor as it operates, but talk about the different elements of the reactor cavity cooling system as it exists.

So the different heat transfer modes that are shown in this diagram, the squiggly line represents radiation, head transfer. The solid darker lines represent conduction, direct contact conduction of heat from one medium to another. The dotted lines are convection of air that is flowing within the reactor system, within the vessel and within the core barrel. And then the larger arrows represent this reactor cavity cooling system airflow.

So starting there, we've got two standpipes represented here in this very oversimplified diagram, where cool outside air comes in. Because it is heavy, it falls down, and as it passes through this chimney or standpipe next to the reactor, it becomes heated, it become lighter, and then the cool air coming in forces a natural circulation flow through this air system. So this would be a natural circulation air cooled reactor cavity cooling system which is comprised of panels around the core barrel, the cement core barrel or concrete core barrel, around the reactor vessel.

So from the core itself, through the graphite, we see the conduction of heat through the material, from the reactor vessel or the reactor core to the vessel. We see the radiation of heat onto the vessel surface, and then from the vessel surface to the reactor cavity cooling system, a transfer of heat both by radiation and by the circulation of warm air within the reactor cavity, which also transfers heat onto the reactor cavity cooling system. Again, a very oversimplified cartoon diagram of this.

Now, this will function both during normal operation, during accident conditions. It is a passive heat removal system during accidents. It is a safety related heat removing system typically in most designs, and there are usually several redundant loops in a design.

Another option being looked at by many designers is to instead of having the reactor cavity cooling system being air-cooled is composed of water panels and it is water cooled. This was in the pebble bed modular reactor design. It's also in the design of the HTR-PM being constructed in China, to have water-cooled standpipes surrounding the reactor vessel. In this case, you see 18 independent circuits, a lot of redundancy there, and in this case also had tanks of water that could, over time, over a long period of time, boil off water to remove the heat generated in the reactor cavity. In this case, it had an active mode that was available with some active movement of the water, but it would also work as in the other case, with natural circulation.

Looking at the second way of protecting the particles is controlling the heat generation. The control of the heat generation in this reactor, like in many other reactors, relies on a negative temperature coefficient of reactivity. Putting that into the simplest terms, the definition is as the temperature increases, the reactor power level decreases. This is a built-in physics effect in this type of reactor, as shown there. The reactivity, which is the tendency of the reactor to increase in power, decreases as the core temperature increase. That provides a negative feedback effect both in the fuel and in the moderator to shut down the reactor or tend to shut down the reactor as temperature increases inside the reactor.

Furthermore, there's a lot of redundancy into the control of heat generation in the reactor. We talk in reactor safety terms about a reactor shutdown system, what would be needed to ensure the reactor shuts down and stays down. And so, as noted here, a reactor shutdown system is only necessary to guarantee a long-term shutdown condition for these reactors. The temperature differential between the operating temperatures and the maximum allowable field temperature is so great that there is not a chance of fuel damage in this reactor. The reactor shuts itself down before the maximum fuel temperature is reached.

This is a diagram here which shows a loss of force cooling with depressurization and loss of feedwater in an HTGR, so this would be a postulated accident where the coolant is no longer being pumped by the circulator, the helium coolant actually depressurizes and lose your helium coolant and you don't have a feedwater system in your steam generator to remove heat from the steam generator.

So this small dotted line here, this is your primary system flow, which it shows going to zero. Immediately, the temperature starts to rise but it will only go up to, say, in this diagram here, about 1500°C, where our buffer to our maximum temperature or our coolant damage temperature far above 1800°C would be much higher. So there is quite an available buffer there that under all postulated conditions would be maintained.

The other things that assist in this are having limited excess reactivity in the core, the amount of fuel, the amount of available reactivity in the core that could cause the core to want to increase in power is very limited, and we have very robust structures between the ceramic core structure, the fuel elements themselves, and a very straightforward simple robust core structure design.

So taking all of this together, you can see that this type of reactor has some safety paradigm shifts from light water reactors that we are all used to, and it's just a different way of thinking about reactor safety, and this has been an issue which has caused us to have to rethink how we regulate these reactors, how we think about accident scenarios for these reactors, the key points being that the fuel, the coolant, and the graphite are all chemically compatible under all conditions, primarily due to the inert aspects of the helium coolant.

The fuel itself has very large temperature margins under normal operation and during accident conditions between the highest physical temperature that it could reach, even under accident conditions, and when fuel damage would occur. As I noted before, safety is not dependent on the presence of the helium coolant. If the helium coolant were to be lost in air ingressed into the reactor, that air would also serve to be able to conduct the heat to the RCCS. This leads to response times for this reactor in the case of an unplanned occurrence being very long, days, as opposed to seconds or minutes.

There have been tests to demonstrate this to show that this reactor has the potential for walkaway safety. Because of the way the temperature coefficient of reactivity works and other physical aspects of core construction that could lead to reactivity insertion, there is no inherent mechanism to allow for the reactivity to go up, which would then lead for power to go up uncontrollably in this reactor. And as we talked about with the functional containment, it has multiple nested and independent radionuclide barriers to radionuclide release, therefore leading to a type of containment, as we discussed, with the light water reactors. In this case it's neither advantageous or really conservative, and there has been a lot of study done on that topic as well.

So moving along to my third major area of the use of these reactors and how they are proposed to be used in commercial form, we have some nearer term uses that are being visualized and discussed with potential industrial partners. Aside from the obvious electricity generation, the production of hydrogen for fertilizers. We have had companies already engaged with us to talk about the potential for this in the future as an alternative to steam methane reforming for hydrogen production. We are looking at process heat for use in industry, for district heating, where it has already been demonstrated in China and in some other countries for district heating. For desalination. A recent study completed regarding the US southwest and the economic promise of using desalination by nuclear process heat for desalination. Also for use in tar sands as an alternative to producing heat by burning natural gas for tar sands.

In the long term, other types of activities that have been looked at are the use in synthetic fuel manufacturing. As I mentioned before, hydrogen, hydrogen in very large quantities that have become available with very high temperatures in an advanced reactor design. Coal gasification, coal liquefaction. Finally in metals production, which is probably one of the key items in some countries that are really working hard to develop the high temperature gas reactor to produce hydrogen for direct metal reduction activities.

What we see as our first step though, what we're working toward today for the initial demonstrations that are planned is a reactor with, say, 725C to 750°C coolant outlet temperature. The activities that this can apply to is for heavy oil recovery, oil from tar sands, other types of industrial process steam, potentially with coal liquefaction and coal gasification. These are all being explored. And the market for this has been shown and studies done in Europe and in the US is very large. In Europe alone, 87 GWth of needed heat could be used from this type of reactor.

In the future, the very high temperature reactor plant, taking temperatures up to, outlet temperatures of 950°C, could be used for hydrogen production, as shown here with a thermochemical process. The one shown here is the sulfur iodine system, which is being developed, very advanced development of this in Japan and Korea. And then there is also the hybrid sulfur or sometimes called the Westinghouse process. And then on the next slide talk about high temperature steam electrolysis. All of these work best, work most efficiently with very high temperature process heat.

So this diagram shows both the need for electricity and high temperature steam to be used for hydrogen production for high temperature steam electrolysis.

So in summary, this technology has a very high technical readiness level. It has been demonstrated before. The licensing is well under way addressing the licensing concerns. There has been a lot of operating experience both with test reactors and with commercial size reactors. The prismatic, as well as the pebble bed systems, have a large common base of technology, and that's why we're comfortable talking about high temperature gas reactors in general. There is no perceived winner or loser between those two. It is based on what design the different manufacturer would like to follow and find out how it works best with the uses that they would like to put it toward.

As we discussed pretty extensively, it has inherent safety characteristics due to its ceramic fuel particles, the graphite core, which is very stable, and an inert helium coolant. We do believe it can play an important role both in the near term and the long term for process heat, as well as electricity applications.

I think the plan now is for time to submit questions, and I believe Patricia has some announcements that she will make during this time.

Paviet: Yes, thank you very much, Carl. So I just need to forward with one more slide. I wanted as the Chair of the GIF Education and Training Task Force to announce this international course on Gen IV nuclear reactor systems for the future. It will be between June 19 to 23 in Paris, in Saclay, in France, actually. And you have the website, so you have it, so the program manager contact information, Claude Renault from CEA is a committee member of the Task Force, as well as Nadia Nowacki, who is the course organizer.

So if you are interested or if you are aware of people who are interested, please do not hesitate to forward the information.

And I'll go back to the previous slide for the upcoming webinars that we are preparing for you, and I suppose we are waiting for some questions, and Carl will try to answer them. Thank you so much.

Oates: Thank you, Patricia, and thank you, Carl, for your presentation. If anyone has questions, you're welcome to type them right into the Q&A pod. Just click on the entry spot and we will address those as they come in.

So, Carl, on your screen you should see a Q&A chat pod. There are two tabs: one is the presenter view and one is a participant view. And if you click on the presenter, view you can see some questions coming in. There's a question from John Kelly. How is the flow of pebbles controlled? Do you see...?

Singer: Yes, to expand the question. There we go. Okay. So, Berta, you can see me, you can hear me okay? I had it muted for a moment.

Oates: Yes, we can hear you.

Singer: Okay. John, thank you for the question. So the flow of pebbles, a couple parts of this question, I think the obvious one that came to mind immediately of the flow through the reactor, there's a pebble, what they call a pebble handling machine or pebble handling device at the bottom of the reactor, which removes the pebbles individually through an exit shoot that has been designed to ensure the free-flow of these pebbles. After the pebbles are inspect remotely, then they are carried back to the top and then fed in individually back to the top of the reactor, where I am led to believe that they form a type of cone or, like if you were piling up a pile of sand, how it would flow from the top, into the top.

As each pebble is removed from the bottom, it allows the pebbles above to flow down through the reactor. There have been many studies done on this of simulated pebbles, also with modeling of pebble flow through a reactor to show how this flow would occur and the uniformity of that flow through the reactor, through the operating experience with previous reactors that are operated, which did have some issues. For example, one that many people may be aware of in some of the early designs, the control rods were inserted into the bed of pebbles. This ended up causing problems that were not foreseen with the control rods actually damaging the pebbles as they were inserted and withdrawn and reinserted into the bed of pebbles.

So new designs have those control rods in the graphite block structure on the outside. A lot of studies done, and more studies hopefully in the future to show how pebble burnup occurs as either instrumented pebbles or pebbles that are uniquely identified so that they can be looked at before they go in and as they come out to see what the exact fate of these pebbles are as they go through the bed, which I know for many people is a concern.

The next question I see is about what range of pressures are built up on the inside of the pebbles?

I would need to have a fuel expert comment on this to give a specific about what that range of pressures are. My understanding is, though, however, it is fairly high, which gives credence to the robustness of the silicon carbide layer within the TRISO particle, that there is pressure buildup, there is a lot of internal – I don't know that damage is the correct word – but internal change of the structure in the particle within that silicon carbide structure because of the environment that exists in there after operation. So, Tim, we will take that question and see if we can get an answer back to you specifically on that of where you can find out more about that topic.

Just a comment on some additional information that is available. Every two years since I think around 2002, maybe earlier, there has been a High Temperature Reactor International Congress that has met. It met most recently this past November, and the amount of information that is available and being shared at those conferences is immense, and it really does speak to the amount of research that's being done worldwide on high temperature reactors, both the potential uses. I meant to comment on the fact that when we looked at the operation of the HTTR in Japan and the HTR-10 in China that I think those would be great follow-up topics for additional webinars about operating experience.

We had a wonderful session at the HRT-16 conference on the commissioning and startup experience with the THTR in Germany, and from someone who was there, who actually did that, and what the lessons learned were. Those lessons learned are fully applicable to future high temperature reactor commissioning and startup and learning from the successes and the unexpected occurrences that occurred there. But overall, the message was, it worked very much as expected and was a very safe reactor to operate. But those presentations can be obtained to look at that material from previous HTR conferences.

Oates: You can have a scroll bar that will allow you to scroll down and see the additional questions that are coming in.

Singer: I am missing the additional questions. Oh, okay, sorry.

Oates: I was going to say, no problem. Do you see one from James Cherniack?

Singer: Yes, I do. So the question is, how do the fission products differ and their production rate differ from a light water reactor?

Again, I think a fuels expert could give a much better answer than I can, but my understanding is, these are both thermal reactors, thermal spectrum reactors. They are both using a UO2 fuel, so I think the types of fission products generated would be the same. The production rate would I think only differ in the reactor power level experienced within the reactor, so I think that would be the only difference in the rate of production would be what power you are operating at or the specific power within the fuel element at any particular point.

So again, I would be almost certain that the types of fission products would be the same. The rate, I would have to check on that and get back to you on that if there is any significant difference there.

Okay, now I see more questions.

Ah, the core coolant flow velocity. [*laughs*]

Things I maybe should know, but I don't. I apologize, Mr. Quincey. I will have to take that as a lookup.

Let's see the next one. From Tim Welty, do you have a sense of the NRC's view toward licensing reactors based on this technology?

A very good question and thank you. We did have an extensive program in the US Next Generation Nuclear Plant program to develop a licensing framework for specifically the NGNP design working with the NRC staff very heavily from 2008 through 2012 timeframe before our DOE program shifted over to a more broad-based Advanced Reactor Regulatory Framework development program which addresses all types of advanced reactors, but that really did build on the successes that we had with working with the NRC and the NRC staff in particular towards licensing these reactors.

We had some major questions that were spelled out in a licensing strategy that was jointly prepared by DOE and the NRC in 2008, and made a lot of progress I believe towards answering those questions and preparing white papers, preparing our positions on that, which were presented to the ACRS, the Advisory Committee on Reactor Safeguards, for the NRC, and I believe the overall conclusion of those discussions were that the licensing basis that was being put forward for this concept was reasonable, and it was, it made a lot of sense to them. They saw how it could be done.

They held back on giving a full endorsement until they actually saw an actual design come in that would be licensed. So I believe that their view toward licensing the reactor is, they are very openminded on this and they see the need to move forward with this. They are now awaiting and we are continuing to work with them toward bringing forward a design that will be one that they can actually examine in a real sense as their specific questions about a specific design and move that design towards licensing.

Let's see. The next question from Sven Bader. Can you provide some background on why all the high temperature gas power reactors are shut down, why no new high temperature gas reactor power reactors have been built, only research reactors, and will the advances overcome the reasons for the shutdowns, including addressing cost?

Again, a very good overview type of question.

Specifically, the power reactors were built because of the competition and the simplicity of the predominant reactor being licensed on the market, which was a light water reactor at the time. Granted that a high temperature gas reactor, its primary economic incentive is not for electricity production, which is why at the time vendors and utilities were purchasing nuclear reactors was primarily for electricity production. It is only that now, after we are finding the attractiveness of the high temperature gas reactor for producing process heat, as I said before, a huge market for process heat and process steam at 600°C or below that cannot be provided by light water reactors but can be provided by existing designs for high temperature gas reactors, is there seen to be a market for this.

But, the big but is that market is currently dominated by cheap natural gas. So it really does come to economics at this time.

So there were also in the history, and it's a very interesting history of those specific reactors, and the design flaws that were found with those, in Fort St. Vrain, problems with steam driven circulators which introduced moisture into the reactor system, which now we've seen as a design flaw, that would not be occurring today in new designs which have closed induction driven circulators and they are cooled by the helium coolant inside and do not need, or do not provide any pathway for moisture ingress into the reactor.

And there were other issues that have been addressed by operating experience and by advances in designs. Your question is why have only research reactors been built, and in this case the purpose of those research reactors both in Japan and in China were specifically as prototypes of a scale reactor, a demonstration, and a commercial reactor to be built in the future to be able to demonstrate and prove the characteristics of these reactors.

So I think your two-part question, were there reasons for the shutdown? Yes. Have these been addressed? And I would say yes.

The cost issue, it will still be a while between when we do first-of-a-kind design until we have Nth of a kind to know exactly what the cost range is for these reactors. We can predict that, and we know today that they are expected to be expensive reactors, but the value of them comes in being able to replace carbon emissions and to provide a very reliable source of power for industry that is not driven so much by market variability as by the availability of a very reliable reactor source of power.

So, I'll make sure I didn't miss a question.

Silicon carbide from Dusan. Is silicon carbide also made by carbon vapor deposition as a pyrolytic carbide?

Yes. All of these layers, this is concerning the TRISO coating layers on the TRISO particle. Those are all deposited by carbon vapor, I mean, not carbon, vapor deposition onto the kernel. The three layers are done separately in a vapor deposition chamber that has been designed and operated.

And the adjoining question, is the silicon carbide layer also made by vapor deposition? And yes, that's a good question. Yes, they are all done by vapor deposition.

And thank you for your backup comment, Tim.

Licensing lessons learned from Peach Bottom and Fort St. Vrain. That question is hard to keep on the screen. I think I missed one of the questions. Berta, maybe you had combined it or something.

But I see one from Peter Hastings: regarding Mr. Welty's question about licensing – as information, there's also a technology-inclusive effort currently underway to develop the NGNP effort further with the goal of establishing risk-informed, performance-based…

Oates: Actually, I'm having some… I don't know if they are connectivity issues, but my keyboard is not able to interact with the pods. So I’m not able to scroll through these questions and help you. Amanda, if you have functionality, can you…? In order to do posting the questions so that all participants can read them, we need to put a period and then reply all. For some reason my keyboard won't interact with the mouse. I'm going to refresh, but it will disconnect me for just a minute.

Spring: As soon as I try to scroll to the bottom of the question, it goes off my screen. Let me see if I can enlarge my box at all.

Paviet: Also me. I cannot read the entire question.

Oates: Amanda, can you resize the… There we go, resize those pods so that we can expand the Q&A pod? Maybe shrink that note pod size up a little bit?

Spring: Oh, here we go. Okay. As I was saying, there's a technology-inclusive effort currently underway to develop the NGNP effort further with the goal of establishing a risk-informed, performance-based, and technology-inclusive regulatory framework for non-light water reactors. The NGNP work is an invaluable point of departure for that…

And this is, as I mentioned, coming right on the heels of work we did for NGNP we started on the Advanced Reactor Regulatory Framework work for all non-LWRs.

…NRC has expressed support for this effort, which is being developed as an industry-led initiative in coordination with NEI and DOE.

And it said, Amanda, was there something more there, Amanda? Okay, so we've addressed that.

So from Kihong Kim, two questions. Is there any provision for preventing a fire accident in the carbon moderator? And second, how much is the probability of the fire accident with carbon as a moderator in a high temperature environment?

And I’m glad someone broached this. This is something that we all in this community need to take a hard look at and spread an understanding of this.

The carbon moderator, which is a graphite moderator, it has been shown, there have been studies across the world, that graphite, and in particular pure carbon, does not burn. There is not a chance of fire. There is a lot of misinformation which came out of reports from the Chernobyl accident about graphite burning. It has been shown without any question that what was burning at Chernobyl was the fuel itself. The fire was in the fuel and not in the graphite that was there. We have, you can see videos and discussions from graphite manufacturers where the graphite as it is manufactured, the large blocks of graphite come out of the forming furnace white hot, white hot, into an air environment to cool. There is some oxidation on the outside of the graphite but very minor. And there is not a possibility for fire.

We've also examined the possibility of a dust conflagration, whether the graphite that builds up in the reactor in the form of dust would burn. It will not. There have been multiple experiments to try to initiate a dust explosion like happens, say, in a flour mill or a sugar mill, where a combustible dust will conflagrate. That will not happen with a graphite dust.

So the question of how much is the probability of a fire accident with carbon as a moderator in a very high temperature environment, I think in our conclusion in our studies we have a white paper that discusses this carefully, that the probability is, it's a nearly incredible accident. The only way to get such an oxidation accident, and it would not be a fire, it would just be a really long extensive oxidation of the graphite, would be a double-ended break in the primary containment, where you had a source of air or oxygen entering at one point in the primary circuit and then being allowed to have what they call the chimney effect through the core where the air flows through the core and allows a continuous oxidation of the graphite moderator around the particles. Even in that case, there is significant doubt that there would be any damage to the particles themselves, but this is something that really needs to be looked into and the information needs to be spread on the correct information, and whatever misconceptions that are out there regarding that need to be corrected as this is a very serious question and a very serious question in the minds of many over time about safety in this reactor.

I apologize I didn't address it directly in my presentation because for the designers, for the safety experts on this reactor, it is not a credible accident. It is not a credible issue. And thank you, Dusan, for correcting me, chemical vapor deposition. I was failing open on what the C stood for there for a moment. A very common process in metals manufacturing. Again we were talking about the manufacturing of the particles using chemical vapor deposition of the materials, the pyrolytic carbon and the silicon carbine onto the kernels to be able to form those TRISO, and I don't think I've actually said the word yet, it's tri-isotropic-carbon particles, TRISO.

So from Sven Bader, neither prismatic nor pebble bed fuel appears to be as easily recycled as LWR fuel, is there any merit to recycling this used or spent fuel? If not, how is this fuel to be interim stored and disposed of?

Another very good question and things that are being looked at by various groups around the world on that topic. I think you are correct to say that it is as not as easily recycled as LWR fuel because of the varying components that are in the fuel.

The merit to recycling the used or spent fuel, I think what is being looked at first off, right now, is the graphite that is used in these cores, both the structural graphite and the graphite in the fuel compacts or in the fuel pebbles, a lot of study done on this by a project in Europe sponsored by the European Union to look at recycling the large amounts of graphite, used graphite, that would become available should this technology go widespread. So that would be a very good merit to recycling that, again, economically, to discuss the merits of using that recycled material versus the cost or expense of disposing of it as a spent fuel product.

The second part of the question, if not, how is the fuel to be interim stored and disposed of? I think what is being proposed in most all cases I'm aware of are air-cooled canisters and air-cooled storage facilities for these fuel elements after they are used.

One other note on this, related to this topic, the difference in burnup is significant between LWR fuel and HTGR TRISO fuel, so that is another aspect of this that needs to be figured into the comparison between LWR used fuel and HTGR used fuel is the amount of burnup that occurs of the fuel material, the fuel energy available in this fuel during operation over its life.

So from Dusan Kicevic again, what would be a waste management issue in this technology?

I think we were just talking about that. The waste management issue would be in the fuel and looking at the long-term fate of this fuel afterwards. The structural components after decommissioning of these reactors would be a waste issue. There is always with any manufacturing a waste issue with the components used, the chemicals used in manufacturing the fuel. I think at this point that is a topic that I personally have not spent a lot of time with, but I'm sure that people who are looking at the lifecycle cost, the issue of looking at commercializing these reactors, they are taking that into account. We will hopefully be able to find some more information on that for you. Thank you for that question.

I see the note from Michael (Pimentel). Thank you. Thank you for your attendance also.

Were there any other questions? Amanda or Berta, do you see anymore that I've missed?

Oates: I'm not seeing any additional questions. So thank you, everyone, for your participation in such an engaging set of quick Q&A. It's always delightful to be on this side of it and know that there's enough interest to participate in approximately 30 minutes of question and answer. That's fabulous.

Spring: So one last question that came in is the presence of Wigner energy in the graphite core, referring to the energy that gets stored up in the graphite structure and has to be released through thermal release of this.

That is being studied, the effect of that, and where the flux and the operating characteristics are for these reactors, where we prevent that, and prevent that from becoming a problem over core life, understanding what the core life is.

Another question from Scott Telofski is, is the uranium enrichment the same as for a LWR?

Current designs are being made to use LEU, low enriched uranium fuel.

Okay, anymore? All right, and I did include my email in the presentation if anyone has any follow-up questions that come to you. Every question is a good question if we can help spread more information about this design. There are many companies that are interested in commercializing it. The goal now is to help them, as someone highlighted, reduce the costs and to develop or reduce the licensing risks for this so that investors will have the incentive to move forward with putting these reactors into the marketplace and being able to prove the value that they propose.

Thanks, everyone.

Oates: Thank you, Carl. It's a very engaging and interesting topic of conversation. We look forward to everyone joining the next presentation on the 22 February. Have a great day.