Gas Cooled Fast Reactors
Dr. Alfredo Vasile, CEA, France

Berta Oates: …your screen. There's just a couple of things to cover. In the Q&A pod, you can enter your questions. Just type them in and we will address questions at the end of today's presentation as time permits. So hopefully, you can see the two comments about the audio, and please type your questions here.

In the Files pod, you can click the file that's there. That is a PDF copy of today's presentation slides you can download directly to your computers.

And last but not least, in the Notes pod is a link to an online survey. We do appreciate your input and feedback and welcome your participation in that survey regarding today's presentation. That helps us continually improve our webinar presentations, know what we're doing right and what you'd like to see in other presentations in the future.

So with that little bit of housekeeping, I think we're about ready to get started.

Doing today's introduction is Dr. Patricia Paviet. Patricia is the Director of the Office of Materials and Chemical Technologies within DOE, Office of Nuclear Energy. She is also the Chair of the GIF Education and Training Task Force. Patricia?

Patricia Paviet: Yes. Good morning, everybody. It's my pleasure to introduce Dr. Alfredo Vasile this morning from the Commissariat à l'énergie atomique et aux Énergies Alternatives. He obtained his master's in physics at the Balseiro Institute in Argentina and his Doctor on Nuclear Engineering degree at the Grenoble University in France in 1977.

He joined CEA in 1981 working at RAPSODIE sodium cooled experimental fast reactor at Cadarache. He held laboratory head positions on core physics and safety studies both for light water reactors and fast reactors.

Dr. Vasile participated at the Gen IV Roadmap definition process as a member of the Light Water Reactors Technical Group and was the French representative of the INPRO Steering Technical Committee for the Joint Study on Closed Nuclear Fuel Cycle with Fast Reactors.

He is presently the Project Manager of the ESNII Plus European Project on fast reactors, the French Representative at the IAEA Technical Working Group on Fast Reactors, the GIF GFR Steering Committee, GIF GFR Conceptual Design and Safety, and the GIF SFR Safety and Operation Project Management Boards. He is the CEA Representative for the ALLEGRO GFR experimental reactor project.

So it's a great pleasure to have you, Alfredo, with us, and without any delay, I give you the floor.

Alfredo Vasile: Thank you. Thank you very much for this introduction and for giving me the opportunity to speak about the gas cooled fast reactors.

The outline of my presentation, we first go through the motivation for the development of gas cooled fast reactors, and then let's go to the past to have an historical perspective of what was done in the past in different countries to come back to the present projects that are being developed in different work of Generation IV.

We will focus then on the performance requirements for this type of system and the R&D needed for such development, knowing that the specific challenges for these systems are focused on the core and fuel, the decay heat removal issues, and on the materials. So then we will move to the conclusions.

So what is the rationale for having gas cooled fast reactors?

First of all, GFRs are fast reactors; that means a closed fuel cycle, and we know that they are needed for the sustainability of nuclear power. That means by closing the fuel cycle, we use more efficiently the fuel, the natural resources, the fissionable natural resources. And on the other hand, we have the possibility to reduce the volumes and radiotoxicity of high-level nuclear waste through the transmutation that is possible in this kind of reactor.

Gas cooled fast reactors have some favorable features linked, first, to the coolant. Helium is chemically inert. It's a very stable nucleus. The void coefficient for the helium coolant for fast reactors is small but still positive. You know, in lead or especially in sodium cooled fast reactors, this is an issue. The single phase coolant eliminates boiling. There is no difficulty with boiling due to the fact that this is a gaseous system. Helium is optically transparent. That is a positive for the operator and for the inspection, service, repair, and operating of the reactor. And last, a very important thing is that the helium coolant or the gas cooled fast reactors in general allow for high temperatures, and this means increased thermal efficiency for economic benefits and allows industrial applications of such high temperatures.

I had some delay on the change on the slides. Sorry for that. But gas cooled fast reactors have some drawbacks that need to be addressed. Typically, gaseous coolants have small thermal inertia; that means that they have a fast heat-up of the core in case of loss of forced cooling. And we need to have a pressurized system, even at normal operation, so it's roughly in the range of 7 MPa, and the low thermal inertia of the core makes difficult the decay heat removal. Of course we related to the HTR reactors, like high temperature reactors, which have a huge amount of graphite in the core that increases the thermal inertia. This is not the case for GFRs. It's not possible to use such graphite for thermalization of the neutrons.

So the motivation for the development of this kind of reactor is two-fold: it's to enhance safety and to improve the performance of the reactor.

Let's have a look at the past projects. I want to say that there were a lot, several projects in the past in different countries and international cooperation, but a reactor never was built. That means there is no operating experience on gas cooled fast reactors in the world for the moment.

Let's start with the US General Atomics project on the GCFR program, which was started in the 1960s using the technology of HTR known at that time, and on the Peach Bottom and Fort St. Vrain, in particular. This is a program that was funded by the US DOE with some collaboration with European partners.

At that time, the design, it was based on a multi-cavity pre-stressed concrete pressure vessel. We will see later why this concrete pressure vessel is needed. And using a vented fuel pin to allow high burnup. So the general pitch of this reactor is on the next slide.

This one. You see the core of the reactor, the main component is the generator inside the main vessel and surrounded by a pre-stressed concrete vessel to avoid strong depressurization in case of loss of coolant accidents.

On the next slide, we see the German Gas Breeder Memorandum in the front of this, a memorandum from 1969. Two German centers were involved in such research. It was Karlsruhe and Jülich with some industrial partners. It was basically based on different... Three concepts were developed at that time with helium as a coolant. The fuel assemblies were using the same type of sodium cooled fast reactors which were developed in Germany at that time in parallel.

So again, prestressed concrete pressure vessels were used and the steam cycle coupled with the primary circuit. Some work was carried out on coated particle fuels and direct cycle power cycles to increase the efficiency.

Another European project was the Gas Breeder Reactor Association from 1970 to 1981. So some European organization joined this association and they developed four different concepts, GBR-1 to 4, but the range of power was around 1000 MWe, helium cooled and CO2 cooled. The last one used metallic clad fuel pins in spacer grids, and some improvements were made at that time on the design of the fuel for increased the heat exchangers by the ribbed surfaces on the cladding.

You can see in the next picture some design of the GBR-2, GBR-3. This is the fuel of the different reactors with the helium. You see the pin bundles here. And the general layout of BGR-4 when again we have the core in the center and the main components like heat exchangers and some blowers surrounded by a cavity to keep the pressure as high as possible in case of depressurization develops a lot of coolant accidents.

On the next slide, the UK ETGBR/EGCR from 1970 to 1990, it was based on the UK Advanced Gas cooled thermal spectrum, neutron spectrum reactor architecture. It used a metallic-clad fuel, carbon dioxide coolant, CO_2, and again, a prestressed concrete pressure vessel around the main vessel.

Finally, on the next slide, we see some picture of the fuel developed by the Japanese from the '60s to 2010. A block type fuel containing coated particles were studied in a solid matrix of silicon carbide. And the fuel was very close to the fuel used for the GBR-2 European project previously presented.

Then, let's move to the next one, which is about the present situation. You know, in the Generation IV initiative that identifies a renewal of interest in fast reactors for sustainability, waste minimization, and non-electricity applications, six systems were selected, and three of them were of fast reactors, with a fourth one which is the molten salt, which has the option for fast spectrum reactors.

So if we look at the different systems selected by the Generation IV on the next, you see that for the GFR here, gas cooled fast reactor, the partners involved in the development of these systems are France, Japan, and Euratom, and the US is associated with these development as an observer for the moment through their participation in the Conceptual Design and Safety Project with a contribution from General Atomics around the EM2 project we will see later.

On the next slide, the main characteristics of such a reactor taken as a reference on GIF is 600 MWth, 48% net efficiency. The range of temperature you see is 850 °. The temperature, this is what is a very interesting characteristic for high efficiency and other applications of feed. 9 MPa, this is the pressure in the primer in the circuit. And the average power density is 100 MWth/m3 in the core, and this must be compared for example with the HTR.

HTR typical values are in the range of 5 to 10, let's say, but this is more than ten times higher. This is why we will see later that this day heat removal in accidental conditions is a challenging aspect. Compared to sodium, let's say that this is lower values because sodium is in the range of 200 to 300 MW/m3.

The reference fuel, and this is the characteristic of this type of reactor, is uranium plutonium carbide with a cladding of silicon carbide. We will see later how is the aspect of this fuel. This is of course a ceramic fuel, a refractory fuel, high temperature resistance.

The burnups, the conversion ratio is self-sufficient. That means we are not targeting the breeding in this kind of reactor, and the burnup is 5% fissionate initial metal atoms and 60 dpa, 60 displacements per atom.

On the next slide...

Oates: Alfredo?

Vasile: Yes?

Oates: Can you speak a little louder, please?

Vasile: Oh, yes. Is that better now?

Oates: Thank you.

Vasile: Okay. Of course this system is high temperature, inert coolant, and of course it's fast neutrons for a closed fuel cycle, we already mentioned. For the sustainability purposes of the Gen IV option, high temperature and non-electrical applications, for other industrial applications.

The helium allows now a very interesting coolant to avoid material corrosion on the structures, but it requires the development of very advanced materials and fuels, so they keep the technical focus for the development of such reactors on the carbide, silicone carbine cladding fuel, the high temperature components and materials, and the decay heat removal in accidental conditions. These are the challenging issues that must be faced for the development of these reactors.

On the next slide, we see the general layout of a 2400 MWth on the indirect-cycle GRF which was developed at CEA last year. And we see again in this reactor the main components here, the primary vessel and the heat exchangers and the blowers. Here we see the decay heat removal loops that are surrounded by a guard vessel. In this case, it's not concrete but it is a metallic guard vessel, again, to have a backup pressure in case of depressurization of the primary circuit as high as possible to operate in natural convection and to remove the decay heat.

On the next slide, we see the performance requirements for the design of these reactors. As I mentioned, self-generation of plutonium in the core, no fertile blankets to limit the proliferation risk, limit the mass of plutonium involved in the core, are loaded in the core, to facilitate the industrial deployment of a fleet in case of... Of course these parameters are strongly linked to the speed at what we need to deploy such reactors in the future in an industrial base.

The ability to transmute long-lived nuclear waste resulting from spent fuel recycling, without lowering the overall performance of the system. We need to improve the favorable economics owing to a high thermal efficiency and diverse non-electricity issues on high-quality heat.

So the proposed safety architecture must fit with the objectives considering the control of reactivity by limiting the reactivity swing over the operating cycle. In case of some specific transients, like the control rod withdrawal, is strongly linked to the radioactivity swing during the cycle because the controls are inserted in the core so much.

We need to design cores with a reduced coolant void reactivity. That is easier for heating that, the sodium for example. And we need to have the capacity of the system to cool the core in all postulated situations, provision of different systems, redundancy and diversification, to face the drawbacks of these concepts linked to the low thermal inertia. And the refractory fuel element is capable of withstanding very high temperatures, robustness of the first barrier and confinement of radioactive materials.

On the next slide, we see the challenges linked to the core and fuel. The greatest challenge of course is to develop a robust high temperature, high power density refractory fuels and core structural materials. It must be capable of withstanding the in-core thermal, mechanical, and radiation environment. And safety and economic considerations demand a low core pressure drop, which favors high coolant volume fractions. This is in particular to this point linked to the ability of the core to operate in the natural convection in accidental conditions. We need to reduce such pressure loss in the core for low-flow regimes.

And again, related to the specifications we mentioned before, the minimization of the plutonium inventory leads to a demand on high fissile material volume fractions. So these two, these two requirements, are somewhat contradictory, so we need to make a compromise in between to answer the two requirements.

The candidates that were considered for these fuels include carbides, nitrides, as well as oxide, but today, the reference fuel is on carbide. And the preferred cladding materials are silicon carbide and silicone carbine fibers.

And the next slide, we can go back to the materials and components and helium technology challenges. Some characteristics of the systems, we have high temperature corrosion resistance, we need corrosion resistant materials on the cooling circuit, heat exchanger, insulation, sealings, and a relatively high pressure in the primary circuit related to highly efficient circulators. This is of course to avoid high power on the blowers, on the circulators. We need to increase the helium density and to have high pressure in the primary circuit.

The design of the core must take into account issues we already mentioned related to the lack of inertia and the high power density.

We will face relatively high temperature non-uniformities along the fuel rods due to the specific configuration and the transfer coefficient on the helium. We face of course the difficulties related to the decay heat removal in the LOCA and the lack of electrical sources. The high coolant velocity in the core can produce some vibrations and several meters per second, and it must be considered also in the design of the core. And finally, some helium related technologies from the system will link to the leakage, the sealings, the helium recycle if possible, and the helium chemistry control.

On the next slide, a view of a typical fuel. We have here a core, which has two zones here, the internal zone with a lower plutonium content and an external zone with a higher plutonium content to have a profile of power as flat as possible, and the control rods. And we have a fuel assembly and what I wanted to show you is this design of the pin. We see the carbide fuel, uranium plutonium carbide in the center in red, and surrounded by a cladding on silicon carbide and silicon carbide fibers to increase the mechanical resistance. And for the tightness of such a pin, we need to add some liner in between the cladding and the pins. In this case we have a liner here of tungsten and rhenium to increase the tightness.

The next slide is devoted to the decay heat removal issue. You know, we already mentioned that the high temperature reactors can rely on the conduction cool-down, but this doesn't work for GFRs. Why? We can see on the next slide a picture we can understand very easily where we see here in red the volume or the core of the GT-MHR, 600 MWth core, surrounded by graphite blocks that makes the big thermal inertia of the whole system compared to a much smaller core with a high power density here in the red in the center, this is the core of the GFR 2400 MWth. So it's clear the decay heat removal will be much easier in the case of the HTR reactor related to the GFR.

So let's come back to the previous slide. We see that for that we need to design very efficient decay heat removal systems, allowing to operate in natural convection. So a convective flow of course is needed in the core at all times. When the transient concern pressurized conditions, that means no lock and no loss of coolant action, the natural convection can be efficient enough. The difficulties arrive when we have LOCA and loss of electrical sources, so under depressurized conditions the challenges are that the efficiency of the natural convection will lower due to the low gas density and so we need power requirements for the blower, very large at low pressure, and the backup pressure, the guard vessel, is needed. That's why a guard vessel or a close containment is needed around the primary circuit to avoid too a high decrease of the pressure and to keep the helium at enough density.

The primary circuit must be reconfigured to allow decay heat removal. We see in the next slide, the next one, this one, this is the primary circuit in the normal operation with the core, the primary vessel, and the heat exchanger, the blower here, the main circulator, and this is the operation in normal conditions with the hot helium in the center, going through the heat exchanger, coming back to the vessel. In accidental conditions, in decay heat removal conditions, the reactor must operate using this decay heat removal system here, which is connected, it's another view here, the primary heat decay heat removal system, with a primary loop connected directly with helium on the primary, on the right of the pressure vessel, a secondary loop on water, for example, a link to the water pool to remove the heat.

That means that a transition from forced convection to natural convection in accidental conditions needs the closure of this valve here, this is a check valve, and the opening of this check valve here to change the flow path of helium in this case.

On the next slide, we come back to another of the challenges for the development of this type of reactor, which is the materials, related to the materials. Of course, the materials issue for fast reactors has some common issues with other fast reactors, the link to the high temperature, the high dose, the neutron dose, and for the gas cooled fast reactors, the temperatures as we saw already are a little bit higher, but the doses are also relatively high.

So the design of the components for long-term aging, 60 years, of course the industrial feasibility, manufacturability, weldability, the environmental effects, impure helium compatibility on oxidation, fatigue, fatigue crack growth at very high temperatures, including accidental conditions, must be taken into account.

The tensile and very long term creep and creep-rupture properties of the plate, forging, weldments, and heat-affected zones of this class of materials in operating in high temperature, and high temperature bolting.

So the candidate materials today for the pressure vessel, we are summarizing here, but the reference material is 316LN stainless steel.

On the next slide, we see that the requirements for the components mainly, high thermomechanical resistance with high temperatures, good mechanical properties for such extreme environments, and again, industrial feasibility. The intermediate heat exchange, it is a very important component and (not) need to have high efficiency, 95%, and low pressure drop, no leakage easy to inspect.

The thermal insulation, the sealing materials, they need to develop to isolate the hot to the cold parts of the different circuits with different candidate materials we can see here for such isolation materials.

Finally, I want to recall some main programs, international programs in the European framework. We have the JPNM, Nuclear Materials Joint Network or joint platform. It's working on regulatory and codification requirements and development of codes, norms and methods, also component design, testing and fabrication issues, irradiation damage on different materials for different components. Addressing also corrosion, oxidation, erosion resistance of such selected materials for long term exposure tests. Thermal aging and thermal shock degradation of fuel. Design and modeling work has been carried out also on using mechanical properties. And material qualifications and development on ferritic-martensitic steels, high temperature materials, nickel alloys, and ceramics.

So now I want to go to the main projects that have been developed today. One is the ALLEGRO project, which is one of the three fast reactors supported by the European Sustainable Nuclear Industrial Initiative. ALLEGRO, ASTRID for sodium, and ALFRED for the lead cooled fast reactor. ALLEGRO is an experimental reactor that has been developed in the framework of the consortium V4G4, Visegrad four countries Generation IV, including Czech Republic, Hungary, Poland, and Slovakia, and associated with France as an associated member of this consortium.

The reference is to build the reactor in Slovakia.

On the next slide are some main features of ALLEGRO. We can see here the main vessel. The three decay heat removal systems and two main primary loops with an additional loop to test high temperature components.

The main circuits, on the next slide, the main circuits... Sorry, the objective of the reactor is a demonstration of key GFR technologies, the core behavior and control, the development of ceramic fuels. I will show you some description of the core to such development, and the development of helium circuits and components and related technologies to address the issue of the decay heat removal.

ALLEGRO will have a fast neutron irradiation capacity, and the potential, as I already showed, for coupling with high temperature components for direct use of heat. And the development of safety standards for GFR, which don't exist today.

On the next slide, we see the main characteristics of the reactor is 75 MWth, no electricity production. The primary helium in the range of temperatures with an outlet temperature of 530 roughly and 7 MPa, 70 bars, pressurized primary circuit with two secondary pressured water loops with an option for an additional high temperature gas loop, as I showed here. The secondary loops, we are looking at the possibility to have also other possibilities than water, that can be another gas, a mixture of gases in these secondary loops.

And the tertiary is the atmospheric air with water/air heat exchangers. So we have three decay heat more loops represented here. And again, all these primary components are included in the guard vessel here than can allow to improve the behavior in case of depressurization on the primary circuit.

In addition to this decay heat removal system we have for the reference design today a safety injection system to have a safety injection of a heavy gas in case of LOCA.

So on the next slide, we have a picture of the core. It's roughly 80 subassemblies here in yellow that the reference is the MOX subassemblies for the first cores, and we have six positions here in red for the irradiation of experimental ceramic subassemblies for the development of the reference fuels for GFRs. Presently, we are looking at the possibility of using not a MOX fuel but a uranium enriched fuel with an enrichment lower than 20% because it's not really needed to have a plutonium load in the first core to the development of the reference GFR fuels.

So this is the range of temperatures that we've seen. When the ALLEGRO core will be loaded with ceramic fuels, we will be able to raise the outer temperature of the helium on the core up to 850°.

This is a picture of the standard fuel. Concerning the reactivity control, the reactor, the core has six control and shutdown devices and four diverse shutdown devices. Each control rod and shutdown device is individually driven. A particular characteristic of this type of reactor is the control rods are inserted on the bottom, from the bottom of the reactor vessel.

So on the next slide, again, we see the principles for the decay heat removal system. We have the same primary and main decay heat removal system connected to a pool with three different decay heat removal loops, and of course they are situated above the core to facilitate the natural helium circulation and decay removal can operate in forced and natural circulation if the decay heat removal blowers are not available.

On the next slide, some words about another project of GFR today by General Atomics which is the EM2; that means the energy multiply module, which is a reactor that combines the advanced fuel and cladding to be really revolutionary instead of incremental advances, related to present reactors.

Another main characteristic of these reactors is that is being designed to have a long life cycle, fuel cycle, at least 20 years' life; that's why it is needed to design a vented fuel, that means to remove the fission gases, fission ??? for the fuel pins during the operation. So the higher temperatures also, all of the GFRs allow a process for heat applications and increased thermal efficiency for economic aspects.

So the components take advantage of the advanced materials, again, silicon carbide, silicon carbide cladding, high uranium-bearing fuels, even if other options for the fuel are being considered at the same time by General Atomics.

On the next slide we see a view of the core of EM2, which we see here, the fuel in the center and the control systems are around the core, and a tri-bundle assembly with a typical hexagonal configuration with 91 rows per bundle, and the fuel pin here, uranium carbide fuel pin with a center hole pellet in silicon carbide cladding.

So now we can move to the general conclusions of what we see. Today the GFR concept is attractive as it avoids the coolant related issues associated with liquid metal coolant fast reactors. Helium is chemically inert. It has excellent nuclear stability, no activation. It's a coolant that is transparent, that is easy for inspection and repair and operation, fuel handling, and so on. And it offers a high temperature heat source possibility for high efficiency electricity generation and high quality process heat.

But of course we mention the main technical challenges of this type of reactor are linked to the high temperature and high power density. We need to develop high resistance fuels and robust decay heat removal systems and the materials associated with the design of the reactor.

So thank you very much for your attention, and I will try to answer your questions now.

Oates: Thank you, Dr. Vasile. You have a Q&A pod where you can type in your questions for today's presenter, and while you're doing that and those are coming in, let's just take a look at the upcoming webinar presentations as part of the Gen IV International Forum.

On 28th March, there will be a presentation by Dr. Laurence Leung from CNL, Canada, on supercritical water reactors. In April, there will be a presentation on Molten Salt Reactors by Dr. Elsa Merle, France, and in May, Fluoride Cooled High Temperature Reactors by Prof. Per Peterson from UC Berkeley in the United States.

We appreciate everyone's attendance, and thank you again, Alfredo, for joining us from France this morning. I'm looking to see if I see questions. Okay, so, Alfredo, in the Q&A pod, there are two tabs. There is a question... Well, Roger has just made a notation of the way things are expressed on your slide. The silicon carbide might be better expressed as SiC fibers, so that is not to be confused with californium.

Vasile: Sorry, I don't see the question.

Oates: Do you see the Q&A pod?

Vasile: Yes.

Oates: When you roll over the icon there is a presenter view, and if you click on that, you can scroll down through the questions.

Vasile: Oh, yes. So, okay. The SiCf might be better expressed as SiC fibers in all cases as Cf is element symbol for californium. Okay. So, yes, the Cf doesn't mean californium but means carbide fibers. Okay.

Oates: So hopefully that's just clear in the context.

Vasile: Yes. Another question, so redundant decay heat removal systems are needed?

Yes, the answer is yes. Of course the safety architecture of all reactors needs, as I mentioned, redundancy needs doubling the system. It is true for the decay heat removal system. It is true for the control loads. And so that's why we need three, in the case of ALLEGRO we need three decay heat removal loops with each one of the three able to remove 100% of the decay heat at some hours of the beginning of the transit.

Another question, what about the use of CO_2 or nitrogen instead of cooling instead of helium?

Yes, of course, CO_2 was considered in some past projects. The advantage of helium is that it allows higher temperatures, and the disadvantage is that the leakage of helium is more difficult to manage, but finally, most of the reactors and most of the projects were based on the choice of helium.

How much operating/testing experience is there with SiC-SiCf cladding?

Yes, the projects that considered this silicon carbide and silicon carbide fiber cladding rely on the development and qualification, but there is no feedback from this. Some experience is already available through the projects like EM2 and a program is being built for the irradiation of such components and in reactors, not only gas cooled fast reactors but also in others to get more information about such cladding.

I have a question, are the GCFRs inherent safe? What about safety passive systems?

Well, the safety passive systems mean relying on, typically, for the question of decay heat removal, we must rely on natural convection, the decay heat removal systems are designed to operate in natural convection, and for the control of reactivity, the control rods should have additional passive systems that rely on passive features like a (Curie) point or other physical properties of materials to shut down the reactor in a safe way. Of course this is being considered from the beginning of the design.

I have a question of Dominic Napolitano: what is the timeframe and cost to build Allegro?

Well, for Allegro we are in the phase of what is called the preparatory phase. That means we are looking at the feasibility of the reactor with different options. We are looking at different nominal powers, different designs for the decay heat removal systems, and even for the fuel, as I mentioned, for the startup fuel. So we are in this phase until the middle of the '20s, 2025.

We don't have today a clear view of the cost of the reactor because too many options, design options, are still open.

I don't know if we have other questions… Yes, I have a question: can silicon carbide fiber cladding last for high burnups?

The burnup, the reference burnup, is around 5%, 5% FIMA. This is relatively low related to the experience gained on stainless steel for the sodium cooled fast reactors. Of course, the materials are different and we don't have experience of such 5% burnup for silicon carbide, but the dpa target is roughly around 60 dpa for such cladding.

What is the power density of these reactors at end of life when shut down? Important for decay heat system, especially since helium does not have high heat heat capacity.

At the end of life, when shut down, well, in fact, when I mentioned the power density 100 MW/m3, even if we are looking at different values, lower values in the range of 100 to 50, I am speaking about nominal conditions, so in the question, you are asking about when the reactor is shut down, that means the end of life and end of cycle, let's say, for a core, the decay heat is not so much affected by ???, so proportional to the power density at nominal conditions. So it's not a specific issue. Power decay heat is 7% at the beginning of the transient after the shutdown, and then it decreases very fast to some percent, 2, 3, 1%.

I have a question about, to what degree does the presence of carbon and the low atomic mass coolant degrade the neutron energy spectrum?

Yes, in fact, of course the gas cooled fast reactors, it's a compromise between the weight of the coolant and CO_2 or helium and the absorption of neutrons for such coolants, but there is no degradation of the energy spectrum. That means it is still a fast reactor, even if the spectrum isn't higher than that sodium fast reactor, due to the fact that the density of such coolants is so low that the absorption and the slowdown of neutrons are not so important.

I have another question: are there any issues related to the production and supply of the exotic materials of the reactor component materials?

Well, for the moment we have not identified such an issue on the production and supply of the materials that are considered for such reactors. I forgot to mention that of course the materials to be used in GFRs have several common points with the materials that have been used for the HDRs, so the experience gained from the programs related to HDR are applicable, partially at least, for the GFRs. So there is no identification of materials with such exotic material.

How will refueling be accomplished in a pressurized environment or will the reactor operate for 20 or 30 years and then be shut down?

No, all these projects consider of course refueling, and the refueling system, the refueling machine, should be connected to the primary vessel to be able to change the fuel assemblies under pressure conditions. So even if, for example, in the case of EM2, the fuel cycle is targeted around 20 years, that doesn't mean the life of the reactor is 20 years; it's just the fuel. That means it can be reloaded with another core.

A question about the vented fuel: how will the gaseous fission products be removed?

Yes, this is a system that is coupled online to the fuel assemblies to collect the fission products and to remove it from the pins, that is, a system that of course has the advantage to keep the pressure inside the pin at the acceptable values for a long period of operating of all the fuel, but it complicates the operation because of the additional systems that are added to the primary vessel.

How often will the reactor need to be refueled and how will that be done in a pressurized environment?

Well, in the case of ALLEGRO, we are looking at a fuel cycle of 660 full-power equivalent days. That means something in between two or four years without refueling. And as we already mentioned, that means that we need a fuel refueling machine connected to the primary vessel and under pressure.

Let me see if we have another… How long will the core have to be cooled before the entire core can be removed after 20 years?

Well, how long will the core have to be cooled…? The operation of refueling is like in other types of reactors of course. The refueling operation is a question of days. That means that after the shutdown, the design of the refueling machine must be done so that the decay of each individual fuel assembly is compatible with the design of the refueling machine with their own cooling system to allow such refueling in a reasonable time, that means some days.

I don't know if we have other questions. I don't see additional questions. I think I tried to show all the questions.

Oates: Yes, for now you've worked through the list of questions. If you have additional questions for Alfredo, please do type them in now. We'll just maybe hang on for half a second and see if other questions come in.

Again, thank you for putting together this presentation and sharing your expertise with us. I know that it is a little bit challenging given the time differences between here and France. I always want to make sure I thank Amanda for running the webinar scenes behind the scenes. She's the one who helps keeping the audio going and addressing people's questions, and I appreciate your help. It's always nice to have a second set of hands running these.

And Patricia, of course, thank you for your leadership in putting together all of these presentations.

Paviet: You're welcome, Berta. A pleasure.

Vasile: Anyway, thank you for your participation, and if you have additional questions in the next days or you feel that I didn't fully answer some of the questions, please send me an email. You have my email on the first page of the presentation. I will be happy to answer you.

Paviet: Thank you so much, Alfredo. We really appreciate your help in conducting this webinar. Thanks again.

Vasile: You're welcome.

Oates: Bye-bye.

Paviet: Bye, everybody. Bye-bye, Alfredo. Bye, Berta.

Oates: Bye.

Paviet: Bye, Amanda.

Vasile: Bye-bye. Thank you. Bye-bye.