Introduction to Nuclear Reactor Design
Dr. Claude Renault, CEA, France

Berta Oates
Hello, welcome everyone to the next Gen IV International forum webinar. Today's presentation is 'Introduction to Nuclear Reactor Design.' We appreciate your attendance very much. Before we get started, there is some housekeeping things I want to talk about. The Q&A pod, you can type your questions right into the pod and we will address those at the end. There are presentation slides available for your download in the presentation slide pod. If you just click that, it will allow you to download that PDF.

We appreciate your feedback and welcome your comments. There is a survey link in the notes pod and if you were willing to participate, I think there is about six short questions that gives us great feedback and helps us improve the presentations and lets us know the target on the material whether we are reaching our audience well. We appreciate your feedback very much. And with that, I think we will go ahead and get started.

The Director of Material and Chemical Technology for DOE Office of Nuclear Energy is Dr. Patricia Paviet. Patricia Paviet is also the Chair of the Education Task Force involved in bringing you these webinars. And without any further delay, I will let her do the introduction for today's speaker. Patricia.

Patricia Paviet
Yes, thank you so much Berta. Good morning everybody. It's my great pleasure to have you today participating in the Gen IV webinar series. It's going to be presented by Claude Renault. He has been working at *Commissariat à l'énergie atomique*, the French Alternative Energies and Atomic Energy Commission for more than 30 years in research and development as well as education and training. He is a senior expert at the CEA and a professor. In 2010, he joined the INSTN, the National Institute for Nuclear Science and Technology, where he is currently International Project Leader. His expertise and teaching experience mainly cover thermal-hydraulics, design and operation of nuclear reactors, including the different families of reactors, in particular the concepts of Gen IV.

Claude Renault came to CEA in 1984 in the development team of CATHARE, the reference CEA-EDF-AREVA-IRSN computer code for the simulation of accidental transients in Pressurized Water Reactors. He was subsequently responsible at national and international level for several R&D projects in the areas of severe accidents and nuclear fuel behavior.

Between 2001 and 2009, he was heavily involved in R&D programs devoted to future nuclear reactors. He intervened at the Directorate of Nuclear Energy in the definition and monitoring of research programs on the different concepts of 4th generation reactors. He chaired the Steering Committee of the Molten Salt Reactor in Gen IV.

So, it's my great pleasure to have Claude today. And Claude I give you the floor and I'm really happy that you could give this webinar. Thank you again Claude.

Claude Renault
Okay, thank you. Thank you very much, Patricia. I have subtitled the webinar, 'From neutron to Gen IV,' which is a rather ambitious program. Welcome to all of you. As a GIF initiative that led to reconsider some of the options adopted in the past and stimulated the investigation of new tracks for long-term sustainable nuclear energy. To better understand to what extent Generation IV reactors should be different and to recognize the main characteristics requires some basic knowledge in the fundamentals of nuclear reactor design. What is behind the terms criticality, breeding, fast, or thermal neutrons. How to select the ingredients, the coolants, the moderator, neutron spectrum, fuel materials, and composition. And how to choose the other combinations to design nuclear reactors in line with Generation IV criteria, in particular, sustainability. This is the objective of this rather technical webinar targeting civil society stakeholders. Please stay with us.

CP1, Chicago Pile-1 is known as the first nuclear pile. In December 1942, Enrico Fermi army led a group of scientists in initiating the first self-sustaining nuclear chain reaction of fission. After piling up bricks of uranium and graphite used as a moderator, they observed criticality, the progressive increase of neutron flux. The process was under control and was stopped very early after reaching a very small power level by inserting neutron absorbent into the system. That is for me the occasion to quote a number of technical terms to be known by the designer of a nuclear reactor, such as, chain reaction, fission, criticality, neutron, moderator, absorbent, and uranium, explanations are coming.

Ten years later, now the first nuclear electricity production dates back from 1951 with the EBR-1 reactor in USA at Idaho. It was a very low power reactor, only 200 kilowatt electrical. But something very peculiar is that EBR-1 was also the first fast neutron reactor. So, nuclear power was removed by a liquid mixture of sodium and potassium called NaK, molten ambient temperature acting as the coolant. The nuclear fuel was made of uranium at high enrichment. The process of plutonium formation, conversion of breeding was also demonstrated.

So, you can see that additional terms have appeared now, fast neutron, coolant, enrichment, plutonium, and breeding. So, that is for the future.

Let's be more technical now. Firstly, it must be clearly understood that the potential of nuclear energy is fantastic. The process by which nuclear energy is produced today is fission. And to give some orders of magnitudes, you can read that the burning of one ton of fossil oil produces 0.5 megawatt day. In comparison, the total fission of only 1 gram of uranium-235 produces 1 megawatt day, twice as much. But this is only 1 gram. So, this means that the energy potential of nuclear fission is 2 million times higher than fossil fuels like oil, gas, and coal. How to take the best advantage of this potential? This is actually the challenge proposed to nuclear designers. This is our challenge today.

The only resource that can directly be used for nuclear energy production is natural uranium. Natural uranium is made of so-called two isotopes, uranium-238 and uranium-235. They differ by the number of neutrons in the nucleus but have the same chemical behavior. Uranium-235, the single fissionable component of natural uranium only accounts for 0.7%; so, this is not a very good start for the story.

Nuclear fuel is basically a mixture of uranium-235 acting as a fissile material and uranium-238, a code filtering material. I will come back to it. It is possible under certain conditions to directly use natural uranium. However, more than 80% of reactors under operation today make use of enriched uranium. Enrichment is the process by which the fissile content is increased from 0.7% to the higher content. For PWRs, for example, the fissile uranium-235 fraction is between 3% to 4%.

As the figures on this slide show the configuration of nuclear fuel for PWRs, the fuel is made of uranium oxide pellets inserted into a zirconium metallic tube. The fuel element pellets plus tube or clad is called a fuel rod. About 50,000 of such fuel rods are assembled to form the core for PWR 1300 megawatt electrical.

Fission consists in splitting of heavy nuclei by neutrons, releasing both energy and free neutrons. Uranium-235 is a fissionable material, that is an isotope capable of undergoing fission after capturing a neutron. The fission of uranium-235 results in the generation of two fission fragments or fission products, for example krypton-92 and barium-141 as seen in the figure. Such fission fragments or fission products are unstable radioactive elements and should be considered as nuclear waste. Fission is also accompanied by the emission of several neutrons. The average number of neutrons produced new is between two and three.

All nuclear reactors use a chain reaction to induce the control rate of nuclear fission in fissile material. This process is possible because the number of neutrons produced per fission is greater than one.

In a nuclear reactor, another essential mechanism is competing with fission to absorb neutrons. This is called conversion or breeding, consisting of neutron capture by uranium-238 or U-238 nuclei. As a result, plutonium-239 or Pu-239 is produced. Pu-239, which does not exist naturally, is a very good fissile material.

So, to summarize, uranium-238 is called a fertile material that is an isotope not fissionable, but which can be converted into fissile isotope.

In summary, when a neutron is absorbed by a uranium-235 nucleus, one neutron disappears and one fissile nucleus disappears at the same time by absorption, fission, or capture. This can be translated into two main challenges. The first is to be able to sustain a chain reaction of fission. This is a feasibility condition also called criticality. That is a matter of neutron balance. The second is to optimize fuel exhaustion or depletion in the fuel in order to increase fuel utilization, taking advantage of the breeding mechanism. This time this is a matter of fissile material balance.

The probability of a specific nuclear reaction like fission or absorption depends on the nature of the interacting nucleus and the neutron kinetic energy. This is expressed by the microscopic cross-section signal. And on this figure, you can see the microscopic cross-sections of uranium-235. And it is very clear, it must be known that the probability of reaction is proportional to this microscopic cross-section and to the concentration of nuclei. The probability for a fission to occur is strongly dependent on neutron energy or velocity and the fission probability is much larger for so-called thermal neutrons.

The figure shows the thermal domain and fast domain. Note that fission neutrons are born fast. And to reach the thermal domain, which looks interesting in terms of probability, neutrons must be strongly slowed down by a moderator like graphite. This was in the CP-1 experiment. The process of neutron slowing down by a moderator is also called scattering.

Fission neutrons, fast neutrons have a very high velocity corresponding to an average kinetic energy of 2 mega electron volts in this range. The energy range in which the majority of neutrons are eventually absorbed, especially to produce a fission is determined by the competition between absorption and scattering. If most fissions occur at low energy, the reactor will be said in thermal neutron spectrum. Otherwise, the reactor is said in fast neutron spectrum.

Now, is a sustained chain reaction possible? The answer is yes. But we have seen that fission on uranium-235 and absorption on uranium-238 are competing phenomenon. Therefore, the feasibility of chain reaction results from this competition. Having a look to the uranium-235 fission probability in red, and the uranium-238 capture probability in green, it can be seen that the capture of neutron by uranium-238 is much slower. However, the fraction of uranium-238 in the nuclear fuel is usually much larger than the fraction of uranium-235, which can be problematic.

For natural uranium, for example, the feasibility of a chain reaction is very questionable because the content of fissile 235 is only 0.7%. So, the content of uranium-238 is about 140 times larger than uranium-235. The overall fission probability of uranium-235 is therefore challenged by the overall capture probability of uranium-238. But the situation can be improved by increasing the fissile fraction in the fuel.

What is the condition for self-sustained reaction? I am sorry, there is a problem of this slide because the equation is not displayed, so I will see what's going on in the future. So, the potential for self-sustained reaction is measured by the multiplication factor k. This multiplication factor is the ratio between neutron production and neutron absorption plus leakage. So, the value of k depends not only on the composition of the fissile medium, but also on its dimensions because of the ability of neutrons to escape out of the reactor. So, to summarize the mechanisms affecting the multiplication factor are fission of fissile isotopes like uranium-235 in the fuel and neutron captures on fuel uranium-238, uranium-235 on the coolant, on the moderator, on the metallic structures, and on fission products. And the last mechanism affecting k is neutron leakage out of the core. The condition for a self-sustained reaction is k is that $k>1$. $k=1$ is called the criticality equation or condition.

I am really sorry for you because the equation cannot be displayed.

Berta Oates
Claude, if you want we can pause the PowerPoint presentation and try loading the PDF version and perhaps that will show up there. I apologize for this.

Claude Renault
Hopefully, yes. Okay. Can you do that?

Berta Oates
Yes. Give me just 1 minute. I apologize people, I am very sorry for this.

Claude Renault
Sorry for everybody. Yes. Okay, I told all of you that this is rather technical webinar. So, there should be some equations, even symbols.

In the other case you could be disappointed. Upload in progress. Patricia and Berta, is it okay? Upload in progress, okay.

Berta Oates
Yes. Sorry, it's loading

Claude Renault
This is the same version?

Berta Oates
Version six, yes.

Claude Renault
Okay.

Berta Oates
I apologize. I ran through these. There is going be a little bit of.

Claude Renault
Okay, I'll check it. Yes, it looks good. Okay. Thank you. Thank you very much. So, coming back to slide number 14, the multiplication factor can be written as a fission rate as the numerator and at the denominator the absorption rate on the fuel, absorption rate on other media, and leak rate.

I have to scroll. Okay. So, the multiplication factor k can be rewritten as follows. Yes, some characters still missing, but not so important. So, k can be rewritten at the numerator, fuel related, only fuel-related effect, and as the denominator other effects like absorption on other materials and leak rate. The parameter at the numerator is called eta, is written eta, and is called the reproduction factor

For uranium fuel, which is a mixture of uranium-238 and uranium-235, this eta can be written like this. So, eta can be written with at the numerator and formula depending only on fissile isotope, which is uranium-235, and at the denominator, that is the effect of the fissile fraction of enrichment e.

So, as a whole, k is a function of the nature of the fissile isotope, in general uranium-235, and fuel composition with enrichment, and the core geometry for neutron leakage. Okay, it's almost good.

So, we have seen that a necessary condition for criticality is that the reproduction factor eta is significantly larger than 1. So on this table, you have the reproduction factor eta for uranium fuel according to the fissile fraction e. It can be seen that using fast neutrons, criticality is impossible with natural uranium because eta is very small. It can be obtained criticality by increasing the fissile fraction above about 15%. So, in that case eta becomes larger than 1. Using thermal neutrons, criticality is possible whatever is a fissile fraction is, and even for natural uranium. Therefore, two main options can be considered to slow down neutrons, criticality is then possible whatever the fissile content. And natural uranium can be used for strict neutron economy. And the other option is to use fast neutrons and subsequently increase the fissile fraction in the fuel. So, today thermal neutrons are the major reactors under operation like PWR, BWR, CANDU etcetera. Fast neutron reactors are today poorly represented.

As a moderation, how to slow down neutrons? To you thermal neutrons appear as an attractive step [ph] to design a nuclear reactor. A neutron moderator, that is a medium that reduces the velocity of fast neutron, is then needed. The primary requirement for a moderator is its capability to efficiently reduce the velocity of neutrons. This can be characterized by the variation of neutron kinetic energy per collision, which is measured by the parameter c. The other factors are high scattering or high slowing down probability Σs and low neutron absorption, Σa. The moderation efficiency can be globally evaluated via the moderating efficiency parameter, which is calculated in this table.

It must be known that the nuclei are the more effective to slow down moderate neutrons, that their mass number is lower, closer to the neutron’s one. A good moderator is thus a material with at least one element of low atomic weight like hydrogen, deuterium, carbon in its composition. The most usual neutron moderator materials are graphite, light water, and heavy water. The winner is heavy water, then graphite because of their very low absorption probability. Light water is very efficient at slowing down neutrons but is very absorbent. However, it has been extensively used as a moderator for light water reactors. Heavy water is a choice made for CANDU; the concept promoted by Canada. Graphite has been used in the past in France and UK, but the graphite moderated reactors are poorly represented today, only in UK.

Another question to address is what is the quantity of moderator required and which core configuration? The figure shows the multiplication factor k as a function of the ratio and nm/nu, number of moderator nuclei over number of uranium or nuclear or fuel nuclei for natural uranium in a homogeneous core configuration.

Homogeneous means that all core constituents are homogeneously mixed, for example, a solution of uranium nitride. The figure shows that with light water and graphite, criticality is impossible. k remains less than one, whatever the moderator content. This is because neutrons are absorbed before being sufficiently slowed down for fission. However, for heterogenous core configuration criticality becomes possible using light water. So, this is a key for the design of light water reactors.

A certain fraction of the fission nuclei are replaced by new fissile nuclei resulting from neutron capture on fertile material. This regeneration partially compensates the absorption of fuel. As you know, neutron capture on uranium-238 produces plutonium-239. The process is called conversion or breeding. The conversion efficiency can be measured using the breeding ratio BR defined as the ratio of fissile production to fissile consumption. This represents a fissile mass balance. If BR>1, the reactor produces more fissionable fuel than it consumes. It is called a breeder reactor.

A necessary, but not sufficient, condition for breeding is that the reproduction factor eta is larger than 2. One neutron for sustaining the chain reaction, another one for breeding the new fissile nucleus. For PWR the breeding ratio is in the range of 0.5 to 0.6. For fast neutron reactors, the breeding ratio can reach 1.2 and this was the case of Superphénix in France for example.

So, what are the ingredients of a nuclear reactor? The ingredients of a fission nuclear reactor are fuel material that contains enough fissile isotopes, essentially uranium-235 and plutonium-239, or even fertile isotopes. There must be a heat transfer medium called the coolant which is a liquid or gas able to extract the heat energy generated in fission fuel. A moderator, that is material able to slowdown fast neutrons or not, this is a choice. And absorbents, that is materials for capturing neutron and especially for the control of the chain reaction.

What is the situation today? The table shows the general characteristics of nuclear reactors brought to industrial development for electricity production and still being operated today. They have been classified according to the fuel type fissile content, natural uranium, low enriched uranium, enriched uranium or medium enriched uranium at the bottom. The table shows in particular the nature of the coolant and also moderator. And some operation parameters like operation pressure and temperature. Families of nuclear reactors can be defined according to the nature of the coolants. So, we have light water reactors like PWRs, BWRs and LWGR, Light Water Graphite Reactor, well known as RBMK, heavy water with PHWR, Pressurized Heavy Water Reactors, better known as CANDU, a gas CO2 like UNGG for France, Magnox for UK. And AGR. This is a GCR family. And sodium for fast breeder or fast neutron reactors at the bottom. Only fast breeder reactors are operating using fast neutrons, all the others are thermal neutron reactors. Both concepts with the exception of fast breeder reactors are viewed as first and second generation of nuclear reactors. As you know, a third generation of nuclear reactors is under development today with BWR, EPR, and so on.

And the winner is. So, the graph shows the distribution of nuclear power plants worldwide operated at the end of 2013 according to the different reactor families. Light water reactors, PWRs and BWRs represent almost 90% of the total installed nuclear electricity. Water cooled reactors as a whole also including PHWR and LWGR represent 98%. Gas cooled reactors are only 2%. Fast neutron reactors consist today of two reactors, BN-600 and BN-800 operated in Russia, representing only 0.2%. So, that is today.

So, why is the new generation of nuclear reactors needed? Why should we do better than the third generation. So, the main drivers for developing a new generation of nuclear reactors can be summarized as follows. The large scale development of third generation reactors challenges uranium resources. Identified conventional resources represent about 150 years of today's consumption, only about 0.5% of natural uranium is used. The management of nuclear waste will have to be further improved. And having in mind a perspective of fossil fuel shortage, nuclear technology should get prepared to answer other needs than electricity supply, like hydrogen production, process, heat desalination and so on. And the last point is larger spreading of nuclear power needs proliferation resistance. As a conclusion, new types of nuclear reactors must be designed in order to ensure energy supply in the context of long-term sustainable development

Regarding natural uranium utilization, this figure shows the uranium mass balance in the so-called open cycle used in PWRs or light water reactors in general. In PWRs, only 5% of the initial uranium set in reactor, enriched uranium is consumed for electricity production due to fuel technological limits. This represents only 0.5% to 0.6% of the initial natural uranium, which is very, very small. In contrast, breeder reactors or fast neutron reactors only need 1 ton of uranium-238, depleted uranium and reprocessed uranium, that is converted into plutonium and burned in the core, due to the breeding mechanism of fissile fuel.

Why fast neutron reactor is a breeding issue more precisely? So, these graphs show the simplified neutron balance for PWR and the fast neutron reactor like Superphénix. For PWRs namely, PWRs and BWRs, the breeding ratio is only about 0.5 to 0.6, as mentioned earlier. So this is mainly because the number of neutrons produced per fission is only 2.5 in the average. For fast neutron reactors now, the breeding ratio can be as high as 1.25.

And why is the fast neutron reactor neutron balance better for breeding? First of all, I would like to strongly mention that this neutron balance is more favorable to bringing [Unclear] spectrum and bringing plutonium-239, both conditions. This is mainly because the number of neutrons produced by fission is higher. In such spectrum, the conversion can be further improved by taking advantage of neutrons leaking out of the fissile core in the fertile blanket. So, this is the reason why we can go from 0.8 to 1.2 and we have done it.

Another essential issue is waste management. The management of nuclear waste will have to be further improved, minimizing the long term potential radiotoxicity and heat load of ultimate waste dedicated to the geological repository. The figure shows the composition of spent fuel for PWRs. As you may know, 96% of the content of spent fuel is recyclable uranium plus plutonium. Only 4% should be considered as nuclear waste, consisting of fission products and minor actinides. Minor actinides are heavy isotopes like americium, curium form is [Unclear] by neutron capture and decay.

In the open cycle, spent fuel is considered as nuclear waste as a whole. Plutonium recycling and additional waste management strategies are based on selective sorting of radioactive isotopes. In this kind of strategy, plutonium is clearly the major contributor to the long-term radiotoxicity of spent fuel. This point can be fairly solved by plutonium recycling. After plutonium, minor actinides have the major impact to the long-term radiotoxicity. So, the solution for minor actinides is transmutation. The ratio of fission/capture is favorable to minor actinide fission with fast neutrons. Therefore, fast neutron reactors can do this job.

GIF reopens the scope and reconsiders the choices made in the past during the industrial development of nuclear reactors as seen in the previous discussion. So we are now facing the blank page. Potential options are listed here in terms of coolants, moderators, fuel components, fissile, and fertile. So, some newcomers appear like for the coolant, molten salt, helium, lead, and lead bismuth, for example, in addition to water, gas, CO2, and sodium. Another newcomer in the discussion is thorium-232 and uranium-233 which is the fissile material associated to thorium. So, you may know that thorium is not fissile in itself but can be converted into fissile uranium-3 by neutron capture. Almost all combinations are possible and many of them were designed and built and most of them have actually been operated sometimes at a very small scale.

The first choice is the choice of neutron spectrum fast or thermal. So, this figure shows typical neutron spectrum. This is the number of neutrons according to their energy. For the PWR in blue and the fast neutron reactors like Phénix. What is clearly seen is that fast neutron reactor is a reactor designed for operation with fast neutrons. This is almost a joke. So, fast neutron or thermal neutrons, the choice would be guided by criticality, breeding and transportation potential as discussed earlier.

The potential of uranium and plutonium as fuel components has been discussed earlier. Another option might be thorium and uranium-3. It can be seen on this table that having a look to the reproduction factor, uranium-3 derived from thorium is a very good fissile isotope. We can also see from this table that bearing in mind that a necessary condition for breeding is that the reproduction factor should be greater than two, it can be concluded that uranium-235 is not well fitted for breeding. Plutonium-239 should be preferred using fast neutrons because the number of neutrons produced by plutonium-239 is much bigger. Uranium-233 is another very attractive option in the so called thorium/uranium-3 fuel cycle.

What about the fuel? So, the choice of the fissile fertile material has been just discussed above. Another parameter to be taken into account is the physical/chemical nature of the fuel. So, the table shows some properties of different mixed uranium/plutonium fuels and vision for fast neutron reactors in particular. So, oxide fuel called UOX [ph] or MOX, have been extensively used. Their thermal conductivity, however, is rather small, about 3.

But the melting temperature is very high, about to 2800 Celsius. In addition to that, the resistance to radiation damage is very good. Other options like carbide, nitride, and metallic fuels are considered for future reactors. So, what is your choice? So, high density is interesting for core compactness and therefore for competitiveness. High melting temperature and high thermal conductivity are important factors for reactor performance. With high temperature you can have high energy conversion efficiency and also for safety with a better margin to melting. So, in Gen IV, the choice is still very important.

So, a coolant is a liquid or a gas with adequate properties to remove heat from fuel elements. The choice of the coolant is a rather complicated issue because many different criteria must be combined. The potential coolant families are water, which is an excellent coolant, but also a moderator at the same time which may not be suitable. Gases like helium, CO2, opening the door to higher temperature. Liquid metals like sodium, lead, and mercury, why not. And the last family I wanted to mention is molten salt.

The table lists the main requirements and provides data of a number of candidates. Among liquids, light water and heavy water which also are moderators have been favored for thermal neutron reactors in the past and today. For fast neutron reactors, liquid metals such as sodium are well-fitted, but some gases like helium can also be considered. As far as gas are concerned, only carbon dioxide and helium have been used in practice. From the thermal-hydraulics point of view, helium and CO2 show a rather similar behavior but helium is much better for its neutronical and chemical behavior compared to CO2.

Let’s go into the Gen IV now. The Generation IV International Forum, GIF has certainly been since 2000s the most active think tank to materialize the goals and concept for fourth generation nuclear systems. The story actually started in 2000 when 10 countries decided to join the efforts to prepare the development of sustainable nuclear energy.

After a while, Russia and China joined the forum. In the first step, GIF setup the new requirements for this fourth generation nuclear assistance and identified the key technologies to be developed in multilateral cooperation. Such technologies should be marketable from 2040 onwards. So, you can see the different criteria or requirements for sustainable nuclear energy. I have mentioned some of them. Such innovative solutions for waste minimization, natural resource conservation, natural uranium, and proliferation resistance perform continuous progress on competitiveness, safety, and reliability and develop the potential for new applications like hydrogen production, syn-fuels, desalinated wastewater, process heat.

After 1 or 2 years, GIF selected six reference nuclear systems having the best potential to match the goals of fourth generation. I don’t want to discuss in details the six systems selected by GIF. You can see the webinar given by John Kelly last September and upcoming seminars in this series. So, I will just mention them by their name. So, the first is sodium fast reactor SFR, lead fast reactor LFR, gas fast reactor GFR, all of them with fast neutrons and the gas fast reactor is with helium. Very high temperature reactor helium plus graphite. So, this is a thermal neutron reactor, super critical water reactor which could be thermal or fast, but very difficult to achieve with fast neutrons. And the last is a so-called molten salt reactor by which fuel components are dissolved in a salt mixture. So, the fuel is liquid.

If you want to know more, this initial selection was documented in the so-called GIF Technology Roadmap that was published in December 2002. For your information, the following table shows some general characteristic of the Gen IV systems. So, obviously, the values in the table are fairly indicative because the design of Generation IV system is presently ongoing. This is a R&D development work. Today there is no Gen IV system under operation in the world. In this table, you can compare PWR which reflects typical nuclear reactors today with reference characteristics to the six systems I have mentioned earlier.

Some conclusions and perspectives now. So, GIF is stimulating the innovative design of new nuclear systems, taking into account the criteria for long term development of nuclear energy, in particular, safety, competitiveness, sustainability, proliferation resistance, and physical protection. The fundamentals for nuclear reactor design, which was a subject of the today's webinar, Gen IV or not, are criticality, which is a feasibility, and breeding nuclear fuel utilization.

To be very brief, fast neutron reactors offer strong opportunities for sustainability because of fast neutrons themselves. They are the best fitted for breeding and transmutation. However, breeding can also be achieved using thermal neutron reactors, but the feasibility constraints are strong. An example of this is a molten salt reactor.

And to conclude, today's webinar was strongly focused on sustainability issues, that is the best use of natural uranium resources and minimization of high-level nuclear waste. Other important issues were not addressed today but should be and are being addressed, like safety, competitiveness, proliferation resistance, and physical protection.

Thank you. If you want to know more about Gen IV system, stay on the line with the GIF ETTF webinar series for which the next sessions are shown here. So, in December, there will be a webinar dedicated to sodium-cooled fast reactor by Dr. Robert Hill from ANL, in January, very high temperature reactors by Carl Sink from DOE and in February, gas-cooled fast reactors by Dr. Alfredo Vasile from CEA, France. You are welcome for some questions. Thank you very much.

Berta Oates
Thank you, Dr. Renault, thank you very much. I've been advised that the download PDF has the variables, the missing equations. So, I invite everyone to take the time and the opportunity to download that PDF and use that for your reference. Thank you for your patience while we worked through the technical issues. We do practice these webinars. So, it is unclear why those equations or why those variables did not display in this meeting room today. But we will continue working through those technical challenges. Again, the PDF that is available for download does have all of the correct variables and the missing equations. I apologize very much for that technical difficulty.

If you have questions for Dr. Renault, please do type them into the Q&A chat box and we will take as many questions as we have time for now.

Claude Renault
Okay. So, we talked about 20 minutes something like that, 15 to 20 minutes.

Berta Oates

Yeah. And I can see along the top in the Q&A chat box, Dr. Renault, do you see there are two tabs, one is a participant view and one is the presenter view and I can see some.

Claude Renault
I cannot see any question at the moment. Q&A, yes.

Berta Oates
So, there's a question, what does proliferation resistance mean on slide 23?

Claude Renault
I cannot see the question myself.

Berta Oates
You see the Q&A pod?

Claude Renault
In the Q&A pod, yes I see the Q&A pod.

Berta Oates
Along the very top there are two tabs, one has presenter view. If you…

Claude Renault
Okay I can see. Okay, it was not active. So, I could not follow. I could not follow questions coming. So, I don't know how to manage this. So you mentioned slide 23.

Berta Oates
Yes. The question is what does proliferation resistance mean?

Claude Renault
Proliferation resistance means that nuclear material should not be taken by bad willing people and should not be used for other applications than civil nuclear energy production basically. So, I did not talk about this point because this is, first of all, a matter of regulations. IAEA is very active in this area.

Berta Oates
There is a question. When will the closed fuel cycle become cost effective?

Claude Renault
Cost effective. This is not a question for me today.

Berta Oates
Exactly.

Claude Renault
But the closed fuel cycle is used today in France, has been used for years in France. So, it's cost effective today. This is not fully closed fuel cycle, but maybe the question was using fast neutron reactors when the closed fuel cycle will become cost effective. I cannot answer this question, but I am very positive on that.

Berta Oates
The next question, can you please highlight or comment on main safety differences between the majority of reactor types used today versus future Gen IV reactors? What lessons learned after TMI, Chernobyl, Fukushima accidents will be reflected in new reactor designs for Gen IV. And in your opinion, do we have a chance convincing the public and getting their acceptance to build Gen IV reactors.

Claude Renault
Yes, I did not talk at all almost about safety and competitiveness, because according to me it should be misunderstood that this is business as usual because present reactors, and third generation reactors have set down the rules for nuclear safety, today's nuclear safety. And for the future, for fourth generation reactors these rules or the level of safety should be at least the same. This is what we say in Gen IV. So, of course a feedback experience from existing reactor families has been taken into account in third generation reactors already most of them. And for fourth generation, it should be at least the same level.

So, how to give confidence? This is our work to give confidence. And safety is always for each of the six nuclear systems a critical point to be addressed by research and development work. You will see that in upcoming webinars because the six system will be presented one by one and I am pretty sure that safety will be at the right place in the presentation to answer your questions.

Berta Oates
Thank you. The traveling wave reactor concept from TerraPower was not categorized in the presentation. Can you provide an overview on this?

Claude Renault
This is not my topic at all. But I know this concept, I have some ideas about this concept, feasibility and so on. But basically this is a fast neutron reactors with specific characteristics for long-term operation without fuel management. Well, no comment today. But maybe you can ask this type of question to the presenter of sodium fast reactor or gas fast reactor. I am sure they will have some answer to tell you. But I think at the present time there are very initial stage of development, the traveling wave reactor. But interesting.

Berta Oates
Then there is a question. Russia just put online their BN-800 sodium-cooled fast breeder reactor. Do you have any insight on why Russia is pursuing this type of reactor?

Claude Renault
BN-800?

Berta Oates
Yes.

Claude Renault
What is the question?

Berta Oates
Russia just put online their BN-800 sodium-cooled fast breeder reactor. You have any insight on why Russia is pursuing this type of reactor.

Claude Renault
What I know, I did not check recently but BN-600 has been operated during several tens of years. And BN-800 operation was started last year, I think in 2015. But I don't know what is the real status today. Was it successful or not, I cannot tell you. This is a question to my Russian colleagues. What I want to tell you is that the BN-600 and BN-800, like Superphénix and Phénix in France, should not be considered as fourth generation reactors.

Berta Oates
Right. Can you please say us few words on who is developing the six concepts? Is their active development on all six?

Claude Renault
Sorry. Could you show me the question? It's a question by whom? By you Patricia?

Berta Oates
Daniel Westlen.

Claude Renault
I could not catch the question properly.

Berta Oates
Are you able to see the questions on your Q&A pod?

Patricia Paviet

I don't see it Berta. I just see, could you please say and then I cannot read it.

Berta Oates
To the right there should be a scroll bar that will allow you.

Patricia Paviet
I see. Okay. Yeah, please Claude.

Claude Renault
Sorry. I could not catch your question. I don't know who is the author of this question. Is it little William or who is this?

Berta Oates
Daniel Westlen.

Patricia Paviet
Yeah. So, I'm going to read it again. Maybe the French accent will help. Could you please say a few words on who is developing the six concepts?

Claude Renault
Okay. In the past I was very much aware about that. But it's changing. Sorry. So, again, I think this type of information was given by John Kelly.

Patricia Paviet
Yes, it was in the first webinar.

Claude Renault
Last September I think because he is still fully involved of course in Gen IV. He has better information about that. Yes, I can say a few words, sodium fast reactors is being studied by many different countries including France, USA, Russia, Japan, and China. For lead fast reactors, it is more restricted, so I think there are some European projects and maybe mainly Russia did something, of course. For gas fast reactors cooled by helium, so France initiated the research on this concept. And now there is a demonstration reactor of GFR under study in Central Europe with different countries including I think, Hungary, Czech Republic, Slovakia and I think Poland with some support by Europe.

For the VHTR today, I think VHTR is being studied by USA and some other countries. I would like to mention China of course because China is constructing a prototype reactor HTR-PM, I know that, which is under completion. For super-critical water reactors, I think the interest is more focused to a small number of people or countries like Canada, of course, and maybe Japan. We have done this in France, but now, we have given up for a while.

And for the molten salt reactor, there is an increasing interest in the world actually. So, molten salt reactor is still studied by France, not CEA, but mainly CNRS. And also China, according to what I know, is studying the opportunity to develop a demonstration reactor of molten salt reactor, and there are other actors in the world. I think this is interesting to follow the progress on the MSR

Patricia Paviet
And I can add to you, Claude, that all the webinars have been archived. So if you go back to John Kelly's presentation on the GIF website, to either the PDF or the recorded version to the slide 25 and you will have all the active R&D collaboration on the Gen IV system.

Claude Renault
Yeah okay. So, what I forgot to mention for the molten salt reactor is that the molten salt reactor should be considered more or less as a family. And there is another type of molten salt cooled reactor which is being studied by USA mainly, with solid fuel and liquid salt as a coolant. So, with Charles Forsberg and so on.

Berta Oates
Then there is a question, can you mention any effects of small percentages of U-234 in natural uranium?

Claude Renault
Sorry, but again, it's difficult for me to understand the questions with my phone and my English may be. So, what's the question?

Berta Oates
Can you mention any effects of small percentage of U-234 in natural uranium?

Claude Renault
234?

Berta Oates
Yes.

Claude Renault
Yes in natural uranium there is a very small fraction of URANIUM-234, very, very small, very, very, very small. So, I did not mention it.

Berta Oates
Does it have any effect? I guess that's their question.

Claude Renault

So, as a fraction of uranium-234. I don't really understand the rationale. So, the fraction of uranium-234 in natural uranium is 0.005%.

Berta Oates
Right.

Claude Renault
Very, very, very small.

Berta Oates
I am not sure of this question. How is the violent reaction of sodium with water handled at today's level of development?

Claude Renault
Again, this is not a question for me today. I can tell you something. But be ready to ask this type of question next month. Okay. I can tell you something anyhow. In France and probably in Russia, we have some experience in the operation of fast neutron reactors cooled by sodium. So, we have many years of feedback experience on that. For Gen IV reactors, there are several tracks being explored to avoid any potential chemical reaction between sodium and water. One way is to cancel sodium for the intermediate loop or circuit and substituting sodium by something else, not reacting with water like lead for example.

So, this is a potential design option for a sodium-cooled reactor with sodium in the primary side, lead or something else not reactive in the secondary circuit, and water for energy conversion. Another option which is deeply investigated in France is to substitute water steam by something else for energy conversion, for example, gas. So in the ASTRID prototype being studied in France with other partners, we are investigating the possibility to develop helium or nitrogen turbines for energy conversion instead of water steam. So in that case, there would not be any possibility of contact between sodium and water because there is no more water.

Berta Oates
What main nuclear-data needs do you see relevant for Gen IV reactors?

Claude Renault
Can you repeat again, very sorry?

Berta Oates
What main nuclear-data needs do you see relevant for Gen IV reactors?

Claude Renault
Nuclear what, sorry.

Berta Oates
Data. It's from Ali Al-Adili. What main nuclear-data needs do you see relevant for Gen IV reactors? Maybe he can type in some clarification. Most BWR, PWR exchange fuel every 18 to 24 months. What would that be for an FNR?

Claude Renault
I don't know. Because there are FNRs of second or third generation, okay, like BN-600, BN-800 and they are FNRs of fourth generation. And FNRs of fourth generation do not exist today. So, this is something to be considered. This is a criterion.

Berta Oates
What's the main driver for new builds including fourth generation?

Claude Renault
What's the main driver for building?

Berta Oates
For new builds.

Claude Renault
For new build in the fourth generation.

Berta Oates
Correct.

Claude Renault
This is it. Probably I was not very clear in my webinar because the criteria for developing first generation reactors have been shown during the webinar and they are mentioned here. And again, such Gen IV systems, they are planned to be marketable only from 2040, okay, be aware of that.

Berta Oates
Is EDF utilized as a long-term storage solution for spent fuel or still storing spent fuel at the individual sites?

Claude Renault
Okay. So, you'd better get in touch with EDF, but in France you may know that we are reprocessing spent fuel. So, spent fuel is thought for a while in the same place as nuclear power plants and then is reprocessed in a reprocessing plant we have in France in order to sort out uranium, plutonium and waste. So, this is very clear. So, the solution is very well in line who is Generation IV requirements.

Berta Oates

There is a question, so what do you think, which concepts among the six will be built finally? Which one will be built first as a demonstrator?

Claude Renault
Generation IV is an R&D process, okay, the objective of GIF is to stimulate research and development on the six concepts and to share as good as possible the R&D results. So, the six concepts were selected a long time ago because they were selected in 2001 or 2002 and they have remained the same until now. So, this means that the six concepts have some potential to be developed in the future and we are still in the R&D process. Okay. Another point is the national context for each country that can be different than those requirements, and the selection criteria could be different from one country to another.

And another criterion is the feedback experience each country can have from sodium fast reactor or lead fast reactors or high temperature reactors, for example, which could speed up the schedule. But all six concepts, they still have some chance to be developed in the future and there are several demonstration reactors or prototypes that are planned or being constructed today. They will be mentioned in the future webinars clearly, but we should not cancel any of them at the moment.

Berta Oates
I think you actually in that response addressed this question as well, which reads, *monsieur* which of the six types of the fourth generation do you prefer and why?

Claude Renault
Sorry, again, can you repeat?

Berta Oates
Of the six types of fourth generation reactors, which one do you prefer and why?

Claude Renault
Me?

Berta Oates
That is what the question reads.

Claude Renault
This is some kind of trap. Clearly I don’t answer this question. But the guy or the lady who asked the question can keep in touch with me and we can discuss about that by phone. But I don’t want to discuss this here today.

Berta Oates

Thank you.

Claude Renault
I cannot read the question on the – maybe I can. I can read the beginning of the question, but not the end. It's very inconvenient.

Berta Oates
On your right hand side, there should be a toolbar that allows you to.

Claude Renault
Yes, to go to go up and down, but the questions are not complete. So I see the beginning. For example, there was a question by Little Williams. Since this was a R&D discussion, why wasn't and then I cannot read. I don't know what to do. Okay. Since this was a R&D discussion, why wasn't fusion discussed?

Now, fusion is not considered as a fourth generation technology, so it was not discussed. So I only mentioned the energy potential of fusion, which is in the same order of magnitude as fission with respect to the quantity of initial material. So, now I know how to display the question.

Berta Oates
Oh good, great.

Claude Renault
Okay, I see. *Monsieur* of the six types of fourth generation reactors, which one do you prefer and why. So okay, I answered. So, let's keep in touch, Michael. So, what do you think, which concepts among the six will be built finally? So I also answer, it is still very open. Which one will be built first as demonstrator? Let me think about that. Maybe ASTRID for sodium fast reactor. There is a demo using the lead technology, which is called ALFRED [ph] I don't know what is the present status. So, there is an HTR-PM being completed, constructed and completed by the Chinese. But they have lowered the target temperature. So, I don't know if it should be fully considered as a fourth generation now, but probably in the future.

What else. Some people are still there. What main nuclear data needs do you see relevant for Gen IV reactors, so nuclear data? Well, I don't really know, but not so much. Maybe to improve our knowledge about the sodium cycle. Okay, I think we went through the BN-800. The traveling wave reactor, safety, proliferation resistance. Okay. Any other question? Any additional question now? Because I think we went through. Okay, I think.

Berta Oates

I think there is a new question, are the PRPP concerns equally high at reprocessing plants?

Claude Renault
Are the PRPP concerns equally high at reprocessing? I would like to say, yes. PRPP relates to all steps of nuclear fuel. Should be. And this is what is being done. So, there are still 55 people online. You are still welcome. But I do not see additional questions.

Berta Oates
I think most of it is accolades for the presentation and commentary at this point.

Claude Renault
Okay

Patricia Paviet
There is somebody from NEA/OECD, Roger Garbil who send us, NEA Nuclear Data High Priority Request List is available at the OECD/NEA website.

Claude Renault
Oh, thank you very much. Very good information.

Patricia Paviet
I think you did very good, Claude.

Claude Renault
Thank you. I was very much disturbed by the display with.

Berta, I don't understand, I don't know what is the reason for that. But it was a little bit disturbing and probably not only for me, unfortunately. Maybe we can do it again in the future.

Patricia Paviet
Okay. I think we are good Berta. What do you think?

Berta Oates
I think we're good. Thank you again for your patience while we worked through technical issues. I will continue to pursue that after today's presentation and find out. I can discover what's the difference between the practice meeting room and live webcast room. I'm honest, I'm not sure at this point, if it's just a font recognition or a display forward and back, but I know the PDF is harder to work through the way and scroll.

Claude Renault

Okay, Berta, please tell me what was wrong according to you after investigating.

Berta Oates
I will follow up with you. Thank you.

Claude Renault
Thank you very much.

Patricia Paviet
I guess we will meet again on the 15th of December at the presentation of Dr. Robert Hill on sodium fast reactor. It will be live at 8:30 a.m. Eastern Time, Washington DC.

And again, thank you so much Claude an excellent presentation.

END