Sustainability, a Relevant Approach for Defining Future Nuclear Fuel Cycles
Dr. Christophe Poinssot, CEA, France

Berta Oates
Good morning. Welcome everyone to the next Gen IV International Forum Webinar in our webinar series. Today's presentation on 'Sustainability, a Powerful and Relevant Approach for Defining Future Nuclear Fuel Cycles' is just about ready to get started.

Before we do, I wanted to take care of a little bit of housekeeping. If you have questions for today's presenter, there is a Q&A pod where you can type those in the chat box and we will address the questions at the end of the presentation as time allows.

In the Files pod is a copy of today's presentation slides in the PDF format. When you click on that, those will download directly to your computer. And finally, in the Notes pod, we welcome your feedback and invite you to participate in an online survey, the link of which is provided for you there. Following today's presentation, in the next few days you should receive a certificate of attendance and that link will be provided to you again to provide feedback on today's presentation.

Doing today's introduction is Dr. Patricia Paviet. Patricia is the Director of the Office of Materials and Chemical Technologies at the Department of Energy, Office of Nuclear Energy. She is also the Chair of the Gen IV International Forum Education and Training Task Force. So, without any further delay, I give the floor to you, Patricia.

Patricia Paviet
Yeah, thank you so much, Berta. Good morning, everybody. It's a pleasure to have you with us today, especially to have Professor Christophe Poinssot from the French Alternative Energies and Atomic Energy Commission, the CEA in French with us. He has been working at the CEA for more than 25 years in the fuel cycle R&D. He is currently heading the Research Department on Mining and Fuel Recycling Processes where he is in charge of developing actinide recycling processes and operating the Atalante Hot-Lab Facility. He is also a CEA International expert in actinide chemistry and a professor in nuclear chemistry at the INSTN.

He graduated from the Ecole Normale Superieure de Paris. He obtained his Ph.D. in Material Science in 1997 from the University of Pierre and Marie Curie in France in Paris, and his habilitation degree in Chemistry in 2007. He first worked during 15 years on the French Geological Disposal Program. And then he moved to South of France in 2008 where he joined the CEA Marcoule where he was successively the Deputy Head, then the Head of the Radiochemistry and Processes Department in charge of the Atalante operation and the development of the reprocessing processes. His responsibilities extended to the whole recycling activity with the creation in 2017 of the Research Department on Mining and Fuel Recycling processes.

He has long been involved in teaching currently on the nuclear fuel cycle strategy in several chemical engineering schools and universities in France. He authored or coauthored more than 50 scientific papers, 100 oral communications in international conferences. He has been decorated as Chevalier des Palmes Academiques in 2016 and was awarded the Roger Van Geen Chair by the Nuclear Center in Belgium, SCK-CEN in 2017.

So, without any delay, I am giving you the floor, Christophe. Thank you again for giving this presentation.

Christophe Poinssot
So, thank you very much for the nice introduction and thank you, everybody for being online with me. So, I am going in my presentation to try to demonstrate to you how the sustainability, a relevant and powerful approach for shaping the future of nuclear energy and more particularly, the nuclear fuel cycle. So, I will first as an introduction describe what is energy transition challenge and how it can be related to the sustainability. And I will therefore describe what can be the evolution of nuclear energy driven by the environmental drivers, by the societal drivers, then by the economic drivers before concluding about potential roadmap or rationale for the future fuel cycles.

I just want to mention at this step that this presentation has been given in Brussels some weeks ago as introduction lecture of the award I have been given by the Belgium Nuclear Research Center.

So, let me first remind you what is the global challenge that we have altogether to face at the world scale which is the energy transition. So, it is created by the contradiction between two aspects. The first one is the need for significant energy increase. And let me give you a few words about that. If you just have a look on the back what has been the evolution of the energy consumption worldwide, you see very clearly in the picture on the left that it has been very significant increase since the mid of the 20th century and it is directly related first to the increase of the population, second to the economic development. And you see that this very significant increase has been accommodated by a new type of energy which has been used in order to be able to meet these needs. So, it was the coal, then the oils, then the gas, then nuclear, and now renewables and so on.

So, it was for the past. What about the future? So, first, about the future, we have to consider that the world population will still increase. It's what you can see on the figure on the left downside. You see that we are roughly in the range of 7.5 billion inhabitants at that time and it is anticipated that we will reach by the mid of this century something in the range of 9-10 billion inhabitants. And new each inhabitant will require energy to live for himself and so on. So, it will mechanically increase the need for energy at the world scale. That's the first very important driver.

Second important driver, when you have a look about what is the relation between human development, by human development I mean the health, the wealth, the education, the economic development, and so on, everything can be aggregated together in an index which is the Human Development Index developed by the United Nations.

When you to try to see the correlation between this human development index and the electric consumption per capita, you see that you have a very nice picture which is just here seen on this slide where you have two regions basically. First, above 5000 kilowatt hours per capita you see that you have more or less a plateau. It means whatever energy you consume; you will have more or less the same type of human development basically.

But you see that you have a range in the figure which is the lower range, lower than 5000, and in this region you have a very tight correlation or relation between the amount of electricity you consume or energy you consume and the level of human development you reach. And you have many countries which in fact are much lower in terms of human development and just anticipate to grow to reach a higher human development. And so, it means that it will mechanically increase their energy needs.

So when you combine these two aspects together, it leads to the type of figure you see just right now on the right part of the slide, which is the prediction of the evolution of the energy consumption worldwide made by the International Energy Agency based on the consumption from 2005. And you see that first, if we just assume that we have a business as usual approach, we are not changing anything. In this case, it corresponds to the continuous line. We will have a need for primary energy, of twice more primary energy basically by 2050. And for electricity, it's still higher. We will need something in the range of 2.7 more electricity in order to be able to meet our needs. Well, you can say that it's not relevant because we will change the economic model. We will promote the green economy and so on. So in this case you just shift to the dotted lines. And you see that for sure you may succeed in stabilizing the primary energy needs, but even in this case you will need 40% more than today, which is quite relevant. But you see that even in this situation you will have a quite high or quite significant need for more electricity and it will not change a lot regarding the need for more electricity.

So first very important conclusion, we will need much more electricity by 2050, by the next century than what we produce and consume today. And for sure we have to think how we can meet these needs. So, it was the first part of the challenge.

Second part of the challenge, everybody I guess knows it very well. It's a problem of the climate change. So, basically the climate change is related to the fact that we have some gases in the atmosphere which capture part of the energy which is received by the earth from the sun. And when you increase the concentration in this case, you will increase energy which is captured by the earth.

So within these gases, the most famous one is the carbon dioxide and you see on the picture here the evolution of the carbon dioxide concentration in the lower atmosphere, in the last 10,000 years. And you see very clearly this dramatic increase which started in the 20th century and which increased the level of concentration from something in the range of 275 ppm up to more than 400 ppm carbon dioxide concentration in the atmosphere. And it means that if you increase the concentration, you will increase energy which is captured by the earth, you will change very dramatically the climate.

We have already a lot of trace of this evolution and they are quite famous. Just to take a few illustrations. The global temperature you see here on the map on the left has been already significantly increased in the last decades and the last century. And so some regions in the world have lower temperature, but on the average the average world temperature is significantly increased.

And we have some very practical consequences already which are visible. I've just taken an illustration taken from where I live in South France. We have a very famous wine, *Chateauneuf-du Pape* and you have just here the evolution of the date for the grapes peaking, and from the end of the Second World War up to 2005. And you see that basically we save one month in terms of the time needed by the grapes to be ready to be picked. And it's not related to any change in the wine production procedure, it's just, due to the fact that we have much more energy, higher temperature, and the grape is ready to be picked much earlier.

And another illustration, quite famous also is the melting of the glacier even in the mountains or in the higher latitudes like in Greenland and so on. So you see here this very famous picture taken from Alaska here. So, it was for the past. What about the future once again? So, here we have the predictions which are based on the models which have been developed by the IPCC, so the International Panel on Climate Change from the United Nations. And you see very clearly that in fact, many times, we speak about what's going to happen within this century, so I mean before 2100.

And so we are expecting with our effort, if we succeed, to limit the temperature increase by 2 degree Celsius. But you see that it's not yet easy to achieve because many models predict much higher evolution. And we have to keep in mind that the end of the story is not in 2100. It will still increase further the center reactor, because in fact the time needed to reach a stable state is much longer. So, basically what we have to keep in mind is that due to the increase of the greenhouse gases, we expect a very significant increase of the temperature and we have to do all we can do in order to mitigate this evolution, in order to prevent, in order to have conditions which are favorable to life.

So, if I try to combine these two facts together, we reach to what I call the challenge of the energy transition, the challenge we all have to face and which are very complex questions. In fact, we have to increase energy production. We have to mitigate the climate change. And the problem is you can't succeed to reach these two objectives if we do not change the energy model.

So, what is the reason for that? You have here complex picture where I just plotted the world energy portfolio. So you see the size of the different bubbles directly correspond to the share of each energy type in the world energy portfolio. And each energy is plotted as a function of the carbon dioxide intensity, so the carbon dioxide emissions per kilowatt hours of electricity produced. And the second is the capacity factor. It means the time, let's say during the plants, the electric coal plant can produce electricity. And for sure, the higher these numbers, the easier we can meet the need for electricity for energy.

So you see very clearly that we have first the fossil energy, so coal, oil, gas and so on, which corresponds to more than 80% of the global energy share worldwide and for which we have very significant carbon dioxide intensity. And if we want to mitigate the climate change, we can't rely anymore on this type of energy or at least as high as we do today. We need to decrease this type of energy and we need to promote during the same time the decarbonated energy, which is first the renewable energy, so photovoltaic, wind power, hydro energy. But you see that for sure they have very low carbon dioxide intensity, but the capacity factor is also very low.

So we have a very important question, which is how we can meet our need with that. And we have another type of energy which is nuclear energy which is also very low in terms of carbon dioxide emissions, but with much higher capacity factor, so quite interesting in fact.

So, basically it's the basis, the root for the energy transition challenge which is decreasing the fossil energies in order to decrease greenhouse gases emissions, so increase the renewables which are under nuclear energy, which are the decarbonated energy. And at the same time that's also something quite important that we do not have to forget, which is increase the energy efficiency in any of our system. And it was the basis for the COP21 meeting and the subsequent world meetings in this domain.

So, if I just stop here we could say, well, so nuclear energy has a great future and is very promising. In fact, we can't stop here and you all know that nuclear energy is very promising in terms of technical approach, technical power, but it's not the only point we have to consider. We have also to consider the increasing concern and opposition of significant part of the population against this type of energy. And so, it's what you can see in this recent opinion survey which has been performed in the United States. It's dated from Spring 2016. And you see very clearly that in fact we have a significant part of the population which is not in favor of nuclear energy and it is directly related to the knowledge they have about this type of energy which we have to recognize, very complex to understand, and with some risk which seems for the population to be quite high.

And so, it means that in fact, if we just have a purely technical approach, we for sure miss part of the problem which is the acceptability of different type of energy and in particular, the nuclear energy by the population, and we have to integrate in our approach, this domain which is a social domain. And it's not the only one. We have also to consider the environment and so on, so it means we can't stop to analyze just based on the technical performance or the economic performance. We need to have a much wider approach.

And that's basically the basis for using the sustainability as a global approach, a systemic approach in order to try to define what could be the future for the nuclear energy and for the nuclear fuel cycle.

So, I just remind here on the slide the definition for the sustainability, which has been demonstrated in fact to be based on three main pillars. So, the first one is the economy. For sure, it's historically a very important pillar for any technical development. So, it's never forgotten, in fact. But we have also to consider the environment. So, we need to develop an energy source which is environment friendly in fact and we have also to consider the society. So our energy system has to be accepted by the society and it has to meet the needs of the society. And the sustainability, which is the way by which we can define a future for nuclear energy is a kind of tradeoff between these three drivers, the economy, the environment, and society.

So, how can we improve the affordability of the nuclear energy, which is a baseline for the technology development? How can we improve the environmental footprint in particular concerning the recent concern for the climate change and the overall environmental footprint? And how can we improve the acceptability by developing the equity, reducing the risk, and basing our choice on democratic votes? And so, can nuclear energy be sustainable is the real question I want to address with you and more importantly, how can it be sustainable.

And so, if we try to think what would be the driver for that, first for the affordability, for the economy, so we need to have predictable, stable, unlimited energy cost and we need also to promote the economic stability in order to help the development of the industry, of the economic society. And this energy independence is quite important in this domain. So, we need also to improve the environmental footprint which means we need to promote some greenhouse gases free energies to preserve the natural resource, to reduce and manage ultimate waste whenever they exist, and to ensure that the environmental footprint will be as low as possible.

And last but not least, we have also to consider the acceptability, and so it means that we need to develop the highest level of safety and reliability for our technological systems. It has to be based on the consensual choice of the society and it needs to promote the international stability.

And so, what I want to do in the following of my presentation is to see what can be the main trends based on these drivers and what can it mean for the nuclear energy and what can be the main trend, the main guideline for the future. And so, I will go first through the environmental drivers, then through the social drivers, and finally I will arrive to the economy.

So, let's start with the environmental drivers which in fact is my first chapter. So, the first important driver is to reduce the greenhouse gases emissions. And we have to realize that nuclear energy is already very beneficial regarding this criteria and it can be very clearly seen on this second figure here. We have the comparison of the greenhouse gases emissions for the different energy sources. And you see that for nuclear energy, it's the lowest one. And even for nuclear energy, you can have quite low emissions if you really optimize your system as we did in France in fact, and it can be in the range of a few grams of carbon dioxide per kilowatt hours of electricity.

When you try to see where do they come from, in fact you see that the main contribution is the reactor. And when I mean reactor, it's not the operation of the reactor. That's the construction of reactor, and in fact it's directly related to the mass of concrete, steel, and so on which are within this type of plant. And the second important contribution is mining activities. In particular, it is related to the need for handling a lot of materials for recovering the uranium.

And in fact, when you look around you see that you have a strong correlation between the development of nuclear energy and renewables with the carbon dioxide intensity.

So, it's what you can see here on this map on the right. So, it has been taken on 12th November this year. But we could have a look on the map yesterday. It would have been more or less the same picture. The greener the color, the lower is the carbon dioxide emissions, and you see very clearly that in fact in France and in often Europe it's where are located the much lower carbon dioxide emissions. And it's directly related to the presence of nuclear energy and renewable energy, but nuclear energy is part of the solution.

And you see that for instance, we very often talk about Germany, but you see that Germany, even if they develop a lot of wind power, solar panels and so on, they still have much higher carbon dioxide emissions due to the fact that they need to back up this type of energy with coal and gas which have much higher carbon dioxide emissions than nuclear energy for instance.

So, let's remind for greenhouse gases emissions nuclear energy is already very beneficial. We still can improve for sure but we have already performed most of the effort and it's probably not where it has to be put most of the development for the future.

So, second important driver is the preservation of natural resource. So, natural resource for nuclear energy is natural uranium basically. And we all know that natural uranium is a limited resource. If you just try to see what are the expectations regarding this type of resource, I just compare on the figure here on the left the lifespan which I derive from the ratio of the reserve divided by the annual production based on the BP statistical review and the NEA Red Book from last year and this year.

And you see that in fact for the uranium resource based on the current reactor without any recycling, we have something in the range of 130-140 years of reserve with the current consumption, which is much higher in fact than oil and gas, so that's good news. But it's still much lower than coal and it's more or less in the range of one century, so it can't be a solution for perpetuity if we just use natural uranium as we do today.

So it means that we have a driver for preserving this type of resource, but here we do not know what can be the potential use for the future for the next generation? So, what about the current efficiency in the way we use natural uranium? I just present here on the right some data which I have taken from the French situation. And in fact in France we have 58 reactors. They produce 430 kilowatt of electricity. It's more or less 80% of our electricity. And in order to feed this reactor we need 1200 tons of fuel. And in order to produce this type of fuel, we need something in the range of 9500 tons of natural uranium. So, it's quite high in fact and most of the decrease of loss of uranium is directly related to the enrichment state.

So for sure we discharge the same amount of spent nuclear fuel at the end of irradiation after 4 years. And when you try to compare the evolution of composition regarding uranium, just focusing on uranium, you see that in fact we consume most of the uranium-225 which is a fissile element, also part of the uranium-238 which is transforming plutonium. But when you see the difference, it's very low, it's something in the range of 70 tons. So if you just try to think about, we produce 80% of our electricity for a country like France just by consuming 70 tons of uranium. So, first, it's a very low figure, we have to keep that in mind.

But in terms of efficiency, in order to consume this type of uranium, this mass of uranium, we need to handle, to enrich, to manufacture something in the range of 9500 tons of uranium ore, which is quite high. So we have a very low efficiency in the range of 0.7%. And for sure we have some place, some room for improvement in this domain. We need to improve the uranium efficiency. That's something which is quite relevant for the sustainability of the nuclear energy.

So, saving the uranium natural resource, how can we do that? So, it's still picture of how we feed the reactor, still based on the French situation. And you see the composition of spent reactor radiation here. In this figure you see quite interestingly that the amount of uranium-235 in many cases is still higher than the natural uranium. So, I think that's really quite worth to recycle, to save and recycle this type of material. And we have also here, in red, 1% of plutonium which also can be used to produce energy. So, that is the basis of recycling, for developing the recycling technologies.

And you know that in France we developed these types of technologies which are already implemented in Areva Plant. So it means that we are able to recycle the plutonium as MOX fuels. We have plutonium compounds in the range of 8% to 9% and so, these fuels are already fed in 22 reactors in France and allowed to produce around 10% of electricity. And we are also able to recycle uranium, so we use a very large part of the spent nuclear fuel as enriched reprocessed uranium fuels which had been used some years ago in four reactors in France and which are also responsible for something in the range of 5% to 10% of the electricity production year after year.

So, that's something quite relevant in fact. And by the way, it means that the ultimate wastes are much more reduced. It's only 4%. And it's only the fission product here in green and the minor actinides, so something in the range of 10 to 15 canister per reactor per year. So, we have very significant industrial feedback in this domain. We have the La Hague reprocessing plants which already treat more than 33,000 tons of spent nuclear fuel, and the Melox recycling plant or MOX production plant which already produce more than 2500 tons of MOX fuel.

So, it's a lot to save. In fact when you look back here on the amount of natural uranium we used or we need in order to feed the French system, it's not anymore 9500 tons, but it's now 8000 tons. So it means more or less that we are saving in the range of 1500 tons of natural uranium, which is quite good news. And the recycled materials allow to produce 10% to 20% of our French electricity.

And last but not least, we have no spent nuclear fuel in interim storage anymore, because they have been treated and that's also a significant reduction of the risk. And you know that risk is part of the acceptability, so part of the societal drivers.

So, how can we perform such recycling? So, it's based on the PUREX approach. PUREX approach or PUREX process has been developed quite a long time ago because it has been discovered at the end of Manhattan project. It is based first on the dissolution of the spent nuclear fuel in nitric acid which also separate the metallic waste which comes from the cladding. We have also separation after which is performed by a liquid-liquid extraction process based on the tributyl phosphate extracting molecules. So, it will also separate uranium and plutonium which are converted to powders and which are used to fabricate the MOX fuels.

And the ultimate way, so the fission products and minor actinides can be conditioned by a vitrification process which is quite efficient in fact.

So, I want to stress that with the PUREX process, we have really high achievements and that's a real success in terms of separation science. So, as I already mentioned, the separation is based on selective extraction by the tributyl phosphate in fact of uranium-VI and plutonium-IV. And we [Unclear] separation of this sediment with the fission products and minor actinides or of these two elements together in particular by the reduction of plutonium by uranium-IV with the presence of hydrazinium nitrate.

And so you have here the types of complex which are formed in the organic phase and which is responsible for the extraction of the plutonium or uranium in the organic phase.

So, very important, the extracting molecule is highly resistant to radiation and to the acidic conditions. So, we can recycle the extracting molecules of TBP, and that's something for sure quite important, because it means that we have a low amount of secondary waste. So, we are able to get some yields of recovery, higher than 99.9%. We have a high decontamination factor with regards to minor actinides and fission products, higher than 10 to 7. And therefore we are able to produce plutonium nuclear grade for MOX fuel fabrication and clean uranium for enriched processed uranium fuel fabrication also.

So it can be a continuous and robust process. It is demonstrated to produce low amount of secondary waste thanks to the recycling of the extracting molecules. We can treat various types of irradiated materials and the supply and operating costs are relatively lower. We will be back on that later on.

So, that's already a good point. It means that we are able to save 1500 tons, so a few percent of fuel, 10th of a percent of efficiency more. But it's not sufficient. We are still far from an efficient use of natural uranium.

Can we go further? Can we go to multi-recycling of the plutonium and to a full use of the uranium-238? In fact, it's not feasible in the current reactor generation due to the fact that when you are still with low energy neutrons, so in the light water reactors, we have a low efficiency in the consumption of the [Unclear] isotopes of plutonium. And therefore it means that we are limited in the number of recycling steps we can implement.

So, it's what you see on this figure here. We have the ratio of the cross-section for fission divided by the cross-section of capture for the different isotopes of plutonium here. So, you see that when you have a light water reactor in green, we are only able to fission the plutonium-39 and 41 and even the isotopes. Whereas if we shift to higher energies for the neutrons, so for instance in fast neutron reactors, you see that you are also able to fission the odd isotopes of plutonium 38, 40, 42. And therefore it opens the door to the multi-recycling and to the possibility of using much more efficiently natural uranium resource. So, that's the basis for the Generation IV systems using fast neutrons. And I just present here a picture of what could be in a very far future such as fuel cycle in France.

So, you see that in order to produce the same amount of electricity, by replacing also the light water reactors by fast neutron reactors. We do not need anymore 1200 tons of fuel, but only 450 because it's much more efficient. And you see that these fuels can be manufactured by the recycled materials, so plutonium and uranium coming from the spent nuclear fuels, and very low amount of depleted uranium in order to complete the uranium which has been consumed in the produce cycle. And in fact we will be able to produce the same amount of electricity with only 50 tons of depleted uranium theoretically. So, it means that you have to consider or to remind that every country which proceeds with enrichment step has already a very large stockpile of depleted uranium. And just by using this stockpile, not having any mining activities anymore and so on, you would be able to produce very large amount of electricity.

What about the efficiency? You have still a picture of the comparison of the potential energy production which are within each of the fossil natural resource which are available. So you find coal, oil, gas, and you have here electricity with uranium in current reactors. You see that if you are just using light water reactors, basically you have 6% of the world energy potential which is within the uranium with this type of generation of reactor. And you also see that you need 150 tons of natural uranium in order to produce 1 gigawatt of electricity.

If you are just changing the generation of reactor or shifting towards fast neutron reactors, everything being constant, you see that the amount of electricity, of energy which can be produced with natural uranium is as high as 7500 gigatons of oil equivalent. And it’s directly related to the fact that you increase by a factor of 100 to 150 the energy production versus the natural uranium. And in fact, it means that natural uranium can represent as high as 90% of the world energy potential. So, it’s dramatically changing the overall picture. And it really means that by implementing the recycling, you can very significantly increase the efficiency in the way you consume, the way you use natural uranium. And therefore, you are in good connection with the sustainability, so very significant improvement of natural uranium efficiency by implementing the overall recycling and what is basically the multi-recycling.

So, another important driver is to reduce the waste impact. So, reducing the waste impact is something very important because the waste is the Achilles’ heel for many people of the nuclear energy. So if we try to compare the case where we recycle, so in this case ultimate waste of the nuclear glass, so the fission products of the radionuclides are within matrix which has been tailored for confining them for the very long term.

If you do not have any recycling, what you have to deal with is spent nuclear fuel which has been tailored basically for producing kilowatt hours, not for confining the radionuclides for hundreds of thousands of years. And so, therefore, we have very different durability of the two materials of the two systems and much better and much longer confinement properties for the nuclear glass. And it’s directly related to the way this type of materials alter. So, I am not going into details of this picture, but just describe what are the mechanisms for the glass alteration. And you see that basically if your glass is within water, as it can be in geological disposal, there will be an alteration of the interface of the glass with the water, formation of gel layer which will act as a kind of diffusion barrier regarding the potential subsequent alteration of the glass, and therefore we will have a very low alteration rate.

If you look on spent nuclear fuel, still first impression, you have a much more complex picture. It's not because it's a different picture. It's in fact much more complex. You have first to consider what is here in orange which is in fact release mobile radionuclides in the range of 2% to 10% of your total inventory. So that's very relevant in particular because these radionuclides are highly mobile. And so it means that whatever you do, you have already a very significant part of the radionuclides which are within the environment.

And second, you see that the alteration of matrix is quite complex. It's directly related to the production of oxidants by the alpha radiation at the interface, the potential interactions with all the materials around. And depending on the conditions and in particular whether you have redox materials around, you may have in some conditions a high alteration rate. And so it means that it's very difficult to demonstrate the very long term stability whatever the conditions, and in particular in accidental conditions if oxygen arrives at the contact with the spent nuclear fuel.

So, second important difference, we have a much different long term toxicity. It's what is presented in this figure. You have the radiotoxicity as a function of time up to one million years. The orange curve corresponds to the spent nuclear fuel on the right, the green curve corresponds to nuclear glass on the left. And you see that by implementing the recycling, you are basically shifting from the orange to the green curve and you are basically gaining one order of magnitude in terms of lifespan if you try to compare to the uranium ore or in terms of radiotoxicity at a given time.

And therefore, in terms of confinement, if you are in the repository, you will find similar difference. So here, it's what we call performance assessment, so prediction of what could be the potential impact of potential long term, potential geological disposal in France on the site of view in measured time. And you see that once again the orange curve is spent nuclear fuels; the green curve is nuclear glass. And you see that be careful we are in logarithmic scale but you have basically one order of magnitude in terms of amplitude for the release. So, even in both cases, we are well below the regulations, well below the natural radioactivity, anyway, it means that the performance of nuclear glass is higher.

And last but not least, when you try to think about the repository resource which is also something we have to think about, it's difficult to find a repository, it's difficult to get the repository accepted and funded. So, you have to save your repository when you get one. And you see that with the recycling the surface area per amount of electricity produced is much lower by comparison of the situation without recycling. And the repository volume once again per amount of electricity produced is much lower by comparison to the case where we have no recycling. So, it means that by filling surface area you are preserving your resource, the given repository will be able to last longer. And second, by saving the repository volume you will decrease the cost of the repository, because in fact it's determining the cost due to the excavation operations.

So, it was for the third important drivers which was reduce the waste impact. The last one for the environment is to improve the environmental footprint. And so, when you think about environmental footprint, you need to think about global approach in which you try to integrate everything, so every facility which has to be in operation within the fuel cycle, so the mines enrichments, reactors or the geological disposal and so on. And for each of these facilities you need to consider the real lifetime of the given facility, so what we refer to as from cradle to grave.

So, in order to perform such assessment we develop a dedicated tool which is referred to as nuclear energy lifecycle assessment simulation. You have the reference here of the publication. And we apply this type of modeling work on the French situation due to the fact that first we have the whole fuel cycle which is available more or less in France. So, we have lots of information. And second, thanks to the French regulations, we have publications year after year of the global impact of each of these facilities, in particular in terms of energy consumption, radiations to environment, withdrawal within the environment, and so on.

So we combine everything together in order to have a whole picture for selected number of relevant environmental indicators of what can be the impact of nuclear energy on the environment in terms of environmental footprint.

So, what are the environmental indicators we worked on? We use generic indicators as in many lifecycle assessment studies. So the land use in terms of square meter per kilowatt hours of electricity, the water withdrawal and consumption, the chemical release in the environment, the technological waste and radioactive waste production, and also we use the maximum potential impact indicators which are here on the line. So, I mean the human and environmental toxicity, the eutrophication of the water and also the production POCP of ozone in the lower atmosphere. And last, but not the least, I forget, but we also calculate the atmospheric release in particular of greenhouse gases.

So, you can see there's a whole fuel cycle. I just remind you the whole fuel cycle, so the front end which we got from the mining activities up to the fuel manufacturing through the conversion until enrichment steps. You have here the flow. For the Europe reference, we use 2010. We have the decay storage after, then the reprocessing and the remanufacturing of multi-fuel thanks to the recycling of the plutonium and the reuse of repository uranium. And last but not the least, we have the storage and final disposal for the ultimate waste.

So, here are the results we get. So, let me explain to you how this figure works. In fact, we get some results for each of the indicators to find here for the nuclear energy system. And in order to compare to the other types of energy, we divide the literature, the data we find for the other types of energy in the literature by the results we get for the nuclear energy. So it means that if the data is higher than 1, it means that the other energy has higher impact than the nuclear energy. If it's lower than 1, it means that it has lower impact than the nuclear energy.

So, you have here the results for the greenhouse gases, for the SOX and NOX emissions in the atmosphere, the acidification, eutrophication of water, formation of ozone in the lower atmosphere, land use, water withdrawal and consumption, technological waste. And you see that we have the data for coal, oil and gas in dark green, photovoltaics in light green, hydropower in light blue, and wind power in dark blue. And you see that for many indicators, it was a surprise for us. In fact, nuclear energy is quite efficient and has a very low environmental footprint even sometimes we have comparison to the renewables energy which is very often thought to be the most cleaner energy.

And in fact, you see that in many cases, you have here the ranking. So, it's within one and third position, the only exception being the water withdrawal and it's directly related to the cooling of the reactor which requires a lot of water. But in fact when you look on the water consumption because you know that most of the water is reused after the cooling, it's still beneficial, because we are in the second position.

So, where does it come from, if I am digging a bit more in this type of result. So here you have the contribution of each type of the fuel cycle for the different indicators. You find the indicators here and you have the contribution. So, in brown, you have mining, in orange, conversion, in yellow, the enrichment, UOX fabrication in violet, you have the light blue for the reactor separation, the dark green for the reprocessing plant, the dark blue for the MOX fabrication, and the light green for the geological repository. And what comes very clearly is that the frontend activities in fact strongly dominate the picture. I mean with the exception of water consumption or withdrawal, most of the environmental footprint is related to the frontend activities. And by comparison, the backend activity is very low, so it means that several consequences.

First, if we want to improve the environmental footprint, you have two possibilities and not more. The first one is to improve the processes in the frontend and you can very efficiently save part of the environmental footprint. And the second is to reduce the flux which goes through the frontend activities and that's more or less definition of the recycling. And so, it means that higher the recycling or the most important the recycling will be, the lower the environmental footprint will be. And so, it's what you are going to see in the next picture which is a combination of different data that we calculated with such tools based not only on the current fuel cycle but also on the potential future fuel cycle with multi-recycling.

And so here you will find the results for the first situation where we have what I call the one full cycle. So, spent nuclear fuel is not recycled and considered as a waste. We have the twice full cycle where we recycle the spent nuclear fuel once in order to produce MOX fuel which is used in light water reactors. And we have the plutonium multi-recycling which is recycled in fast neutron reactors indefinitely.

And here is the evaluation of the environmental indicators. And you see very clearly that for all of them it's decreasing when you increase the recycling, in particular when you shift towards multi-recycling. And the improvement can be higher than one order of magnitude, for instance, of water pollution, the human toxicity, and so on. So, we have very beneficial impact on the recycling activity on the overall environmental footprint of the nuclear energy.

So, what about the radioactive release because I just described previously the generic general environmental indicators. In fact, when you are improving the recycling, you have a drawback – you have always a drawback somewhere – which is a contribution to the radioactive release in the environment, in particular in the atmosphere and so, it's what you can see in this figure. You see that 100% of the rare gases emissions for instance come from the recycling and so on. And so, it means that if you increase the recycling, you are going to increase this type of release. So, what can we say about that?

This release is directly related to these types of gases, so krypton-85, carbon-14, iodine-129, tritium for the liquid release. And we know from the operation of the current reprocessing plant, in particular from the La Hague reprocessing plant that the impact of such type of release is very low on the environment and can be neglected. In fact, a lot of health survey has been conducted around the reprocessing plant of La Hague and we also have a lot of impact study. And they all demonstrated even in very conservative assumptions that the impact in the range of 1% of natural radioactivity, which means in the range of 17 to 24 microsievert per year.

For the most exposed situation of population, we have a very conservative scenario. So it means that for sure, you have an increase of the release in the environment. This increase is in terms of becquerel, so it does not say anything about the impact. And when you have more precise assessment of the real impact on the environment, it's very low, and it's much lower than the natural radioactivity in the region.

So, it's what I wanted to describe regarding the environmental drivers which are in fact very important in the current population. You all know that the most important concern for the population based on the survey is really this type of issue. What about the societal drivers now? So, when you ask people what are the main drawbacks for nuclear energy or why they are not in favor of nuclear energy and so on, you find this type of result. So, here it's taken from an opinion survey from the French Research on Nuclear Safety, IRSN from 2014. And you see that the main first reason against nuclear energy is nuclear accidents which is in other words safety. The second is nuclear waste. I already mentioned a lot regarding this topic. We have then the facility vulnerability and the lack of transparency. So if we want to improve the acceptability, if we want to have a higher acceptance of nuclear energy, we have to think about how we can improve safety.

So, first in order to improve safety, we need to have independent and skilled safety authorities. That's something which is quite abused in many countries now. But we still have to remind this important statement. We need, second, to improve the safety of the reactors. Most of the accidents up to now occur in reactors. It's where is located most of the risk and that's the main driver for shifting from the current reactor generation towards the next generation, Generation III, in which we would have a decrease of the probability of the core fusion. So, it's one thing.

You can see in this figure here which has been taken to Mr. [Unclear] and you see here is the probability of the carbon age per reactor year as a function of generation of reactor. So, before TMI was here. And you have the improvement with the last PWR reactor in France here. And four, and you see the new generation of reactor EPR and so on. And you see that basically when you shift from one generation of reactor or one type of reactors to the next one, we are always trying to decrease the probability of core damage. So, that's a first a very important driver, but it's not sufficient.

Second, we need to ensure that we will not have any radionuclide released in the environment even when we have core fusion accidents and that we could therefore prevent any population evacuation. And that's was also a very strong motivation or driver for the development of the third generation reactor. And I am just taking here as an illustration, but it's not the sole one. The European Pressurized Reactor which has been developed by German and French design teams and safety authorities in the last decades and which are now in construction in Finland, France, and China, and they basically try to meet these very strong requirements which is quite different from the second generation.

So, it was for the reactors which is quite important because it's where is located many of the risks, but it's not the sole risk and we have also some risks in the nuclear fuel cycle facilities. So, it means that we need also to think about how we can improve the safety in the nuclear fuel cycles facilities so when we implement some process, for instance, the recycling process.

And I think we have two main directions in which we need to go if we want to improve this domain, the first to shift from empirical correlation to predictive phenomenological simulations in order to design and operate the process whatever they are and in order to make the safety assessments, safety calculations, and ensure that we will not have, whatever occurs, any release in the environment.

It also means that if we have such predictive tools, that we can shift from a procedure based piloting approach to a simulation based piloting approach which is much more robust towards any potential perturbations. So, I am just taking here an illustration of the type of development we are performing in France. It's directly applied here to the liquid-liquid extraction process, so the core of the PUREX process. And we developed for years now a dedicated predictive tool, the name of which is PAREX and it directly describes and accurately describes all the chemical and physical reactions which occur in such a complex system describing the chemical reactions by thermodynamics including the kinetics rate, the heat exchange with the environment, the simplified hydrodynamics and so on.

So, it means that based on these tools we can predict in any situation what's going to occur to our system and we can design our system in order to ensure that we will not go towards a dramatic situation. And it's probably not sufficient for the far future. We probably also need to move towards what is called a multi-scale approach. I mean in such a code here, part of the parameters are still derived from experimental data, so they can be biased basically by the experimental measurements.

And so, we also try to develop a multi-scale approach, the aim of which is to derive some of the parameters which are used in the thermodynamics calculations.

For instance here, you have an illustration for the activity coefficients directly from the modeling at the lower scale and in particular at the atomic and molecular scale. And by non-scaling [ph] approach here based on the Coarse Graining and BIMSA models which are able to directly calculate some of the parameters from modeling work and at the lower scale. And the interest of being at the lower scale is the fact that the chemical reactions, the phenomenon which occurs at this scale should be stable over time over different chemical conditions. And therefore, we can directly use this type of model in order to make predictions.

Well, so, the first important topic is safety. Second important topic is improve the waste management. So, regarding the waste management, we all know that the waste is severely questioned by public opinion. It's considered the Achilles' heel of the nuclear energy and it can be very clearly depicted here on, once again, the results of opinion survey on nuclear perception which is already 10 years old, but in which you see that if you have a solution for the nuclear waste, the proportion of the population that would be in favor of nuclear energy is much higher than the case where you have no solution. So, we have to find a solution for nuclear waste.

And when you look in more details what is the reason why population or people are against geological disposal and fear by the nuclear waste, it's directly related to the very long lifetime of the waste. And so it means that if we can find a way by which we are able to decrease the waste lifetime, it will significantly increase the acceptance of the nuclear waste solution. And therefore, the question can be translated to the following, can we reduce the waste lifetime in order to be back within the human history. Because of the waste – as you can see on this very nice picture, we have to handle and to manage radionuclides. Some of them have a lifetime much higher than the lifetime of the human beings on Earth. And therefore, it can't be based or it can't be understandable by any people when you are dealing with such long period of time. You need to find the solution which remind us or which is located within the human history which can be understood, but not within the Earth history. And so, it was directly the motivation for the development of the recycling of minor actinides, because in fact when you look in details of what is responsible for the radiotoxicity of spent nuclear fuel as a function of time up to 1 million years – so first you have to plutonium in orange, but it's already recycled; and second, you have here the americium and curium, the minor actinides.

And so if we are able to recycle these types of elements, it will decrease the waste lifetime and toxicity. And by the way, it will also decrease the hit power or residual power of the waste and could allow to have a much denser repository. And it's still a significant contribution to the preservation of the repository.

So, such an option can be directly applied in fast neutron reactors even in homogeneous recycling approach in which you are including minor actinides at low concentration in the whole fuels or as heterogeneous recycling options in which you are separating a dedicated flux of minor actinides that you can use in order to produce specific blockade to be irradiated at the boundary of the fuel core. I have to sort of mention that accelerated drilling system can also be a solution in particular if no fast neutron reactors are available.

So, in order to answer these types of developments, very significant research has been developed in many countries, in Europe, in the United States. And basically we have these two types of approaches which are available. So, the first one is based directly on the homogeneous recycling which first assumes that we have a separation of uranium, then the recovery of plutonium with minor actinides. And for the heterogeneous recycling, we are first to recycle or to separate uranium and plutonium by PUREX or COEX like processes, then to operate a two-step separation which is based on the DIAMEX, SANEX approach and which has been very significantly improved since the first development in the 90s and which are usable now in one step to directly recover americium and curium or americium.

So, I apologize. I am trying to get the picture on the screen, but it seems not to work anymore. I hope you have the PDF file in order to follow. So, I am shifting now to the slide 29. I don't know if Berta or Patricia can correct the situation. So, on slide 29, you have a synthesis on the beneficial impact of the recycling activities on the waste management. And you have two pictures, the first one on the path illustrates the way the recycling from orange to green, then green to blue curve allows to decrease the lifetime and toxicity of the waste due to the fact that you recover plutonium, then you recover minor actinides.

And second from the figure below, you have the impact on the overall volume of the waste, so in red the high level waste, in green the long life intermediate level waste, and you see that in fact when you are implementing the recycling, so you are shifting from the right to the left, you are very significantly decreasing the amount of high level waste, increasing the amount of long life intermediate level waste, but it has very strong advantage to decrease the repository surface, which is a violet curve and it decreases the repository volume which is the blue curve.

And you see that when implementing the mono-recycling, you are already saving a lot in terms of repository surface and volume. And if you are shifting towards the recycling of the americium, so the minor actinides, which is the last figure on the left, you are still saving a lot regarding the volume and surface of the repository.

Okay. So, it was all what I wanted to say regarding the societal drivers. Let's move to the final chapter which is the economic drivers. So, if you can shift to page 30. I want to say first that the economic optimization is the root of the research and development for the industry and of the industrial process. So it means that in fact it's already included in any of the developments which is performed. Anyway, if we want to move forward, the first important step is to ensure that we have a stable and predictable cost, what you see on the left. And I want to say that the recycling is decreasing the dependence to the uranium market and to the potential volatility of uranium cost.

It's directly related to the fact that when we plan on the recycling activity, you are decreasing the amount of natural uranium which is needed in order to figure systems. And so it's what you see on the figure here on the left. You see that the four types of reactors points on to the four types of generations. You have the first generation, natural uranium graphite gas; you have the second generation, the current PWR; you have the third generation, EPR; and you have the fourth generation, fast neutron reactors. And you see that the amount of uranium which is needed is strongly decreasing. And in fact here you are with fast neutron reactors where you have a lot of recycling. You only need one ton of uranium in order to produce 1 gigawatt of electricity. It's very low and so it means that you are going to be more or less dependent on the uranium market and it's something which is an important driver.

Second, we have to ensure that the costs are affordable. So, it's what is on the right side of the slide. And I want to stress also that the backend cost is quite limited and it has a limited influence on the overall kilowatt hours cost. So you have here a picture which is more or less the cost that we have currently in France. And you see that the recycling activities are in the range of 2.9, so let's say 3% of the total cost, which is not so high in fact and which can be affordable by the industry and by the whole economic system.

If we want to decrease the cost of the nuclear energy, because I know that's an important question for the future and in particular due to the fact that renewable costs are decreasing very fast. We have to think about simpler processes and in particular for the recycling processes. And we have to keep in mind that nuclear industry is still young and complex and so we have still a lot of room for improvement. And I am just taking here one illustration, but you have to keep in mind that many illustrations can be given.

Here for instance for the recycling step, for the core of the recycling, the separation, we are able to design in the future a separation process in one step without any involvement of redox reactions which are more complex to master. And such a type of process, it can be very flexible. I mean, we should be able to treat light water, but also fast neutron reactor fuels without any deletion. We do not need anymore any chemical wagons which are not environment-friendly. And we have a much simpler process. Only in one step we can get the same purification efficiencies than what we do in three steps currently in the current industrial plant.

So it means that it's potentially very significant improvement for the investment and operation cost and it clearly illustrates that we have a lot of potential improvements in terms of economy for the future.

So as a conclusion, I will try to draw for you what could be the potential rationale for future nuclear fuel cycle in view of sustainability. So, on my mind the first step is the plutonium mono-recycling, but you have to keep in mind that's not the final step, so do not assess what is the advantage of recycling just based on the situation. That's the transient stage. It's already allowed to have the first step towards uranium resource saving and an efficient waste conditioning, but it's not yet sufficient.

So, if we want to go further, we need to move towards plutonium multi-recycling. For that we need to change the type of reactor, which is the main breakthrough. We need to develop the fast neutron reactors. And it would allow to have major improvement in terms of natural resource saving, energy independence, and economic stability.

And if we want to still go further, we can move towards plutonium and minor actinides recycling, so minor actinides for transportation. And the breakthrough in this situation is the fuel cycle processes. You need to be able to separate the minor actinides. And the main incentive is not anymore technical or economic incentive or whatever, it's only to decrease the waste burden towards the future generation to optimize the repository, and by the way to increase the public acceptance. So it means it will not change the overall safety of the nuclear energy system but it will decrease the waste lifetime and it will improve the public acceptance.

So, as conclusion, sustainability is an efficient framework for deriving a robust roadmap for future nuclear fuel cycles, because it implies to consider from the early beginning non-technical issues like the societal issues, like the environmental indicators in the overall balance. The future will be an overall tradeoff between the economic, the environment, and the societal drivers. And if we want to be able to handle such a complex decision-making process, we need to have some indicators or figures of merit for enlightening the respective benefit of the different options.

And so, I just remind you that we go through some major drivers for each of the pillars of the sustainability. That's not the only one for sure, but just reminds that nuclear energy has already very low greenhouse gases emissions, has already a very low environmental footprint, is able to preserve natural resources very efficiently. We are able to develop a nuclear energy system with much lower waste volume, toxicity, and lifetime. And the implementation of the recycling can improve a lot the long-term overall environmental footprint.

For the economy, nuclear energy can be used in order to produce base-load electricity. It has been demonstrated in many countries. We can have long-term predictable cost thanks to the recycling which allowed to cut the link with the uranium market basically. The recycling cost is affordable but can still be decreased probably, thanks to the process simplification.

And regarding societal acceptance, we have to improve the safety by design, to improve the safety by simulation and understanding the phenomenon which are involved in all the processes all around the fuel cycle, and we can also improve the acceptability by decreasing the waste burden towards future generation by actinides recycling.

And based on this presentation, you see very clearly that on my mind, the actinides recycling is really the keystone of any sustainable nuclear fuel cycle and you all know that keystone is quite important for the construction in the past and in particular for the old abbey or church as on the picture on the right.

So, I thank you all very much for your attention and I will be very pleased to take your questions and I want to also take the opportunity to thank my colleagues which were involved in this overall fruitful thinking about the future of nuclear energy, Stephane Bourg, Bernard Boullis, and Stephane Grandjean. Thank you very much.

Berta Oates
Thank you, Christophe. If you have questions for the presenter today, please go ahead and type those into the Q&A pod. And while those questions are coming in, we'll take a look at the upcoming webinars. Next month, in January after the 1st of the year, a presentation on the Design, Safety Features, and Progress of HTR-PM by Professor Dong from China, in February, Gen IV Reactors' Materials and their Challenges, a presentation by Dr. Maloy from the USA. And in March, a presentation on

SCK-CENs R&D on MYRRAH and that will be presented by Professor Abderrahim from Belgium. Dr. Warin has a comment of this post.

Christophe Poinssot
Okay, I think we shift to the questions. So, we have the first question.

Berta Oates
Yeah, Dr. Warin noted you have very well explained the advantages and inconveniences of different energy sources, and the level of information for people is directly connected to the level of support of nuclear energy. Don't you think the nuclear energy experts should produce large audience television shows or even movies which explain and demonstrate the advantages of nuclear energy? We'll have to resize the screen a little bit. I don't see the bottom of that comment.

Instead of the existing shows...

Christophe Poinssot
...instead of the existing shows that only present systematically the supposed threats of nuclear energy. So, that's a very good question in my mind and in fact there is a lot of possibility in terms of improvement in this domain, but it's not so easy. And we had a very good demonstration some years ago. I guess some of you or many of you may know the movie, Pandora's Premise, which has been produced 2 or 3 years ago, maybe a bit more. And so it was a very interesting movie. In fact, it describes the way some opponents towards nuclear energy just change their mind when they just go in more details about the supposed drawback of the nuclear energy. And just it demonstrates basically at the end that we have to make a choice between either trying to mitigate the global climate change or trying to close the nuclear energy, but we can't do the two together.

Well, I am not here to describe the movie. But I just want to say that in fact when you have such a movie, it's very difficult to have it accessible to many people. And I just know that the movie was not – for instance, it was not possible for the movie to be broadcast on French TV, because French TV companies were not in favor of presenting such a movie. So, the question is not only how the experts or the specialists can communicate and give more information. We have also an important question to know how we can have access to the communication media and television, newspaper, and so on, in particular considering that in many situations you have a few minutes or a few sentences to explain your position. And we all know that nuclear energy is very complex and it takes much more time if you want to address these questions and to explain much more to the population.

Last but not least, I want just to stress one point which is quite important for me. I think the future is within the young generations. I mean for sure we need to communicate in mass media and so on. But we also need to be much more present in schools, universities, engineering schools, and so on in order to explain more in detail what is really nuclear energy and what it is not, and try to kill some of the dreams or some of the threats which are just not true. I am in fact involved a lot in this type of teaching and just realize that it's very efficient. But it will take time, because it means that it will take years for people to change their mind year after year. But that's a very good question in fact.

Berta Oates
Thank you. That's the next question about thorium reserves. Thorium reserves are at least a factor of ten greater than uranium reserves. How will the use of thorium fuel reactors change the economic and environmental benefit of nuclear power production?

Christophe Poinssot
Well, that's a very good question. We have very often some questions regarding thorium. So, first, that's right that thorium is more important than uranium on earth. That's for sure. It's not located in the same areas, which means some country have access to uranium, some of them to thorium, and it makes plain part of the difference of positions of the different countries.

Second, thorium is very often thought to be very beneficial because of lower amount of ultimate high level waste or this type of argument. I just want to say that it's not fully true, because when you make much more detailed description of the different types of radionuclides which are present, you have really to deal with, for instance uranium-233 and their protactinium decay products. And so, for sure, thorium can be developed, but it's not much more easier than uranium fuel or uranium fuel cycle or uranium based systems. And I think when one country already starts with uranium, if it has access to uranium, it's probably much more beneficial for it to stay with uranium, at least for some decades instead of shifting to thorium which will require very significant change in terms of technology, in terms of processes, plants, and so on.

And final point, just keep in mind that thorium is not fissile. So you need first a fissile element in order to feed and transform thorium to uranium-233, which is a fissile element. So it means that you can't start from scratch with thorium. You need a source of neutrons to transfer thorium to uranium. And it's very well described by the Indian situation, for instance, which aims to increase the amount of fissile materials first before shifting to thorium.

Berta Oates

Thank you for your feedback, David. There's a question. Are there collaborative discussions that you are aware of occurring between countries that allow reprocessing in the US? If so, can you characterize the level of interest?

Christophe Poinssot
For sure there is some contact between the different nuclear countries I think that's of use. I don't know whether there is contact and discussions regarding the reprocessing. I can just say that reprocessing is included in France in our law which has been voted in 2006 and it's really the basis for the nuclear energy production system and it is a source, a route for development of fourth generation. So, any country willing to move or to shift towards fourth generation will require to have reprocessing activities or recycling activities. Okay?

Berta Oates
There's another question regarding this. Do you see them? Will thorium play any role in the future of nuclear fuel cycle?

Christophe Poinssot
That's a good question. It really depends from one country to the other, I guess. I am not sure we will shift for instance to thorium in France because we have already access to uranium. We have already a large stockpile of depleted uranium, of fissile materials, which means that we will be able if we want to produce electricity based on the plutonium material recycling and the depleted uranium stockpile for thousands of years. So, we have no question to access to the natural resource. But the situation is quite different in India, and India for instance plans to use thorium which is present in India at high stockpiles. So, yes, I think in the future we will see probably some thorium nuclear fuel cycle appearing and playing a role in parts of the world. I am not sure any country is aiming to have exactly the same nuclear fuel cycle.

Berta Oates
Thank you. What is the effort of the IAEA on the education of a society with high level of illiteracy on the acceptance of nuclear energy?

Christophe Poinssot
So, the question should be addressed to the IAEA. I am not living in the IAEA. I can just say that for sure IAEA aims to develop the safe use of nuclear energy. And so, based on this strong motivation they are producing high level documents in order to educate people, in order to communicate about the advantage of nuclear energy, and also in order to prevent any potential use, non-civilian use. So, they are contributing a lot to the education of the population. More in detail, you should ask the question to the IAEA.

Berta Oates
There is a follow-up – discussion of specific efforts for non-proliferation.

Christophe Poinssot
Excuse me.

Berta Oates
There was a follow-up to that same question. Secondly, what specific effort is tailored towards containing the issue of non-proliferation?

Christophe Poinssot
Okay, so a very important question, in fact. So, we all know that we are not living in a safe world I will say and so we are for sure taking into consideration the potential threats coming from the terrorism or whatever activity. So, it means that any nuclear site is very well protected and you will very well understand that it's not public information. So, I will not go into much more details, but for sure the risk is taken into account.

Berta Oates
There's a question. How about transmutation of actinides by placing spent fuel in the periphery of the fast neutron reactors?

Christophe Poinssot
I went a bit fast in this part of the presentation because I had no slides on my screen at that time. But when you move back to the slide 27, in fact it's what is called the heterogeneous recycling. And so, there have been lots of activities in many countries, in France, in Europe, in the United States based on this approach and they were directed in two directions. So the first one was to develop a dedicated separation process for that and we have the family of DIAMEX SANEX separation process which are quite efficient to perform such a separation. And second, and I did not detail in my presentation but there has been also a lot of work on the behavior of this type of fuel in reactors, what about the transmutation rate, what about the evolution of the fuel micro-structure with high minor actinide compounds in the range of 20% and so on.

So yes, it is feasible to transmute the minor actinides at the periphery of the fast neutron reactor in minor actinides bearing blankets. So, that's more or less the reference in fact scenario for many countries. And there is a lot of literature which is available and a lot of experimental results in order to support this option.

Berta Oates
Thank you. I think that was the last of the questions that have at least come in thus far. I thank you everybody for your attention. Thank you again, Christophe for your marvelous slides and energy in putting this presentation together. Amanda, thank you as always for running the

show behind the scenes, and Patricia and John Kelly as well. Thank you, all.

Christophe Poinssot
Well, thank you all for being online and for your attendance to this presentation.

END