General Considerations on Thorium as a Nuclear Fuel
Dr. Franco Michel-Sendis, OECD / NEA, France

Berta Oates
Welcome everyone to the next GEN IV International Forum webinar. I apologize for our delay this morning. We are getting started a little bit late, we're having a little bit of connectivity issues with our presenter who is joining us today from France.

By way of housekeeping, kind of a few things. There is a Q&A pod that you can type questions in, during the presentation if you should have any questions. We will address the questions at the end, as time allows. There is a file pod that if you'd click, the PDF slide deck will download directly to your computer station.

And we, as always, welcome your feedback and invite you to participate in an online survey and there is a link in the notes pod that'll take you directly to SurveyMonkey, where you can provide feedback. We appreciate the feedback and we do endeavor to make improvements with each of the guest webinars as we move forward.

With that I think we will go ahead and get started with today's presentation. Doing today's introduction is Dr. Patricia Paviet. She is the Director of the Office of Materials and Chemical Technologies at DOE-NE, and she's also the Chair of the GEN IV International Forum, Education and Training Taskforce.

Patricia Paviet
Thank you, Berta, and welcome everybody.

It's a pleasure to have here today Dr. Franco Michel-Sendis, who agreed to give the webinar. He is responsible for the co-ordination of Nuclear Data Services and Criticality Safety Activities at the OECD-NEA under the Data Bank and the Nuclear Science Division, since 2010. From 2011 to 2016 he also served as NEA scientific secretary to the Generation IV Steering Committee for the Molten Salt Reactor System.

Dr. Michel-Sendis coordinated the 2015 NEA report, 'Introduction of Thorium in the Nuclear Fuel Cycle.' He holds a B.Sc. and M.Sc. in physics from the University of Paris and a Ph.D. in Nuclear Reactor Physics from the University of Paris-Sud Orsay.

Thank you so much Franco for volunteering to give this seminar and I give you the floor.

Thank you, again.

Franco Michel-Sendis
Thank you Patricia, thank you for having me and thank you everybody for attending.

First of all, I would like to start by saying some words about why it is that we are talking about thorium today. There is no doubt some of you may have noticed that the use of thorium as a nuclear fuel has become a fashionable topic in recent years, again. This topic often provokes a debate between thorium proponents against thorium opponents that sometimes unfortunately takes place outside of the scientific arena for its most visible part, and that is the one taking place in the general media.

So there's this situation of low signal-to-noise ratio about the thorium question. And this can be perhaps understood by considering the fact that if you take a step back, we are a generation that presently has to face in our lifetime a very complex and extremely important problem. And that problem is the one of quickly solving the planet's energy challenges while meeting climate goals of decarburization of energy – all that in a rather distressful post-Fukushima context for nuclear energy when the solutions that can be proposed are sometimes already late, meaning that there this added sense of urgency for action.

So when faced with such complex problems, the prospect of finding a miracle solution that just needs to be deployed is a concept that is very appealing to the mind. And if you could see this context in our internet era where information can be spread around very quickly by non-specialists, then I would say that we have all the necessary ingredients to create a balance. It is not my intention to take part in this anti versus pro-thorium debate but rather to give you the scientific basis today of why thorium can be interesting, but also to make you very aware of the many challenges that it's facing.

A key aspect of one of those challenges is how long it will take to develop and deploy thorium fuel technologies for them to be able to play a part of any solution. So is thorium a new miracle solution that is somehow the ‘super fuel’ that is cheaper than coal, which could have prevented Fukushima? Well, certainly not. And when you see these kind of publications, I would say that rather than to educate the public, their target is just to sell their own books. So it would be a euphemism to say that misconceptions abound in the general media.

Now, is thorium a trendy subject? These are just two graphs that I put one next to the other. I don’t know if there is any relationship between them. But on the top one, you can see that the worldwide monthly popularity of the search term ‘thorium’ over time for the past 15 years in percentage of the maximum. And in the picture below it is the evolution of uranium spot prices over time are given by the International Monetary Fund.

Now, you can see that in the beginnings of the year 2000, just when the nuclear renaissance period was at its best and when uranium started to become very expensive, you can see a surge in the popularity – at least in the search term popularity for 'thorium' around the year 2005. I don't really explain why there was this surge around that year. But what I also I notice is that around March 2011, the all-time popularity peak for 'thorium' at least in Google trends was reached and this corresponds of course with the Fukushima incident.

So this illustrates just the point that 'thorium' becomes trendy whenever we are considering an alternative to uranium or an alternative way of making nuclear energy that is sometimes perceived as dangerous.

The purpose of this 1-hour talk is only to give the audience a series of general elements around which you may build your own understanding of the question. So I will spend probably half of the presentation talking about the general scientific background on neutronics, talking about fissile/fertile nuclides and cycles. I will not do a lot on the historical context of thorium development and I will give some general considerations on different aspects that are key to understanding the potentialities of any fuel cycle, really.

Let's start from the beginning. All nuclides heavier than hydrogen – and that really means all nuclides – are created in stellar nucleosynthesis processes involving fusion for the light to nuclides and neutron-capture for the heavier ones. Nuclides heavier than lead are formed by very rapid sequential neutron-capture processes that can only take place in neutron fluxes that are so high that they are only found in the supernovae. The fluxes involved in these so-called *r*-processes are many, many orders of magnitudes higher than the neutron fluxes found in a nuclear reactor, whatever its kind.

So I would say that it is perfectly accurate to say that the actinides that we can find on Earth, were created long before the creation of our own solar system and that this inventory was fixed somehow at the creation of our solar planets, and has been decaying ever since. In particular, a concept that we can easily relate to is the internal heat of our planet, a significant fraction of which is produced by radioactive decay of the uranium and thorium isotopes that are found in the composition of the Earth's mantle and core.

There are thousands of nuclides that we know of, most of which are unstable and decay with different modes for varying half-lives. This graph represents the familiar shape of the nuclide chart that classifies nuclides according to the number of neutron on the X-axis, and protons on the Y-axis and where each dot represents a nuclide whose properties have been measured. The color code here relate to different categories of half-lives depending on where each nuclide falls, ranging from milliseconds to billions of years.

I appear to have lost connectivity. Bertha, can you forward the next slide where we have the mention of the nuclide chart? Thank you. I'm back.

So we have made this chart by going from very short half-lives in red, to very long half-lives or stable nuclides that are depicted in black. We see that all nuclides came down into what is called the 'valley of stability.' What is represented here in black are nuclides whose half-life is graded at 1 billion years or that are stable. It is in this black series represented here that all isotopes naturally present on Earth in significant quantities are found, since our solar system was formed between 4 billion and 5 billion years ago.

We notice in the upper right corner of the chart two dots that are separate from the group and that represent the most massive nuclides naturally found on Earth. They belong to the actinide family and are uranium-238 and thorium-232. Another important actinide, uranium-235, is not represented here since it didn't make the cut in the representation of the 1 billion-year half-life threshold. The half-life of uranium-235 is only 700 million years and that also explains why its proportion in the uranium mineral is so small. It is because it decays much faster.

The two isotopes of uranium and thorium are the only three actinides found on Earth. Now, we also know from our understanding of the forces that tie nuclides together and of the resulting bonding energy per nucleon, which is represented here in the upper left, that only very heavy nuclides can fission and release energy by doing so.

So if we were to look for candidate nuclides to be good fissile nuclides, we would necessarily have to look among the massive ones. It so happens that out of the three actinides that exist on Earth, only one is fissile with thermal neutrons and that one is the shortest lived of all three – it is uranium-235. So I have always found remarkable even if today we understand very clearly why that is so, that out of the thousands of nuclides that can exist in the universe, there is in fact only one found on Earth that would allow us to start any nuclear energy era.

In fact, we could say that the existence of nuclear fission technologies was a question of timing in the history of humanity on this planet. Had we been 2 billion years late, uranium-235 would have only been present in very small trace amounts; much more rare, more difficult and more costly to mine. In fact, if we had been 2 billion years before, the isotopies of natural uranium would have been much more favorable and very similar to what is found in present-day enriched uranium fuel that is needed for light-water reactors, so that means between 3% and 4% of uranium-235 in the uranium mineral.

This was demonstrated by CEA in France in the 1960s in somehow of an interesting story where routine chemical isotopic measurements of uranium samples extracted from a mine in Oklo in the Gabonese Republic, found an abnormally low uranium-235 concentration. This was initially thought to be a mistake in the measurement. But it was later confirmed to be correct with subsequent investigations and it was therefore proven that a very long-lasting and very low-powered continuous fission chain-reaction had occurred naturally and without any human intervention inside the mine, where neutrons had been moderated by phreatic water currents at time in history where the natural enrichment of the uranium mineral was 3.6% of uranium-235.

So the existence of facts within the mine where natural fission reactor occurred was later confirmed by showing the existence of trace amounts of fission products. So it is clear that uranium-235 is the only possible match we have to start nuclear industry.

In a moment I will explain the concepts of fertile and fissile nuclides. You may think of fissile matter in a reactor as the ‘match’ that allows you to initiate woodfire. And once the woodfire was started, you could always keep it running under certain conditions by adding more wood. In this very limited metaphor, the wood would be the fertile nuclide and the woodfire would be a functioning reactor. But you will always need a match, fissile material, to start the fire.

So there's this false notion around that somehow the industry chose to develop the uranium fuel cycle in detriment over thorium fuel cycle from the start and that is something that is very naïve and very easily discarded. Today because we now happen to have fissile inventories that can be made available, we may consider the use of thorium but always necessarily with an external fissile input that cannot be found in natural thorium. Thorium has no fissile isotopes.

So let me go back and make that point very clear. Now, uranium-235 mean no nuclear fuel cycles of whatever kind would have been possible. Because it also means no fissile plutonium as plutonium is created in reactors. And if there is no fissile uranium and no fissile plutonium, it means there is no possibility at all, of whatever kind, of using thorium as a nuclear fuel. So the existence of today's nuclear industry and of any future nuclear industry is only made possible by the existence of uranium-235.

So let's go back to our three actinides naturally found on Earth, which are displayed here as scores on the top of this slide. We have the two uranium isotopes 235 and 238 and thorium-232. They have different half-lives which like we said also directly impact their abundancies on Earth. We will come back to this question of thorium resources, but for now let's say that thorium is known to be abundant, that is not an issue.

But only uranium-235 is fissile. I am representing in this graph in the lower right the neutron-induced reaction cross-section of uranium-235, which is an estimation of the likelihood of nuclide to undergo a given reaction – in this case the fission reaction – upon the impact of nature.

You will notice the logarithmic axis in both axis, in this and other figures that I will be showing. And that gives you an idea of a very broad range of energies and cross-section magnitudes that can be considered.

Now, I would like to take some time to explain an important concept that is central to the idea of regeneration of fissile matter within a reactor. Neutrons can not only trigger the fission of fissile nuclides, they can also be absorbed by nucleus in a process that is called 'radiative neutron capture,' where the absorption of the neutron is followed by the emission of gamma radiation. This reaction is represented here by the symbol 'n, γ.'

Let's focus on the actinides that do not fission on the thermal neutrons – they are the two on the right. Under neutron irradiation, they will absorb a neutron through radiative capture, transforming themselves into a short-lived isotope, which will undergo better decay. Notice how this sequence of neutron capture and two consecutive better decay results for both uranium-238 and thorium-232 in the creation of fissile isotopes, which are respectively plutonium-239 and uranium-233. Because they can result in the production of a fissile isotopes through the absorption of one neutron, these two nuclide: uranium-238 and thorium-232 are called 'fertile.'

This process establishes an important relationship between a given fertile nuclide and its resulting fissile isotope, which is at the basis of what we call the 'uranium-plutonium fuel cycle' on one side and the 'thorium-uranium-233 fuel cycle' on the other side. And this is the way these two fuel cycles have the potential to become self-sustainable in terms of fissile inventory needed.

Now that we have established the similarities, let's focus a little bit on the differences. Notice that if the process is exactly the same in the case of uranium-238 and thorium-232, there is one significant difference to highlight. The immediate paired nuclide that will decay into uranium-233 is the nuclide, protactinium-233, which is 10 times more long-lived than the immediate [Unclear], plutonium-239, which is neptunium-239. So it's a little bit of a 2 days half-life for neptunium-239 in comparison to almost a month half-life for protactinium-233.

What does this mean? This means that by existing for a longer time in the reactor, protactinium-233 has much more chances to capture a neutron and not to decay into fissile uranium-233. Now added to this longer half-life is also a higher capture cross-section that in the case of neptunium-239, in particular above thermal energies, protactinium-233 captures more. This is represented in the graph on the upper left. So this higher loss of fissile creation by protactinium capture has to be taken into account when considering thorium-based fuels.

Now there can be some strategies imagine which basically will insist on taking the protactinium out of the neutron irradiation, either by targeting shorter burn-ups or for the more advanced reactor concepts which use liquid fuel, establishing online chemical filtering of protactinium. As you may understand, these different strategies all represent very different challenges.

Now, let's go back to – let's say that we have irradiated either uranium or thorium and that we have somehow recovered two corresponding fissile isotopes that have been created – so, plutonium-239 and uranium-233, respectively. This graph shows here the comparison of fission cross-sections of these two nuclides in comparison to uranium-235.

Now I am showing here the same graph in an enlarged energy range also covering the five neutron energy ranges and also considering the cross-sections of radiative neutron capture reactions, which are shown at the bottom, which are very important to consider for fissile nuclides as well as they are in direct competition with fission. Let's highlight the two important energy regions where nuclear reactors typically operate. The fast energy regions for fast reactors is centered around 2 mega electron-volts and a typical thermal neutron energy region is usually way below 1 electron-volt.

The first thing that we notice is that nuclear reaction cross-sections, in particular fission and capture cross-sections exhibit a similar structure. So we have this middle part, lower energies. Then you have a resonant part at intermediate energies, here and there some individual resonances which can be very important. And then, again, a smoother part at fast energies.

The second thing that we observe is that in order to make any sense of this, any qualitative assessment on which one of these three nuclides is a better fissile, it really would depend on looking rather at the ratio of these two competing reactions. And I will show later a graph showing a function of this ratio. But it also greatly depends on which neutron energy range you are looking at. So that means in which neutron spectrum is your reactor going to operate? And we will see in a minute that the two fuel cycles, either thorium or uranium, do exhibit some differences depending on which neutron spectrum we consider.

But before we do that, let me just say one comment on neutron-induced fission. Here are three graphs that show very relevant nuclear data quantities that are essential, among many others, to our understanding and modeling of how reactors operate, and they are observables that are directly linked to the fission phenomenon.

On the upper left I have represented the fission product distribution resulting from fission of different nuclides – uranium-233, uranium-235, uranium-238 and plutonium-239. Now, I don't know if you can see which one is which, but the first thing to notice is that they all exhibit similar shape with some difference in the lighter mass peak on the left.

And we know the total power output of any reactor being directly proportional to the fission rate that is imposed on the system. Please note that in terms of fission production base, very little difference regardless which fissile nuclide is considered.

Consider the following graph on the bottom left. Fission fragments will emit neutrons. And this is a typical saw-toothed shape of neutrons emitted as a function of the mass number of the fission fragment. This is an essential contribution to the total average number of neutrons emitted per fission, usually called 'nubar' and which is shown on the right as a function of neutron energy.

The first thing to notice is at baseline, that is the green curve, that is clearly above the others. It corresponds to the average number of neutrons emitted by the fission of plutonium-239. The other three curves are closer together but all of them stay clearly above the value of 2. And this fact, the fact that nubar is greater than 2 has huge implications, which we will briefly mention now.

The first of them is that under the right conditions, a pile of fissile material can become critical and sustain a continuous fission chain reaction. This is why therefore they were called 'reactors.'

It is interesting to note really that this word 'nuclear reactor' did not exist from the beginning. They were called 'piles' in the 1940s.

Now the fact that nubar is greater than 2 makes the concept of 'breeding' possible. What is breeding? A breeder reactor is a reactor, which compensates the loss of fissile material burnt to during normal operation by making sure or enable that an equivalent or higher amount of neutron-captures in the fertile nuclides happen since this will result on first approximation in the creation of fissile nuclides and will therefore compensate the initial fissile losses.

Now it can be easily demonstrated that again on the first approximation, which is not position [ph] but a necessary condition, it can be shown that breeding can only be possible when the following quantity displayed here – and the quantity is nubar minus 2 factor of 1 plus alpha, alpha is the ratio of the captured to fission average cross-section values for the fissile nuclide when this equation is greater than zero.

Now, this simply states that there needs to be enough neutrons left after fission to compensate the fissile losses. It doesn't ensure that these neutrons will end up being absorbed by a fertile nuclide. But certainly if this quantity is negative, then certainly breeding cannot happen. The neutron economy will not allow for it.

Now this quantity is interesting because it only depends, like I said, on the properties of the fissile nuclide and because we can plot it as a function of neutron energy for both of the fissile nuclides of interest which relate to both fuel cycles. So this is what I am showing in this graph here, uranium-233 for thorium fuel cycle and plutonium-239 for the uranium fuel cycle. We display here the same quantity in continuous energy and using a multigroup energy structure for easy readability as it is usually hard to make any sense visually of the resonance region.

So we see that the green curve, which represents the thorium-uranium fuel cycle stays above zero although not by a very large margin, meaning that neutral economy theoretically allows breeding but remains very tight while that is not the case for the blue curve, which represents the uranium-plutonium fuel cycle which becomes clearly negative at thermal and intermediate energies. But on the other hand, it's clearly superior in the fast neutron energy range. I am highlighting the two energy ranges here.

Now this is just some calculated numbers of the previous graphs in what I call the ‘quick and dirty napkin calculations’ just to show orders of magnitude.

Here are the choice for spectrum and it's perhaps not the best because I did it with Maxwellian Thermal and fission-spectrum which are not really neutron distributions found in reactors. But it is what I have in hand to illustrate the point.

So we see that a positive number of neutrons available for breeding in the case of plutonium-uranium fuel cycle and are much more favorable value for the uranium-plutonium fuel cycle in the fast range. And an almost no and very often negative value for uranium-plutonium in thermal spectrum.

Here's another interesting quick and dirty calculation that we can do in order only to see potential differences in the orders of magnitude between both cycles. And the quantity relates to the initial concentration of fissile matter that we need to establish breeding. And this directly relates to the amount of matter needed to start a breeder reactor and is therefore a very important parameter.

Now, if we suppose that breeding conditions are true, then we can suppose on a first approximation again that the equation on the top is true that the rate of capturing in the fertile nuclide equals the rate of losses of the fissile nuclide.

Now it is easy to show that this establishes a relationship between the concentrations of fissile matter as a function of the cross-sections of the nuclide in the fuel that will depend on the average cross-section values and therefore of the neutron spectrum considered. This is the quantity that I am representing here, this quantity called 'C *fis*,' concentration of fissile.

Now this is something that we can also plot as a function of energy and this is what I am representing here where we see that the values for the thermal region – I am going to try to grab the arrow – the values for the thermal region for the thorium fuel cycle are around of the order of 1% whereas the values found for breeding conditions for both fuel cycles in the fast energy spectrum are more of the order of 10%.

Notice however that since we established this expression assuming breeding, since the neutron economy of the uranium-plutonium cycle does not allow breeding condition, the red curve in this region here, in the thermal region does not really represent anything and should be ignored. So what we have established is really lower concentration of fissile theoretically for the thorium fuel cycle and higher ones in the frankly football [ph] cycles in the fast region.

If we run some numbers again, which simulate the neutron spectrum for this quantity here are the values that we found which confirm our observation, around of a value of 2% for thorium-/uranium-233 fuel cycle and there's another thermal column for uranium-/plutonium-239 since it does not allow breeding and we see that similarly 10%-11% theoretical values for both fuel cycles in the fast energy range. Of course, this is only true provided all other technological and safety aspects allow for it.

So by now we have established that there could possibly be a thorium thermal breeder and why is this such a big deal? Well, we have theoretically established that two important advantages of the thorium fuel cycle that are clearly behind the historical interest in thorium. One is that breeding conditions can exist in thermal spectrum for the thorium-/uranium-233 fuel cycle and this is important because thermal neutron technologies are the existing technologies that we know are very developed and we have more operational experience at the time and still today, although today fast breeder reactors exist.

And second, because in the case that they have demonstrated, it could be expected that the initial fissile quantity needed to start such breeder reactors could potentially be much lower than the one needed by fast breeder reactors.

So these really are the reasons that in my view motivate the study of the thorium fuel cycle and that have motivated the study of thorium fuel cycles since the beginning of the nuclear energy era.

We should, however, highlight again, in order to be fair that the uranium/plutonium fuel cycle clearly exhibits a more favorable neutron economy in fast spectrum. So let's keep these aspects in mind as we now leave the pure neutronics side to review some other aspects of thorium-based fuels.

A well-known issue related to irradiated thorium-based fuels is the presence of a strong gamma emitter that is found in the decay chains of both thorium-232 and uranium-232. Uranium-232 can be created through end-to-end reactions on uranium-233 and even in small proportions the presence of uranium-232 is known to pose radiological issues.

In particular, the very energetic gamma line at 2.6 MeV, which is displayed here, is part of the discrete gamma spectra emitted by thallium-208, poses severe issues which would require remote-handling facilities of the irradiated fuel.

Here's a picture of such a facility, here is the ATALANTE hot cell lab at CEA Marcoule. Needless to say, these type of facilities are very costly and there is currently no experience of the use of these facilities at the industrial scale needed, if thorium fuel cycles were to be developed. Well, we will come back to this point later.

Whenever we are comparing the properties of let's say, two nuclides and even more for two entire fuel cycles, there will be some obvious similarities and some differences. And what I have often found in literature is that sometimes these differences are given a twist with, ‘You are a thorium defender or a thorium opponent. You will portray this difference in a positive or negative way.'

So what we usually hear is, 'Is uranium-232 counted in irradiated thorium fuels? Is it in very high quantities? That's excellent news because it makes uranium-233 fuel proliferation-resistant.' So let me just say that I will stick to what the IAEA says concerning the convention of the physical protection of nuclear materials 'Uranium-233 is an excellent fissile nuclide, and it is categorized under the same basis as plutonium.'

So really the claim that high uranium-232 content in irradiated thorium fuels would be self-protecting, is really a modest anti-proliferation claim in my view and not a really compelling argument.

And the reason is that the degree to which this protects against the theft of uranium-233 depends on the threat scenario, the facilities available, and willingness of proliferators to take a risk and expose themselves to a radiological dose. Now we know that there are various significant dose rates to personnel, but they do not guarantee to cause rapid incapacitation – evolution from thallium – sorry, there's a typo in there.

So the situation is rather a very serious remote handling and shielding issue for fuel fabrication and processes rather than an asset for anti-proliferation claims. In order to be careful and prudent, we should say, that proliferation resistance of thorium fuel cycles are more likely to be comparable to uranium-plutonium fuel cycles. So really, it is incorrect to assert that thorium fuel cycle is proliferation-proof.

There are other thorium properties that we can mention and it is useful to compare the properties of thorium dioxide, which is a ceramic material, also referred to as 'thoria' versus those of uranium dioxide, and these forms would be the preferred tools for solid fuels.

Thorium dioxide ceramics over uranium dioxide. This is well known. They have a higher melting point of the order of 3300 centigrade versus 2800 centigrade for uranium dioxide. They have a higher thermal conductivity that can results in lower fuel operating temperatures. Thoria is chemically stable. It is in its highest oxidation state. It means it does not oxidize when it is exposed to water or steam of air at high temperatures, and this is not the case for uranium dioxide. Thoria is known to have some higher fission product retention in thoria matrices.

And these are interesting aspects that may translate into fuel performance improvements under the normal operating conditions of a reactor, but also in postulated accident scenarios. Now, whenever we say that thoria is chemically stable, this is a difference that will also translate into known difficulties at the reprocessing stage of thorium-based fuels, which are much more difficult to dissolve, and this is a well-known issue.

But in other words, they are interesting to consider the use of thoria-based fuels in existing reactors also because it is logically the first implementation that thorium could realistically have. We need to start using thorium in the existing platforms of reactors.

For the reasons cited in the previous slide, thoria-based fuels for light-water reactors and pressurized heavy-water reactors exhibit improved defect performance in terms of reduced fission product release – and are a highly prospective technology for consuming or transmuting transuranic, that is, plutonium plus minor actinide nuclides.

However, thoria-based fuels must first be qualified to assure that they can perform safely in a reactor. That means they have to go through a qualification and licensing process before we can start implementing them into the industry. These processes will require a significant further development and test programs to manufacture and ensure that we have optimal thorium-based fuels for industry use.

There is a private company called 'ThorEnergy,' which part of a consortium that is conducting presently, irradiation tests of thorium-based fuels at the OECD Halden Reactor in Norway. And this is a picture showing that the fabrication process of thoria-based pellets is correctly done.

Now, minor actinide production.

One often claimed advantage of the thorium cycle is that it produces less plutonium and other actinides which significantly reduce the radiotoxicity of the waste. This is absolutely true and it is well understood by the fact that thorium-232 is 6 atomic masses below uranium-238 and that leads to a less likelihood of production higher mass plutonium and minor actinides because simply, they would need six subsequent neutron captures on the fuel, which makes it less likely.

This is true for a pure thorium/uranium-233 cycle. It is not clear for other forms of fuel which are the traditional fuels that must be used if we are to transition to the long-term thorium/uranium-233 fuel cycle. Remember, uranium-233 does not exist and we must find a way of producing it by using all these fissile feeds in thoria.

This is a very simple example of a calculation showing a comparison of three types of fuel for the same discharge burner. We can see that in the case of thorium it's usually plutonium. There's much increase of minor actinide production per unit energy produced. It is less clear for thorium using enriched uranium fuel as compared with two standard MOX fuels.

Now, let me show you some exercise calculation for dealing with radiotoxicity of spent nuclear fuel. This one now, that minor actinide production drives the long-term radiotoxicity of spent fuel. What is shown here is the same type of calculation conducted for the same type of reactor, using different types of fuel at the same discharge burnup.

And we can clearly see that for the long-term, in the case of once-through fuel implementation, that means that there is no uranium-233 recycling in the case of a thorium-based fuels here. We can see that the radiotoxicity of thorium/uranium-233 PWR fuel in this example peaks at a time of around 100,000 years and 200,000 years and peaks above all the radiotoxicity of all the other fuels represented here.

So really, the message here is that these types of comparisons really depend on the type of strategies and the type of fuels and the types of fuel management scenarios that are used in order to really make any sense.

The relative differences between radiotoxicities resulting from the use of both cycles vary greatly, like I said, depending on recycling strategies and recycling efficiencies considered and must therefore be interpreted with great caution.

Also, our usual lack in the analysis that I sometimes show is the consideration of the very long transition period that must take place using other forms of fuel – for instance, thorium/plutonium, thorium/uranium, enriched uranium fuels. And these long transition phase must be considered and integrated into the comparison for any comparison to be meaningful.

So I would say that on this it is clearly demonstrated and we really specify, which type of strategies we are considering, which type of reactors, and which type of fuel including fuel enrichment we are considering.

If we are to say a general conclusion, that would be that the long-term radiotoxicity of thorium-based spent nuclear fuel is therefore more honestly described as being comparable to that of uranium-based spent nuclear fuels.

Again, it will depend on the specifics of the scenario and on the specifics of the fuel and type of reactor. Yes, the longer term pure thorium-uranium-233 fuel cycle because they have less minor actinide production could lead to advantages in long-term radiotoxicity.

Now let's speed up a little bit.

'Thorium Fuel Reprocessing.' We have already mentioned the characteristics of thorium fuel that would be considered an 'advantage' for fuel behavior, they will pose a challenge when reprocessing because the same stability that gives thorium the advantages for good behavior in a reactor makes it very difficult to dissolve.

There are processes that have been used at the laboratory scale, at the final scale. This is the so-called THOREX dissolution processes. It is a process that requires the combination of a very corrosive hydrofluoric and nitric acids that have not been demonstrated at an industrial scale at all. So there is some real experience with THOREX that does not compare to the very large, existing PUREX industrial experience that exists, for instance, in the recycling of uranium spent fuel and MOX.

Pyro-processing has only been used at the laboratory scale only, and really basic data is still needed, there is still a lot of R&D needed before a demonstration of these processes of thorium-based fuel reprocessing could happen at an industrial scale. The technology nor the understanding is mature enough behind it.

This also will impact the re-fabrication of used thorium fuel. As we mentioned, irradiated thorium fuel re-fabrication will be severely complicated by the presence of uranium-232 decay daughters with highly penetrating gammas. Some studies show that U-232 abundances can be as high as in the order of thousands of parts per million. And this is just to compare the current experience that we have with reprocessed uranium fuel fabrication, is one that considers concentrations of U-232 of less than 0.01 parts per million, at which the radiological dose is already significant.

This very high abundance of uranium-232 will pose not only an irradiation hazard, not only a contamination hazard so that re-fabrication processes cannot be done in boxes like they are done for MOX shields. In this case, like we mentioned, remote operation and shielding will be required and these are very costly processes and they have not had any industrial demonstration.

Let me highlight the lack of industrially sound processes for the reprocessing and re-fabrication of thorium fuels is a very, very significant impediment, an obstacle, to closing the fuel cycle and closing the thorium fuel cycle, and therefore of implementing a clear driver to go towards that fuel cycle from the start.

Now in the past of course, many reactors have used thorium-based fuels. I will not dwell a long time on detailing all of the statistics [ph]. These can be found in literature and it's interesting to consider the experience that we have had in the past with this type of reactors and fuels.

Let me just mention that a thermal breeder pressurized water reactor with uranium-233 has functioned in the past. This is the case of the Shippingport Power Station. Shippingport was the very first commercial PWR that was adapted at the end of its lifetime to use thorium fuel from 1977 to 1982, demonstrating breeding in using the thermal spectrum.

Now, the Shippingport fuel management strategy used a very complex geometry of axial and radial zoning of different types of fuel in blanket assemblies. No use of control roles, basically everything that could capture a neutron outside of the fertile element was discarded. This made for a very, very complex way of operating a reactor. But it was an engineering feat to prove that breeding in a thermal spectrum could occur.

This was proven by post-irradiation analyses which revealed 1.4% more fissile content in spent fuel than initially loaded. It was also proven to be extremely complicated and our understanding today that this would not be a way of operating a commercial reactor nor could it be licensed for safety reasons, for instance.

There is of course the well-known existence of the MSBR, a thermal breeder project. This was the paper reacted [Unclear] on the study in the '60s, specifically in Oak Ridge. I will go very quickly on this one as there was a previous webinar on molten salt reactors. What I would say is that really at the end of the '70s, the banning of suspension reprocessing by the US effectively terminated the possibilities to close the fuel cycle and also terminated the farming for these type of studies.

Now, these types of studies around molten salt reactors were started again, at least 15 years ago in France, particularly at the CNRS. Again, I will direct you to the past webinar by Professor Elsa Merle in May that really went into much more details about this concept.

In fact, I have taken this slide from her presentation, just to mention that these studies have started for considering a thermal spectrum molten salt reactor which was found really to pose many problems in the design really by exhibiting a positive feedback coefficient, which is something that is completely forbidden for any reactor to operate safely or even to be seriously considered. And they also started some epithermal spectrum configuration, so intermediate spectrum configurations that apparently resulted in a very short graphite lifespan that of course poses the question of the economic viability of the concept.

So currently, the molten salt reactor group within the Generation IV International Forum is studying a fast spectrum configuration, which has no moderator. It is a breeder concept. However, I would mention that by switching to a fast neutron spectrum, we are losing the potential advantages or the theoretical advantages of the forum in the thermal spectrum. But it appears that at least for this particular concept there really was no other alternative.

Let me just sat that the molten salt fast reactor is today the reference concept studied in the Generation IV International Forum and it does consider different fuel types to be started that use uranium-233 of course, but also enriched uranium and also MOX. Again, for a much more detailed presentation, please go and see the seminar by Professor Merle.

Now, let me just mention before we move on that there are some very specific technological concepts studied under molten salts that are not really linked to the fact that a reactor would use thorium. So molten salts can be used by the reactors using uranium or they can be used as salts or they can be used in other applications. So this development of molten salt reactors will have applications even outside of thorium implementation.

We do not need to necessarily reach breeding. It could be interesting to reach simply higher conversion for the sake of improving the use of fissile resources and also to improve the volume of waste per unit energy produced. This is the concept behind the high conversion systems that are also on the study.

These are evolutionary concepts of existing reactors such as CANDUs or boiling-water reactors and they all revolve around the idea of hardening the neutron spectrum, allow it to go into a neutron energy range that is a little bit more favorable to the use of fissile resources.

I seem to have lost connectivity here. I apologize. I hope that you are still seeing the slides.

Let me just conclude by saying that these higher conversion systems can exhibit reduced fissile requirements. They would represent a step towards sustainability.

And really, the fact that they consider the use of once-through fuel cycles makes it simpler to really start the development in that direction. In the longer term, breeder systems can eventually get to a self-sustaining mode of operation with zero fissile requirement.

This is achievable only after a very long transition period which would require input of neutrons from other fissile materials, which today the only ones to consider really are low-enriched uranium or plutonium. A side note is that the utilization of thorium with enriched uranium as in the current reactors, seems to be not economically viable really.

And of course, closing the cycle will be needed before a breed reactor can operate. This supposes that we dominate or know how to do the recycling of spent fuel and fuel re-fabrication.

Here's just a very conceptual graph, the message of which really is that if we are to develop thorium fuel technologies into the future, they would take many years and resources. Many years because there will be a duration in time during which we need to breed uranium-233 before it can remain available to put in use into other systems. And many resources of course because there a lot of studies that are still needed and these will start small before they can become bigger.

So the idea is to foresee what the applications in the future of thorium fuels would be. It is really to start once-through fuel cycles. Perhaps they are using, the initial step would be not to couple chemically both cycles. That means, to keep thorium fertile rods separate from mixing the fuel with plutonium since in fact there is no reprocessing fuel available.

And as time develops and as we find more solutions to this question, we could start implementing these mixed fuel forms in once-through thorium/plutonium or in once-through high conversion systems if these arise. Really, up to a stage if thorium fuel reprocessing and recycling becomes a reality or a viable reality that would open the door to considering really closing these cycles with dedicated high conversion systems whatever be the reactors.

But in any case, the pure thorium/uranium-233 fuel cycle with online processing such as in the case of molten cell reactors would be a very long-term prospect.

Now, what would be the drivers today, really the incentives to make the industry go into that direction where we could identify just basically in – the fact of improving fissile resources utilization it could have some added benefits in terms of waste volumes but also in order to develop plutonium management alternatives.

And as we will see, if we are competing against fast breeder reactors which require plutonium, the fact that for whatever reasons these fast breed reactors may not take place if a country, for instance, starts developing plutonium and then decides to step away from nuclear energy, then plutonium management alternatives would be very useful, and here's where thorium fuels could play a role.

In any case, the message here is it will take a very long progressive time and clear drivers still need to be identified.

This is very well-illustrated by the Indian strategy which considers an inherently long transition process to a thorium fuel cycle. Here, I will not detail the different reactors and different strategies here. The basic message is that nations that have the will to go into that direction necessarily consider that this can only be done really towards the end of the century and will require several types of reactors to function together, symbiotically.

Now it is interesting to note that recently India has bunked uranium fuel light-water reactor technology. So whether this means that they are stepping away from this thorium fuel cycle direction or simply strengthening their capacity for existing production, really it is not for me to comment.

Whatever happens, what we know is that in the next couple of decades we will be decommissioning existing nuclear reactors in the hundreds. Whether nuclear energy gets to play a role for the future strategies that may result in achieving climate goals, really has to be decided now. So in that sense we do not have the time to consider solutions that would take many decades yet to be proven.

Here's just a picture showing that really the final answer to the world energy problems will be a mix of different energy sources and we can consider whether nuclear has to play a larger part. Really, again like I said, it is technologies that are ready today that will at least exist for the remaining part of this century that need to be deployed. We must consider that when we are thinking about other thorium solutions really.

Let me just say one thing about resource availability of thorium. I have willingly kept this at the end because whenever you listen to any thorium presentation, many of them, they start by saying from ‘It's very abundant’ and this is why we're using or considering its use.

Really, it's difficult to compare uranium and thorium resources for one very simple reason is that categories of uranium resources actually depend on the price of extraction that one is willing to pay, and therefore on the uranium market. Now since there is no standard classification for thorium resources, that is because there no thorium market there's no thorium spot price. This has also resulted in the fact that thorium has not been as prospected as uranium. And really in order to be correct, we should say that our current knowledge of thorium resources is incomplete. Nevertheless, it is very safe to assume that the exploitable uranium and thorium mineral resources really are within order of magnitude at least several million tons.

Now we'd like you to make a note that few people consider really is that we are nowhere near the need of mining so much thorium that we are of mining uranium. Because when we mine for uranium, we are actually mining to get the 0.7% of uranium-0235 in the mineral. So that means whatever thorium mining requirements would exist in the future, they would be orders of magnitude less than those that we know of uranium.

Really, we are not mining again for the fertile uranium. We have tons of fertile uranium, impoverished uranium after the enrichment process are just sitting there. If we were to mine for fertile thorium – if we needed to mine for 1 ton of fertile thorium, we would just need to mine 1 ton. The current ratio is for 1 ton of enriched fuel we need to mine for approximately 100 tons of uranium. So this will not be case in the case of thorium.

There is currently a limited, non-nuclear thorium market. Few incentives exist to open new mines with thorium as a primary product. Nevertheless, we already know that the near-future thorium recovery will utilize pre-existing mining operations which currently surface thorium, but route it to waste because of the very small demand.

This is a very important aspect because the by-product production of thorium from other industrial mining activities such as rare earth production can provide more than ample quantities of thorium for whatever potential use of thorium in the nuclear industry for the foreseeable future. The future should make it clear.

For the past 20 years, we have had ever-changing habits. We are using electronic devices, we are using smartphones, we're using computers, and we're using a lot of different screens. All of these devices, they require rare earth in order to be fabricated. And as a result, there has been a huge explosion in the production of rare earth mining. Here's a graph that shows the progression in the past 30 years or so.

Notice the magnitudes that in the hundred thousand of millions of tons. This is rare earth production in China and in the U.S. Nowadays, without any doubt, China is the leader of rare earth production. The message here is that if only one small fraction percentage of this rare earth production results in by-product production of thorium, then there is no problem in providing thorium for any kind of nuclear application in the future. This is a picture of thorium sitting in some stocking place waiting for a reason to be used.

We should also mention the resource availability of uranium, since thorium is always considered in case of there is uranium scarcity. Now, as the years go by and as prospection of uranium continues, our understanding of resources gets better. And in fact we seem to be finding more and more. This is a compilation of the numbers in the IAEA/NEA Uranium Production and Demand books. They are also called the 'Red Books.'

I'm just going to read that conclusion from the 'Red Book' which says, 'Regardless of the role that nuclear energy ultimately plays in meeting future electricity demand, the uranium resource base is more than adequate to meet projected requirements for the foreseeable future.'

Let me prepare to conclude.

Hope you would have understood by now that the 'thorium question' is a very complex question, that the thorium/uranium-233 cycle is a long-term endeavor if we ever get there. In order to get there, we must develop or find the drivers to develop thorium-based fuels. But the question would be really to say, for which system in which fuel form, which fuel management strategy, in which deployment scenario, for which drivers, and for which objectives?

And if you want to speak of thorium more precisely and of a less general form, we will need to answer these questions before we can draw historical conclusions, really.

The thorium fuel cycle is based on uranium-233, a non-existing fissile nuclide which can be bred, provided thorium is first used with other fissile seeds and for a very long transition time. It is certainly neutronically interesting, it is chemically very complex. It is today technologically and industrially yet unsound and it is economically uncertain.

Really, is the 'thorium question' the wrong question?

Failure to look at the complete picture, if we just enumerate latent advantages or disadvantages of a resource we are confusing the question with the real question, which is the readiness of the technology really.

One does not retrieve energy from a mineral, one does not retrieve energy from a rock, one retrieves energy from an industrial technology that has to be economically competitive for it to be deployed and supported.

In order to meet climate challenges at the scale needed, the nuclear industry needs to provide flexible and well-financed industrial strategies to deploy its solutions in the appropriate time scales.

So, can thorium play a part in the answers nuclear industry needs to provide? That I think would be the more correct question.

We would need to consider the competition from other advanced reactor systems or Generation IV systems, which really today still exhibit an uncertainty around the readiness of the technology. Also, an uncertainty around the fissile inventory needs for deployment that would also be very important in order to quantify the sustainability.

But really, the message is that there is no ‘skipping’ a generation. Before we got to Generation IV, we will need to deploy and understand and correctly operate Generation III and III+. The introduction of thorium into nuclear energy systems, if it occurs, will need to happen progressively. None of the scenarios currently envisaging a full transition towards a pure thorium/uranium-233 fuel cycle in the near or medium term are realistic, both for scientific and for industrial reasons.

Any industrial application of thorium as a nuclear fuel would continue to require the input of fissile materials from the existing uranium/plutonium cycle until the required amounts of uranium-233 could be produced and ultimately make the thorium cycle self-sustaining. Well, we have to consider that before we go in that direction, there will be competition from other systems such as fast breeder reactors that require plutonium. We currently see that the strongest case for thorium fuels is the thorium/plutonium fuels.

The limitations imposed by fissile plutonium availability point to very long transition periods that would also need to consider whether we want to burn plutonium and thorium instead of selling it for future development of fast breeder reactors. So these are really national strategies that need to be decided among the nuclear nations.

With uncertainties around large scale deployment of fast reactor and the lack of geological repositories, we see that alternate plutonium management strategies can arise as valuable options.

The introduction of thoria-based fuels can represent a credible option for plutonium management solution for the existing technological platform while also providing potential better utilization of fissile resources in high conversion systems.

So thorium can play a role in enhancing the flexibility of future nuclear energy existence through symbiotic scenarios, although very significant R&D is still needed and for this to happen we need to identify the proper economic incentives.

With the lack of clear short-term economic incentives and no change in preferred future strategies, we must be aware that the present industrial development of thorium is likely to remain very limited. I hope I have made it clear to you that thorium is clearly no silver bullet. And this is perhaps the chance of thorium because utilities are not looking for silver bullets. Really, they are looking for options and options have value in an uncertain context. In this sense, the thorium option should be kept open insofar it represents an interesting complement to the uranium fuel cycle to strengthen the sustainability of nuclear energy in the medium to longer-term but certainly not to replace it.

Again, we can see that the full recycle requires THOREX reprocessing and remote fuel fabrication still needs to be proven industrially. In general, the closed uranium-233/thorium cycle will be best realized in Gen IV systems, especially molten salt reactors, but this is only viable on a long timescale if we ever choose to go in that direction.

I would like to now finish my presentation by quoting a famous remark by Admiral Rickover when he was addressing Congress in June 1953. Admiral Rickover was known as the father of nuclear navy and also involved in the Shippingport building power station. I will just read it if you allow me.

'Important decisions about the future development of atomic power must frequently be made by people who do not necessarily have an intimate knowledge of the technical aspects of reactors. These people are, nonetheless, interested in what a reactor plant will do, how much it will cost, how long it will take to build and how long and how well it will operate. When they attempt to learn these things, there appears to be unresolved conflict on almost every issue that arises.

I believe that this confusion stems from a failure to distinguish between the academic and the practical.

An academic reactor almost always has the following basic characteristics:

- It is simple.
- It is small.
- It is cheap.
- It is light.
- It can be built very quickly.
- It is very flexible in purpose.
- Very little development is required.
- The reactor is in the study phase: it is not being built now.

A practical reactor, on the other hand

- Is being built now.
- It is behind schedule.
- It is requiring an immense amount of development on apparently trivial items.
- Corrosion, in particular, is a problem.

It is very expensive.
It takes a long time to build because of engineering problems.
It is large.
It is heavy.
It is complicated.

It is worthwhile to bear in mind this distinction and to be guided thereby.

I would like to thank you very much for your attention. If you'd like to learn more, please consult the two reports I have based my presentation today on. These are two reports that we published in 2015 and you can find then for free on the OECD MEA website.

Here are for reference, some other studies. Visit our sites or send me an email. Thank you very much.

Berta Oates
Thank you, Franco, thank you very much for your presentation. if you have questions regarding any of the material in today's presentation, please feel free to type that in the Q&A pod now and we will take those questions as we have time.

While you are typing in questions, let's just take a quick look at the upcoming webinars. In August, 'Metallic Fuel for SFRs,' by Dr. Steven Hayes. In September, 'Energy Conversion,' by Dr. Richard Stainsby. And Dr. Geoffrey Rothwell, will present the 'Economics of the Nuclear Fuel Cycle,' in October.

I see some comments coming in. Do you see those as well, Franco? In the Q&A pod, there are those two tabs. One is the participant view and one is the presenter view. So I will share –

Franco Michel-Sendis
I don't see questions. I see some comments.

Berta Oates
Yeah, some accolades are coming in.

Franco Michel-Sendis
They seem to be appreciation comments. Thank you very much. Okay. Do you see anything?

Berta Oates
There is one, 'Thanks very much for your presentation. My question is, what is the thorium produced in China used for?'

Franco Michel-Sendis

Okay, I guess that has to do with a slide I showed, which would be this one showing a graph of rare earth production. Perhaps I did not make much it clear. This is the production of rare earth in China for other applications, which are non-nuclear at all. Currently it is not part of this rare earth but it is a by-product production of this mining industry. So currently, I would say that is not used for any nuclear applications, really.

Thank you.

Berta Oates
There's a question – do you see the question from Dr. Roelant, the issue related to graphite lifetime with epithermal reactors?

Franco Michel-Sendis
I don't see it, I'm sorry.

Berta Oates
David Roelant has asked, 'What is the issue related to graphite lifetime with epithermal reactors?

Franco Michel-Sendis
I would direct you again to a presentation of [Unclear]. I suppose that you are referring to the epithermal molten salt reactor concept that was studied by the CNRS. Well what I know is that the lifetime span of the graphite under this condition was very low. And that meant – I don't have the values in mind but really under 10 years perhaps and it was deemed uneconomical to have to change reactor every 10 years. Basically you cannot just change the graphite inside a reactor.

Thank you for your nice comments.

I see Professor [Unclear] thank you very much for your interesting comments.

Berta Oates
There's a question perhaps that we won't be able to answer. I'm not certain regarding why no more in the USA, but that may be more of a political answer than anything else.

Franco Michel-Sendis
Okay. Thank you. Please mark my email and I would be more than happy to interact with you directly, if you should have any questions. I am finding it hard to read the questions really, I'm having connectivity problems here.

Patricia Paviet

Yeah. Thank you so much, Franco. Thank you very much for a very excellent presentation.

Geoffrey Rothwell
Thank you. Thank you everybody for attending and for your patience. It was I think a long webinar but I hope you find it useful. Thank you very much.

Patricia Paviet
Thank you. Thank you, Berta. Thank you, Amanda. Bye-bye, everybody.

Berta Oates
Bye-bye.

Patricia Paviet
Bye.

END