SCK•CEN's R&D on MYRRHA
Prof. Hamid Aït Abderrahim, SCK•CEN, Belgium

Berta Oates
Today's presentation is going to be conducted a little bit differently if you've attended GIF webinars in the past. Due to some scheduling conflicts, our presenter today is not available to do the live broadcast. So we have for you today a recorded version of the presentation, and then Professor Hamid will join us at the end for our live question and answer session. So when we get started, what you will be watching is a recorded version and then we will stop that and open up this same audio broadcast to do questions and answers as time allows.

As always, you can enter questions during the presentation and into the Q&A pod, if you type those in, we'll take them at the end. In the middle pod, you can download the PowerPoint presentation directly to your laptop or to your desktop where you are sitting. There are a couple of slides which may display better in that PDF due to some formatting issues and since we are doing the recorded version today, our inability to do any editing of that recording. So, your PDF will have a couple of displays of some equations that are inadvertently covered up or animation didn't work properly in the pre-recording. So those are available to you in that PDF copy.

And last and certainly not least, there is a link in the GIF seminar survey pod where we will ask you to fill out an online survey. We appreciate your feedback and we take your comments and suggestions very seriously. And with that, I don't think we have any other housekeeping issues. So, I think we can get started.

Welcome, everyone to the Next Gen IV International Forum webinar presentation. Today's presentation is on MYRRHA, an Accelerator-Driven System Based on LFR Technology. Our presenter, Dr. Hamid, is from Belgium. Doing today's introduction is Patricia Paviet. Patricia is the Director of the Materials and Chemical Technologies Office at the Department of Energy, Office of Nuclear Energy. She is also the Chair of the GIF Education and Training Task Force.

Patricia Paviet
Thank you so much, Berta. It's our pleasure today to have Professor Hamid Ait Abderrahim with us. He is the Deputy Director General of SCK CEN, the Belgian Nuclear Research Center. He is also a Professor of Reactor Physics and Nuclear Engineering at the Universite Catholique de Louvain at the Mechanical Engineering Department of the Ecole Polytechnique de Louvain.

Since 1998, he is the Director of the MYRRHA project. He is partner and a co-coordinator of various projects of the European Commission Framework Program related to advanced nuclear systems or to partitioning and transmutation of high level nuclear waste management. He chaired the Strategic Research Agenda working group of the European Sustainable Nuclear Energy Technology Platform from September 2007 to December 2011.

Since 2015, he is the Chairman of the Governing Board of SNETP. He is the representative of Belgium in the Governing Board of the project, Jules Horowitz Reactor. He has also more than 100 scientific publications in peer reviewed journals and international conferences. In April 2014, he has been honored by the King of Belgium who nominated him as Grand Officer in the Crown Order for his contributions in progressing science and knowledge in the field of nuclear engineering of innovative systems for high level waste management.

On February 15, 2016, he received the title of Doctor Honoris Causa to the Kaunas University of Technology for his personal achievements and long-term collaboration with Kaunas University, especially with the Barlauskas Ultrasound Research Institute. So, it's really my pleasure to have Professor Aid Abderrahim with us today. And thank you again for volunteering to give this webinar. I give you the floor, Hamid. Thank you again.

Hamid Abderrahim
Thank you, Patricia for this very kind presentation and it's really a pleasure for me to contribute to the GIF webinar and try to bring some information on this MYRRHA project which is based on the lead technology, because the subcritical reactor we are designing in there is based on this technology.

So, on this first global picture, you see the site of SCK CEN, the Belgian Nuclear Research Center. And where you see actually the MYRRHA facility, how this will be looking like. So this is the project. It's about in total 350 meters from here to there. This is the injector of the accelerator, the linear accelerator 250 meters, and then the building of the reactor. Here, you see our existing BR2, the Belgian Reactor number 2 which is the material testing reactor with 100 megawatt thermal power, the second most powerful material testing reactor in the world after the American one, the MTR in Idaho.

Here are the hot labs where we actually do research on the material we irradiate in BR2. Therefore you see that the reactor in there of MYRRHA will be just the opposite side of these hot labs, which is very important. The design team is in this technology building and this gives you a global idea.

So, the outline of the presentation, I will just give you some worldwide energy facts, because it's important when we are dealing with Gen IV, why we need to invent a new nuclear energy, because it is needed and what we have to address in it will be becoming very obvious. And I will talk about the background of MYRRHA at SCK, then what is an ADS system, and then, MYRRHA project at a glance, the reactor, the accelerator, and the licensing which is very important in any innovative project we are developing and how we are intending to implement this project and I will be concluding.

So, let's start, worldwide facts for energy. The energy demand is increasing continuously and will do so for a long time. The other concern we have when we deal with energy is energy security of procurement of this energy. And then the third constraint we have in this modern world, the relation between energy we are consuming and the impact it has on the environment and we will try to illustrate those elements.

First thing, when you talk today in political world and with environmentalists, they generally start talking about the color of electricity. Some people think there is green electricity, even considering what comes out of the world can be distinguishing the green electricity from the brown electricity or whatever.

There should be an animation here that apparently disappeared. Oh that's it.

So, the electricity can be white, because you have electricity, like you see these very shining zones; United States, Europe, China, Japan and a certain extent, India. Or the color of your electricity is dark, is black, because you don't have electricity. That's the only two colors of electricity. All the rest is discussion between politicians and people that are rich enough to discuss about the color of electricity. So, another thing to look to the energy and to politics and geopolitics.

Look if we put the dimension of the countries proportional to their oil and gas reserves, and then many things become very clear, why the Middle East is dominating actually the energy sector. And even with, I would say, large countries, Russia, we consider in Europe being a gigantic country in terms of gas, but in reality it's not that big. And United States and Canada despite the shale gas is still in terms of capacity potential remains small countries.

So this give us actually a perspective to look to the world in a different way. And because this other picture of the world shows you why there is such a big concentration of wars in the Middle East, because of the previous picture you have seen. And then so energy, if you want to secure energy, you want to avoid wars. These are very basic things to understand about the importance of energy and we should not forget that.

So when it comes to environment, one thing that all times we worry about and some people believe in it, some others less, the impact of the human activity on the global warming and this is correlated to the CO2 emission. But there are other gases, greenhouse gases like methane. If we are going to use a lot of gas, not only the CO2 we produce, but the methane that is escaping in the nature will also contribute to that. And when you look here, the amount of total CO2 per gigawatt hour emitted, and I put the yellow bars on those numbers because sometimes people are having discussions, is it really that number that you show which is correct. And I am okay, even when you add yellow bars on them, and you see there is no miracle.

When you are burning fossil fuel, you produce more CO2 than if you are using either renewable energy, solar, biomass, wind, or the water dams, the hydroelectric, or the nuclear. This is then what we have to see. Today, sometimes when I hear, look at this fighting between the renewables and nuclear, I find this game completely irrational. The game is between the non-emitting sources of energy, means those guys here; and the ones emitting, which are those guys here.

Okay, you can say that natural gas is better than coal or lignite; but nevertheless, if I compare this number to those guys, it remains very evident. So, if you want CO2-free energy sources, therefore besides the renewable and the hydro, we need to add the nuclear in it, and so that to make a balance and save the planet if we are serious about the CO2 issue and problem.

Then, another I would say thing that we all the time talk about. Or without seeing, some people tell you oh, we stop emitting CO2 if we stop traveling and do teleworking. But if I stop to avoid these traffic jams, then reduce the emission, I need not to travel myself but my work through electrons that are going through the net will be traveling and this requires energy, electric energy. I replace my gasoline car with an electric car, good. I am doing good for the environment. But I increase the electricity production needs.

I suppress my lorries which are polluting and use electric trains for transporting the goods. Once again yes, I am reducing the CO2 of this direct use but churning more electricity. And what you see here, all the years in the different parts of the world, whenever we increase the development of, let’s say, new technologies, the electricity consumption is increasing. So, it will be in the future more and more important to look how you are producing your electricity, because to decarbonize all those sectors you will increase the electricity production. So, if we use fossil fuel for producing electricity, we are not solving the problem.

Okay, this being said – here, the story goes to 2014, but other people after him, after Ban Ki-moon said that renewables and nuclear energy combination could be, maybe the appropriate mix for the future. And personally I said not maybe, for sure. We have to invest in those renewable sources as well as in nuclear energy. But we, nuclear people, we have to invent a new nuclear that will meet these demands but solve our trade legacy of the nuclear that we have used successfully during 50 to 60 years up till now. And among them we continuously are put under scrutiny for our safety. We have to increase the safety. We have to continuously have the safety as part of our, I would say, concern in the nuclear energy. But we should not make it as the only topic of research to avoid innovation. Safety, yes, but blocking innovation, no.

So, the other thing, maximize the use of proven technology means our reactors that are producing, for instance, in Europe, 31% of clean electricity, and at the world level, 16% of the clean electricity. We have to continue that. But the long-term operation or plant extension in some countries we call them, okay. But we should not say we have solved the problem, because we are not innovating. We haven't yet a new technology on our table that we have to do certainly rapidly.

The other problem we are facing in nuclear energy is the nuclear waste legacy. And that we have also to address it. Geological disposal is a technical solution but seems very difficult to be accepted by the populations. And when you tell them you will store these waste in geological disposal for hundreds of thousands of years, it's something that doesn't come in the mind of people easily, even with educated people etcetera. So, we have to accept that we have an issue and we have to come with innovative solutions for that.

About technologies, to enhance the use of the resources etcetera, I will not tell you this because it comes from GIF. But the way we can look to it that plant life extension is one part of the Gen II systems, deploying the Gen III is okay, the next step. But to my opinion the Gen IV and in particular, those with the closed fuel cycle, the fast spectrum reactors and burning also the legacy or specific devices like the MVAs [ph] helping to do that is certainly something of interest. But today, the SMRs is popping up in various countries. We have to look which SMRs we have to deploy for economical reasons, but also for safety reasons, and reducing also the most important element, the quantity of waste we will be producing. Therefore, to my opinion in the SMRs we have also to look to table the fast spectrum [ph].

Now, coming to Belgium, why in this country we got this fantastic idea to make MYRRHA? So, in Belgium, we have the Belgian Nuclear Research Center called SCK CEN. As we are a bilingual country or trilingual, we should also add it in German, but SCK is in Dutch in Flemish means Nuclear Research Center and CEN in French, Nuclear Research Center. And we are based close to the city of Mol, what you see on the Belgium map here. And actually, we are north-east compared to Brussels and we are very close to some extent to the border with the Netherlands, our neighbor country.

And the good thing or the most renowned aspect of this research center, we are renowned as a pioneering center. Some people don't know that the first PWR ever constructed outside United States was in our place, the BR3 reactor. It's a small unit like shipping port actually unit, 55 megawatt, thermal producing 11 megawatt electric during 25 years. The MOX fuel, the technology most used today in the world has been invented in Mol. The BR2 reactor I pointed out in my first slide is the highest flux reactor in Europe, the second after ATR in United States. So, we have fluxes of 10 to the 15 in the core of this reactor, neutron per square centimeter per second, because some people, they have 10 to the 18, but they speak in square meter. But we speak, like everyone, in square centimeter.

The other thing is the underground laboratory you see here for the waste management. This underground laboratory has been started in '74 when our first commercial nuclear power plant went on the grid. So you see, we anticipate and we pioneer in the field of nuclear energy large in advance. This accelerator-driven system coupling a lead reactor to a generator of deuteron is already built since 2009 as a platform for testing all the reactor physics and the safety approach that we are going to develop inside MYRRHA, which is our next pioneering project.

So, MYRRHA, we wanted it as an innovative research facility at Mol to replace our BR2. Today, thanks to BR2, we are doing material testing experiment for fission as well as short fusion, fuel testing for light water reactor Gen II and III, irradiation services, medical radioisotope production, fundamental research, and others. And that we would like to continue this portfolio. And having MYRRHA as a followup of our BR2 will continue this capacity of innovation in nuclear energy and nuclear applications beyond energy by adding the dimension that this is an accelerator-driven system and this is a fast neutron irradiation machine.

So we open, enlarge our portfolio for material towards fusion thanks to the very fast neutrons we create thanks to this spallation source. We enlarge the testing for ADS demo and P&T testing, and we continued these services are foreseen to be conducted in MYRRHA.

But as I said in my title, MYRRHA reactor is based on the lead fast reactor technology. Indeed, we are using lead bismuth. I will explain why lead bismuth and not pure lead. If we want to be in shorter time available to the community, we better use lead bismuth because of the melting temperature which is 123 degree C instead of 370. Then this means that the structural materials we can use are from the shelf instead of inventing them during 20 years.

And therefore, we say we can test the elements for Gen IV, but the LFR needs what we call an experimental technology pilot plan and MYRRHA reactor can play this kind of role also for this technology. And then, I said also that MYRRHA is an accelerator-driven system. So, what is that beast? The accelerator-driven system is simply a reactor but which is subcritical and therefore, we need to create an external source. Subcritical reactors have the K-effective less than one. In our case MYRRHA, it’s 0.95.

And therefore, we need an external source of neutrons to maintain actually the reactor going on. And to do this in external neutron source, we should charge particles like protons that we can produce thanks to a linear accelerator, into the center of this core on heavy metals, be it actually lead, lead bismuth, tungsten, tantalum, uranium, all those heavy materials are suitable to make spallation source. And doing so, you have your primary neutrons that will be showering the reactor core and initiate the reaction of fission in the core. But you will tell me why this complication of ADS, and is it something new, is it something unique.

When in Europe, we started working or restarted working on ADS in ’93 thanks to the very first idea coming from Carlo Rubbia from the CERN, he is a Nobel Prize winner in ’84 for the discovery of the W particle, but he found maybe that those guys of nuclear energy are not very innovating. So, he came with the idea coupling an accelerator to a subcritical reactor and we call it energy amplifier. And since then other people followed in Europe to look at this idea of ADS. For instance, at our place in ’94, we looked with IBA company, Mr. Yves Jongen is the founder of this company, to produce radioisotopes with this idea of coupling cyclotron and subcritical reactor.

Then, Massimo Salvatores who is known in our community as a master of reactor physics and experimental reactor physics in particular. I had the chance and the honor to have him as professor. He was the first to build an ADS experiment which we called MUSE in the MASURCA facility for the people of the fast reactor. They know MASURCA. And we coupled a generator of deuterons to this facility and we ran there a program from 1995 to 2002 exactly on all the physics of subcriticality systems, etcetera.

Then, Carlo Rubbia, the same year, actually realized two experimental facilities at CERN, FEAT, and TARC. Actually what is bold means has been built. What is not bold, he didn't realize, but has been studied. Carlo Rubbia in '96 proposed the energy amplifier 80 megawatt. Then we had myself who proposed MYRRHA in '98 and we are still working on it. In '99, Bernard Carluec, Massimo Salvatores, and other guys from France proposed the EFIT gas from AREVA-CEA and CNRS. And Carlo Rubbia came back with TRADE experiment in Cassacia, Anna Kievitskaya from Belarus, and his colleagues proposed the YALINA and has been built in Belarus. And we even take profit of that to make some experiments in this facility at that time. And then, Valery Shvetsov from Dubna came with the idea to do something in Dubna with that. Then, we came with the GUINEVERE which has been constructed in 2009. We decided in 2007 to start it. It has been finished in 2009 and is producing experimental research since then.

MYRRHA that we started in '98 actually here has been receiving the support of the Belgium government who declared to support the construction of MYRRHA for 40% in 2010. Therefore, I bold it, but it's still blue, it's not black because it's not yet built. But we are investing a lot of money and heading in the next month to getting maybe a very big news for construction. Then we have this proposal in 2011 and 2015, another proposal on the table.

So, ADS is actually a long story nearly 20 years in Europe and progressing. And the first idea, we want to build the legacy, the minor actinides. And what is important to see, actually this is the captured cross-section of americium-241 and this is the fission cross-section. And what you see, capture is higher in lower energy than fission. And if you want to transmute, you need to fission. Therefore, you have to work with actually fast neutrons. So, normally we need fast neutrons. So is it done in critical or subcritical doesn't change anything. You need only fast neutrons to transmute the minor actinides. But then, why are we bothering with this?

The very first thing, if I take my used fuel out of my reactor and you see actually this curve, it will take me 300 years to get back to the natural uranium ore toxicity that I used as the starting point to make energy. I put it in PWR or BWR, I increase this relative radiotoxicity by a factor of 1000, and it will take me 300,000 years to get back here. I do the reprocessing but is today industrially applicable, the PUREX separation of plutonium and uranium, you drop to this blue curve. The blue curve tells you that after 10,000 years, you are there and you got your vitrified nuclear waste colleagues [ph] to store them for 10,000 years, underground geological disposing.

You can do maybe more. Get out the minor actinides from this waste and you drop to 200 years, 300 years, and you come back to the radiotoxicity of natural uranium ore. So, that's the challenge. And we are not saying that you can suppress the geological disposal. What is interesting in the topic is you bring the problem from geological times to human times, manageable times at the human dimension, 300 years. And this is important. We all know churches in Europe that are more than 1000 years. We are still visiting them. We can go to Egypt to visit the pyramids which are more than 6000 years and so on.

So, we are in things that a human knows in terms of time dimensions even though some people will find that 300 years is still too long. But I think we are coming from geological times to human time schedules. And on top of that, you reduce the volume that you have to manage by a factor of 100 in terms of volume reduction by 100, in terms of timing and duration factor of 1000. That's what sits behind the transmutation of minor actinides and that's all okay. For this, I needed the animation, but nevertheless.

This is the equation of the flux for a subcritical system where you see the term which is related to the K-effective here. It should be appearing. I will try to send the PowerPoint to be clear and here is the term related to the subcriticality. And here should appear the S, the term of the source, the external source, and here the [Unclear].

So, if you are critical this term doesn't appear in your equation whereas this one remains. And if you have a subcritical system, this is the term that will be dominating where you see the S which is actually the source intensity. Then, if S goes to zero in subcritical system, your flux goes to zero. That's what I wanted to show thanks to this equation. Unfortunately, the animation is not there. I apologize for this. But for the reactor physicists, they know how to find this.

Here, maybe it's not a way to explain it. Here, it's an equation of diffusion with two groups. So now that I don't want to bother you with Monte Carlo, I am going down to earth with my diffusion equation. So, what you see here appearing is the source intensity. And this source if you shut down the accelerator, the Sn is equal to zero. Then, your phi 1 and 2 will go to zero. And if the flux is zero, then this means that the reactor is off. So the accelerator goes down, the flux disappears. Then this means that you are having an easy power control in your system. And why you have to do that? You can do that in critical reactor also. I will tell you why.

Actually, if you look to the equation of a kinematic equation or kinetic equation of a reactor where the flux is depending from the time, you see here the time dependence, and your time dependence is driven by an exponential where you see actually this term, omega M. And this term is correlated to the period of doubling time of your neutrons in the reactor. And this doubling time is proportional to what – to the delayed neutron fraction. And it happens that nature has foreseen that once we will be willing to make reactors, so when you fission elements, there is a little fraction of neutrons that are emitted in a big delay compared to the prompt fission neutrons.

And it happens that you really [Unclear] this fraction is something like 1.4% of the neutrons; in uranium-235, 0.7, but in americium, this number drops to 0.3, and in curium it drops to 0.1. If I put a lot of minor actinides in my reactor core, these doubling times will become very small because the betas here will become smaller. And so as such, I will have a reactor which is very difficult to control. Therefore, we play with subcriticality and then we can load a large amount of minor actinides in the core without jeopardizing the safety of our system.

So why we need subcriticality? Because we want to load a large fraction of minor actinides in the core. And the only way to gain that, to avoid criticality accidents is to go to subcriticality. And this is the reasoning behind making ADS for burning the nuclear waste and getting rid of the minor actinides.

Okay, and you can see from this study, actually there was a reference somewhere here. It's a study conducted by Los Alamos a very long time ago comparing the different potential donors, a light water reactor with high burnout, MOX fuel, inert matrix fuel in light water reactor, and so on and so on, fast reactor with different conversion factors and the ADS.

And this what you are seeing here is burning. Here we are talking about burning plutonium, the blue lines, and this is for minor actinides. This has disappeared also. That's the difference. Here we are talking about burning plutonium and here we are talking about burning minor actinides. And you see for burning minor actinides, the ADS heavily loaded with minor actinides is the most performing beast, because we burn 140 grams per megawatt hour. This is the unit that you should be reading here, kilograms per megawatt hour that we are burning and thus this is the most efficient way to burn.

The other thing I wanted to say, also this is something that we are looking in Europe. As I told you, actually we can burn minor actinides in fast reactors as well as in accelerator-driven system as long as we have fast neutrons in the system. And here we compared fast reactors and ADS systems. And here in heterogeneous mode means that I put the minor actinides only at the periphery of the core, and I can then put minor actinides, a proportion which is higher because the safety of the reactor is driven by the large part which is not with minor actinides, or I can put also homogeneous spread of my minor actinides in the system.

And here for ADS, we are putting minor actinides in all the core. Because of the subcriticality, this is the position of spallation source. And what we see? In fast reactors between homogeneous and heterogeneous, we can come to burn 2 to 4 kilogram per terawatt hours, whereas in an ADS we can burn up to 35 kilogram per terawatt hour. These numbers are based on a critical sodium fast reactor of about 1200 megawatt electric and these are based on the EFIT design of Europe, the lead-based European Fast Incineration and Transmutation machine. We call it EFIT which has been designed in the European Framework Program that we are using.

But transmutation is not the only thing you have to do. It's fantastic to have fast reactors or ADS with fast neutrons, but prior to do that you have to make advanced separation. The minor actinides should be separated after the PUREX. And in Europe, we developed a global strategy for P&T for looking to the industrialization of this technology by 2030-2035. And this strategy based on these four building blocks has been developed in 2005, because in Europe, we spend a lot of money, a lot of effort of R&D at the European Commission level, but also at the member state countries, France, Belgium, Italy, Germany, Spain, Sweden.

A lot of countries worked hand in hand together with the European Commission for, let's say, more than 20 years. And in 2005 we established this next step. If we want to do something serious about P&T, we need to do the engineering level demonstration, preindustrial level. And we said the advanced practitioning that we had done at lab scale in Atalante in France, there are other places but the major place is Atalante in France in Marcoule. We have to go to industry, semi-industry or pre-industry and scale. Instead of 40 to 60 kilograms per batch, we would like to go to one ton of used fuel.

The minor actinide fuel loaded; we do production today. The best place we have in the European Union is the MA-lab at the JRC in Karlsruhe, The Institute for Transuranium, and we can handle few grams, let's say between 4-20 grams per batch. And we need there to go to 100 kilograms. And the best place we think that could be happening is the JRC in Karlsruhe. Then, we have the third building block. We have the MYRRHA for the ADS and I am pointing here MYRRHA, because I am responsible for and the presentation is dealing with MYRRHA.

But you know that we are working in the European Union and for the GIF community also on the sodium fast reactor. The ASTRID project can be actually also a machine where we can trust transmutation of minor actinides. But with what I had said before in terms of quantities, we have to look at the difference. Then we haven't finished. We need this advanced fuel to be reprocessed and then we think that pyroreprocessing and electrorefining will be a better solution than the aqueous reprocessing. And there today in Europe we have some work but we do not have, let's say, a crucial or important facility for that. I think US, Japan, and South Korea, are better equipped for their pyroreprocessing and electrorefining. So, we can enlarge the project and the strategy beyond Europe.

So, another attractive aspect for this approach at European level, we tried to show it thanks to this scheme. Because in Europe we have different policies in different countries towards nuclear energy. Then we studied the Group A are countries willing to quit nuclear like Germany, like Switzerland, Belgium, etcetera, and others that are willing to continue nuclear energy, Group B. And those countries like France, like the Czech Republic, Hungary, and even Poland willing to stop nuclear energy. So even in Europe, we have nuclear energy going further and even new countries entering in nuclear energy. So, what is the added value for dealing with transmutation of nuclear waste together?

I don't know if I have the animation. Let me check. Yes, look there. What is the advantage? If we do share those facilities together between Group A willing to quit nuclear, and Group B of countries willing to continue nuclear, what is the gain for each of them? If we do ADS, ADS can accept a large quantity of minor actinides, I said, for safety reasons, very controlled. The spent fuel is very specific and contains large volume of minor actinides. It deserves then a special fabrication of the fuel.

Then you put it in your ADS, the spent fuel, you do reprocessing by pyroreprocessing and electrorefining. And then the minor actinides and plutonium you get, out of that you redo it here. But from your classical reactors, be it the PWR with UOX, UO2 or with MOX, if you want to get some plutonium consumed with your PWR. And even if you have fast reactors, you can burn them there and then you send your actually minor actinides to here to do the reprocessing. The plutonium is a resource and I use it as a MOX in fast reactor or in PWR and the minor actinide enters here. Here, the countries' leading in nuclear, they can give part of the plutonium we need here and some plutonium which is a resource can go the countries continuing.

So, ADS will be facilities and this advanced reprocessing and special fuel fabrication, all those facilities can be shared at regional level among I would say, the countries quitting nuclear and those continuing. That's the advantage. So the investment is shared. Second, the ADS can get you lead more rapidly because you can burn large quantities in the cores. So, the countries willing to quit nuclear, we have calculated for instance for Germany, if we build 7 EFITs, so 400 megawatt thermal, 7 ADS of 400 megawatt thermal, we can burn all the minor actinides of Germany in something like 42 years. And they used nuclear energy, I would say, for 60 years or a bit more than 60 years.

So, to get rid of the legacy, they make it in less time than what they used, which is rational. And so, this will be an advantage for those countries. The countries that are willing to continue nuclear, what are their advantages to go to share this investment? Well, they have also the minor actinides issue and the geological disposal issue. If they would apply it, they send their minor actinides to be treated in something which is shared, so also economically interesting. And the volume of fuel containing minor actinides is limited only on one centralized side. Instead of sending in our fast reactor fleet of reactors, plenty of fuel with minor actinides.

So this closed fuel cycle, the second strata is very small fuel cycle unit and is shared with the countries quitting nuclear. That is the advantage of this solution. And you avoid transporting all these minor actinides all over your park of reactors. Then as I said it before, if we do not only MYRRHA, but the four blocks, 300,000 years to 10,000, if we stay with the classical reprocessing, to 300 years. That's the interesting thing for P&T.

But as I said now let us know what is MYRRHA. MYRRHA then is an ADS. We want to demonstrate the ADS for pre-industrial scale and that can operate in critical and subcritical mode. The power of the reactor is ranging between 65 to 100 megawatt, so maximum power of the reactor 100 megawatt thermal, K-effective 0.95, fast spectrum, because we are using lead bismuth technique as a coolant. As it is subcritical, we need a source in the center which is this source that we create by shooting a proton beam of 600 MeV, 4 million at the maximum, on a lead bismuth target in the center that generates as these actually intense neutron sources in the center of our reactor.

Are we going to make only P&T studies which is here? No, we said that MYRRHA will be a multipurpose research machine. Therefore, MYRRHA means Multipurpose Hybrid Research Reactor for High-tech Applications because we want to stay high-tech. We will make research material, for fission Generation IV. But as I said and I will show it that we have a flame of very intense neutrons under the spallation target. Therefore, there we are going to be more close to mimic the 14 MeV neutrons that induce a high helium production per dpa. And therefore we say MYRRHA can also serve for the fusion research material.

The accelerator we are having will be also serving for fundamental research among others with radioactive ion beams that we can be producing thanks to the very intense accelerator intensity we have. As I said, the technology of LFR, I said that MYRRHA is a lead bismuth technology-based reactor with 100 megawatt thermal, so that's what we can call an SMR. And all the learnings we do there can serve the technology of LFR-based SMR.

Last but not least, we are today a champion in radioisotope production thanks to our BR2. We want to keep this capacity. Thanks to MYRRHA, 25% of the medical radioisotopes produced in the world are produced thanks to our BR2 reactor and we want to keep that. But as I said spent nuclear fuel waste, high level waste is the main application that we want to use for MYRRHA and we are developing it for this purpose.

So, the reactor of MYRRHA is a pool reactor, pool type reactor filled with lead bismuth. You see here the core; you see the heat exchangers and the primary pumps which are there. These are fuel handling machines. And what you see on this picture is the design that we achieved at the end of 2014. But the dimension, the diameter here of the vessel is 12 meter in diameter and the hanging ring here we have approaching 14 meter. And this is too big and the height is about 10 meter. Yes, it was something like 12 to 14 meters.

And so we said we need some optimization to reduce the size of this reactor. Besides that, we had some issues of potential release of polonium in case of heat exchanger tube rupture because we are using water as secondary fluid. And I will then show you where we are today in the design of this reactor. So we tried to simplify in 2015 the reactor by studying an option zero, just updating this revision 1.6 through using an innovative double wall heat exchanger for suppressing the problem of the water ingress in case of tube rupture of the heat exchanger and go with one innovative in vessel fuel handling instead of having one to reduce the global diameter of the reactor.

The option two we studied was to look to a pool type reactor and use all the tricks you can use for the size limitation. We wanted to go to as small as possible even though if we are deviating too much from our existing plan.

Then the option two, we even allowed our designers to go to loop type and a bottom loading with conservative technical choices. So, that became this external double wall heat exchanger and one existing in vessel fuel handling.

And then option three, we even said the goal, think out of the box, change everything if needed, and come to us with what you have discovered.

And what they have discovered is evolutive design from the existing revision 1.6, putting only one interim vessel fuel handling machine, making the core a bit outside of the center, and rearranging all the components inside would do the job for us.

And that's what you see on this schematic view. So the core is not anymore in the center of the reactor, it's a little bit out of center that accommodates the fuel handling machine with a double articulation and we rearrange the components inside and that has led to a drastic reduction of the diameter. We are now at the diameter of close to 9 meters in diameter instead of 12 and 14.

So, this being achieved, now we have advanced this design, but you see it here in more detail, I can show you, but I don't have 3 hours of time. But there exist duplications that you can find in open literature on our design. This is to give you an idea that it is not only the core that has been worked out, all the primary systems, the conditioning systems for the LBE, the secondary system based on water at the reasonable pressure, 16 bar at the secondary side is doing the job.

So, the reactor is well advanced. The spallation target, you can see that we are shooting through this beam line. This is at the head of the beam, which is this end of the red tube is this one. And the protons are getting through this window, which is in steel, T-91 steel is there. And then what you see the grey here is the place where the neutrons of the spallation are produced. And these are going to be here somewhere and we have these grids here below at this level because we have to mix correctly, the flow before it comes to heat the window. But you should see that this is very challenging. We have 2.1 megawatt of heat which is deposited in half a liter of volume. So, it has to be carefully cooled and therefore, we need all those structures to mixing the flow to do the job.

This is the total core, how it looks like, so hexagonal fuel assemblies with MOX fuel, 30% enriched fuel that we are using. And as I said, it can operate also in a critical mode. Therefore, you see those green dots in the core which are the ones containing the control works of the system. We have the white dots here, these three dots which are the safety rods to shut down the reactor, and the yellow dots you see here are seven central, what we call in-pile sections including the one in the center; otherwise, we have six in subcritical mode, because the central place is then occupied by the beam tube of the spallation target.

And those are accessible positions from outside the reactor. This means that in those in-pile sections we can change the irradiation conditions compared to the ones of the reactor.

So here what you see is the MYRRHA accelerator. It's a linear accelerator with two injectors and then we have what we call the support bearing unit until 100 MeV here. And then from here on, I don't know if we see. Yes, look how it's moving to this part until 600 MeV. And normally, you should see the reactors. Apparently, the reactor disappeared. But at the end of the accelerator, at the end here comes the reactor, the beam comes up and enters into the reactor, but you can imagine that.

The accelerator is frozen since 2014 and the challenging aspect in this accelerator of MYRRHA are those things, high current. Energy is okay. There are no energetic accelerators today up to GeVs and even terra electron volts, but generally they are pulsed mode whereas we want a continuous wave and we need such a high intensity.

The other big challenge, so this is the high power proton beam in CW. But even worse, this is the killing aspect of our accelerator compared to the existing one. Among others, beam trips we don't like. Every time we have a beam trip, this means a scram of our reactor. And a scram means shut down of your reactor, request actually a restart procedure that can be very lengthy. And so we say that if it is longer than 3 seconds, this is equivalent to a scram of a reactor. And therefore, we said to our accelerator designer, we can tolerate only 10 of them in a period of 3 months, which is the cycle operation of MYRRHA.

So actually beam trips which are shorter than 0.1 seconds, or between 0.1 and 3, we can tolerate 100 per day without a problem. If they are shorter than 0.1 seconds, unlimited number, we don't care. That means to achieve this very, very demanding reliability, we need meantime between failure of 250 hours and this is very challenging compared to existing accelerators. If I compare to the one of the SNS accelerator, the spallation neutron source of Oakridge, actually this is very resembling accelerator to ours and therefore we are very keen to look to this accelerator as well as the one of J-PARC in Tokaimura. And they trip about 2000 times a year. So, you can imagine that what we are asking is really, really very demanding.

So, we are going to address that to get to the reliability we need. We got around the accelerator of MYRRHA, the major accelerator labs in Europe working with us as well as industrial partners from day one. We incorporated what we call the full tolerance schemes in our design from day one, and we do validation with reliability models of high precision and we review regularly our accelerator by panel of international experts.

What we have done, all the components have been designed individually and prototyped with a big concern about the reliability, or what can disturb the reliability of the individual component has been suppressed or we gave more tolerance or we get more operating the components to delink them during the operation.

And then, one thing that we decided to build the full accelerator empty 100 MeV, but what you see here, in order the individual components that we prototype will be ongoing prototyping together of the system. And that's what is shows on this screen, all the components that we have already fabricated and are operating. Our PCR source is operational. The low energy beam transport line is also operational. The chopper of the beam is operational and individually takes part and recognize that we have made significant improvement, this to create what the safety authority call focus points, addressing new or non-natural enough techniques or technologies that we want to use in MYRRHA and that we defined on work to be conducted for this part of the system.

Then, we elaborated what we call the Design Option and Provision File, DOPF which is also something very known in the GIF, to actually limit what we can call the pre-PSAR, Preliminary Safety Assessment Report is based on this. And so this DOPF, Design Option and Provision File is made of five volumes but all of them had been produced and submitted to the safety authority in this pre-licensing phase. And the focus points, at the mid of 2017, we have identified actually the total for the moment about 75 focus points addressing different aspects, the accelerator, the lab technology, the material of the fuel, the fuel, the fuel handling, and so on. I will not enter into all the details. If you are interested and if you are working on lab technology, we can exchange on this.

But we produced 46 deliverables that have been accepted. We produced in total actually 170 deliverables, 46 of them have been accepted. In 2017, 50 deliverables are in Q&A with the safety authorities, 5 deliverables should be still delivered that was in 2017, in the meantime have been delivered. And 69 deliverables are scheduled to be issued after 2017. It means by the end of 2019, 2 years, '18, '19, we still have to give 69 deliverables. So, you see, we are really, really producing so much deliverables, 170 deliverables and some of them undergo pre-iteration with this Q&A with the licensing authority.

What we can conclude about this stage of the pre-licensing and licensing, so we have a fully consistent and coherent design of the MYRRHA which had been submitted to this approach. The focus is shifting towards the realization of prototype and subcomponents. We had the large MYRRHA R&D support program, but actually which was put with priorities driven by the licensing and the focus points that were put on the table for us in 2010 with our licensing authority.

The good thing, the safety authority recognized that we have made significant progress in the pre-licensing and they have issued for us the first opinion on licensability of MYRRHA in 2017 in November that says they don't see, let's say, blocking point or critical things to accomplish the licensing of MYRRHA in Belgium. It doesn't mean that it is already in the pocket. It doesn't mean that it is done. But for the moment and based on all what we have delivered, they don't see, I would say, a blockage for licensing this. But the licensing of this first part of the MYRRHA I will talk about, is part not anymore in pre-licensing, but in direct licensing since 2016 and I will come to explain you this.

So, the total MYRRHA, as I said the accelerator with two injectors normally and in 100 MeV, then we continue with these, these are spoke cavities you see here and the modules containing each of them too, 28 of them here. Then after that the Myobuim [ph] and that will be done in second phase, and phase 3 will be the reactor. And what we wanted to do is to realize this part by 2022 and test the reliability with one injector to demonstrate that it can do the job with our approach of cold tolerant design plus a very keen prototyping of all our components.

And that's what we say, it is a key milestone here by 2024, I will show you. And by doing so, we reduce this technical risk because without this reliability our ADS will never work or will be more idling than working. But we can't take such a risk, therefore we decided to build this phase 1, first of all and that we spread also the investment cost. And the first R&D facility will be present in 2024 in Mol. Why, because coupled to this accelerator we will have an ISOL target and a fusion material research target and the fundamental research for radioactive beams also constructed. And that gives us what is shown here these accelerators and each station targets for material radioisotope will be finished by – actually the construction, 2022, actually here, the testing for the reliability.

And then we are here in 2024 to take the decision to realize phase 2, upgrading the accelerator to 600 and constructing the reactor for which we will be working in this period. You can see here the pre-licensing and the licensing of the reactor will be finished in here. Then, we can get the permit for construction also by 2024. So, it's not that we are working only on phase 1, but phase 2 and 3. We will be also spending a lot of money in this period in order to get here for a decision by 2024 for full MYRRHA construction after having constructed phase 1.

How much money are we talking about? For phase 1, 375 million for which we will spend actually 219 for the accelerator and the target. And for the reactor, this one you see here, yellow, we will spend 100 million further in this period for the reactor development. The research on the accelerator of 600 MeV is tiny, 13 million. There is nothing extraordinarily complicated to demonstrate. And then, the project management is estimated to be for this period about 21 million. And the accelerator cost is 200 including its building, 100 MeV, and the target stations are about 219 million.

Phase 2 and 3 together, so from 2025 to 2030, we will spend €1274 million, so 1 billion 274 million we have to spend. And the major part is for the reactor, 835 million, whereas we spent about 300 million for the accelerator to upgrade to 600 MeV. So in total, the project is costing €1.65 billion for the period 2018-2030. And I think I am coming to the end of my presentation.

We are recognized in the extreme at the European level. Also we are contributing to the SET Planning, ESFRI. MYRRHA is present in the ESFRI of the SMTP [ph] and as such, it makes us eligible for actually loans from the European Investment Bank. We have already introduced a file for making the due diligence for the MYRRHA project, because we are on the ESFRI roadmap. The Belgium government have put us as well as the European Commission, DG Research, on the list of the Strategic Investments of Europe, what we call in our jargon, the Juncker Plan. Mr. Juncker, who is the President of the European Commission wanted the Relaunch Program for Europe of about €315 billion and we have to select the projects. And our MYRRHA has been put on this list and we can hopefully benefit from funding from there.

We have a very large network working with us, industries in Europe, research center in Europe, industries, research centers, universities. And beyond Europe, we have relations with South Korea, Japan, DOE. Now it's going down I would say. We hope to renew some collaborations with Jefferson Lab and Fermilab on the accelerator. We look forward to Los Alamos with whom we were working a lot in the time we were working on the lab technology. So, we hope that this will be a new level of interest for the lab. I heard that from the chief engagement of United States back. And we are also working with the Chinese Academy of Science, I would say, on the ADS approach and with Kazakhstan about using some of their research reactors, among others, the IGORR reactor for extreme safety testing of the fuel of MYRRHA.

So to conclude, ADS is not anymore the emerging nuclear energy system. You have seen 20 years of work in Europe, four of them constructed. The accelerator technology, we are making serious progress. We are going to prototype the accelerator of MYRRHA up to 100 MeV. Lead and lead bismuth technology are present in many countries, many loops are existing in Belgium, Japan, Italy, Germany, Korea, and South Korea, China, and USA. Heavy liquid metal instrumentation, oxygen meters, flow meters, ultrasonic visualization, sub-criticality monitoring is not anymore something to invent. We have them.

Material behavior in heavy liquid metal, corrosion, erosion, liquid metal embrittlement, etcetera are delivering their results. When it comes to very innovative results, we are missing some data under irradiation, but we are doing already efforts. But for existing materials and in the conditions of MYRRHA, we feel comfortable that we can make them working. Zero power reactors experiments with subcritical systems have existed or are existing like FEAT and TARC and CERN, MUSE in France, YALINA in Belarus, GUINEVERE in Belgium, KUCA in Japan. Large scale, heavy liquid metal reactor mock-ups. We have in Mol, the ESCAPE 16 dimension of the reactor of MYRRHA. We have also CLEAR-S in China in Hefei, which is even bigger than ESCAPE, containing something like 200 tons of LB yield whereas the ESCAPE model of MYRRHA contains 25 tons.

What is then the danger for this technology? One, to succeed to cross the death-valley for moving from R&D enthusiasm and compensating small money to the pre-industrial scale which is needing larger money. As I showed you, for MYRRHA only we need €1.6 billion. We need rigorous industrial approach in the project management, in the project approach, and also responding to the severe safety and licensing judgment. Because sometimes we see in some projects, people coming with very fantastic ideas like new materials or ideas like we don't need that or we don't need that. Is it really necessary?

Yeah, maybe on a paper reactor it's not necessary. But when you have a design to present to safety authorities, it's another story. And we are doing that since more than, I would say, 18 years and in a very structured way since 2010 with our licensing authority. I can guarantee you it's my exercise and that brings you in your decisions to more severe approach than what we were doing at the very beginning of MYRRHA. So, that's the challenge, enthusiasm of R&D and people working very hard without counting their hours. They do a lot but at certain moment when you come to this level and you need much more money to get here. And so how to bridge between the enthusiasm of research and the market penetration, you need governmental money and maybe some investors from the private sector can join. And that's what we are trying to do for MYRRHA, by enlarging the portfolio of MYRRHA beyond only the technology demonstration. Therefore, we included the R&D multipurpose approach and we hope then to bring you in 2030 around here. But in 2024 for sure this part will be constructed up till here and we will have our target stations in this place, so we need to plant some more trees at SCK. But good thing is that this project is open for participation and Belgium has offered already to the international community 40% of this 1.6 billion and calls for international partnership in this fantastic project that we would like to share with you. Thank you very much.

Patricia Paviet

Thank you very much, Hamid for this very, very good webinar presentation. I am taking this opportunity also to remind our audience about the 4th GIF symposium. It will be in Paris on the 16th and 17th of October. I invite the audience to really participate and be proactive by submitting an abstract. You have the website here. We have 11 different tracks and the objective of this symposium is really to review the progress that has been achieved against the R&D goals of the 2014 technology roadmap update and also to identify the remaining challenges and associated R&D goals for the next decade.

Also, the students are strongly encouraged to participate. They are our workforce, the next generation for these advanced systems. So we really welcome all the students, PG students to apply. With that, I think Berta will announce the next webinar.

Berta Oates
Yeah, thanks, Patricia and thank you, Hamid.

I've paused the playback at this point because we've had a change in the upcoming webinar schedule. The presentation plan for April has been delayed. The correct upcoming webinars are also available on the PDF copy of the slide deck. So, our next presentation will be in May and that will be on the Proliferation Resistance of the Gen IV Systems by Dr. Bari. And in June, Molten Salt Actinide Recycling and Transforming System with and without Thorium-Uranium Support, MOSART, will be presented by Dr. Ignatiev from Russia.

And at this time, today's presenter will join us live to address any questions that you might have. So, we can go ahead and dial in and unmute the phones. But please for the people who are on the phone together, please use your computer speaker so we don't get that feedback echo as we continue the broadcast now live. If you have questions based on today's presentation, please go ahead and type those into the chat box. Again, thank you for your patience and reference to the PDF copy for those few slides where we had the animation difficulties in the recording. Hamid, have you joined us?

Hamid Abderrahim
Yeah, I am there.

Berta Oates
Thank you for your presentation.

Hamid Abderrahim
You're welcome.

Patricia Paviet
Yeah, thank you, Hamid.

Hamid Abderrahim
Thank you, Patricia. So, I am waiting for the questions. I have the Q&A pad open in front of me.

Patricia Paviet
Very good. And like I said if you click on the presenter view, you see a few questions appearing, Berta and then what you are marking. Thanks, Berta and to all.

Hamid Abderrahim
How am I supposed to respond? Is this by writing?

Patricia Paviet
No, Berta is going to read the questions and you can see them and you will answer orally so that everyone can benefit.

Berta Oates
So, the first question is what are the fuel materials under consideration for MYRRHA, purely metal, or oxide, or nitride, or carbide?

Hamid Abderrahim
This is oxide MOX fuel, PO2, PuO2 MOX fuel. We are considering with around 30% plutonium contents. You heard my response?

Berta Oates
Yes.

Patricia Paviet
Yes we did. Thank you, Hamid. You have very nice comments from a lot of people thanking you for your presentation.

Hamid Abderrahim
Yeah, I see that. Thank you, everyone. That's well appreciated.

Berta Oates
So, there is a question, when is the simulator of MYRRHA scheduled for commissioning?

Hamid Abderrahim
Can you repeat please?

Berta Oates
It says when is the simulator of MYRRHA scheduled for commissioning?

Hamid Abderrahim
It depends what is meant by the simulator. We have already built a zero power lead reactor coupled with an accelerator and has been commissioned in 2009 and is delivering already results for us for our licensing and our code validation since 2010. So, the zero power mockup, which is called GUINEVERE, has been built in 2007, 2008 and finished

commissioning in 2009 and got the final license in 2012. But the commissioning exercise 10, 11, 12 delivered already results for us and now we are running validation experiments in it. And we don't foresee, I would say, a numerical simulator for the moment for MYRRHA.

Berta Oates
Thank you. What is the standard followed for the vessel design?

Hamid Abderrahim
RCC-MRx. Actually, these are the design codes for research reactors. We could use also ASME. It's also another possibility. But we use RCC-MRx. Next?

Berta Oates
I think you've got one more coming in.

Hamid Abderrahim
Gang Zheng has another question?

Berta Oates
Yes.

Hamid Abderrahim
Let's say.

Berta Oates
For level 1 or level 2 design for the vessel, it is in normal pressure?

Hamid Abderrahim
This is a non-pressure vessel. It's not a pressurized vessel actually.

Berta Oates
How about the safety system design for MYRRHA, like the emergency residue heat removal system?

Hamid Abderrahim
This is based on passive systems. We have two independent passive systems, one connected to the use of the heat sink, of the heat exchanger. And second, the heat sink is based on air connected to the external chimney. We have two independent decay heat removal based on natural circulation.

Berta Oates
Any additional question? If there are no additional questions, I want to take a minute to thank you, Hamid for your efforts to pull this presentation together. I know you had a set of visitors and delegation at

your facility today and we greatly appreciate your accommodating us to continue with the scheduled presentation.

Hamid Abderrahim
Yeah, it was a real pleasure. And actually, I would say that few minutes previous to joining the discussion, I was explaining MYRRHA to the Director General of IAEA, Mr. Amano who was also very pleased and amazed to see all what we are developing, especially the support program for this system, and impressed by what he had seen in here. And that's what I was telling in my presentation. We are welcoming international participation and opening this project for everyone who wants to be in the adventure. But I don't believe it's an adventure, it's an innovation and pleasure of project, enthusiastic for young people.

Patricia Paviet
Thank you very much, Hamid and I think everybody has your email address. So, if people want to participate, collaborate with Hamid, I encourage them to contact him directly. Thank you. That was a very, very great presentation.

Hamid Abderrahim
And if there are people willing to still have questions, they can feel free to send them to me by email. Everyone I think can find easily myrrha@sck-cen.be and we will be doing our best to answer the questions.

Patricia Paviet
Thank you, Hamid. Thank you again, Berta. Thank you, Amanda.

Hamid Abderrahim
Thank you. Bye-bye.

Patricia Paviet
Bye-bye. Okay.

Hamid Abderrahim
Thank you.

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