International Molten Salt Research in Support of MSR Development
(Panel Session)
Mr. Aslak Stubsgaard, Copenhagen Atomics, Denmark
Mr. Edward Pheil, Exodys Energy, USA
Ms. Isabelle Morlaes, Orano, France
Dr. Jeremy Pearson, San Rafael Energy Research Center, USA
Dr. Markus Piro, McMaster University, Canada

Berta
Welcome everyone to the next GEN IV International Forum Webinar presentation. We have a panel discussion this morning or this afternoon on international molten salt research in support of MSR development. Our moderator today is Dr. Patricia Paviet. Patricia is the National Technical Director of the Molten Salt Reactor Program for the US Department of Energy, the Office of Nuclear Energy, Managing Research and Development to support development of Molten Salt Reactor Systems across six national laboratories within the US.

In addition, she's the chair of the GEN IV International Forum Education and Training Working Group, which she has managed since November of 2015. The efforts of this group focus on the GIF webinar series, Pitch your Gen IV research competitions as well as Knowledge Management, Knowledge Preservation of advanced reactor systems. She has 30 years of experience on the nuclear fuel cycle, actinide chemistry and repository sciences. She earned her Bachelor's and her Master's in chemistry from the University of Sophia Antipolis in Nice, France, and Ph.D. in radiochemistry from the University of Paris in Orsay, France. Without any further ado, it's my privilege and pleasure to introduce my dear friend and cohort in these webinars, 92 of them. Patricia Paviet.

Patricia Paviet
Good morning everyone, and good evening, good afternoon. I'm sorry for one or another reason, my camera is not working. I'm very happy to introduce and moderate this webinar, which is hosted by the Gen IV International Forum. And this forum was created 20 years ago, a little bit more than 20 years ago, and can you believe it? This webinar is very special to me today. Really special. First, of course, as the GIF education and training working group chair and as the national technical director of this Molten Salt Reactor Program, I feel

really privileged to have external panel featuring Isabelle Morlaes from France, Markus Piro from Canada, Jeremy Pearson and Ed Pheil from the US, and Aslak Stubsgaard from Denmark who are going to discuss this international research on molten salt reactor.

But I would like also to dedicate this webinar to you, Berta [ph]. I'm happy I don't have the camera, otherwise I'm going to cry. We supported GIF webinar series for the last 8 years. I'm happy to call my friend who have been working together for 14 years. Thank you so much Berta, for all the support. I don't think this webinar series would have been successful without you. You have been really instrumental. Thank you very much again.

Next month we will start with a new platform, Zoom from NEA. Alexiei Ozeretzkovsky from the GIF secretariat will be our moderator. Without any delay, we're going to start this webinar. We had a panel session at the last American Nuclear Society Meeting last winter. And on this topic, I had a lot of requests to see if this webinar was recorded, which was not. So, that's the reason we are doing it again. Thank you to all the panelists to take the time to present today, and I'm sure we'll have a very interesting Q&A session.

Without any delay, I'm going to start with our first presenter, Aslak Stubsgaard. He's the co-founder and Chief Technology Officer of Copenhagen Atomics in Copenhagen, Denmark. Aslak earned a Master of Science in theoretical and mathematical physics from Aarhus University. In addition to the distinctive approach to thorium energy, using molten salt, Copenhagen Atomics fabricates and then sells to other players some of unique components, both in molten salt energy storage, concentrated solar power and molten salt reactor industries. Without any delay, Aslak, I give you the floor, and thank you very much for being here today.

Aslak Stubsgaard
Thank you, Patricia, and thanks for that introduction. Long time listener to the webinar, first time presenter, so this will be fun. Copenhagen Atomics is a Danish Molten Salt Reactor Developer Company. We just recently had our 10-year anniversary, and there's still no reactor yet, but we're getting quite close, and definitely the next 10 years will be quite interesting for both us and the industry.

Next slide. Can you forward the slide? Yeah.

In Copenhagen Atomics, we're developing thorium molten salt reactors that are intended to be mass manufactured on an assembly line and breeder reactors. And we are pursuing this technology because we see it as the only technology that can scale global energy production to be majority nuclear within a few decades. So, molten salt reactors are among the chosen Generation IV thorium reactor groups. But we really think that the thermal molten salt thorium breeder stands on its own in its ability to scale nuclear extremely fast. And so, that's the market that we're going for.

Forward, can you forward the slide? Thank you.

Berta
There's just a little bit of lag.

Aslak Stubsgaard
No worries. This is how we envisage a deployment of our reactor concept. So, it's 100-megawatt thermal reactor where the salts are reused because it's a breeder reactor, while the reactor vessels are discorded every 5 years and replaced with a new one. And this is illustrating a 1 gigawatt equivalent plant. And those are the minimum size that we think that we'll build. Like we're going after large markets that are predominantly commodities such as ammonia, steel, desalination, aluminum. Such markets that are the only ones that can really scale for the amount of production that we are targeting.

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Today, it's a little bit more modest than world domination. We're in a facility in Copenhagen, in Denmark, just next to the airport, where we have our test facility, which is 11,000 square meters, where we're building and testing prototypes of reactors and a lot of other molten salt equipment. Currently, we're around 70 employees working full speed to make molten salt reactors a viable product.

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Some of the things that we're doing in this facility is salt production. When we started, we couldn't find a supplier of purified salts, which is required for our systems. So, we had to start at thimble scale and then over the past many years, scale that up to a 1 cubic meter batch size scale, which is the scale that we need for commercial deployment. And those are the tanks that you see here. So, we both do the powder handling from the powder that comes from a supplier, and then we mix that in the ratios that we need, and then we melt and purify the salt. And we developed our process ourselves for purification, where we can get the oxide and transition metal impurities down to PPM levels, which is important for corrosion. And what you see down on the right-hand corner is stainless steel 316 samples that has been exposed to a lithium thorium salt at 700 degrees for 3000 hours. And if you extrapolate the corrosion rate, we end up around one to five microns per year. And that is more than enough for the type of reactors that we are building, where we swap out the vessels every 5 years. So that is sort of one of the key pillars that we need for commercial reactors.

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Another one is our prototypes. We've built several non-fission prototypes. So, these are full test reactor scale systems that are not currently designed for going critical. So, they are just running with non-radioactive salt and testing all the normal technology developments, finding all the bugs, improving the systems. And we're then planning to also test these with radioactive salt, but without any fissile material at our facility in Copenhagen to prove out the same system, but now using the same salts that we use in reactor, but still without it being able to go critical. Before we go on to test reactor and for our first test reactor, we're planning to do a 1 megawatt thermal test. And we actually recently announced a collaboration with the PSI Institute in Switzerland to run a test at their facility as soon as 2026. And that would be criticality experiment running at roughly 1 megawatt for around 1 month.

We, of course, hope to do many more tests running at higher power and longer duration, and we also hope to do these tests in more than one country. But this is sort of the first step on that journey. And we would then like to increment the system up to a commercial reactor. And what you see on the right picture is a view of the prototype seen from the top, where you see the core, which uses molten salts and heavy water as a moderator, where the heavy water is unpressurized and cooled and circulated through that core. And you also see in the picture some of the pumps and heat exchanges, and those are sized for a 1 megawatt test, while the rest of the system is sized for a commercial 100 megawatt reactor. But the pumps and heat exchangers are sized smaller just for that test.

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When we started, there wasn't any suppliers in the market that at least we could find that made molten salt components that can operate up around 700 degrees celsius. So, basically, most of the things we had to build or develop ourselves. And this is example of salt valves that are pneumatically actuated that we use in the smaller systems. But we actually have eliminated the valve from the reactor design.

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These are another one of the key components we had to develop. It's molten salt pumps. And this design is a little bit unique in that it uses a canned electromagnetic pump. The version on left still has a hydrodynamic bearing, so that means that the motor is sitting inside the furnace, and then the rotor is being actuated from a stator that is 700 degrees, or up to 700 degrees, and then the rotor is levitating on a film of salt, and the salt is also cooling the stator. So, it's a quite unique design. And we are now also implementing electromagnetic bearings into this design so that the rotor will be levitating instead of using a hydrodynamic bearing. But for most of the systems we built, we still use hydrodynamic bearings. And we also plan to use this for the first test reactor, but then gradually move over to electromagnetic bearings because they have a much longer service life and a much more predictable failure rate. So that means that we could operate pumps in a commercial reactor 5 years at a time without needing any online maintenance or repair.

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These are then our molten salt loops, and that's really the workhorse of the development we've done up to the point of the test reactor. So, these are small furnaces, the size of a Euro pallet, which have a roughly 25-liter molten salt tank, pump valves, pressure sensors, flow rate sensors, and a bunch of other equipment that you need to operate a molten cell reactor. But in this system, it's basically testing all those components, electronics and software in an integrated system where we can gain a lot of test time. While it's much less expensive than running a prototype or even a test reactor, we can eliminate most of those bugs. And those are then the components that we use in our bigger systems once they've proven out their reliability on the smaller and cheaper scale.

And these are also something that we make available for purchase to the industry. And this is really because we want to see the industry as a whole advanced, and we want to help the great researchers that are out there at universities, national labs and even companies to further their research, which then in turn helps the industry and helps us. So, it's sort of a net benefit for everyone. So, we sell these, and we've sold them to a bunch of different companies, universities, national lab, including University of Leeds in the UK, INL in the US, MIT, Berkeley, North Carolina State University. And this is something that we hope that if there's people out there that thinks that they can build a molten salt loop in a month or a year and get it up and running, then I'm sorry to say that it took us much longer, and it will likely also take you a while. So, that's why we hope that people will come to us, and we can sort of help them get them up and running, pumping salt, and utilize this setup to do whatever science they are trying to achieve.

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I can also say that we are currently close to having one loop that has been operating for a year without any maintenance. So, we're very happy with that. This is sort of looking inside some of those loops. You can see pumps, valves, sensors. It's quite compact because it's a small system, but we can usually modify it to achieve quite a few things. So, if you have some special use case, just reach out to us, and we'll be able to sort of figure out if our systems can be modified for your purpose.

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Patricia Paviet
Thank you very much, Aslak. Very happy to have now our second presenter, Edward Pheil, is the Chief Technology Officer and founder at Exodys Energy. He graduated from Penn State University with a Nuclear Engineering Fusion degree. He has 32 years of experience earned in multidisciplinary reactor technologies at the Naval Nuclear Laboratory KAPL. Ed has spent the last 9 years dedicated to the development of molten salt reactors, first with the lithium industries, and now with Exodys energy. So, Ed, you have the floor. Thank you.

Edward Pheil
So, my name is Ed Pheil. I'm Chief Technology Officer of Exodys Energy. We have a reactor design, but we are currently doing fuel development, and we are looking at using what is considered nuclear waste as a clean energy solution, because there's so much energy left in it.

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We're dedicated to converting used nuclear fuel. And wherever you see to use nuclear fuel, since that's kind of a standard, think of it as slightly used nuclear fuel, because it's only 0.75 to about 4% used, and the rest of it is still new fuel. And we plan to convert that into valuable assets for nuclear site owners. So, nuclear site owners being reactor companies needing fuel, or utilities that have slightly used nuclear fuel, that need a solution for the material that they have on hand, they have to store and pay for to some extent, depending on how new it is. As Exodys Energy, we were founded in October 2022 for nuclear recycling, and we are in the process of developing upcycle modules, and this is capital efficient, and deployable recycling solution. So basically, we make everything in modules and put them together depending on what type of fuel that we're making or what type of fuel that we're recycling as needed. We're composed of nuclear power and waste recycling experts from both the civilian and defense sector. And we have a global presence, as you can see there in the United States and France and Japan.

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This is a picture of the nuclear fuel cycle. The solid lines are the parts that are existing and going to stay the same as they are today. The dotted lines are how it's going to change if we're recycling the fuel. You can see the mining, conversion, enrichment, or not enrichment in the case of CANDU. And then you make the fuel, and you put it in a once through power reactor, and you make power for a while, then you take it out and you put it in the pool. And after a number of years, either 3 to 5 years for light water reactors or 10 years for CANDU, because they have a different dry storage canister design. And that's all the same as now.

But after that, it was intended that the fuel go into a deep geologic repository. And that, as you can see in red, is something that we expect to eliminate. We expect to take that fuel from the wet or dry storage into our upcycle system. That's shown as like, one shipping container, but it's actually several modules that we would have to stick together, depending on what we're doing. And then we would recycle that back into fuel for next generation of reactors, whether it be water reactors with MOX fuel or metallic fuel, or even nitride fuel, or fluoride, or chloride fuel for that. And the output of those reactors then would come back the upcycle module.

And we would also be able to take in depleted uranium into the module, for example, to make fuel for these other systems. If you don't need a high enrichment or to dilute certain materials that we can do. One of the materials we'll see later is you could take weapons-grade fuel, and you can dilute it with slightly used nuclear fuel, and that then will denature the weapons-grade material. But the reason why we have depleted uranium also coming in is because, like, a fast chloride reactor, which is our concept for reactor design, once you get it started up on a plutonium cycle, you only need to feed it depleted uranium or natural uranium or CANDU, slightly used nuclear fuel or depleted uranium from the fuel cycle after recycling.

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All right, so this is fuel inputs. So, use nuclear fuel. We would take in. We have done MOX fuel that we would recycle. Depleted uranium

CANDU. Use nuclear fuel and separated plutonium, whether it's reactor-grade or weapons-grade. Like I said, the weapons-grade would be denatured. We have different modules. This is just kind of a simple example of throughput. You have one module where you chop up the fuel cells, which is mechanical chopping. That's already done today. That's very well-known technology, electrochemical chamber, where you would separate things out like uranium and plutonium.

And you might have a chemical stage where you remove more of the uranium. So, you end up concentrating the plutonium so that you have a higher fissile content in it without using, doing enrichment activities, and then output of that at this point is intended to be fuel ingots. So, either metal ingots, or uranium oxide ingots, or uranium chloride, or uranium chloride ingots. And those will be sized so that you can package them in a subcritical configuration and sized container.

So note that the fast spectrum MSR allows for the use of the natural and depleted uranium at steady state power. And that allows countries that don't have enrichment infrastructure or don't have any fuel infrastructure to use this material because you would need enriched material to start it up. But once it's operating, you can fuel it with non-enriched materials. That makes it easier. It also allows for a fuel take-back program for countries that don't have a fuel infrastructure in, like, a fast chloride MSR, because at a fast chloride MSR, you only recycle the fuel a factor of 10 less than for a solid fuel reactor because the fuel is not damaged. So, every 40 to 60 years, you would take the fuel back to a country, recycle it, and send it back out in various different parts, depending on what is needed.

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All right, this is an example of where we took burned MOX. So, you go through a light water reactor one time, you recycle it like they do in France, and you put the plutonium in as MOX, and you burn it a second time in the reactor, and the burned MOX that comes out is what we recycle. And we used our process, which is a chlorine process, chloride process, which does not have a lithium chloride component, like, a lot of the stuff for IFR, FFTF, and all those we're using. And the intent is to use materials that you could use in a chloride reactor, but in particular, make sure that you don't end up with any lithium in the fuel that might make tritium or other materials that you don't like, like helium.

These are just pictures of those processes at INL. And Argonne was also helping manage that project. That report is export controlled, so technically available to the US, but the Argonne report is available, in general, not export controlled, but it's much simplified because to get rid of the export controlled information.

Next slide, please. So, in the US, we've been gradually increasing investment and focus on the molten salt reactors since about 2014; 2015 timeframe. The US is fortunate to have a lot of national labs, 17 of them, working on various forms of nuclear technology, and at least nine of them. And I'll take correction on that if there's more of the national labs are working on molten salt related research this year, whereas in 2015, I believe there were only, like, three of them. There are two liquid fueled molten salt reactors that expect to be operating by 2030 at Abilene Christian University, and TerraPower's Molten Chloride Reactor experiment, also known as MCRE, that will be started up at INL on HEU. And that particular reactor is basically a chloride reactor, like, our reactor, except for the fact that it's using HEU, and we started up with plutonium fissile.

Next slide, please. So, challenges of international collaboration. Every country has their own priorities on what they need to do. The nuclear programs typically benefit from significant government investment with a focus on local development of workforce and industry. That means, basically, if the government's investing in it, it has to benefit the people in that country or in that entity as far as jobs and development work. Several vendors have encountered difficulty balancing the benefits of each host country. But as an example, the UAE had reactors built by South Korea employing imported labor from places like the Philippines and Indonesia and that sort to actually build the reactor. So, they didn't really have the restrictions that say 70% of it has to be in country labor. So, that allowed them to get it done basically on time and on budget, and use experienced people, in that case, at least, to build the experience of that country when they're not doing it.

In reality, the US and Europe really aren't at this point, experienced countries for building. France authorizes the large – I'm sorry – differences in regulatory regimes and standards. So, we run into this a couple of places, and this is kind of like a double-sided thing. France authorizes larger amounts of Krypton emissions because Krypton doesn't interact in the body, and it decays fairly quickly. So, there's not really much of it left. In the US, they restrict the release of Krypton. Cesium and sulfur is another story. Both of them kind of limit how much of that is released, and tritium is another one that's quite different.

One of the other difficulties is export control complicates cross-border technical conversations. I kind of already mentioned this in those reports is that they were marked as export control. So, we need to get permission to send that out of the country.

Next slide, please. All right, so there're also advantages from international collaboration because every country has different skillsets and different specializations. Exodys is a US company with a French subsidiary to bridge US expertise in reactor development with French expertise in recycling and waste management. Because France still does that today and the US doesn't do that.

Most MSR vendors have embraced an international approach with headquarters and offices in multiple countries. And that's kind of true also in most advanced reactor areas, because they want to be able to export to those other countries. Having international collaboration allows for a diverse workforce and specialization where each country is very good at certain things. European counterparts like Italy, and Switzerland, and France developed the initial multi-physics tools to couple neutronic and CFD calculations for molten salt reactor design. And we worked with that company because it had that capability. And so that was a European capability that was developed. Other countries are still working to catch up to that capability. And some of them may be that far at this point, but just other countries looking and emphasizing different things is a benefit.

International teams allow for input of diverse regulatory frameworks, and that helps us basically, if we have other countries that have different assumptions about what the regulations are, then we can develop for sales in any country, at least any country that we're involved with. Or at least it helps to get more independent of a single country regulatory framework. The France 2030 has invested in a higher proportion of its resources in several MSR concepts in comparison to other countries. And currently, there's thermal and fast. But my understanding is that France is kind of leaning towards the fast chloride reactor in the design currently, but they support both. And so, they will develop France EU based suppliers, and those suppliers will benefit other MSRs in other countries. As an example, AslaK just mentioned, he's supporting salt loops for other countries.

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Recycling is a team sport, requires many different facets of expertise, but the reason why we want to look at it is because of the different fuel cycles and the cost of the fuel cycles. The fuel cycle one is basically a once through, like, a CANDU or a light water reactor in most countries. And you can see that's a fairly high cost. Cycle two is more like France does, where they recycle once, and so they have an increased cost of recycling in that, and that the overall cost is increased. And then a fuel cycle three is multiple recycles of both original uranium and MOX multiple times. So, reuse, I believe that we would call it RepU, reuse of plutonium after it comes out of the MOX reactor. That's possible. It's just difficult for, at the current time, to do that.

And then fuel cycle four is multiple recycles exclusively using fast reactors. Fast reactors have an advantage because they have a lowered cross-section for things that poisons that tend to absorb neutrons relative to the fission cross-section. All cross-sections are reduced. It's just that the absorbers tend to reduce further in a fast spectrum than the fission cross-section does. And so, you can do more cycles in that system. Now, if you go to a fast chloride reactor, you actually, instead of a solid fuel, that red section that's in there is recycling cost for solid fuels, because you have to do it so often. But if you go to fast chloride, then you're doing one-tenth of that recycling, so the cost drops down quite a bit.

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This is the question of, who do we want to collaborate with? And there's a broad spectrum of areas and stuff that we would like to collaborate; storage and transport of SNF or slightly used nuclear fuel and new fuel, because our fuels are going to be in different kinds or might have intermediate steps of fuel accountancy and safeguards, sensors, probes. And how do you guarantee that the reactor and the fuel recycling system doesn't divert any material? Advanced reactor vendor fuel input, we need to know what types of fuel other reactor vendors want so that we can look at what it takes to make that kind of fuel from slightly used nuclear fuel, whether it be a plutonium based fuel, plutonium plus minor actinide based fuel, which is different, and whether it's not just enriched depleted uranium or RepU that you can reuse in certain reactor designs. Hot Cells, gloveboxes, electro and pyro processing, engineering expertise that we don't have a lot of that these days in most countries, and regulatory experience, we need input from many different countries.

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So, that's me, that's my contact information. And below that is the Exodys Energy general info line for contact. On the left, there is a picture of our reactor.

Patricia Paviet
Thank you very much, Ed. All the questions will be asked and answered at the end of this webinar presentation. Our next speaker is Isabelle Morlaes from France. She has 30 years of experience in

the nuclear business in both reactor design and maintenance field and fuel cycle field, so both front and back ends. She holds several management and strategy positions in different business units of AREVA and Framatome, then Orano. Since 2000, she is the Senior Vice President, MSR Project Manager in Orano. She works in the Innovation Department of Orano.

Her mission includes exploration of new business models for Orano on the fuel cycle using MSR burning capabilities, coordination of initiatives to develop partnership and business with MSR designer, and the search for international collaboration and co-financing schemes to accelerate the development of MSR technology and its fuel cycle in synergy with the La Hague plants in France. Without any further delay, I give you the floor, Isabelle. Thank you very much.

Isabelle Morlaes
Thank you, Patricia. Good morning, good afternoon everyone. Thank you for the introduction and giving me also the opportunity to present Orano's perspective [ph] with respect to molten salt reactor.

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First, I would like to remind what Orano is doing today. Orono is an international group. Its purpose is the transformation and control of nuclear materials, and clearly the core business of Orano is the nuclear fuel cycle. As you can see here, schematically, Orono is present on every segment of the fuel cycle which means the front end part of the fuel cycle, mining of uranium, conversion and enrichment of uranium and also, what we call, the back end part of the fuel cycle, which is the processing of use fuel, which is done in Orano, La Hague plant and the fabrication of MOX fuel based on the plutonium that we recover at La Hague in the Orano Melox plant. So, this is the backend part of the fuel cycle.

Orano is also present on nuclear packages and services and engineering services, decommissioning services. All these services being at the service of our customers that are light water reactor plant manager and other kind of reactor plants operators. In the circle, if you click once more here, you have the key assets [ph] of the backend of the fuel cycle. Of course, I could have written another cycle with uranium that is also recovered at La Hague plant. But what is very important here is to know that we can use plutonium to do MOX fuel. So, mixed oxide fuel based on plutonium and uranium that can be used again in light water reactor. These are s two key assets for the circularity of the fuel cycle. We can separate the plutonium. And let's now focus on the La Hague plant for a minute if you wish.

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Here, you have schematically what La Hague plant is doing. In fact, it's a huge site with two lines, two plants each with an industrial capacity of 800 tons of heavy meters per year. It's based on the PUREX process. So, you extract uranium and plutonium. It's the top of the box, the gray box, and you separate them from ultimately what we consider waste, which is today the fission product and minor actinide on one side that are vitrified and the Hulls and end pieces of the used fuel that are compacted in the same kind of conditioning container to go to the waste disposal. So, we have been doing this for more than 50 years. We have reprocessed a lot of tons of heavy metal of fuel as you can see, not only in France but also other countries abroad. And with this process, and you can click again on the issue. Yes, we can save and recycle 96% of the content of the used fuel, leaving only 4% of ultimate waste. And this allows also to save up to 25% in natural uranium. It allows also to reduce the volume and radio toxicity of high level waste at the end, giving a safe and secure ultimate waste conditioning without plutonium in the deep geological disposal.

So, due to our worldwide position on the fuel cycle, first, I would like to say that we are keen to cooperate with all the new reactors developers and there are a lot of development ongoing for SMR and advanced modular reactor in the world. But more specifically because we are key actor in the closure of the fuel cycle, as you can see with the La Hague plant and also Melox plant, we want to cooperate more closely with the developers that are designing reactors that are compatible with the closure of the fuel cycle, which is clearly the fast spectrum reactors. And in this respect, molten salt reactor, using liquid fuel in chloride and fast spectrum are very promising reactors.

If you go to the next slide, in fact, we have been exploring the potential of these fast chloride molten salt reactor since 2019, because we think this kind of reactor has a potential to use not only the plutonium, but also minor actinide as fuel, and to provide a global solution where finally the customer will have to take care of vitrified residues only with fission product. That could be the ultimate vision, I would say. And this is a very interesting complementary option to the recycling of nuclear fuel that we are doing already in France. This could be proposed to our customer in addition, or in complement to the multi-recycling in light water reactor.

We consider that cooking the fast molten salt reactor with the services of La Hague could be an additional service to light water reactor for the management of their used fuel. And this is why we have this ambition to further [ph] or to enable the emergence of this kind of reactor that we think are very promising. So, here you can see what we envisage, at least as a first step. We think that the advantage of La Hague is that it exists, it's working. So, we could use already functions that are implemented in La Hague, performing some of the key missions we need to transform, for example, the plutonium in plutonium chloride, same finally with uranium, and maybe in the longer term, minor actinide too, when separated from the flow of waste.

What we could imagine is to add functions in the La Hague plant, to synthesize the fuel, the chloride fuel for the molten salt reactor, transport this salt to the chloride fast molten reactor, wherever they are, and to finally take care of the used salt or the irradiated salt, either online or offline. This is to be assessed. But what we can imagine in the first step would be to send the used salt to La Hague, to transform it in a chemical form, that is compatible with the live process, and to recycle it like this, separating again uranium, plutonium, minor actinides, etcetera. That could be the first step. And in the longer term, we could imagine that we polish the salt on the molten salt reactor on site, and we only transport the use salt with fission product to La Hague plant to take care of it. That means to vitrify the flow.

In any case, we consider that to use La Hague plant could accelerate the development of the technology because we have some technical bricks already existing in this plant. And so far, of course, the compatibility with the La Hague plant needs to be fully assessed. But at this point, we have identified no show stoppers. We continue to develop the fuel cycle for these molten salt reactors.

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Just to assess the potential of molten salt reactor in reducing the volume and long-term toxicity of high-level waste, we have done in the previous year some simulation at least to give some trends in the reduction of reduction factors. So, here you have a small example of comparison of three scenarios. The first one is the open cycle. The second one, we just mono-recycle plutonium in light water reactor, so we do MOX. And the last one we do like in scenario two. But we go one step further, and we take care of the plutonium and minor actinide coming from the MOX in molten salt reactor. And we balance all this plutonium and minor actinide in the fleet of light-water reactor and molten salt reactor. So, it's notion of, what we call, symbiotic fleet, because the purpose of this scenario, is to balance the streams of plutonium in the second case, and plutonium and minor actinide in the last case.

What we have simulated in these three cases is what finally will have to be taken care in a deep geological repository at the end of life of this reactor. So, of course, in the case of the open cycle, it's all the used fuel coming from the reactor, light-water reactor. Second case, you have the most used fuel and also the compacted and vitrified waste that have been produced by the La Hague process. And in the last case, you have obviously also ultimate waste, vitrified and compacted waste. But you have finally no minor actinide at the end because we have removed and burned all these minor actinides in molten salt reactor. And you have no used fuel [Unclear] because you have used all the plutonium coming from the MOX fuel.

First, you can imagine that there is a reduction in the volume of waste, but also there is a reduction in thermal impact. And which means that in the geological repository, you will have more objects that you can store on the same place or footprint. This was just an example, of course, of scenarios. There are a lot of scenarios possible. Here, it was done with SMR size reactor, but we could do it with a fleet of large reactor. It seems to be very promising to continue to explore these molten salt reactor scenarios, because you can see a significant reduction in volume and radiotoxicity. And now this is why we think it's worthwhile to go one step further and to do R&D, and ultimately demonstrate that it can work in this, like, it is shown in this slide.

If you go to the next slide. What we would like to do is to enable the emergence of this kind of reactor. Of course, we are not developing reactor ourselves, we are developing the fuel cycle, globally speaking. So, we have to cooperate with molten salt reactor designers, which is what we are doing now. Our vision or strategy would be to have first demonstration of this kind of chloride fast molten salt reactor in the ’30s. There is a lot of work to do, because the maturity of the technology is low. It's the case on the reactor side, but it's also the case for the fuel, because the liquid fuel is quite innovative too. And there is no experience. There is some experience with fluoride salt, but not with chloride salt.

As I said, there is a lot of R&D to be done on technological issues, on performance aspect, safety aspect, etcetera. We are in this phase now, but our vision is clearly to enable this first step of demonstration in the ’30s. We are ourselves working on the fuel cycle. We are part of some international projects, like, the MIMOSA project, founded by Euratom. We are also cooperating with US labs and also TerraPower to the success of their first critical mock-up and the next steps. We are part of project in France funded by French state. It's the case of the ISAT [ph] project with, for example, CEA, CNRS, EDF, FRAMATOME, but other projects too. So really, we consider that international cooperation is vital to succeed in the R&D programs, if we want to achieve pilot phase or demonstration phase in the ’30s.

Last but not least, as Ed said, there was a French program launched 2 years ago, and we are now in consortium with two startups in this program, with funding by the French state. So, it's called France 2030, to work on the first pilot that we will need to demonstrate the technology in the ’30s. So, what we think is that these kinds of reactors are ideal candidates to close the fuel cycle and reduce the long lived high-level waste. This is our vision. And we think also that using the synergies with the La Hague plant can accelerate the development and the deployment of this technology. And in particular, we are in view that it could offer complementary services for the multi-recycling of light water reactor in the world.

This is why we think it's a unique value in terms of sustainability and public acceptance for the nuclear energy in the future. We consider, of course, that's the beginning of the journey, but it is an exciting journey, and we are very happy to see a growing interest in the world on molten salt technology. Thank you very much for your attention.

Patricia Paviet
Thank you very much, Isabelle. Like you said, it's an exciting journey and we are all happy to be part of that. Our next speaker today is Dr. Jeremy Pearson. He serves as the Director of the San Rafael Energy Research Center in Emery County in Utah, where he works with local leadership and university to research and commercialize groundbreaking sustainable energy technologies. Dr. Pearson earned an undergrad degree in Chemical Engineering from Brigham Young University and a Ph.D. in chemical engineering from the University of California, Irvine, studying used nuclear fuel recycling.

He has worked in the energy field in nuclear energy and advanced unconventional fossil fuel as well as in energy policy, having served in 2015 in Washington, DC as science and engineering fellow in the American Association for the Advancements of Science in the office of Senator Orrin Hatch. So, without any delay, Jeremy, I give you the floor. Thank you very much.

Jeremy Pearson
Thank you so much, Patricia, for that kind introduction. As Particia mentioned, during my graduate studies, I did work on the back-end of the fuel cycle and recycling and become something of an advocate of the potential for recycling that it has, especially here in Utah. And I did my graduate studies under Mikhail Nielsen [ph] from Sweden, and also during that time gravitated towards MSRs as having significant potential. And so excited to present to you today. And I'll

say, welcome to Utah. If you can see my picture, I'm actually presenting outside so you can see beautiful mountains. It looks like the sun's fading out, but you can see a picture here.

And next slide.

You can see our individual buildings that we have here at the center. Like many national labs in the United States, we're not a national lab, but similar to them, we are in the middle of nowhere. Yet, we are located just 40 minutes away from one of the top rated welding programs in our country, which is set up to support two gigawatt scale coal nuclear power plants.

Next slide, which you can see where we're located here in Utah with these two power plants just north and south of our center within 10 to 15 minutes, which, similar to the Kemmerer facility in Wyoming, are owned by Pacific Corp. And have entertained moving to nuclear power just like the Kemmerer plant is moving to Bill Gates TerraPower nuclear design.

And so this facility – Next slide, please – was set up to help commercialize the molten salt reactor design and work with various partners as a public user facility and to work on advanced coal and power cycle designs, including the supercritical CO2 Brayton cycle. We just completed last week. As far as we know, the longest running supercritical Brayton demonstration in the country, which ran for in the last run for 240 hours continuous. And so, this research center was set up to help diversify the economy and energy, keep the community a national leader in energy production in the case that we moved away from coal.

And you go to the next slide, please.

So, $20 million overall has been invested into retrofit and purchase equipment and develop these facilities about 10 million for our nuclear research side, invested in glove boxes and fume hoods and various analytical equipment for molten salt property analysis and purification. We'll just click through these slides, so I can show you the suite of equipment that we have. We have for molten salt properties, STA, LFA, TMA and dilatometer?

Next slide.

And rheometer for viscosity, inertial gas fusion analyzer for oxygen content, and a suite of potentiostats over four different glove boxes for help in electrochemistry and purification and separations processing.

So, next slide, please.

And also, ICP-MS for elemental analysis and a Neoma ICP for isotopic ratio analysis.

And next slide, please.

And just in a month, we're receiving a new FIB-SEM as well for imaging.

And next slide.

Here're some images of our glovebox and lab setups that we have with ICP in the background.

Next slide.

Here's our STA rheometer in the background in the other glove box.

Next slide.

And of course, our Neoma ICP as well.

And so next slide, please.

And then adjacent to the smaller research laboratories, we have a high bay room where we could do larger scale piloting of purification and processing processes, as well as operations that could be formed in a hot cell that we could have built and up into, and potentially including the construction of a test reactor. When I think about a test reactor, as you've seen from our other presenters, there're other reactors that are being built in the US and globally. You have Abilene Christian University and the MCRE experiment. If we were to do a test reactor here at our research center someday in the future, I asked myself the question, what would we add? So we're not duplicating efforts, but contribute something that's complementary.

And I think that perhaps we could be an ideal location due to our interest in recycling and having a test reactor that prototypes online fueling and online recycling to close the fuel cycle. And so, let's move.

Next slide, please.

So, we're all aware of many valuable elements that are present and use nuclear fuel, from medical isotopes to reusing the fuel to radioisotopes for RTGs, radioisotope, radiothermal generating systems and rare earth elements. And so, our lab is interested in working with collaboration to develop the processes that help make these recycling steps economical so they can be introduced commercially in the future.

And so, beyond just research…. Next slide, please.

I like to view Utah as a potential host for the commercial recycling industry in the future in the United States, not just research. And so, the question then comes, where would such a recycling facility best be located in Utah?

And the next slide, please.

The location that comes to mind for me is location called Delta. This is where we have our other third large gigawatt scale coal-power plant, which provides most of its electricity to Los Angeles, California. This is just a little more west than Utah. What makes this location unique is that it's currently under the ACES Delta project in the process, in collaboration with Mitsubishi and Chevron, in converting it to hydrogen power, and in a combined cycle, combustion natural gas hydrogen blend mix fully supplied by renewable hydrogen. And so, some details on this project. Hydrogen will be renewably produced and stored in underground salt domes, and it will be able to produce initially from 210 megawatts of electricity, about 100 tons per day of hydrogen, and that's stored in underground salt caverns, which have the capacity of 300 gigawatt hours of energy. So that amounts to what we understand is the world's largest renewable energy storage project, larger than all the battery projects combined, and just about 10 times larger than the largest pumped hydro storage operation in Fengning, China.

And these underground caverns, there're two of them that are the size of the Empire State Building and capacity to build 40 times more, which would raise it up to about ten terawatt hours of storage capacity and associated with expanded production in hydrogen. For those of you who know Professor Charles Forsberg from MIT, he is very outspoken about the need to identify the best location in the United States for a nuclear hydrogen gigafactory that's co-located with recycling and underground storage. I view potentially this delta facility has that, that Kemmerer location where hydrogen gigafactory coupled with molten salt reactors and giga-scale hydrogen production as well as reprocessing could be located.

And so, another thing we need to be working on developing is thermal processes that can produce hydrogen from nuclear heat. I'll try to move fast through these last slides. So, we have room for our last presentation and questions. Here's a picture of our coal furnace that has the piping that carries CO_2 for our supercritical CO_2 demonstration.

Next slide.

Integrated energy systems is this use of nuclear heat for hydrogen production and other products.

Next slide.

So, ways that we could demonstrate production of hydrogen, an integrated energy system faster could be threefold. At our center, we could take heat from our coal furnace and apply it to a system producing hydrogen as a simulant of nuclear reactor. We could do an electrically heated unit like they do at INL. Or we could even build a test reactor that directly couples to hydrogen production process and test that's here. I just wanted to leave you with one point for my final slide, is that in my observation, I feel that the global dialogue has lost sight of the central importance that maintaining and reducing costs of energy play and human prosperity. And I feel that this needs to change.

If you can go to the next slide. I think author, Steven Pinker, points out very astutely in his book 'Enlightenment Now,' that energy channeled by knowledge is the elixir of life, and that is understood to be at maintaining energy cost and reducing energy costs. And that applies very importantly to nuclear reactors and recycling processes, that they must be economical to be of utmost help. And then he also points out that entropy is the enemy of life. It's not humans that we're fighting against. So, rather than working towards political or national dominance, we should be focusing on working together synergistically and interdependently as nations and people to support energy production. And here, as we take this human-centric energy approach, here in Utah, Governor Cox has been promoting Disagree Better Program, which I think is laying the foundation for successful nuclear mega-scale projects in our state. And so, we're really excited about this transition.

Next last slide. I do feel that the largest problem we face as a globe this century is this conversion to sustainable energy. And we look forward as a state to research center, to working together with everyone worldwide on this goal. Thank you.

Patricia Paviet

Thank you very much, Jeremy. And our last speaker today, Markus Piro. He's currently an Associate Professor at McMaster University in

Canada, where he's conducting research in nuclear fuels and materials for conventional and advanced reactors. Previously, he was the Chair of the Energy and Nuclear Engineering Department and Canada Research Chair in Nuclear Fuels and Materials at Ontario Tech and Head of the Fuel Modeling Section at the Canadian Nuclear Laboratories. He earned his Ph.D. in nuclear engineering from the Royal Military College of Canada and did a postdoc at Oak Ridge National Laboratory.

In addition to research in academia, he is the President of Piro Consulting, a consulting firm supporting the nuclear industry primarily in safety and licensing. Without any delay, I give you the floor, Markus, thank you very much.

Markus Piro
All right. Thank you very much, Patricia, for the introduction. Much appreciated. So, what I'll be doing today is offering an academic perspective on molten salt reactor education and training to complement the excellent presentations we saw from our industry partners here.

Next slide, please.

So, before I get into any of the content, I want to thank both Patricia and Berta for the kind invitation to give this presentation and also doing all this organization. For a number of years, I'd be listening to these webinars, and there have been some fantastic presentations. So, it's an honor to be here. Thank you both, Patricia and Berta.

I also want to thank some, many colleagues, both within Canada and abroad, for technical discussions that have informed the work I'll be talking today and also a number of students and postdocs that have contributed to this.

Next slide.

As a quick disclaimer, when this panel discussion took place in person at the ANS conference last year, as Patricia mentioned earlier, I was with a different employer on TerraTech, and I'm currently with McMaster University. Just want to state that these opinions are that of my own and do not reflect either my current or previous employer.

Next slide, please.

Okay, so, talking about nuclear education and training, there's a number of different pathways that could be taken to support the industry. And, like, the way that I see the role of the university is that our mission is to provide the best educational experience while preparing students for the workplace. And in that interpretation, one could view the universities as being a supplier to the industry. And what we're supplying is talent. So, there's a few pathways that students could be taken. The traditional pathway through an undergraduate program is familiar to us all. Here at McMaster, we have an Engineering Physics Department where we train students in nuclear engineering. We're also in the development of a nuclear minor. The whole idea there is to take all the other engineering students that the utilities and other stakeholders and industry needs. They need civil engineers, chemical engineers, electrical engineers. But what they keep telling us, they want those engineers to know something about nuclear. So, we're in the process of developing that nuclear minor.

The other traditional pathway is through graduate research, through a master's or Ph.D., which I'm sure is also very familiar to others. It's just kind of worth acknowledging the fact that the undergraduate programs tend to be very streamlined, whereas the graduate programs, you tend to have a very unique individual experience for each student where each student would have a specific type of thesis project specific to them. There's also industry-oriented pathways that folks can take, such as industrial training and the example given here in Canada, it's called UNENE. It is a nonprofit organization that interfaces between the industry and academia here in Canada, and they provide industrial training for folks working in industry so they can upskill. I'm not representing UNENE today, but just acknowledging that they exist and provide a great pathway for upskilling.

Next slide, please.

So now, a lot of these programs I was just talking about there, they're very much guided by the needs of the industry because, again, our objective is to train students so that they can enter the workforce. So, a simple question is, who's hiring our students? So, reflecting on a number of years here, at least for our cases, mostly the utilities are hiring our nuclear students. To a lesser extent, the suppliers, the national labs, the regulator, and other stakeholders, and an even smaller fraction of that are hired by SMR vendors. Now, again, so if our mandate is really to train this workforce, it's worth ensuring that the design of those programs are really aligned with the nuclear sector. One major challenge we're faced right now in Canada, which I suspect is the same in other countries, is that the industry is growing at such a fast rate right now with various units being deployed and all sorts of other activity, that the nuclear supply chain of talent is a bit of a bottleneck and is a concern for the industry. We can't get enough talent to meet the job growth. So that's a challenge that we're faced with at the moment.

Next slide, please.

Now, in this webinar, we're talking about molten salt content. I think it's worth talking about a few areas where we can incorporate MSR content in the education programs. Looking at the undergraduate program, there's been a few cases where some MSR content is sprinkled in a few courses. Pretty limited. Same goes for some of the graduate programs we've had. There're some case studies that might include molten salts, but it's pretty limited content. The primary pathway for integrating MSR content in the education at the universities is really through research, doing various types of research projects with graduate students.

Next slide, please.

To give a few examples of some of the graduate research. Over the years, we've done both computational and experimental work on molten salts, but what I found is worked really well is to do both, have students, at least within the group, do both computational and experimental work. So, as an example, the student on the right is preparing some salt samples for differential scan and calorimeter, where those measurements provide valuable data than for models and simulation type of capabilities. The figure on the left shows some analyses that were done with Sandia National Labs to look at severe accident behaviors in a TRISO-fueled, salt cooled type of reactor. It's important to acknowledge that this is a two-way street where the experiments can inform the models. But also, what's useful is that some of the simulations are helpful at identifying knowledge gaps, which can then feed-back to some of the experimental programs.

Next slide, please.

There's been a number of opportunities in the academic landscape. It's great for the students to get involved with MSRs. We've been supporting various types of MSR programs to try to help fill knowledge gaps, develop new capabilities. So, as an example, we have a former Ph.D. student shown here. He was supporting the European Commission coordinated research project called SAMOSAFER, looking at molten salt reactor safety, and he was developing some pretty cool multi-physics capabilities. There he is standing outside JRC in Karlsruhe, fantastic partner in Germany, and it's a great way to train the next-generation of scientists and engineers, especially through international partnerships. This has been a very effective way to get the students involved with different types of technologies, because it's worth acknowledging as well, at least for Canada, that we didn't have any experience really in molten salt technologies for several years ago. So, it's really good for the students to partner with international collaborators that do have some of that experience.

Next slide, please.

So, with opportunities come some challenges within the university. First one is to think about the content of different nuclear technologies, as it's used in undergraduate programs. The common question is, how do you balance some different types of nuclear technology? So, as it stands today, there's only one technology for nuclear power generation in Canada, which is the CANDU design. The Ontario power generation is a pretty advanced state in their licensing process for a boiling water reactor. So, now we have two upcoming designs. And so, it's a bit of a question of how much of different reactor technologies do you include in an undergraduate program? It doesn't make sense for us, for example, to put significant effort into lead-cooled fast reactors when there's no utilities supporting that, at least not within our country.

Another point that needs to be, is a challenge is that the instructors themselves need to be sufficiently trained and competent in a particular technology. We got to train the trainer. How do you do that? How do you do that effectively? So, from my experience, I found that that's mainly done through research, which is great, but the universities need to think about as well if there's a concerted effort to support different types of technologies, that not only do they have to train the students, they have to train the trainer. So, that's something to think about.

The last one was something I call this Catch 22 effect, which applies to some molten salt work, but also other technologies where some technologies may require a lot more research and development activities, but at the same time, the students, like, they need to be able to get a job, which is part of our mission. The anecdote I've given before was that so far I've trained 13 grad students in molten salts, and none of them got a job in Canada to do molten salt work. Only one of them got a job doing molten salts, and then now is in the United States. We have to kind of balance and think about, how do we balance some of the research projects in developing the student themselves, not just the research output and how that helps them, with their job prospects.

Next slide, please.

To summarize, what we ended up doing with a lot of these different educational programs is to try to focus, at least at the undergraduate level, having a solid foundation in nuclear science and engineering, which is really technology agnostic, at least for us. The application space has been very much focused on CANDU and is evolving more to boiling water reactor technologies, but also trying to expose them to other technologies as well. What we found is that's worked well for MSR. Technology integration into the educational programs is really through student research, where the student research theses are related to that technology.

International collaborations have been extremely valuable in getting a lot of those things off the ground, especially, again, because there wasn't really any experience within Canada in molten salts given 10 years ago or so. And last one, again, the nuclear job market is incredibly competitive right now in at least where we are, where, just being able to provide enough engineers and scientists to the industry is a concern and something to be thinking about. So, that's it for me. I think there's a last slide for contact information but want to thank you for your attention.

Patricia Paviet
Thank you very much, Markus. I think, Berta, you take the floor for the next webinar's announcements.

Berta
Yeah, we have three webinars that are on the books that are upcoming. One in September on the overview and update of sodium fast reactor activities within the GEN IV International Forum, a presentation in October on prospects and challenges of a GFR technology, and in November, overview and update of SCWR activities within the GIF. With that, we'll take questions. I might invite the panelists to alter their cameras on now so that the audience can see. We have several questions that have come in. Patricia, I will let you take the lead on moderating how you want to fill those.

Patricia Paviet
Yeah. Thank you very much, Berta. I'm happy I changed the computer so now everyone can see me and see the panelists. First of all, thank you very much to all the panelists. It was a great presentation. We have quite a number of questions, so I'm going to start with a question for everyone. So, who wants to take the floor will let me know. First question, what is the expected emergency planning zone for thermal and fast molten salt reactors?

Edward Pheil

Well, I'll try that one first. We're mostly working on fuel, but the fast chloride MSR is expected to have the emergency planning zone be the fence boundary, and that's fairly small. It'll probably be well inside that. It's a low-pressure system, and the gases which are the most likely thing that could escape is at least double barrier and stored in the reactor. So not a lot of probability of release of significant materials to the public.

Patricia Paviet
Okay, thank you. Someone else wants to add something? Okay, so next question again, for everyone, considering the ongoing development in molten salt reactor technology within the nuclear industry, is there a common framework or set of standards that can be adopted to streamline efforts and avoid reinventing the wheel for further development of MSR?

Aslak Stubsgaard
I can jump in there. I personally, and at Copenhagen Atomics, we don't think that standards are applicable to molten salt reactors currently. I think as an industry, we need to get many different designs up and running and license and test them out and figure out what works. And then at that point, look back and see does it make sense to implement standards for this technology but not at the current state.

Patricia Paviet
Okay, very good. Yes.

Edward Pheil
US actually developed an initial set of standards for molten salt reactors as for the NRC. I don't know that those have actually been published as official NRC documents yet, but it has been released to the NRC for their consideration. And then the NRC asked for those. I was on one of the development committees, and I'm trying to think of the guy's name from – it used to be from Oak Ridge, now is at INL that was in-charge of that.

Patricia Paviet
David Holcomb, and he's listening, yes. It’s David.

Aslak Stubsgaard
It’s ANS-20.2 standard. If anyone's interested, you can google it.

Patricia Paviet
Okay, very good. A question to Markus. Markus, have you considered educating students for careers in fuel cycle chemistry by

adding some nuclear engineering education or minor to a chemical engineering degree?

Markus Piro
Yes. The minor that I was describing earlier would be applicable to all of the engineering disciplines and a few others within the university. That's the intent. So, a chemical engineer student that would take that for their major could have a nuclear minor.

Patricia Paviet
Very good. Aslak, please, can you detail more advantages of EM pump you are developing versus currently tested technology?

Aslak Stubsgaard
Yeah. The amount of currently tested technology is, of course, quite limited. The only thing that has been in operation was the Oak Ridge MSRE pump and the aircraft reactor experiment, and both of those used cantilever style pumps. So, that's why you have a traditional motor that is driving a shaft that is penetrating into the furnace and into the salt and running a centrifugal style pump. And that works, and it's been demonstrated. The disadvantage is that you have a dynamic seal, so that shaft that is penetrating has a dynamic seal, and that is a potential source of leakage from the salt out, which also happened at the MSRE. And more importantly, it also leaked inwards.

But the other disadvantage is that traditional motors and this sort of shaft assembly has bearings that need maintenance once a year. And what we want to do is to do reactors that can operate for up to 5 years without any maintenance. And so that becomes sort of not so good design path. What electromagnetic bearing pumps provide is a design that doesn't have any wear and tear because you're levitating the rotor. And you can also, as what we have done, put the motor inside the furnace so that it's a very short assembly without any dynamic seal so that you can weld up the assembly. And this style of pump or motor is also used in other industries, for example, in oil and gas. They're at the bottom of the sea, where they have been running for more than 10 years without maintenance. And that's really the style of pump that we want for our molten salt reactor. And the reason for that is because we believe it's actually more expensive to design the reactor for maintenance than to just scrap a whole unit if something breaks.

Patricia Paviet
Very good. Thank you Aslak. A question to Isabelle. Isabelle, what is the prospect for producing highly enriched chlorine 37 for the future chloride based molten salt reactor? We don't hear you, Isabelle.

Isabelle Morlaes
It's a good question because it's a key topic for the developers of reactor, and it's also a key topic for the recycling of the fuel itself, for the waste, in fact. So, it's part of the R&D. There are several processes that could be used. We are investigating these processes, and we will develop a roadmap for this particular topic, which is important. Thank you.

Edward Pheil
Just note from a historical perspective, chlorine 35, chlorine 37 enrichment was the first isotopes ever enriched in the world. So, it's been done.

Patricia Paviet
A question to all. In reference to the last sentence of Markus' presentation, could you explain what difficulties students face when entering the nuclear industry?

Markus Piro
Happy to take that one. That could be partitioned in, let's say, undergraduate students versus graduate students. But I think the main thing that I've seen is the difference in culture and the level of professionalism. That's probably one of the biggest, like, stepping stones that they have to face once they enter industry.

Patricia Paviet
Okay, thank you.

Edward Pheil
We'd like to take a stab at that, if I may. The nuclear students today, basically, at least in the United States, only learn water reactor technology in undergrad, and they do a skim of what other reactors are, but they don't really have the basis for going to do MSRs. But the technology of MSRs is so different because you have a liquid fuel that doesn't get damaged in the reactor, and that changes the concept completely. And closing the fuel cycle instead of using a tiny fraction of the fuel is huge, as is the simplification. Because it's a liquid fuel, you can take it, clean it, and put it back as a liquid fuel, and you don't have to remanufacture solid fuel all the time. And so, that's a huge difference in perspective that the students in the universities and stuff really have to get. It might be a benefit of more universities going to chemistry and nuclear as opposed to mechanical and nuclear, because of the fact you're eliminating a lot of the mechanical part of the fuel development.

Jeremy Pearson

Patricia, adding on to what Ed and Markus said in the theme of specially tailored programs for what this new workforce is going to need, one very interesting development here in Utah is Utah State University, just hired as their new president Elizabeth Cantwell, who has executive research at Oak Ridge and Lawrence Livermore National Lab. And her first action was to institute a brand new energy engineering program and hire nine professors, which was still in process, to work with the state and preparing the next generation nuclear workforce, among other energy fields. And so, we're in the process of making sure we have the right professors to do this right training that Edward talks about.

Patricia Paviet
That's very good. Yeah, it's good to hear.

Aslak Stubsgaard
I'll also jump in. And to anyone on the call who's not working in nuclear or educated in nuclear that the industry needs a lot of other disciplines, especially mechanical people, people who are good at building and fixing stuff and so don't be discouraged. Like apply to the companies, not just nuclear people are needed.

Patricia Paviet
Yeah, everyone is needed. For sure, everyone is needed. And for the students who are listening or it's not because you start in an undergrad field that you will not be finishing in nuclear. It's really open, and we need everyone. A question to Ed. Ed, given that fuel recycling is currently not permitted under US regulations, how would you approach the practical implementation of your work, particularly addressing the challenges related to fuel reposition?

Edward Pheil
So, that is a memory from when Carter was in office. He banned nuclear fuel recycling. The very next President Reagan totally reversed that. So, it is legal to recycle nuclear fuel in the US. I just went to a meeting this spring where they emphasized that you can recycle commercially nuclear fuel. The US government, other than covering things like high enriched uranium to down blend them, doesn't support nuclear fuel recycling today. That doesn't mean they won't in the future. But that does not mean that you cannot commercially recycle fuel today in the US, you can.

Patricia Paviet
Yes, I agree with you. When I was teaching, there's a misunderstanding about the policy. Yes, we can recycle. Like you said, Reagan changed the whole thing. But people have still the

perception that we cannot recycle in the United States. Another question?

Edward Pheil
The real issue is that economic, to recycle, right, because the cost of enrichment has plummeted since they were starting to recycle. So, you need to get your recycling costs way down. PUREX, or at least brand new PUREX plant is not going to cut it on the economics front, you need to do something much less expensive.

Patricia Paviet
Yes. Aslak, you mentioned in your talk that your reactor vessel would be disposed of every 5 years. I presume this would be disposed and this is for the United States as a greater than class C waste, high level waste. Have you evaluated waste implications of disposing of so many vessels over the long-term?

Aslak Stubsgaard
Yeah, that's definitely something we think about. So, at Copenhagen Atomics, we hope to build hundreds of thousands of reactors over the next coming decades. So, that's definitely a big part of our roadmap, is how do we dispose or reuse of those vessels? They're mainly made out of steel, so they can be left to decay and then re-smelted or repurposed. Alternatively, they can be compacted and disposed of. And it's part of our cost model. And still taking this into consideration, we believe that long-term we can reach LCV price of $20 per megawatt hour given that we breed with the fuels, that means that we only need an initial fuel load, and that, of course, offsets some of the costs associated with disposing of the vessel. But we're not disposing of the fuel. We're in a traditional reactor. You're throwing out the fuel every 1-1/2 years, and the disposal of that is even more expensive than activated steel.

Patricia Paviet
Thank you, Aslak. For Isabelle, is Orano or La Hague currently engaged in pyro reprocessing research activities? Will pyro reprocessing capacity, would it be established at La Hague in the near future?

Isabelle Morlaes
Near future, no. But yes, we know that pyro processing could be a solution, especially for molten salt reactor. It could be very adapted to this kind of technology. So, obviously, we are looking at this technology, and we will compare both options. But today, hydrometallurgy exists. It's working. So, this is why this is what we focus first, clearly on the roadmap.

Patricia Paviet
Thank you, Isabelle. Markus, does the training at McMaster include training for health physicists and HP technicians?

Markus Piro
Yeah. I don't represent the health physics departments, but we do have a fairly large program related to health physics and health sciences. We have quite a few facilities as well, research reactor, hot cell facilities, and do a lot of nuclear medicine work. We have a hospital right on site. So, it's quite a bit. Welcome, everyone, to come visit.

Patricia Paviet
Thank you, Markus. Aslak, how do you overcome the curie limits of the electromagnets in the bearings for your molten salt pump?

Aslak Stubsgaard
I think the person here is referring to that ferrous material demagnetizes when you heat it up into temperature. And for regular silicon ferritic steel that is used in stators, this point is actually above the melting point of the salt or the operating temperature of the salt. So, the pump can either be at the cold leg or the hot leg so at 600 or 700 in our case. But even at the 700 leg, we are not at the curie limit left where the magnets demagnetize. And this is something that we've tested in our dozens of salt loops. And there are other materials that specifically…

Patricia Paviet
Very good. I'm trying to see a question. Yes, please. I'm trying to find a question. Isabelle, is the scenario comparison that you showed for open cycle monorecycling in light water reactor combined then with molten salt reactor available publicly? Looks like a nice study.

Isabelle Morlaes
It was presented during a conference. I will check, but it was global, if I remember well.

Patricia Paviet
Okay. I see something with chlorine 37. We already answered. Let me see. Because some of the – again, for Isabelle, some years ago, Orano for offering so called precycling, the customer was provided with MOX fuel based on Orano plutonium stockpile. And firstly, later the customer returned his own spent fuel to equalize the plutonium balance. Is such product still considered offered by Orano?

Isabelle Morlaes

Well, it's still ongoing, if I'm not wrong. So, yes, it's a possibility. There are a lot of possibilities, in fact, yes.

Patricia Paviet
Okay, very good. Let me see. Isabelle. So, Isabelle, you have a lot of questions. How would design of future geological disposal facilities be affected if the material to be stored there contain only fission products? How could this improve public acceptance for nuclear energy?

Isabelle Morlaes
Well, what we think for the design of deep geological repository, I don't think it will change because, for example, we still have a lot of high-level waste to store. It will not change the design itself. It could allow to pack a little bit more the condition vitrified waste that we are doing at La Hague, for example, because of the thermal impact will be far lower after some tens of decades, yes. This is the only point. But no change in the design? I don't think so. But we still have to make the study.

What we think is that the fact that we are producing waste with a radiotoxicity that is decreasing quite fast compared to today, obviously, compared to the used fuel with plutonium, it's obvious. But even with the vitrified waste with minor actinide, it will be very much reduced. We think it's something that could really be important for the society, in general, to accept the nuclear because we know that waste is a hurdle for nuclear energy in the world. It's one of them.

Patricia Paviet
Okay, very nice. I think we're going to – last question, again, Isabelle, thank you for your speech. Do you know what are the capacity productions expected for 2030 in terms of plutonium trichloride per year?

Isabelle Morlaes
No, I cannot say no. We are at the beginning of the study and the R&D is not finished, so I cannot answer these questions.

Patricia Paviet
Okay. I think that's it, because I see recycling. We talk about that in the US. Okay, maybe Aslak. Yeah. The economic competitiveness of TMSR is uncertain. The high initial development cost coupled with the need for new infrastructure, supply chain, technical expertise, could make thorium reactor more expensive than other energy sources. What are your thoughts on this?

Markus Piro
He appears to be off.

Patricia Paviet
Oh, did I lose Aslak?

Isabelle Morlaes
I know we lost his camera, but I wasn't sure if he was still on phone. We've lost him.

Patricia Paviet
That's fine. We have the email address of the person who asked the question. So, we'll make sure that Aslak has your question, and he will answer. I think we're good, Berta, with all the questions. I would like to really thank all the panelists who participated in this very interesting panel session. A bit longer because we had five presentations, but the Q&A is the best. It's really the best. It's recorded. It's archived on the GIF portal as well as YouTube. We have a YouTube channel and Bilibili channel in China. So you will be all over the place. Feel free to share the webinar, and you have access to the slides. Thank you very much, everyone. Berta, I leave you the last words.

Berta
Thank you. Thanks for everyone who joined and participated. Thanks for the speakers for your wonderful presentations and sharing your expertise. Patricia, it's been a run, I'll tell [ph] you. Twelve years of this between NAMP [ph] and GIF, and I don't know what I'll do with my 6:30 in the morning time slot once a month. We've created webinars that have been presented. We've presented hosted from hotel rooms. I've been in the Albuquerque airport where we've snuck away to present webinars. I've done it from conference room floors. During COVID, we did them from home. It's been a journey. It's been a wonderful adventure. I look forward to see where things go from here.

Patricia Paviet
Yeah.

Berta
Thank you.

Patricia Paviet
Thank you so much. Thank you very much Berta.

Berta
The tears [Multiple Speakers] showing.

Patricia Paviet
Yeah, we're just human, and it's the way it is. Thank you very much, everyone. And I wish really molten salt reactor the best. There's a future. There's no doubt. Sustainability of the fuel cycle. Closing the fuel cycle is really important, and nuclear energy is part of that. Thank you again to the panelists. Thank you, Berta, and I will see you soon on the 25th of September with the Zoom platform. We'll be a little bit different, but we'll continue the GIF webinar series. I wish you a good day, a good afternoon, a good evening. Thank you again. Goodbye, everyone. *Merci*.

Berta
Bye, bye.

Jeremy Pearson
Thank you, Patricia. Thanks, Berta and everyone.

Patricia Paviet
Merci. Bye, bye.

END
