MACRO Voices
with hosts Erik Townsend and Patrick Ceresna

Thomas Jam Pedersen: Advanced Nuclear Reactor Designs For Energy Transition

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Erik: Joining me now is Copenhagen Atomics founder and CEO, Thomas Jam Pedersen. We have prepared a slide deck to accompany this interview, registered users will find the download link in your Research Roundup email. If you don't have a Research Roundup email, it means you're not yet registered at macrovoices.com. Just go to our homepage, macrovoices.com and click the red button above Thomas Jam's picture that says, *looking for the downloads.* Alternatively, the YouTube version of this podcast will have the slide deck on the screen as we're speaking. You can find that on our MacroVoices YouTube channel.

Thomas Jam, it's great to have you back on the show. We're really excited about this special. We're going to spend this week talking about advanced nuclear reactor designs, and then next week, we're going to get really deep on the fuel cycle, particularly the thorium fuel cycle, which is very much central to your reactors design. So, it's great to have you back on the show.

Thomas Jam: Thank you.

Erik: Slide 2, we are going to discuss in this episode, most analysts are talking about, whether or not tripling nuclear energy, which is the talk of the town these days, is too ambitious, or if it's realistic, if it can really be done. That, of course, started at the COP28 conference in Dubai in late 2023. My argument is that three times nuclear isn't enough. If you wanted to fully replace all of the energy that we now derive from fossil fuels, that would take 24 times as much energy from nuclear, not just three times. Thomas Jam and I disagree on that point. We'll come back to that in just a few minutes. So, the purpose of this episode is going to be to explore, is it even possible, and frankly, is it even desirable to try to solve all of the base load energy needs of energy transition, replacing all the energy that we get from fossil fuels with advanced nuclear energy. Is that even a good idea? Is it possible? And if so, which advanced nuclear energy technologies would enable that? Then next week, we're going to go really deep on the fuel cycle, page 3, talking about what the different kinds of fuels are for nuclear reactors. It's not just uranium, and it's not just one kind of uranium. There are several different fuels that are made from uranium, and also, thorium is a very important fuel to understand. So ,all of the fuel conversation, and particularly the thorium energy conversation, we're going to save for next week's podcast, and we definitely encourage you to tune in for that one as well.

I want to start here on page 4, on a chart. Thomas Jam, I know this is one of your favorite charts, as well as one of my favorites. Let's just talk about energy consumption. What blows my mind is, some people will say, yeah, but this is all going to turn around. We're going to start conserving energy, and this is going to peak, and we won't be consuming as much energy in future years as we do today. I think that's crazy. What do you think?

Thomas Jam: Well, this is for the last 120 years, and we can see that it's just been going up and up and up, and the number of people on this planet has also been going up. And as more and more people get more prosperity, they get refrigerators and cars, and running water or toilets, and we will use more and more energy. The question is, what is the composition of that energy? Is it mostly fossil fuels, as it is now, or has been in the last 120 years? Or will there be other forms of energy in the future? And I think that's a very interesting discussion.

Erik: I think it's fascinating too, that this whole energy thing is turned into almost a religion, where we take a very valid and legitimate idea, which is, so long as we are consuming energy, which is derived from burning fossil fuels, which means you're depleting a finite resource that can't possibly last forever, and you're also polluting the environment with carbon emissions and greenhouse gasses and so forth. Obviously, that's not a good thing, but the fact that it's desirable to reduce the extent to which we consume fossil fuels seems to lead some people to this quasi-religious belief that it's bad for human beings to consume energy. And I would say the exact opposite. What we need to do is get back to a steadily increasing amount of per capita energy consumption, because that's the best proxy that we have for human prosperity and for our standard of living. We can't continue to do that irresponsibly by burning fossil fuels, but once you get a cheap and abundant source of energy which is effectively limitless and doesn't pollute the environment, my argument is that means it's time to consume as much energy as we can in order to improve society and improve the prosperity of all of the people on this planet. And particularly, to lift the billions of people who live in poverty around the world out of poverty, so that they can enjoy the same standard of living that we have in the United States and other developed countries. Thomas Jam, let's talk a little bit about the expectations that some people have of solving this whole problem with wind, solar and batteries. Is that realistic? And if not, why not?

Thomas Jam: I believe it's completely unrealistic. And this chart in front of us kind of shows that where a few percentage points of global energy is wind and solar, and the problem is, wind and solar is, of course, that it's intermittent and it's not possible to place it everywhere, especially in the very northern regions, there's not enough sun, and in the sort of more towards equator, there's not enough wind. And a lot of places, people don't want the solar panels or the wind turbines in their backyard. I think wind and solar will continue to be part of the energy mix, and it will also continue to grow, like you say here in this chart, is probably getting close to 5% now, and I think it will continue to increase till 10% or maybe even 15% before I die. But I see it as completely impossible that it can replace all of fossil fuels for many reasons, and that's, of course, also why I got involved in nuclear energy, because eventually we will run out of coal and oil and gas, and then nuclear energy will be very important. I've said many times that I believe before we reach year 2100, more than half of all energy in the world would be nuclear energy. But that's, of course, my belief.

Erik: Well, I think something that a lot of people miss is, we're trying to fit the square peg of an intermittent supply source into the round hole of base load demand, and that requires using batteries to supplement wind and solar, which just isn't economic. And furthermore, it consumes precious battery metals, which, frankly, we need in order to make electric vehicles. So, I think it's a question of a time and place for everything. Clearly, wind and solar should have a place. Some energy demand is inherently base load. That's better suited to base load sources of supply. And there's also some inherently intermittent types of energy demand, those are best suited to intermittent sources, but we're trying to fit a square peg in a round hole.

The other thing that I think a lot of people have missed in this whole energy debate is, because of this fascination with wind and solar, which are producing electricity directly, people have gotten this idea in their head that this is all about electricity. They make the assumption that we're just going to electrify everything. We'll electrify all the vehicles. Everything's going to be electric. It's all going to run on electricity, and we'll use wind and solar and batteries to make that electricity. First of all, the arithmetic doesn't work. You can't make that much energy from wind and solar and batteries economically to supply everything. But it's also true that a lot of people don't realize that most of energy demand, or I shouldn't say most, but a lot of energy demand is not for electricity.

Moving on to page 5, I asked ChatGPT to give me an analysis of how much global energy actually goes into electricity generation, and it's less than 40%, a lot of the remainder is transportation fuels for vehicles. And people will say, yeah, but we're going to take that whole 27% there, that's transportation fuels, and that's going to be electrified, and so that'll all become electric. That's simply not realistic. There are some kinds of vehicles, like airplanes, that are just not realistic to electrify. You can't really fly a battery powered airplane from London to Sydney. It's not a realistic engineering problem to be able to solve. So, I asked ChatGPT to take the most ambitious, and remember ChatGPT has been criticized for being biased by its San Francisco creators to have some political values that may bias the accuracy of its data. So when I said, give me the most ambitious build out of electric vehicles possible, that's moving on to page 6, even ChatGPT only got to 51% of global energy, maybe someday being electric, if we completely electrified everything that's possible to electrify. And I think probably the ChatGPT numbers are unrealistic. I think 51% is probably more like 45%, not 51%, but what most lay people don't understand is there's this idea called industrial process heat, which consumes a huge amount of global energy demand, and it has nothing to do with electricity. Thomas Jam, explain, what does process heat refer to? Why is it important, and how does it fit into this story?

Thomas Jam: Yeah, when we go to these shops and we buy all the goods we need, and the food we need, we have to think about, where does all that stuff come from? And some of the very, very important materials that goes into building everything, I mean, building factories, building houses, building roads and bridges, and everything is steel and concrete. Other two important materials are aluminum and ammonia, but there's many other chemical factories that are needed to produce all the different products that we consume, and all these different factories that make steel and cement and aluminum and so on, they use a very large percentage of the global energy, we see here that it says industrial process heat. It's 26% in this chart on page 6. And I think that's probably about right. But those factories also, on top of the heat, they also consume electricity. So, for example, an aluminum plants mostly consume electricity, whereas a steel plants mostly consume coal and electricity. And then ammonia plants, they mostly consume gas, natural gas and cement plants, it depends. They consume all kinds of fossil fuels, but mostly dirty fossil fuels. But those were just some examples. Of course, lots of different chemicals that are being produced and raw materials, in order to, when we do the mining, we usually use a lot of diesel driven excavators and dump trucks and so on in the mining industry. And then they have huge crushers and solders, the things that sort all the dirt, to release the iron ore from the dirt, for example. And all those machines use huge amount of energy, and it's a mix of everything. And sometimes it's heat, sometimes it's electricity, and you need a lot of chemicals to make these simple separations work, and those chemicals are made at other factories, chemical plants that uses a lot of oil and gas. So, it's a mix of a lot of different things, and it's really difficult to electrify all of it.

Erik: Well, there's a really important technical nuance to this that most people don't understand. I certainly didn't until I really started to dig deep into this, which is, it would be easy to say, well, look that 26%, it's industrial process heat. We'll just electrify that too, just like we did with vehicles. What people are missing is that when you electrify vehicles, you're getting rid of internal combustion engines, which are incredibly, incredibly inefficient, and you're replacing them with more efficient electric motors. And as a result, you can make the whole system a little more efficient than it was when it was running on gasoline powered vehicles. It gets more efficient as a result of that. But for these industrial process heat applications like making concrete and making steel and so forth, they need a huge amount of heat. And converting heat from burning fossil fuel into electricity, and then converting that electricity back into heat is incredibly, incredibly inefficient. You lose more than half of the energy by going through that process of converting it to electric and back again. So, although converting vehicles into electric makes sense, trying to take those industrial process heat applications and electrifying them in order to stop burning fossil fuels really doesn't make sense. So, one of the things that was really a striking lesson for me, as I got deeper into exploring this whole question of energy transition, is what we need to do in order to make steel and in order to make concrete and so forth, is figure out a way not to produce electricity but to produce really high temperature heat that can be used in those processes without burning coal or natural gas or oil in order to do so, which is the way it's done today. Those things pollute, they consume a finite resource that can't last forever. We definitely need a better way, but it's a better way to make heat, not a way to make electricity, and that means the solution that we focus on has to be a solution that can be used to generate electricity for the parts of the economy that need electricity. But also a solution for producing heat for the very important parts of the economy that most people don't see, which require that industrial process heat. Jam, have I missed anything there?

Thomas Jam: Well, I wanted to make one comment, is that during the last half a century, or 50, 60 years, we've been trying to make things more efficient, improving electrical motors, using more insulation, making air conditions more efficient, making airplanes more efficient. I think we will continue to try to drive up the efficiency of different systems. So that's one way where we can save energy instead of changing from one source of energy to another. And I think that will continue. And I would also say that there's a lot of wasted, so whenever you generate electricity from coal fired power plants and nuclear power plants, you have to convert heat into electricity. And when you do that, this is the laws of physics, that you lose more than 50% of the energy in that transition, and that means you have a lot of waste heat. And that waste heat is, a lot of times today, it's used for district heating, but it can also be used in industrial applications, for drying things, for example, when you're painting different materials, or if you’re drying like corn or other produce from agricultural industry. So, a lot of times we also use part of the energy to make electricity and another part of the energy for heat to dry things, or district heating or whatever. So these systems are quite complex, because you can't just change one of them, because then the whole other part of it gets screwed up. So that's also why making changes to the energy sector takes many decades. It's not like a quick fix.

Erik: Moving on to page 7 and then page 8, please talk us through these two slides, which come from your deck. Thomas Jam, tell us about electricity, what we are consuming today, and also where it's headed and why we both agree it's going to dramatically increase in terms of how much we need to produce.

Thomas Jam: Yes. So, this is just a simple chart starting 1985, and showing what the mix of the global electricity market and the roughly the market value today. So, selling all that electricity would generate $4.5 trillion, and you can see that more than half of that is gas and coal today. And gas and coal has been growing even in the last few years. We also see that oil and nuclear is basically not growing, maybe even stagnating a little bit. Hydropower has been growing a little bit, but we know from a lot of surveys that hydropower is almost fully built out. There are not many more opportunities around the world to make a lot of hydropower. And then, of course, there's these new ones, the orange colors, wind and solar and bioenergy and so on. And those have been growing in the last years, and they will continue to grow in the next few decades. But I strongly believe that gas and coal will also continue to grow in the next decades. The one that I really like, nuclear has not been growing for the last four decades at least, and I think that's going to change now. I think nuclear is going to be one of the energy sources that's going to grow the most over the next 3, 4, 5, decades, and I'm very excited about that.

Erik: Let's move on to page 8, which is showing your projections, and I agree with them of why we're going to see so much more electricity demand. Talk us through page 8.

Thomas Jam: we listed a lot of the things that are driving the changes in the world right now, AI and electrical vehicles and drones and Power-to-X. Power-to-X is basically where we try to make many of the chemicals and liquid fuels that we need for the world. We try to make those using electricity. It has been really hard. People have been talking about this for 20 years now, and it has been really hard to make some of these fuels a competitive cost so they can compete with natural gas, for example. And then, of course, there's data centers and cryptocurrency and all the other things that we want, self-driving cars and air conditions and all of those things, in addition to more and more people around the world living a more prosperous life, more and more people get a refrigerator, more and more people get an electrical bicycle or something like that. So we just need a lot more electricity. And I think the growth that we have seen in the last 3, 4 decades is going to change now, I think that's the biggest thing in the green transition, is that we will see a huge increase in the amount of electricity. But that is only going to happen if we can continue to provide electricity at a fair price. And that is, of course, the whole part of the discussion here, which energy technologies can provide electricity, I would say below $50 per megawatt hour, because those are the ones we have to look at, because they will determine how this is going to grow. If we cannot provide electricity below $50 per megawatt hour, I also doubt that we can triple this before 2050 and

Erik: And I think it's important to note that there's a really deep humanitarian aspect to this. There are more than a billion human beings on this planet who live with no access to running water, no access to a toilet, no access to electricity, and they live in what we would consider to be horrific living conditions. In order to pull those people out of poverty requires an immense amount of energy. That's really why they're in poverty, is because they can't afford the energy that would be necessary in order to give them the standard of living that we're able to enjoy. And so, I think it's really important to appreciate how much it changes the entire course of human history, if we can make energy cost not just a little more than it costs now, but dramatically less than it costs now. And I've long argued that the real solution to this is to figure out how to make nuclear energy not cost the same as fossil fuels or the same as renewables, but to cost half as much as we're currently paying for fossil fuel energy, because I'm convinced that the reason we have people living in tents, on sidewalks, on the streets of San Francisco is because energy, even after adjusting for inflation, cost twice what it did when I was a kid. We need to get back to those boom years of the 1950s and 60s, when the economy was growing and everything was great. That's when energy was cheap, and that's what we need to get back to.

Moving on to page 9. I think something you and I agree on, Thomas Jam, is we need a game changing technologies. I probably should have said we need the smartphone of nuclear reactors instead of the iPhone. Maybe you like Samsung Galaxy better than iPhone, or maybe you like the Android phones better than the iPhone. But the point is, these smartphones give society a completely new set of capabilities that we didn't have before, and they changed everything. And I contend that we need a much bigger change than that. We need some economic nuclear energy technology that could be mass produced in massive quantity, so that we're not talking about a 3x nuclear by 2050 but rather a 24x nuclear enough to replace all of the energy that we get from fossil fuels today. So that would be, you know, a workhorse nuclear reactor, and in order for it to solve that problem that we talked about on those pie charts earlier, it has to be suitable, not just for making electricity, but it also has to be able to deliver process heat. So I want to see a small block Chevy of nuclear reactors that can be used to make electricity, but by the same token, it can equally easily be used to create process heat for a steel smelting plant, or for a concrete plant, or for whatever else it's needed for. Thomas Jam, I know you disagree with me on this point. You don't think we need 24x nuclear. Let's get your side of this story.

Thomas Jam: Well, I think it would be great if we can make 24x nuclear quickly. But I think it seems a little bit unrealistic. In this day and age, there's been four decades of no progress in the nuclear industry, almost no progress in the nuclear industry at all. And now people are talking about, let's triple nuclear. Even that seems almost impossible with the current type of nuclear technology we have. Of course, there are some companies now coming with something called small modular reactors. We will talk about that later, but it's basically still the same technology as these bigger reactors we used to build. And I agree that it's very challenging to triple classical nuclear. Let's call it classical nuclear. I, of course, part of a movement that wants to bring some new types of nuclear to the market, and I think with that, we can do 3x nuclear before 2050. And I think in the long term, like before 2100, we can do 24x, I think that's possible. But I see that as a sort of a very big goal in a lot of very long-time scale. So it's sort of, maybe the time scale that we disagree a little bit on, but the thing that we do agree on is that the iPhone came and some people were a little bit skeptical when Steve Jobs presented the iPhone first time around. And there's an ad, it's just not really a game changer. But I think today, everybody agrees it was a game changer. It didn't take long. I mean, 2, 3 years after the first iPhone came out, we had the Android smartphones as well, and all the other phone manufacturers more or less died off. Everybody wanted smartphones, and it took over the entire global market in a matter of, I would say, less than 5 years. And I think the same is going to happen if we bring a new nuclear technology to the market that is so much better than the old technology we have today. I think it's going to take over the market really quickly. And I don't think people will appreciate that until it happens.

Erik: Well, I think we're in closer agreement than I realized then. Because what I feel absolutely passionate about is we need to do not just a 3x nuclear and as you said, 3x nuclear on conventional nuclear technology is almost too ambitious by 2050, that means, to me, it doesn't mean it's too ambitious. It means conventional nuclear technology is not good enough. We need to ditch the conventional stuff, move on to Advanced Generation IV nuclear reactor designs that do give us the opportunity to do a 24x nuclear. I think it is possible by 2050. It's incredibly ambitious, but even if we don't do it by 2050, we have to do it. That's the most important thing. And I don't think 24x is even enough, because what I want to see is a dramatic increase in human prosperity, where we lift billions of people around the world out of poverty. That's going to require more energy than we get from fossil fuels today, not just replacing it, but having more. So, I really think we need more than that.

Moving on to page 10. This is why I think we are at an absolutely pivotal moment in history. And the analogy that I use is Henry Ford's invention of the assembly line. Ford knew perfectly well, when he invented his assembly line, that there simply was not enough demand to justify an assembly line. It didn't make any sense, but he also knew that if he could bring the cost of the automobile down to the level where the average common man could afford one that would create the demand that would more than justify his assembly line. And I think the same thing is true for nuclear energy. Today, this industry is 75 years old, and we don't even have 500 power reactors operating today in commercial service worldwide. Now, if you wanted to replace all of the energy we get from fossil fuels with nuclear base load, that would take, if we're talking about small reactors, like the ones that your company is going to build, that would take about 127,000 more nuclear reactors. That's the equivalent of Henry Ford saying, okay, wait a minute, there's only automobiles for the super richest people in society today. But if I can make it so that everybody can afford one, then we're going to be selling them by the 1000s. And I think the same thing is true for nuclear energy today. The way that we get to 24x nuclear is the same kind of revolutionary change that took us from custom building an automobile to some rich guy's personal specifications, to assembly line manufacturing of standardized designs, where you go into a dealership and just pick a car out and drive it off the lot. What we've got to get to is mass, mass, mass production of nuclear energy in what I think need to be fully robotic assembly lines that are mass producing nuclear reactors. And because I knew you, we had a little bit of disagreement on this. Thomas Jam, I took a slide of yours out of next week's slide deck on page 11. And this is showing what we'll get into the details of all the earlier steps next week, folks, when we go through this slide in detail. But what I wanted to point out here is the thing that you cite is mass manufacturing is the great big, huge cost saving step that's going to get us all the way down to $20 per megawatt hour of electricity generation. And I think the way you get to mass manufacturing is when you can deliver nuclear energy that costs dramatically less than energy from fossil fuels cost today. If you say nuclear energy is the cleanest, safest, greenest, most responsible way to produce energy. Okay, that all sounds good, but the reality is, it costs almost twice as much as energy from coal costs today, if you can make it cost half of what energy from coal costs today, I contend that's what creates almost unlimited demand. And as fast as you can possibly manufacture the nuclear reactors, there will be demand for them. They will be rolled out. So, I think we're at a pivotal moment in history, I call it the nuclear Henry Ford moment. Using your own slide here on page 11, Jam, do we disagree? Or is it just that I think maybe 2050 is realistic, and you think that's too soon?

Thomas Jam: So we fully agree about the thing with the price and getting the price down, and then there will be a lot of demand, and also mass manufacturing is one of the important things in getting the price down. The thing where we maybe disagree a little bit is also that I don't think we will replace fossil fuels. I think, like you actually said that, you said that we're going to increase the total amount of energy in the world, so much that I think even the next 20, 30, 40, years, I also think coal and oil and gas will continue to increase, but nuclear will increase so much faster that I hope that we will get to a world where half of all the energy is produced by nuclear. And like you also had that other slide earlier from ChatGPT, I also hope that half of the energy in the world is made as electricity, and we convert many of these industries to use electricity. But I don't think we will entirely remove fossil fuels. I know that there are some people who believe that will happen. We will have to wait and see, but that's not part of my prediction, but I would definitely like to see a world where we have a lot more energy for everyone, including all the people who barely have any access to energy today.

Erik: I don't believe that it makes sense to try and eliminate fossil fuels. What I think is that we need to stop being constrained and unable to grow. So, because of fossil fuels, right now, we've got a few billion people on this planet enjoying a much better standard of living than everybody else, because we can afford the fossil fuel-based energy economy that other people can't afford. We can't get the rest of the planet out of poverty until we solve that problem by delivering energy from other sources besides fossil fuels, because we're out of growth capacity with fossil fuels. The other thing is, there are certain things like making asphalt to pave roads with. We don't have a good replacement for that yet. That requires refining crude oil. Natural gas is used to make fertilizer to feed crops with. In order to make plastics, you need petroleum products. So, we're going to need some of it. The point that I'm trying to make is we need to get out of this mode where the thing that's holding the growth of the global economy back is the limitations of how much petroleum we have. We need to get to the point where we can achieve unlimited growth potential that is not constrained by petroleum, but I don't think eliminating the consumption of petroleum completely is ever a necessary goal. Some people do believe that, and I guess what I would say to them is, look, the solutions we're going to talk about next could achieve that if you think that's what's important, I don't happen to think it's what's important, but we could certainly achieve that with the kind of technology that we'll talk about.

Next thing I want to come to is on page 12, there's still a lot of people who think that the problem with nuclear is dangerous, and they just need to get real and do their homework. Let's talk a little bit more about this, Jam. One of the things that I don't think most people understand is that most of our electricity today comes from coal fired flower plants. A lot of people would say, well, we don't want to go nuclear because they're afraid of the radiation. The thing is, coal fired power plants reduce a huge amount of radioactive contamination from coal. Burning coal produces radioactive contamination in what goes up the smokestack. Nuclear power plants don't have any radioactive emissions, so a lot of people just have it backwards. They misunderstand the safety of nuclear energy. Tell us more about this chart on page 12.

Thomas Jam: This chart on page 12 shows how, on average for the whole world, looking back many decades, on average, how many people die from different technologies for electricity production, and this is the number of deaths per terawatt hour of electricity produced. So, it's a sort of a statistical chart, but you can see, if you compare the first bar up there, the coal, to nuclear energy, which is second bar (from bottom), then there's about 1000 times different. So, coal fired power plants kill 1000 times more people, on average, than nuclear power plants. And nuclear power plants in this survey include the two accidents from Chernobyl and Fukushima, and I should say that almost nobody died from Fukushima. There were some people who died in traffic accidents when they tried to escape, which was terrible. And there was one guy who willingly went to go into an area where there was high radiation, and then he died some years later, but he was already old, and he knew what he was doing, because he was a nuclear engineer, and maybe he didn't have to go in there, I don't know. I don't know the exact details about what he did in there, but very few people died from Fukushima. But still in the media, it's been used as this hate story, I would call it, against nuclear energy, which is sort of wrong. I think who is really to blame is the Japanese authorities that handled that accident really poorly. And so, it was not a nuclear technology problem or nuclear engineering problem. It was a, I would say, authority or politicians’ problem, which is, yeah, not the first time we see that.

So, the problem with this chart here, we're looking at page 12, is that it sort of defies logic. I mean, we try to make nuclear energy so safe that it becomes super expensive and super slow to build. And then what ends up happening is that then most countries look at this and they say, oh, this is too slow and too expensive, let's build some coal fired power plant. So, by trying to make nuclear safer, we actually kill more people. So, every time these people have meetings about how to make nuclear safer, you know, while they're having those meetings and the actions they're taking in those meetings, they end up killing 1000s of people, and they even know that. I've spoken to some of those people who work in the nuclear industry and try to make things safer, and they say, we know that we're doing sort of a bad thing. What we end up doing is basically the wrong thing for the world. But it's sort of, I think it's because of the media who has been misinforming the public about nuclear energy, and I think that's going to change soon. That's my feeling. I think there's a lot of people who have realized that they've been misinformed, and now they want the real information. And I think that's going to change the nuclear industry. And also, part of the reason that so many people die from coal is, of course, that some of the coal fired power plant doesn't have any filters. And you're right, that there's some radioactive materials in the ashes from coal fired power plants. So as some of those ashes go up the smokestack, then they get spread. But it is, of course not, the main killer is not the uranium and thorium in the coal fired power plant smokestacks. It's more all the particles, soot and SOx and knocks and these other chemicals in the smoke that kill people. And you can put filters on coal fired power plants, and then they become more expensive. So that's why, in some countries, maybe China or India, some other big countries in the past, they didn't put filters on, but I think they have also started to do that now. So even these statistics and coal fired power plant here, we can also improve on that.

Erik: Moving on, what we want to accomplish in this podcast is to explain the advanced nuclear technologies that really do have the potential to grow nuclear power by 24x, or 50x for that matter, over the longer term, you can't do it with conventional nuclear reactor technology. So, we're going to start by explaining conventional nuclear reactor technology and its limitations, and then move on to some of the advanced reactor designs that have more potential. Starting on page 13, I just want to go through how the fuel cycle for a conventional nuclear reactor works. What we see here on this slide, it starts on the left hand side, where you see that natural uranium, uranium that's mined out of the ground, has about 99.3% of that is a isotope of uranium called U-238, which is actually perfectly good nuclear fuel for advanced reactors, but for conventional reactors, that all gets wasted. It's less than 1%, just 7/10 of 1% of that natural uranium is called U-235, that's the kind of uranium that's fissile. That means it can sustain a nuclear chain reaction. So that natural uranium that gets mined out of the ground, it takes about 13.8 units of that, and exactly how much depends on the conversion and enrichment process. If you listen to some of my interviews with Justin Huhn or Mike Alkin about under feeding and over feeding in the enrichment process, you'll understand more of this. So, it's not necessarily a fixed number, but it's at least 10 to 1 in terms of how much natural uranium it takes to go through the conversion and enrichment process to make just one unit of low enriched uranium, which is 5% U-235 and 95% of it is the U-238. Now, again, U-238 really is good stuff, it can be consumed as nuclear fuel by advanced reactors, but the conventional reactors that are, 99% almost all of the reactors in use today waste all of that U-238. The conversion and enrichment process ends up delivering us for that 13.8 kilograms of U-308, which is the yellow cake uranium we start with. That gives us one kilo of low enriched uranium that we can burn in a reactor, and we end up with 12.8, almost 13 kilograms of depleted uranium. That's the U-238, that's had the U-235 sucked out of it, so it only has about 0.3% U-235 left in it. The rest is U-238. Now, that is, frankly, very valuable nuclear fuel that we ought to be saving and using in advanced reactors. Instead, it's considered waste. The only thing we really do with it today is make bullets out of it, because it's even heavier than lead, and it's good for making armor piercing rounds for guns. The enriched uranium that we produce in this process is obviously very expensive. It's around $3500, is my number, dollars per kilogram. I think, Thomas Jam, you have a higher number from some of your sources. So, let's say it's somewhere between $3500 - $4500 per kilogram on today's market for that 5% low enriched uranium, which is what fuels one of these conventional nuclear power plants like the Westinghouse AP1000. that enriched uranium is processed into fuel pellets, which are inserted into these zirconium alloy tubes that you see at the far right of the picture, and that creates a fuel bundle. And of course, it takes a whole bunch of kilograms of those fuel pellets in order to make that big fuel bundle. That's what fuels a nuclear reactor, is that great big bundle of zirconium alloy tubes full of low enriched uranium. And for every kilogram of that, there's about 12 or 13 kilograms of waste product, which is the depleted uranium that gets left over in, which unfortunately, mostly goes to waste.

Moving on to page 14, what happens then is that fuel bundle gets loaded into one of these big conventional reactors. Now, the Westinghouse AP 1000, which is the current flagship model that everybody's talking about, and a lot of people are building more and more of these things around the world. Plans are growing in this nuclear renaissance to build a lot of these things. It takes a fuel load of about 80 tons of those fuel bundles. So, 80,000 kilograms, about $320 million worth of fuel goes into this thing, that's an 18-month supply. This power plant is only 33% to 35% efficient, which means only about 1/3 of the heat energy that gets produced from that nuclear fuel is going to be turned into electricity. The rest is going to be wasted as waste heat. What comes out of it is that same fuel bundle, 18 months later, only less than 5% of the energy of the fuel that's contained in that bundle was burned up because these old school nuclear reactors are very, very inefficient. They burn less than 5% of the energy that's contained there because they don't know how to burn any of the U-238 fuel, they only use the U-235. What you end up with is 80,000 kilograms, 80 tons of nuclear waste. Now, if you see nuclear waste depicted in the popular media, it's always this green or purple slime that's bubbling and looks like it might seep into the water table and poison everyone. That's just Hollywood fantasy. Nuclear waste is these big metal things that look like the picture on the right. They're stored vertically in cylindrical containers called dry casks, where they sit indefinitely, basically to stop the radiation from getting out and hurting any human beings, and they just sit there. And the reason that they sit there, and they have to be managed this way, is because they're radioactive and they contain a little bit of plutonium. What happens is, as the reactor is operating, about 3% of that U-238, that's the great big orange wedge of the pie chart, gets converted from uranium into plutonium. Two thirds of that, or 2% gets burned up and consumed as fuel. It helps run the nuclear reactor. It helps make electricity. 1% as leftover, that leftover plutonium freaks everybody out. They're afraid somebody is going to steal the nuclear waste from the nuclear power plant, somehow extract the plutonium from it and make a nuclear bomb. We're going to explain in next week's episode why that's not really realistic, but that's the fear. And because of that fear, nuclear power plants are required to have armed guards surrounding them at all times, 24 hours a day. That's why you see the armed guards in the picture here. So that's a quick overview of how a conventional nuclear power plant works.

The main point that I want everybody to take away is that that waste that we're throwing away is really not waste. Only 5% of the energy that it contains has been consumed. And what we've done is, we've taken a huge amount of U-238 that should have been perfectly good energy producing fuel, all we did is we contaminated it with some plutonium, we made it radioactive for as long as 100,000 years, and we put it in a dry cask to be stored, as opposed to using it for something useful. Wouldn't it be great, if you look at the bottom things that are in that waste are the right side of this chart, where it shows the pie chart that says spent nuclear fuel waste. The bottom three things, Plutonium-239, Plutonium-240, and the other long lived actinides, they're called, are transuranics. That's about 1% of that waste, and it's only that 1% of the waste, which is radioactive for 10s of 1000s of years and causes all the problems. Wouldn't it be great if someday, somebody invented a way to separate that 1% out so the rest of it could be recycled and used for something productive? Well, there's no need to wait for someday. Someday happened in the 1940s, but thanks to political decisions gone wrong, mostly in the 1970s, we've almost outlawed that around the world today. So, we don't do the responsible thing. France still does, because France refused to sign the nuclear Non-Proliferation Treaty, but all the other countries that are beholden to US foreign policy are forced not to recycle their nuclear waste, despite the fact that the process for doing that was invented in the 1940s. So that's a quick overview of how conventional nuclear power plants work. Jam, anything you want to add to that description?

Thomas Jam: Yes, I think it was a very good description. There have been other countries that tried in the past, and UK have been doing reprocessing. Japan thought about doing it, but then stopped. And then Japan actually sent fuel to France to allow France to reprocess Japanese nuclear fuel. And the US also built systems of factories to do reprocessing, but they never got started, because it was decided before they were operational that they shouldn't do it. So, several countries have been working on this, but France is the only one who's doing it today.

Erik: We're going to go deep on reprocessing and spent nuclear fuel waste and everything about nuclear fuels is coming up in next week's podcast. Let's move on now to what I call, small misunderstood nuclear reactors, or SMRs. SMR is a marketing phrase that definitely caught on, but it really doesn't have any specific meaning. So, I'd like to talk through four different possible meanings of this word *modular*, because everybody's using modular in different ways, and it means different things to different people. Page 16, the first definition of modular is the one that really seems to have caught on, and I think now at this point, the phrase small modular reactor really refers to what we see here on page 16, which is an old school nuclear power plant, a slightly smaller version of that, about 1/3 the size that supposedly has been built out of components, where a lot of the components were manufactured in a factory, rather than being custom built on site. That reduces the build time for these reactors from about 6 or 7 years down to only 4 years. Oh, boy. Whoopty-doo. So now, Westinghouse can do in 4 years what the Koreans have always done in 4 years, which is basically to build a small sized nuclear power plant using outdated 1950s nuclear technology. This is still a water-cooled nuclear reactor. It is still a technology which does not use the U-238 as fuel, it wastes most of the fuel. Still needs to have armed guards, and it's still only about 33% efficient. So, what we're really talking about with SMRs today is building smaller sized, old school nuclear power plants, conventional nuclear power plants, but slightly improving the process for building them to make it a little bit more efficient so we can build them in 4 years instead of 7 years. It is progress. I don't mean to naysay it completely, but it's not nearly enough progress. SMRs at this level, on page 16, are not going to solve any major problems. They're not going to get us through energy transition. They're not the Holy Grail by any stretch of the imagination.

Moving on to page 17, the next meaning that people were using this phrase SMR for were these micro reactors. Now, we've got the phrase micro reactor to distinguish it. It seems like people are calling micro reactors, micro reactors, calling SMRs, SMRs. The idea here is, you take a very small nuclear reactor, one or two megawatts, make it portable, put it on a truck where you could drive it around. It competes with the diesel generator set market for remote mining sites and small applications and so forth. That's the idea of micro reactors. There are a few companies like Oklo that were talking about micro reactors based on Generation IV advanced reactor technology, but most of them were based on old school conventional nuclear power. The thing that gets left out of this conversation is, if they're going to produce nuclear waste that contains plutonium, current rules require 24/7 armed guards surrounding them. So how is that going to work if this thing is like a generator that's on the back of a truck? Nobody talks about that, and I think that's a missing part of the conversation that the salesman for these never discuss.

Moving on to page 18, another use of the word module or modularity is this idea of each nuclear reactor being a module. Now, we're getting closer to a kind of modularity that I think could actually help us to solve energy transition and make nuclear energy cheaper. The idea of small nuclear reactors, where if you want to have a big power plant, you have a bunch of them. If you want to have a small power plant, you only have two or three of them. The point is that each of those nuclear reactors could be built in a factory and shipped in with a minimal amount of on-site construction so that if you want to build a big power plant, you can build a big one. You want to build a small one, you can build a small one. Most of the parts and most of the components of that nuclear power plant, entire nuclear reactors are modules that get built in factories and are trucked in, rather than being custom built on site. NuScale is one of the first companies to have its small modular reactor design approved. They're going on what I think is closer to the right approach to modularity. My favorite approach to modularity is Thomas Jam’s company, Copenhagen Atomics. Ironically, in a video that I produced, I gave Copenhagen Atomics credit. I said, look, if all the SMR manufacturers, I think that it's Copenhagen Atomics that really understands modularity the best. What I didn't know is, at the very same time, Thomas Jam was out saying, look, please don't call Copenhagen Atomics an SMR company. We don't want to be part of that whole thing. That's not what we're doing here. The approach that Copenhagen Atomics takes is each nuclear reactor is a module in the form factor of a standard 40 foot shipping container. That means they can be shipped anywhere in the world. All you have to do in order to build a gigawatt size power plant is gang together about 25 or 30 of those reactor modules that each one of those produces about 100 megawatts of thermal energy. You gang together 25 or 30 of them, and you can produce a 1-gigawatt electric power plant, and you can build that power plant in 6 to 12 months, as opposed to 6 to 12 years, which is what it takes for conventional nuclear power. Now, I think we're really getting much closer to solving the real challenges of energy transition.

Let's move on now to page 20, and talk about Generation IV or advanced nuclear reactors. The common theme here is replacing water as the reactor core coolant with something better. I suppose there are some advanced reactor designs that are still water cooled, but most of them are replacing water. That begs the question, okay, what's wrong with water? Moving on to page 21, the problem with water is it boils at 100 degrees Celsius. So, before you can absorb very much heat into it, it's at boiling temperature. The solution that was conceived back in 1952, I believe, to solve that problem, was the invention of the pressurized water reactor, where the reactor core is pressurized to over 2000 PSI, about 150 atmospheres of pressure. That increases the boiling temperature of the water to over 350 degrees. That makes it possible to build a nuclear power plant, but it still doesn't have anything close to the energy producing capacity of other coolants that have much higher boiling temperatures. The other problem with water, remember what water is, H2O, normally the hydrogen and oxygen in water molecules can't possibly separate into pure hydrogen gas and pure oxygen gas, which would be the explosive mixture that blew up the Hindenburg, because those hydrogen and oxygen atoms are held together in water molecules by covalent bonds that can't possibly break, except under the most extreme conditions of heat and energy. Well, those are the exact conditions that exist inside the core of a nuclear reactor during a meltdown accident. That's exactly what happened at Fukushima Daiichi, is the water coolant separated into pure hydrogen gas, that pure hydrogen gas exploded and literally blew the roof off of the reactor building. That video everyone's seen of the roof being blown sky high, was not a nuclear explosion. It was a hydrogen explosion because of water being the coolant in those reactors. Those were boiling water reactors in Fukushima. So even when it's pressurized, you're limited to about 350 degrees Celsius, we need to go much hotter than that for those process heat applications that we talked about earlier, and also, just to make the reactor more efficient for producing more electricity, and also for being able to produce hydrogen, which is very important for energy transition. Let's go ahead and dive right into some of the features of these advanced reactors on page 22. Thomas Jam, I've gone on for quite a bit here about water and so forth. Anything you want to add about coolants before we get into the reactor designs?

Thomas Jam: Yes, so, we call these advanced reactors a Generation IV, but most of them were actually invented all the way back in the 1950s and 1960s, but it is true that at the end of the 1990s, there was a group of people who said, let's make sort of a selection of these different reactors that are not being built. So the high temperature reactors, or the sodium cooled or lead cooled reactors, let's make a palette of those, and call it Generation IV. And this has been going on since the end of the 1990s until now, and we haven't really built any of them. I mean, the Russians have built some sodium cooled reactors, but that started way before this Generation IV discussion forum. So, it's a little bit odd group, and molten salt reactors is one of them. And the molten salt reactor, the first one, was built in the 1965, but some of those reactors are more advanced, and some of them are running at higher temperatures, and some of them have some things that are maybe better than the pressurized water reactor. But let's talk about them.

Erik: Let's go into it. And before I leave slide 22, I do want to make this point that's highlighted in green, which is, there's a huge amount of propaganda in this industry. A whole lot of people in the nuclear industry have been led to believe that the pressurized water reactor design, which is really the primary one that's in use today and its close cousin, the boiling water reactor design, those light water reactors people believe were chosen for their superior safety. They believe that scientists and engineers use the scientific method to choose the best, safest design, and that's the way we standardized on the pressurized water reactor. That's 100% unadulterated bullshit. According to none other than the inventor of the pressurized water reactor, Alvin Weinberg, who wrote in his book to claim that light water reactors were chosen because of their superior safety, belied in ignorance as to how the technology actually evolved. And he went on to explain the way that reactor design was chosen was because it fit in the Nautilus submarine. That's it. Then when they wanted to commercialize it, they said, let's take what's already proven to work in the submarine, and let's not fix it. If it ain't broke, we're not going to change anything. We'll just go with the design that worked in the submarine. That's how we got to the standardization of the pressurized water reactor, and it's absolutely not the right design. We've been using the wrong stuff for decades, and it needs to change. It's finally starting to change, and that's called Generation IV. Let's move on to the first popular one. I'd say maybe the most popular one, if you've heard about Bill Gates and his natrium reactor, which is TerraPower. If you've heard about the company, Sam Altman from OpenAI has invested in, called Oklo. If you've heard about a number of other exciting new generation nuclear companies, they're all doing these things called sodium fast reactors. Thomas Jam, tell us more about sodium fast reactors. Why would you use sodium instead of water as a coolant? And how do these things work?

Thomas Jam: The primary reason for using sodium instead of water is that you can avoid the pressure, because, like you put here, sodium doesn't boil until 884 degrees C, so you can go to quite high temperatures without having any high pressure, and that really reduces the complexity and the size of the machine. But then now, you win one, but you also lose one, because it actually happens that sodium will burn if it's in contact with air, because there's moisture in the air or in contact with water. So you have to keep the sodium in a very close loop, and you have to have several barriers, so even if it escaped from the first loop, then it will not get in contact with air or water. And that's, of course, one of the issues with sodium, that it's a little bit more difficult to handle than water. And then on the plus side, is that you can run at higher temperature. But the thing with sodium is also that it creates a different neutron spectrum, which means that neutrons in a nuclear reactor is the really, really important thing when you design a nuclear reactor. That's the center point of nuclear engineering, is figuring out where those neutrons go, and also the speed of those neutrons. And in a light water reactor, or a water-cooled reactor like we were talking about, they have different names, that sometimes called, light water reactors, sometimes called boiling water reactors, sometimes called pressurized water reactors, and sometimes called heavy water reactors. But they are all using water in different ways, and because you're using water, the neutrons will slow down, and that means it's a slow neutron reactor or something called thermal spectrum reactor. But this one here, that if you use sodium, the neutrons will not be slowed down. And then it's a fast reactor, and then the neutrons react differently with the uranium and the plutonium and so on. And that's very, very important when you design the reactor, and it has a lot of implications on cost and the way it's constructed and so on. So, choosing sodium is mainly for the temperature, but it has a lot of, sort of follow on things that, once you select sodium, then you have to select a lot of these other things. And then one more thing I want to say, all the reactors we talked about before, they were solid fuel reactors and the sodium cooled reactors are also solid fuel reactors, which means that you don't have the uranium fuel or plutonium fuel as a liquid, you have that as a solid pebble or a pellet. We’ve talked about pellets and fuel rods before.

Erik: And I think it's important to understand, too, that the benefits of that fast neutron spectrum can be significant in terms of how the fuel gets consumed. Because when we talked about the light water reactor, I explained that only about 3% of that U-238, that was the great big orange wedge, that's most of the uranium, only about 3% of that actually gets consumed. It gets converted from U-238 into Plutonium-239, which then gets consumed as a fuel that helps to run the reactor and make electricity. The rest of the U-238 all went to waste. And that meant, number one, you're wasting perfectly good fuel, but it's really in the most literal sense, it's wasting it, in the sense of taking the tons and tons of U-238 and making it radioactive for the next 100,000 years, so somebody has to worry about storing it. So, you've got this whole nuclear waste management problem that arises out of the inefficiencies of those water-cooled reactors. These fast spectrum reactors, convert a much higher percentage of the U-238 into plutonium. That means they produce less waste, and they make much more fuel-efficient use. They have a higher burn up ratio, so they consume much more of their uranium, leaving over less waste, producing more electricity. But it also means that they need a much more enriched fuel to start from, because those fast neutrons need to have more U-235 in order to interact with, that means they use a special fuel called HALEU, high assay low enriched uranium. Which basically means, instead of enriching it to 5%, we enrich it to about 19.75% just below the 20% legal limit, which defines high enriched uranium, which is considered off limits because it's a weapons proliferation risk. So going to the high-test fuel, if you will, really gives these reactors some significant benefits. I think, if you're looking at it on a design table, looking at it on the drafting board in practical terms, if you think about what that means to the challenges of developing the supply chain, what if we were not just building one or two of these sodium reactors, but what if we were mass producing 10s of 1000s of them? So, we needed tons and tons and tons of this HALEU fuel, which has to be enriched to 20% that would require so much enrichment and conversion facilities. If you go back to my early December interview with Justin Huhn, when we talked about the coming crunch that Justin and I are both predicting in the uranium enrichment and conversion market, it would dramatically exacerbate that, so thinking about the fuel considerations of these reactors is very significant. We're going to go much deeper into that subject next week. Thomas Jam, any other comments on the sodium cooled fast neutron reactor before we move on?

Thomas Jam: I just want to say one word of caution, because you said a lot of things here, and they are correct, but we have to remember that there are many, many different designs of sodium cooled reactors, and some of them are really big, 345-gigawatt, big power plants. And other ones are, like the Oklo one is tiny, tiny reactors, and when you look at the fuel economy of those, and in the sodium cool reactor, the fuel economy is very different. And some of the things you said were not always true, depending on whether it's a big one or a small one. So, it's much more complex when you get into the details, but let's move on.

Erik: Okay, let's move on. Before I come off of this slide for investors who are interested in this technology, examples of companies that are working with the fast sodium reactor design, the biggest one is probably TerraPower, with their natrium reactor, Oklo GE Hitachi Prism reactor, NewCleo dual fluid energy, are all examples of companies that are working in this space. The next popular one is what a lot of people call the pebble bed reactor, which is one kind of high temperature, gas cooled reactor. Thomas Jam, tell us what the story is on this kind of reactor.

Thomas Jam: Yes, the pebbles were invented also many, many years ago. I don't know exactly the 60s or 70s, but something like that. And the idea is that if you encapsulate these small uranium slugs into a pebble, it's much more protected. And then you could, first of all, run at higher temperature, but the proliferation risk would also be smaller. And there are some people who like those two benefits. So, they like pebble bed reactors. And you can use pebble bed reactors with gas, like you have shown here, but you can also use molten salt, for example, as the fluid that removes the heat from the pebbles. So, there's a number of different types of pebble bed reactors, but I would also say that it's a little bit of mixture, because high temperature gas cooled reactors can sometimes occur without pebbles, but where it's solid fuel rods. So again, there's a lots of details, but I think really what you want to talk about here on this slide is pebbles and because it's a different fuel choice than the sodium cooled fast reactors, for example, now you have to manufacture a new type of fuel, and you have to have a new way of storing that fuel afterwards, or reprocessing, or whatever you want to do with the fuel afterwards. And producing those pebbles are quite expensive, so it's a very expensive fuel form. But of course, if you can go to very high temperatures, then there might be some industrial applications where you can get some of the benefits by going to high temperature.

Erik: Let's also talk about regardless of whether it's a pebble bed or another design. Let's talk about the benefits of very high temperature gas cooled reactors, as opposed to moderate or medium temperature reactors or lower temperature light water reactors. Why is high temperature so important to things like hydrogen production and concrete and so forth?

Thomas Jam: Yeah, because those concrete and steel and hydrogen, well, hydrogen may be less weight with that, but concrete and steel, those processes happen at high temperatures, like 1400 degrees Celsius, something like that, way above 1000 degrees Celsius. And in order to provide process seed for those, it's not possible with molten salt or sodium. So, you really want to go to something else. And of course, gasses can easily go to very high temperatures. You can have gasses that go to 2000 degrees if you need to. But then the fuel is a problem. You know, can you create a fuel that can go to such high temperatures? And that's what high temperature gas reactors are trying to do. I think most of them are actually trying to run the first versions around 1000 degrees Celsius, so not enough to go for steel or concrete right away, but maybe helpful for other types of hydrogen. For example, hydrogen is when you want to produce hydrogen from water. Basically, split sea water into hydrogen. You need a little bit of low temperature heat to desalinate the water. And then once you have fresh water, then you need high temperature to split it. And the amount of electricity you need to split water becomes less and less the higher the temperature of that water. Well, then it's not water anymore. It's steam. But if you have the steam at almost 2000 degrees, then you need very little electricity to split hydrogen and oxygen, whereas if you have it at, let's say, 500 degrees Celsius, then you still need a very significant amount of electricity to split those. So that's why people want to go to high temperature for creating hydrogen.

Erik: So I would categorize this whole idea of high temperature gas cooled reactors as very important in the sense of for high temperature process heat applications. It's kind of a specialty reactor that makes super high temperature process heat, but I think that comes at a very significant cost. I don't see these high temperature gas cooled reactors as being the small block Chevy, the iPhone of nuclear reactors. I see them as more of a specialized device that is for certain types of applications, but probably not for the lion's share of the heavy lifting it's going to take for energy transition. Some examples of companies in this space are X-energy and Ultra Safe Nuclear. And again, not all of them require these TRISO fuel pebbles. So there really are two different ideas that are being illustrated on this page 24, one is the concept of using gas, rather than a liquid, as the coolant. The other is putting the fuel into these little pebbles. And basically, the pebbles are a chunk of uranium fuel that is surrounded with a ceramic which protects it. It kind of provides the same function as a containment building. So, it basically is a meltdown proof reactor design, because instead of a solid fuel rod that could melt down, the fuel is all contained inside of ceramic pellets that are designed to essentially weather the storm if there is an accident, and protect that fuel from what would otherwise be a meltdown accident. As Thomas Jam mentioned, another company, KAIROS, is doing a molten salt cooled reactor that still uses these TRISO pebbles as its fuel source. So, you can combine the pebble idea with other coolants as well.

Let's go ahead and move on then to a little bit more about these fast reactors. Because the whole idea of why so many people are focused on fast reactors, fast sodium reactors, that's where the heart of the Generation IV industry seems to be headed. I think a lot of it is motivated by the quest for eventually getting to breeder reactors, which would be very, very important to energy transition. Well, that begs the question, okay, what's a breeder reactor, Jam? You want to tackle that one?

Thomas Jam: Yes. So, a breeder reactor is a reactor that can convert, like you said, U-238 into fissile fuel, which is for U-238, it converts into Plutonium-239 which is fissile and which can be used. And you explain very well that that happens already today in Light Water Reactors, but it's a small percentage of the total energy that is produced that come from that reaction. And if you do this in fast reactors, you can convert more of this U-238, into plutonium, and have a bigger percentage, so it's called breeding fertile fuel into fissile fuel.

Erik: Jam, let's move on to page 26, and maybe you can talk us through how this breeding process works with the fuel rods in the red and the breeding blanket in the green that are shown in the middle of page 26 here.

Thomas Jam: Yes. So, when you have to start the reactor, you have to have some fissile fuel to get the chain reaction running. And once you have the chain reaction running, then in some reactors, you have excess neutrons. That means you have more neutrons that you need for the chain reaction itself. And then you can use some of those extra neutrons to breed new fuel from fertile fuel. And in this picture here, the fertile fuel is U-238, and that's the in the green bars, or the blanket of the core, or the reactor core. That means that out there in the green part, it captures the neutrons and converts U-238 into P-239 and then that can later be swapped out. So, those pins that are out there at the edge can later be inserted in the middle, because now they have been converted into fissile fuel. And in this way, you can sort of continue to make new fuel in your reactor, and you don't have to dig it out of the ground and keep on enriching uranium. But now, the reactor can make more fuel for the next cycle or the next reactor. But the problem here again, is that it takes a long time for this breeding process, for example, for most of what is called fast breeder reactors, it would take 50 to 100 years to double the amount of fuel you create. So, it's very, very slow way of making more fuel.

Erik: Let’s go a little bit deeper on this. Because, as you've described, what we're doing here is we need to start this reactor with a more enriched fuel, the HALEU fuel, which costs about $25,000 per kilogram in today's market. That's the red fuel rods in the center. The big advantage of this is, once you've got the reactor running on that stuff, you can then feed it the fertile U-238 that's the incredibly cheap stuff, because it's the leftovers, the waste product from the enrichment process that is piled up all around the world as leftover tailings from that enrichment. You can put that in into the green breeding blanket around the reactor, and it gets transformed from $10 a kilogram stuff into $1,000 a kilogram, useful fuel that can then be burned. Now, everybody used to assume, back in the 1960s, that the only way you could do this was with a fast spectrum reactor, one that used fast neutrons, which meant that you needed a sodium coolant, or some very expensive kind of technology. There was one guy, Alvin Weinberg, the inventor of the pressurized water reactor, who had a different idea. Tell us more about that, Thomas Jam.

Thomas Jam: So, Alvin Weinberg said that it should be possible to take thorium, put thorium in the blanket instead of U-238. Thorium is also cheap, and then you can use those neutrons to breed new, what is called U-230, free fuel from thorium, and then use that as the breathing cycle. And he said that now you don't have to do it with fast neutrons, because thorium can actually do it with slow neutrons or thermal neutrons, as I sometimes call, and therefore you would need a much smaller reactor. But he was the only one who believed in that back then, or maybe not the only one, but he was the main voice behind that. But most people didn't believe him. And back then, they didn't have computer simulations, so they had no way of figuring it out. They could do some calculations on a piece of paper, but they couldn't really prove whether it worked or not, and it was not until 2022 that we were actually able to show in software simulations that it would work. You could make a breeder in thermal spectrum or with slow neutrons if you use the thorium fuel cycle instead. So that's a kudos to Alvin Weinberg that he believed in this all the way back in the 1960s before he was even really able to prove it.

Erik: But what I want to know as an investor to understand today's market is, what percentage of nuclear engineers working in this field today know and are aware that he was proven right in 2022?

Thomas Jam: Less than 1% I think, very few know that we've come this far in the development and very few new difference between the simulation tools that we were using in around the 2000s and the new simulation tool that are available now, where you can actually show that this works.

Erik: So my hypothesis, and tell me, if you disagree, Thomas Jam, is that really a lot of the reason that we're seeing so much emphasis on fast sodium reactors is because people see the need in order to get to breeder reactors eventually, breeder reactors are so much more economic. It's clearly the way of the future. If we can get there, I think they're barking up the wrong tree. They're pursuing fast sodium reactors, thinking that's the best path to a true breeder reactor, when in reality, they would be better off to pursue the approach that you're taking at Copenhagen Atomics. Obviously, I'm biased, and you're biased. Your company focuses on the thorium fuel cycle. I'm an angel investor in your company, so we've got a biased perspective, but I think the rest of the industry is missing something. I don't think they're aware that Weinberg was proven right in software simulations in 2022, and that there's a better way to do this without requiring the complexity and cost of a fast sodium reactor.

Thomas Jam: Yeah, I think it's true. The majority of people who have been taught in nuclear engineering, whether in graduate school or PhD level all over the world, have been taught for five decades that it's only possible to make breeders in fast spectrum, which we now known as not true. They've also been taught that you can only burn plutonium or transuranics in fast spectrum. We also know know that that's not true, so it's not their fault. They basically were not told the whole story when they went to university. And now we all have to, sort of start reacting to this new reality.

Erik: Well, there's another reality we have to react to, which is the market is telling us that smaller physical products are going to be the way of the future. SMRs have really taken off, despite the fact that SMRs are really just old school nuclear reactors based on 1950s nuclear technology. The fact that they're small and modular has really given them a boost in the marketplace. Let's assume that smaller physical size is the way of the future that has implications that have to do with nuclear physics on the benefits of those fast neutron reactors. Because everybody that was thinking, boy, in order to get to the breeder someday, we got to go with fast spectrum reactors. What are the implications of that in a world where the reactors need to be physically small, on page 27?

Thomas Jam: Yes, the problem is that the fast neutrons, they fly really far before they interact. And that means that if you have a small reactor core, most of your neutrons will fly out of the core, and it's difficult to catch. If you have a blanket, you have to have a really, really big blanket in order to catch minority of neutrons. And since now people want to build small reactors, then they end up in a situation where it becomes impossible to make a breeder even in fast spectrum, because they want to make it small. So, you sort of have to choose, do you want a small reactor or do you want a breeder reactor? You cannot have both in the fast spectrum.

Erik: But you can have both in the slow spectrum, in the thermal spectrum, and most nuclear engineers are not aware that that's been proven now through software simulations going back to 2022. Let's move on to your favorite, and mine, which is the molten salt coolant, which unlike water, which boils at 100 degrees Celsius, or sodium, that boils at 884 degrees Celsius. There are several different salts that can be used, but the popular ones boil at around 1440 to higher. I'm not sure which one is used in your reactor. What's your boiling temperature?

Thomas Jam: I actually don't remember the boiling temperature. But you're right. It's sort of in the realm of 1500 degrees Celsius.

Erik: High enough that the other parts of the reactor would melt long before you would get to the coolant reaching a boiling point. So it's almost like it's not a gating factor anymore.

Thomas Jam: No, your heat exchangers would melt before then.

Erik: So, tell us more about Molten Salt Reactors, their history and benefits, and why your company focuses on using molten salt rather than sodium or gas as the coolant for the reactor?

Thomas Jam: Yeah, again, I should highlight that it's a little bit complex, because you can make Molten Salt Reactors both in fast spectrum and in slow neutron spectrum, or thermal spectrum, and the ones that we are pursuing is the slow neutron reactors, and you need different salts. So if you have a fast neutron molten reactor, you need chloride salts, and if you have the slow neutrons, you need fluoride salts. So that makes it a little bit complex. But the main reasons why people are interested in using salts are because of the high temperatures, so you don't need to have it under pressure, and that means your system can be smaller and less complex when you're not working with these high pressures. The second thing is that you can dissolve the fuel in the salt, and this means now you have a liquid fuel. All the other reactors we talked about until now, they are solid fuel reactors, but now we suddenly get to something completely different. Now you have a liquid fuel reactor, and this enables some new possibilities, because now it's possible to remove fission products, it's possible to do online refueling, it's possible to change the composition of the fuel salt as it's running over the years. And for example, this breeding that I talked about before, now you can just siphon off some amount of fuel if you breed more than you need. And so, every year, you can tap off a few liters of salt, and then you can use that for another to start another reactor. So suddenly you get some other benefits, because it's a liquid fuel. And the most important benefit, I should say, is this one about removing fission products. When you split uranium into two things, you get two different elements that are the byproduct. There's a statistic about which element you get. It's not always the same elements, but we know those statistics very well, and those fission products, they capture neutrons. So, you don't want to have those inside your reactor, because they capture those precious neutrons, and they worsen your neutron economy. So, if you could remove the fission products while the reactor is running, you can get a much better neutron economy of your reactor and therefore a lower electricity price. And that's only possible in molten salt reactors, and you can do that both in chloride salts and in fluoride salts. But it's most important with the slow neutrons to remove fission products, because if you have a reactor with fast neutrons, then the fission products is less of a problem, and therefore it's not as important to remove them. So, it's really, really important for the slow neutron molten reactors with fluoride salt to remove fission products and that gives you a completely different neutron economy than all the other reactors we've talked about before.

Erik: I'm going to, in the interest of time, skip over slide 29 because I think you've already really made most of those points. I want to talk about slide 30, which is, I think, and I know you agree that if you go back to our original proposition of, is there a nuclear reactor design which could both be a very economic way to be mass produced in very large quantities in order to make electricity, but could also provide process heat for those applications, for the 25 or 30% of the global energy market, that's about heat as opposed to electricity. I think the molten salt cooled reactor, the type that your company is working on, is really that workhorse reactor, the iPhone of nuclear reactors. What else would you like to say about that?

Thomas Jam: I believe so too. Because, like we talked about before, some of these advanced reactors, they need this high enriched uranium, or not high risk, but the 19.5% enriched uranium, which is called HALEU, or sometimes called medium enriched uranium, and that's very expensive and there's not enough of it, so it's difficult to scale out those type of reactors. So, whether you go with the classical nuclear reactors using water, then you have the problem with the pressure and all these other things we talked about, or the advanced reactors, they have some different problems. But the thorium molten salt reactor is really the one that solves most of those problems.

Erik: I agree. And moving on to page 31, I think that breeder reactors are ultimately going to be what's most important. We really need to get into the fuel. And we decided to break this into two sections this week and next week, because the deep dive on the fuel is, I promise, going to be even more interesting than the different kinds of reactors. We'll talk about why thorium instead of uranium is, when you see the economics, it's just going to blow your mind as to how much we can reduce the cost of energy by using thorium fueled molten salt reactors as the workhorse of energy transition. So that's coming in full detail on next week's podcast. What I want to do with the rest of the time we have available this week is just to talk a little bit more, Thomas Jam, about your company and the things that you're doing, because I'm really excited about this company. Frankly, as an angel investor, it's the most interesting nuclear company by far that I'm aware of. I think that your idea depicted here on page 32 of how you approach modularity is actually just as valuable as all of the work you've done in the nuclear space. Because I think you get the modularity concept and how to roll this technology out in a cost-effective way, better than pretty much anyone else in the industry. Tell us about page 32. What is this concept of how to build a modular power plant out of nuclear reactors that come in the form factor of shipping containers?

Thomas Jam: One of the things that has been really difficult for the existing nuclear industry was this on-site construction with 5000 workers and many, many, like some of the projects, have more than 100 different companies working on the site. It's a very, very complex thing, and it takes a long time, and we've seen delays and cost overruns like crazy in some of the existing classical Light Water Reactor constructions. So we thought about, how can we make a concept where we can really get the price of nuclear down, and also where we can mass manufacture this and make fast deployment, so where it takes less than a year to build a one gigawatt power plant. That was basically the goal. And in order to achieve that, everybody agrees that you need to make the components in a factory. You need to make, simply a line production of components, and you need to do as little assembly work on the site as possible. And for many different reasons, we came to a concept where each reactor is in a box called a cocoon. So, what you see here in the picture is a long row of 30 reactors, and each of those gray boxes, or dark gray boxes, are the cocoon. And inside there, you have a sort of a containerized reactor. So there, if you look at the sort of in the middle, in the lower part of the picture, there's a truck coming where it says, reactor being delivered by truck, and that's sort of the size of the reactor is roughly the same size as a 40-foot shipping container. And then that is inserted into these big cocoons. The cocoon is what protects the reactor from things that are happening on the outside, could be airplane crashes or things like that, hurricanes. And the cocoon also protects the outside from the radiation. So, it's a radiation shield for the reactor radiation. And that cocoon is just a really big heavy metal box, but that one is also being constructed in modules in the factory, and they're delivered to the site, and they are assembled. And we are going to show next year that we can assemble one of these cocoons in a day. So if you can assemble that cocoon in one day from modules, and then you can insert a 40-foot shipping container inside of it, that tells you that you can deploy this really, really fast. The building that is surrounding the whole power plant is just a regular storage building or distribution center building. I mean, every city around the world has lots of these building built outside, and we know from other companies, for example, Amazon, that they can build these buildings in less than 60 days. So those buildings can be built really quickly. And the building itself doesn't have the nuclear protection. It's the cocoon inside that protects the reactor. So, the building is sort of not really any special Nuclear Grade building.

Erik: That's a really important point, because in the cost of nuclear energy, a lot of that cost is the decommissioning fund that's necessary in order to take that all of that nuclear concrete and eventually demolish it and treat it as low-level nuclear waste. When you put all of the nuclear stuff inside these cocoons, it means the building surrounding it is no longer low-level waste. It doesn't have to be decommissioned through a very expensive process the way big concrete nuclear power plants do today.

In the interest of time, I want to move fairly quickly and just go through this next series of slides here. They're really just intended to show a little bit about your company and the things that you're doing, most of the people in this advanced nuclear reactor space are, they've got an office with a bunch of CAD systems where they're drawing drawings. They're not actually building stuff. If we look at page 33, which is your team, page 34, which is shot of some of the bays where you do work inside of, you've got about 12,000 square meters, or about 120,000 square feet of factory and office space in Copenhagen. Page 35, you are the biggest producer of molten salt today, you're selling that to other Molten Salt Reactor companies. You're producing the cleanest and purest molten salt reactor coolant that there is. You're also producing the molten salt circulation pumps which you've designed and built, in house, in order to meet that very demanding need of taking 700 or 800 degrees Celsius molten salt and circulating it in a pump that has a continuous duty cycle life of as much as 15 years. So that's a very demanding pump design that you've created. You're selling those to other companies and to researchers. I know you're working a lot with MIT. Page 37, your test loops which circulate molten salt around in a test in order to prove out that that technology works, and to test it, those circulation loops are something that you've produced for other companies and for researchers. Page 38, we've got more examples of the molten salt test facility that you have. Same thing, I think, on page 39. what is that showing on page 39?

Thomas Jam: 39 is sort of our test tubes. That's where we started many years ago. So, this is where we have static salt test. So, inside these tubes, that's basically a furnace where we can keep the salt or other materials at 600 or 700 or 800 degrees, and then they just sit there for many months to see how much corrosion that generate. Do the sensors work like they should do? The gaskets work like they should? And so on. So, we've been running a lot of these tests with static salt for eight years, and these pictures of some of those tests running, and they're a little bit boring, because it takes 1000s of hours.

Erik: As I move on to page 41, you see the Onion Core® reactor. We had to make a decision for this podcast, folks, to not go into the design details of Thomas Jam's reactor. The reason we're not going into that in this episode is to appreciate why it's as cool as it is. You really need to understand the economic arguments favoring thorium, and particularly the eventual goal of a thorium breeder reactor. We're going to go deep next week on next week's podcast about the fuel cycles, about the fuels, and particularly about the thorium fuel. Once we've done that, at the end of next week's podcast, we're going to take a deep dive on the design of the Copenhagen Atomics' Onion Core® reactor, which is a molten salt cooled, liquid thorium fueled reactor that will eventually become a full Breeder Reactor. On page 42, you're not just drawing stuff on CAD drawings, you actually are building a prototype. This prototype reactor in a shipping container is real. I've been there, I've seen it myself. It works by circulating molten salt that's been heated electrically because you're not yet at the point of doing a live nuclear chain reaction, so you're basically testing all the plumbing with this design. Moving on to page 43, there's a picture of the two of us standing in front of that Onion Core® reactor. I think that's the second one that's being built there behind the two of us, and you see me on the right-hand side of page 43. I've actually climbed inside the operating prototype of the Molten Salt Reactor. I can hear the molten salt flowing around my head. It's rather warm inside. I'm on the cold side of the reactor here, where it's only about 45 or 50 degrees Celsius, as opposed to several 100 degrees Celsius on the other side, and I'm standing there amongst the controlled equipment inside the operating reactor. So this prototypes that you're building are very much real. Now, if this was an actual nuclear prototype, as opposed to an electrically heated one, I'd say you must have a radiation leak, because the aging on my face there clearly shows me as being much older than I am in the picture we have on the Macro Voices website. I'm blaming that on something with your nuclear technology, as opposed to old age. You look young and fresh. I don't know what happened there. Thomas Jam.

Thomas Jam: Yeah, I'm invisible to radiation.

Erik: Yeah, I guess so. Tell us quickly, though, where you are in this process, just to give our listeners a sense, on page 44, of where you are in the company's growth. And we'll go into much more detail on this next week when we talk about thorium and the Onion Core® reactor design.

Thomas Jam: You're absolutely right that we are one of the few nuclear companies around the world that are already building physical models of the full-scale reactor and testing that. And we expect to, in 2027, to start the first test reactor in Switzerland, and that's going to be a big milestone for us, because that's where we really prove that all the technology works like we have simulated now for more than 10 years. And really, our company is one that focuses a lot of building stuff and showing that it works, and also making sure that we can get the price down. You're right that some of the other nuclear companies are mostly sitting in offices and they don't even have a workshop, some of them, so they are different type of, as you say, developers. If we move to slide to 45, there's a few items here where it shows the superpowers of Copenhagen Atomics. We've done a lot of testing. We've done more testing on Molten Salt test systems than all the other Molten Salt Reactor companies combined. We sell some of this equipment so that we can help the other, well, both to universities and national labs, they are most of our customers, but we've also sold some of these test systems to some of our potential competitors. But we don't see it as competitors. We see that sort of all ships rise with the tide. I mean, we need to get the nuclear industry up and running again after it has been sort of dormant for more or less 40 years, or we haven't built very many new reactors for 40 years. So, we need to get up and running again. And we think the best way we can do that is to help everybody succeed. And then we also make Lithium-7, which is something that is needed for our type of reactors. So, we make Lithium-7 enrichment, and of course, we have invented this Onion Core®, which is really what makes the electricity cost of our type of reactors much lower than any of the previous reactors we talked about. But we will talk about that next time. So, let's wait with that. Slide 46, the four founders who started Copenhagen Atomics 10 years ago, and some of the companies around the world that we're working with, some of these are also universities and national labs. And then I want to end by saying that the Copenhagen Atomics is currently doing a capital raise, it's on slide 47, we are open for investments. The investments currently need to be minimum 100,000 euros if you're based in Europe, if you're based in the US, there's a little bit different rules, but it's accredited investors. Please feel free to contact us on our website or send an email to invest@copenhagenatomics.com then we will talk to you about the opportunity to invest and the pros and cons of this company.

Erik: And I'll give Thomas Jam an opportunity to do a proper pitch on his company at the end of next week's podcast. Frankly, you really need to understand the fuel story and the economics of thorium before this value proposition will really make sense. I do want to mention, because we have a capital raise slide here, that I am, in the interest of full disclosure, I am an investor in this company myself, so I do have a vested interest in this as an angel investor. We're going to leave it there for this week's podcast. I really encourage everyone to tune in next week, when we're going to go deep on nuclear fuels, talk about LEU and HALEU and TRISO fuels, and particularly the thorium fuel cycle and the economics of the thorium fuel cycle. If you think people didn't know about thermal spectrum breeder reactors, they really don't know about the economics of thorium, and we're going to go deep on that in our New Year's Special, which will air next Tuesday, December, 31 2024 but right now, be sure to stay tuned for our post game segment when Patrick Ceresna and I will discuss the investment opportunities in this sector, in both public and private markets. That's coming up next, right here at macrovoices.com