MACRO Voices
with hosts Erik Townsend and Patrick Ceresna

Thomas Jam Pedersen: Nuclear Fuels and Fuel Cycles for Energy Transition

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Erik: Joining me now is Copenhagen Atomics founder and CEO, Thomas Jam Pedersen. We've prepared a slide deck to accompany today's 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 haven't yet registered at macrovoices.com, just go to our home page 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 Macro Voices YouTube channel. Thomas Jam, welcome back. I think our first interview last week was well received by the audience. I'm really excited to dive into this one. Let's go ahead and start right into the slide deck at page 3, talking about thinking at scale. You know, something I've noticed is your presentations almost always start with the same slide. I like to start with, which is the Our World in Data Series that talks about global energy consumption by source and breaks down how much energy we're using on a global basis. It seems like you and I both like to think, in terms of the big picture, of how much energy the world needs, how much we need to supply, how we're going to do it. I've noticed that almost nobody else in the nuclear space thinks that way. Why do you think that is?

Thomas Jam: Thanks, Erik, for having me back. Yes, you're correct that this slide is the one that got me started many, many years ago, because that was when I personally started to understand how the global energy system works. So, I went back to that slide many, many times. This is 15 years ago now, and it gives you a good picture of how the whole world works, because the whole world is built on a fundament of energy. And therefore, by understanding the history of how we got the energy as humans, and how this is supposedly changing over the years, you can sort of make the strategy for, in my case, Copenhagen Atomics, into the future. Because from that strategy, we can kind of understand how the energy systems globally are going to change.

Erik: Thomas Jam, I couldn't agree more. And if there's one point that I think really summarizes what I want the audience to understand about this episode and the motivation for it, it's that we're thinking about what it would take to solve the energy problems for the whole planet, not how to sell the next nuclear reactor or how to start a company in the high tech business, but how to take on this energy problem that so few people really have their heads around. So, thinking about the scale of the whole problem is what gets us, I think, to a view that's very different from the mainstream, which is that you really have to be on a thorium rather than uranium based nuclear energy strategy in order to solve the biggest problems that we face as a society. And I think the reason that very few people think that that's true is because they haven't really thought it through at scale. Moving on to page 4, I'm going to borrow one of Elon Musk's favorite quotes. He always likes to say that when people talk to him about Tesla, they always assume the hard part was engineering and designing the electric cars at Tesla, but actually it was, getting the manufacturing right was the most important part and the hardest part for that company to take on. The analogy here is that when contemplating nuclear energy transition, most people, as we look at this nuclear renaissance and talk about Generation IV nuclear technology, they're looking at the reactor designs. They're looking at, okay, how cool is the sodium fast reactor? Oh, wait a minute, look at these pebble bed high temperature reactors. That's really cool. I like the way the design works. If you really want to solve this problem, you've got to look at the fuel cycles and think, not about the design of the car, but about the design of the network of gas stations that are going to supply those cars, because that's the much harder problem to solve. And once you understand that problem, you reach very, very different conclusions than you reach if you're just looking at the design of the reactors. So, I say the fuel cycles and supply chain challenges are the most important part, and those are the things that very few people have gotten their heads around at scale.

Folks, I know Macro Voices is not an engineering podcast, but a finance podcast, so I promise slide 5 is the only one where we're going to ask you at all to focus on nuclear physics. And it's going to be really quick, short and to the point, all we need to do to make the rest of this make sense is to get this word ‘isotopes’ into your vocabulary, if it's not already there. So very briefly, atoms is what everybody thought was the smallest unit of matter, until we realized there are actually particles inside those atoms. Those atoms come in different flavors called elements. Everybody knows this from high school chemistry, so you've got the number one in the periodic table is hydrogen, number two is helium, number three is lithium, and number four is beryllium, and so forth, all the way up to eventually number 92 is uranium, and number 94 is plutonium. It's not listed there, but it is, and so on and so forth. Well, those numbers are actually referring to the number of protons inside the nucleus of the atom. That's what you need to know in order to know which element a given atom is. What most people don't even think about, because it frankly, doesn't matter to chemistry, but it matters very much to nuclear science is the number of neutrons inside the nucleus of each atom, and it's the number of neutrons that determine which isotope it is, or probably a better way of saying that is the word ‘isotope’ is defined simply as a word or a description for a specific type of element that has a certain number of neutrons in its nucleus. The example shown on the left side of the slide here is for hydrogen, the simplest atom because it only has one proton. The common isotope of hydrogen is the one that doesn't have any neutrons in the nucleus at all, that's shown on the left. We call it just regular old hydrogen, although technically it does have another name, which is protium. If you add a neutron to the mix, as we see in the middle of the picture there, that one's called deuterium, and that's just another isotope of hydrogen. If you add a second neutron, then it's called tritium, or hydrogen three, ^{3}H. So, the number after the name of the element is the number of the total number of nucleons, the total number of protons and neutrons together. So, tritium is also known as hydrogen three, ^{3}H. Similarly, as you go further up the table of elements, you get lots and lots of protons and lots and lots of neutrons, and that's where those big numbers come from. So, something like Uranium-235, well, it has only 92 protons, because that's what makes it uranium. The rest of what makes up that 235 is all of the neutrons that are in the nucleus. So that's what's meant by the word isotope. And that's really all of the nuclear engineering or nuclear physics that we need to learn in order for this episode to make sense.

Thomas Jam, let's dive into slide 6, and I want you to get your help with this one. There are only three isotopes that are called fissile isotopes, meaning that they can sustain a nuclear chain reaction. The first one is Uranium-235 and that's the only one that occurs in nature, but it only occurs in small quantities. Tell us a little bit more about Uranium-235 and why it's so important.

Thomas Jam: So you talked very briefly about isotopes before, and it's right. So, we have all the things we burn fossil fuels and all the other things, when we burn something, it's a chemical reaction, and that has to do with the electrons, but when we do nuclear reactions, it has to do with the core of the atom, and that's the protons and especially the neutrons. And we also call that burning when we burn atoms. But, and like you said, Uranium-235 is the only one that we can find in nature that can do that, which can create a chain reaction with a nuclear reaction instead of a chemical reaction. And we should also mention, I think, we didn't do that last time, that when you make nuclear fission, you generate more than a million times the amount of energy per kilogram than you do when you burn things. If you burn fossil fuels or even explosives or whatever you can burn, usually nuclear reactions, there's a million times more energy per kilogram. So of course, it's a much more powerful type of energy, and that's also why it's used for atomic bombs. But anyways, the only isotope that could do that from nature is Uranium-235 and it's very rare, or very scarce. The good story is that there are two other isotopes, Plutonium-239 and Uranium-233, which humans can make inside nuclear reactors. And they have pros and cons, of course, and they work in a similar way as Uranium-235. But of course, the price is different, and some of the waste is slightly different, and so on.

Erik: So, the thing that's frankly, crazy to me is, despite this industry being 70 years old, we only use Uranium-235 today, despite the fact that it's the rarest of these three isotopes that could be used as nuclear fuels, and we're basically using it up pointlessly when we could be making the other two isotopes. We make a little bit at a conventional nuclear reactor, a little bit of Plutonium-239 gets made, kind of almost as a side effect of the nuclear chain reaction. So, Plutonium-239 is the next fissile isotope. It's a man-made element. The only Plutonium-239 that exists is that which human beings have produced by, I love this word, transmutating. It sounds like it's directly out of Star Trek. So, you take the Uranium-238, that's the 99.7% of natural uranium that is not fissile. It can't be used as fuel by itself. You run it through a nuclear reactor, you make it absorb some more neutrons. It turns into Plutonium-239 that is fissile, and it can be used in order to run a nuclear reactor. Now, about 2% or 3% of the Uranium-238 that goes into a nuclear reactor as fuel, and we discussed this last week, does get used, turned into plutonium and used as fuel. But all the way back in the 1940s, they figured out how to design nuclear reactors that would be much more efficient at converting more of that Uranium-238 into fissile Plutonium-239 so that we wouldn't have to use up all of the Uranium-235, which is so scarce, in which we only have a limited supply of. You'd think that if we figured out how to do that way back in the 1940s, and ironically, the very first nuclear reactor, which demonstrated the generation of electricity was the Experimental Breeder Reactor, one that was designed to do exactly this, to turn Uranium-238 into Plutonium-239 so that we could use the 99.7% of natural uranium that would otherwise go to waste. Yet despite that, it was demonstrated on December 20 of 1951 that that was possible. We haven't been doing it that way. We've been doing it the much more wasteful way of just using Uranium-235 almost exclusively. Now, there's a third fissile isotope, which, frankly, I think Thomas Jam and I agree, is the best of the bunch. It is the Uranium-233, which is a different isotope of uranium that one can only be made inside of a nuclear reactor. But it's not made from uranium. It's made from another heavy element called Thorium-232. Thomas Jam, tell us a little bit more about why Uranium-233 is so important, and why is it that, if it is so important, we really don't use it, and very few people even know about it.

Thomas Jam: Yeah, that's correct. It was discovered all the way back in 1942 that thorium can go through the cycle and generate Uranium-233, it's the best fissile isotope. So, we have these three fissile isotopes, but of those three, it's the best one in thermal spectrum. Thermal spectrum means slow neutrons, and that means that if you slow down the neutrons, then you get the best neutron economy with this last Uranium-233, and that's really, really important, because this means that now you can build what is called the breeder reactor in thermal spectrum. And that means you can build the reactor smaller. You need less amount of fuel to get the reactor started, and therefore it's more economic. Both, you need less fuel to get it started, but also, thorium is much less expensive than uranium for various reasons. So, if you build a breeder reactor in thermal spectrum, you can get the energy price really far down compared to any uranium-based reactor. And when I say uranium, I mean Uranium-235 so that's why thorium is so important, because from physics and from simple math you can do on a napkin, you can show that it's sort of an order of magnitude better than any uranium reactor you could ever build. And that's, of course, why we should be looking at it.

So, there's been a lot of misunderstandings over the years, because for many, many decades, people didn't believe or didn't, try to figure out if you could make a breeder reactor in thermal spectrum. The first guy to suggest that was Alvin Weinberg back in the 1950s and 60s, but back then, they didn't have computer simulations. But he thought, ah, this is probably going to work. And it was not until 2022 that we knew for sure at Copenhagen Atomics, that it would be possible because we had made simulation tools that could actually do the right simulation, so we could figure it out. Before then, we also had to sort of rely on calculations that were not 100% correct. But yeah, that's why Uranium-233 is super important. I want to make one more note that, of course we can find Uranium-235 in nature, and there's many countries who have that. So that's the easy place to start for all countries. Then there are some countries who have separated out Plutonium-239 and the problem with plutonium is that this is also used for most nuclear bombs, so it has a lot of bad reputation. And then Uranium-233, there's a little bit of a stockpile of that in the USA, and maybe a little bit of a stockpile in Russia. We don't really know about the Russian stockpile, but in US, the crazy people in Oak Ridge are trying to down blend it, it's really valuable stuff, like way more valuable than diamonds, and then they're trying to destroy it. It's really a horror story, but that's because they don't really understand it. And I don't blame them too much, because most of the nuclear engineers that have been educated in the last five decades, they didn't really hear about thorium and Uranium-235, during their education, it has been sort of suppressed. And I think it's because there were some people in back in the 70s who tried to put some of this thorium and Uranium-233 in regular light water reactors. And if you do that, it doesn't create any better fuel economy than good old Uranium-235, so it actually doesn't work in the existing fleet of reactors we have around the world. You need a new type of reactor to make thorium and Uranium-233 work in this way where it's like order of magnitude better, but we will get to that and some of the next slides.

Erik: Now, Uranium-233 does actually have some bad histories. A failure in its history that very few people understand, and it's very important to understand that failure is that Uranium-233 was considered by the Manhattan Project for building the bomb with, and what they concluded was that Uranium-233 although, as Thomas Jam just said, is the best isotope for making nuclear energy with, it's the worst of these isotopes for trying to make a bomb with. And what they concluded is, although it might be technically possible to make a bomb from Uranium-233, it would be so much more difficult that it really wasn't worth it. So, they abandoned U-233 from the Manhattan Project for bomb making. Now, when you stop and think about it, that's not a bug, it's a huge feature. It means that if we were working with Uranium-233 as the basis of our nuclear energy programs, well, you'd be working with an isotope which, although technically, it might be possible to make a bomb from it, it's much more difficult to make a bomb from Uranium-233 than it is from plutonium or Uranium-235, that's a really good thing in terms of mitigating nuclear weapons risks. But I've actually heard nuclear engineers say, oh, the Uranium-233, now they ruled that out in the Manhattan Project, it's no good. It's not worth using. Well, it's no good for making bombs. That doesn't mean it's no good for making nuclear energy. Let's move on to page 7. Thomas Jam, explain where we said you get this stuff out of a nuclear reactor. Talk a little more detail about how that happens. What do you do with thorium in order to turn it into Uranium-233, page 7.

Thomas Jam: Page 7 explains how you convert thorium inside a nuclear reactor to this Uranium-233 fuel, and it basically happens if you have slow neutrons. So ,neutrons that have been slowed down with something called a moderator. A moderator can either be water or beryllium or graphite or some material that is great at slowing down neutrons. So, if you have a slow neutron, natural Thorium-232 can capture that neutron, and then it automatically converts into Thorium-233 and then that also decays. So, there's a radioactive decay from Thorium-233 to Protactinium-233. Protactinium-233 is also an element that doesn't exist in nature, but you can create that in the nuclear reactor, and then that Protactinium-233 then takes an average of 30 days as half-life. So, after 30 days, it will convert into Uranium-233 and this is then the brilliant fuel, or the great fuel, for nuclear reactors. So, it's sort of automatically created inside the stomach of the nuclear reactor. But it's not a quick process, because it has this half-life of 30 days. So, it takes some time to be generated, and then slowly, you generate more and more fuel. And this, the picture we have here in slide 7 is called a fuel cycle when it's converted from thorium to uranium. And like I said before, this is the most efficient fuel cycle in thermal spectrum. And why thermal spectrum is important is, that you need less fuel per gigawatt of energy you create to get that whole reactor started. So, the upfront cost of buying the fuel is less per kilowatt hour, a megawatt hour of energy you generate. So that's why it's important.

Erik: And of course, there is no enrichment required on thorium in order to produce the Uranium-233, so all of the conversion and enrichment bottlenecks for those of you who heard my interview with Justin Huhn back on December 5, we talked about what Justin and I think is going to be a coming bottleneck in the global uranium market when there's not enough conversion in enrichment facilities. Well, thorium doesn't need any of those enrichment facilities, and that is a major differentiator by itself. Let's do what we promised at the beginning of this podcast now, and think about the really big picture. Moving on to page 8, this pie chart shows all of the nuclear fuel that is available to supply humanity for the rest of forever, because we're moving from the age of oil into the age of nuclear. I think the age of nuclear is going to power humanity almost indefinitely. But look at what we're doing now. If you're viewing this on a mobile device, you might not even see that there's actually three colored slices to this pie chart, the green one in the top, which is 24.82% that's Uranium-238, the common form of uranium, which is most natural uranium mined out of the ground. The 75% of nuclear fuels that are available to humanity are thorium. That's the amber colored gigantic wedge. There's an itsy, bitsy, you can barely see it, dark blue wedge, which is fissile Uranium-235, that's 0.18% less than two tenths of 1% of all of the nuclear fuel available to the world, is Uranium-235 and that's the only kind that actually gets used in conventional light water nuclear reactors. What goes into those reactors is not just U-235, U-235 is only 5% of it. The other 95% is we take a whole bunch of that green fuel in the 24.82% and we waste it. All we do is, we make it get radioactive, and we don't burn more than about 2% or 3% of it is fuel, because those reactors are not designed to make good use of these fertile nuclear fuels, which are U-238 and Thorium-232. Thomas Jam has probably a much better graphic taste than I do. He's got essentially the same idea on page nine that I just was my slide on page eight. Thomas Jam's graphics are much more esthetically pleasing on page 0. So why don't I let you talk through this? Thomas Jam, what's going on page 9? With 5% of global energy comes from that tiny sliver. Why are we not using the rest of the natural uranium or any of the thorium, which is where most of the nuclear fuel is, that's available to humanity?

Thomas Jam: So, that, like I said, that there has been a few attempts in the past history, all the way back from 50s and 60s and 70s, to try to use thorium in sort of the traditional solid fuel reactors. And it doesn't work. I mean, well, it does work, you do produce energy, but it's not economically favorable over using good old enriched uranium. And that's why we've stuck with those solid fuel reactors, and that's why we're using uranium. And like you said, in most of those reactors we use around the world, we need to enrich the Uranium-235, before the reactor can even start on that. So that enrichment is a very expensive process, but there are some reactors that they have, for example, in Canada and India, that are called heavy water reactors that there's also some more countries that have them where you don't need to enrich the uranium, but then you need heavy water. And heavy water used to be super expensive back in the day, and therefore, they were not super economic against the light water reactors or the reactors where you have enriched uranium. So, that's why those two types of solid fuel reactors work. But in order to make thorium work, you need what is called a Molten Salt Reactor, a liquid fueled reactor, which is something very different from the solid fuel reactors that most countries and most companies are talking about. And that's really why we made this podcast today, because we want to explain the difference between solid fuel reactors or classical nuclear reactors and these new liquid fuel reactors or molten salt reactors. They have different names, but it's a shame that we don't even talk about how we could use the thorium, because there is, like you said before, there's almost 1000 times more thorium on this planet than there is Uranium-235, and if you look at when we will run out of thorium, if we wanted to make the same amount of energy from wind and solar, we would run out of steel and all the other materials we need for wind and solar way before we would run out of thorium. So that means that thorium is actually also a renewable energy source. It's way more renewable than wind and solar, but we don't really talk about it like that.

Erik: Well, and I think it's really astonishing that even within the nuclear industry, some of the best experts are not aware of a lot of this. There was a Senate hearing where they pulled in this guy who was supposed to be the super nuclear expert witness guy, who came in before a congressional hearing, and they asked him about thorium, and he kind of scratched his head, and he says, well, you can make a nuclear reactor work with thorium instead of uranium. And he just said, I just can't figure out why anybody would want to. Well, let me answer his rhetorical question on page 10. This is my slide that I use when talking about Copenhagen Atomics reactor. This one is not from Thomas Jam. And what it shows is Thomas Jam’s reactor design, which is 100-megawatt thermal energy nuclear reactor that comes in the form factor of a standard 40-foot shipping container. Now, if you wanted to produce that same 100 megawatts of thermal energy in a coal fired power plant, it would take 131,000 metric tons of coal per year. That's about $20 million worth of coal, or a railway train 20 kilometers long. That's how much coal it takes to make 100 megawatts thermal 24/7 for a year. Thomas Jam’s reactor produces the same amount of energy from 36 kilograms of thorium. And I'll say that again, it's not 36,000 metric tons. It's not 36 metric tons, it's 36 kilos of thorium. The amount of thorium that a strong man my size could physically pick up and carry across the room, the cost of that full year's supply of thorium is not $20 million worth of coal. It's 1800 bucks. And if you normalize that, because something like the AP1000 is a much larger reactor, it's about 11 and a half times the capacity of the Copenhagen Atomics’ reactor. If you take that 1800 bucks and multiply by 11 and a half times, you get to $61,200, fuel cost of Thomas Jam’s reactors. It would take about 34 of Thomas Jam’s reactors in order to match the power of an AP1000 reactor from Westinghouse. But Thomas Jam’s reactors can do that on $61,000 worth of fuel, as opposed to $194 million worth of enriched uranium fuel that it takes to run that Westinghouse AP1000.

Now, the Copenhagen Atomics reactor runs on thorium as its primary fuel source. That's obviously where the big economic advantage comes from, but there is a catch. And that catch is, the way I like to think of it, is like kindling in a fireplace. You can't just start the fire by holding a match up to a giant oak log. You've got to have some kindling, in order to get the fire started before those big logs are going to catch fire. The same thing is true of these thorium-fueled reactors, they have to have something called Kickstarter fuel, which I think of as the kindling in a fireplace. You can use the same low enriched uranium fuel that goes into a conventional nuclear reactor as that kindling, in order to get Thomas Jam’s reactor started. But the advantage of the Copenhagen Atomics design is, you also have the option of using recycled spent nuclear fuel waste, so you can use the waste that's left over from the old nuclear reactors of yesteryear, and essentially recycle that waste, turn it into kindling, in order to start up these Copenhagen

Atomics reactors. Now, for the moment, that's easier said than done, because there's a lot of regulatory hurdles. We'll come to those in just a minute. But this is the reason this slide really says to me, you take what takes 20 million bucks worth of coal, and you do it for a fuel cost of 1800 bucks. That is the reason, Mr. Whoever your name is, the guy that was testifying as the expert witness and has far more credentials than I do, that it makes sense and why you would want to do this with thorium rather than uranium. It is shocking to me how few people understand this. Thomas Jam, you know, this is not new, and it's not you guys that figured it out. Everything I'm talking about in this slide was figured out in the 1960s and you would think any degreed nuclear engineer who studied history of the industry would know everything I just said. In your estimation, Thomas Jam, what percentage of degreed nuclear engineers already know about all this?

Thomas Jam: It started back to sort of around 2010, that the engineering schools around the globe started to see a lot of young people applying for nuclear engineering. And a lot of the old guys, they couldn't understand why, suddenly young people applied for nuclear engineering, but it was because there was a number of videos on YouTube about thorium, and they got really excited that this was a huge opportunity in the future, and so they wanted to study nuclear engineering. And you're absolutely right that most of those old people who taught nuclear engineering, they didn't talk about thorium at all, but these young people now demanded to learn something about it. And, of course, the old timers, they could look it up and start explaining it, because they understood the sort of, the nuclear physics behind it, and the math and everything. But it was just not commonplace. It was not something that was talked about. So, I think everybody who got a nuclear engineering degree between, I don't know, 1980 and 2010, they probably didn't hear about thorium at all during their whole nuclear engineering education. And if they heard about it, it was sort of put down and said, you know, we're not using it. And it was not explained why we were not using it. But like I said before, you can do the calculation on a napkin to show that it doesn't make any sense in a solid fuel reactors. And all the reactors we have in the world today are solid fuel reactors. So that's why they didn't bother to teach people about it. But then these young people came in after 2010, and they basically demanded to hear about it. And quickly, they also came to the realization that you need a liquid fuel reactor, a molten reactor. They also wanted to learn about those, and so I'm actually one of those, but I got my engineering degree way before that, so I had to study the whole thing about molten reactors on my own. But, yeah, that was also quite an eye opener for me.

Erik: Well, I've been really surprised myself. As you know, I have a niece who's studying nuclear engineering, she went to the Molten Salt Reactor workshop in Knoxville, Tennessee recently, as did your CTO, who spoke there. And she showed up in a thorium t-shirt on my suggestion, I figured it'd be a good conversation starter, since she's looking for a job when she graduates from school in June, And she took a fair amount of ribbing from people, even at the Molten Salt Reactor workshop, saying, oh, you're one of those thorium true believers, huh? Well, look, if you're not a thorium true believer, yet, let's move on to page 11 and talk about what it costs to run this planet in terms of fuel cost. The answer on fossil fuels is $6.25 trillion dollars per year. That's the size of the global fossil fuel markets, coal, oil and natural gas aggregated. $6.25 trillion dollars is the annual size of that market. If you wanted to run the entire global economy on nuclear, using solid fuel nuclear, uranium fired nuclear, you could get that fuel cost down to about $2.3 trillion or to almost a 63% savings. If you ran it on thorium, you could run the entire global economy for $312 million a year worth of thorium. Now, that's not counting the Kickstarter fuel. It's not counting the kindling to start the fire in the fireplace. And ironically, it ends up that the kindling costs way more than the actual cordwood in the fireplace cost. So, if you have to pay for low enriched uranium to use as your Kickstarter fuel, well then, it's $144 billion instead of $312 million. But once we get enough of these thorium reactors running that we don't need any more kindling to start the fires, you can run the entire global economy on $312 million a year. That's the cost of a sports team, as opposed to $6.25 trillion dollars a year. So yes, I'm a thorium true believer, that's why. And I don't think hardly anybody understands these numbers. Thomas Jam, you've got your own slides that tell this same message. Why don't you take the stage with 12 and 13 in the deck? Talk about your arguments for the economics of thorium energy?

Thomas Jam: Yes, so slide 12 is basically to give people this perspective of what is the difference between a thorium breeder reactor cycle and all the regular solid fuel reactors. And you see that there's these two dots, there's the thorium, up in the upper left-hand corner, and then there's the big uranium dot down in the lower right-hand corner. And the size of those dots give you some idea of how long it usually takes to build those type of reactors. So not only is thorium a lot cheaper, it's also a lot faster to build from reactors, at least the ones that Copenhagen Atomics are proposing to build. So, that's why the economics of getting all energy in the whole world from thorium would be orders of magnitude better. But of course, I should say that here, we only look at the fuel cost. This slide doesn't talk about the cost of the reactor that you need, or it doesn't talk about the Kickstarter fuel. It only talks about the fuel cost. And there's a number of different solid fuel reactors, we have to admit that. And here, we just take sort of the average, you can see in the lower left-hand corner, it says 60-gigawatt day per ton of uranium, and some of the most average reactors, they can generate 60-gigawatt days of energy per ton of uranium. And if you want to calculate that into gigawatt hours of energy per kilogram, that's what is on the Y axis. So that's the 1.44 gigawatt hour of energy per kilogram that you can get out of solid fuel reactors using uranium. And of course, there are different reactor designs, and we talked last time about advanced reactor designs, actually, even though they are called advanced reactor designs, some of them have a worse fuel economy and some have a slightly better fuel economy. But if you look at that big green uranium.it would move a little bit to the right or a little bit to the left. It wouldn't move very far, up and down, maybe a little bit up and down, but not very far.

So, depending on all the other solid fuel reactor designs in the whole world, you can move that uranium dot sort of a little bit around, but not very much. But there's no way in hell, or anything anywhere else that you can get the green dot for solid fuel reactors to move anywhere near the thorium up there in the right-hand corner. And that's simply because thorium is very plentiful, and we already mined for other materials where we get lots of thorium out of the ground. So, the cost of thorium will never become very high. And right now, if we are, Copenhagen Atomics is the biggest customer in the world for thorium, and we've already bought thorium from several different sources, and the current price is right around $50 per kilogram. So we expect that price, actually, over the years, to come down. Once that market for thorium becomes bigger and there are more suppliers and more customers, I expect that that price to come down, but maybe not down to half, but yeah, $40 or $30 per kilogram. And as I show there, each kilogram of thorium in a thorium breeder reactors can generate 22.5 gigawatt hours of energy, which is a whole lot more, 10 times more than solid fuel uranium reactors. So, that's why, you know, if you make the simple calculation, it's 1407 times more efficient to use thorium fuel cycle than to use the solar fuel, uranium fuel cycle. And that's really mind blowing. I mean, we've never seen anything like this in the industrial history of the man. I mean, even transistors, when we invented transistors instead of radio tubes, they were slightly more efficient. And you could see sort of, maybe 10 years down the road, they could be a little bit better. But of course, the transistors have this gone on more rule where it doubles every 18 months, which is great, and that's why we've gotten to having mobile phones in our pockets with billions of transistors. But still, it was a slow growth. But with nuclear energy and thorium, we can get this 1400 times better fuel economy right away as soon as we change those new reactors.

Erik: Thomas Jam, that's covering, as you said, just the fuel cost, but what about the CapEx? Let's move on to page 13.

Thomas Jam: Yes, correct. So, we compare the most common base load types of nuclear plants. So of course, we started with coal, which is the most common electricity generation. Base load plants are coal plants, and you can see sort of both the CapEx and the OPEX, and you can also see the electricity costs that comes out of those. And of course, depending a little bit on the generation and where in the world you built them, coal fired power plants usually have an electricity price between $30 and $60 per megawatt hour. You can see that they have sort of the fuel cost, the raw fuel cost. When you buy the coal and it arrives on train carts, it costs roughly $400 million per year to power a 1 gigawatt coal fired power plant. And I say up there in the subtitle that it's a 1 gigawatt electrical power plant in Europe or USA, because actually in places like India, you can even get it even cheaper, also in China. So, to operate one of those plants, the operational cost, the maintenance and the people who run it, it's like roughly $50 million per year. Of course, that also depends on what country and how old the plant is. And then you see down there, in the orange colors down at the bottom, you can sort of see a depiction of how long it takes to build one of these plants. And it also depends, but on average, it's two years to build a plant like that, to get it approved and build it and everything until it's up and running. And it costs roughly $2 billion in the Western world to build a coal-fired power plant. But of course, in the Western world, we don't want to build any more of those, even though they're actually still very economic. And we also saw that, even though Germany tried to get rid of fossil fuels, now they get most of the energy from coal. So, they had to go back to using coal again, because they couldn't get the gas from Russia.

So the next one is the gas-fired power plants. Gas is slightly more expensive. On average, it's like between $60 to $100 per megawatt hour. Of course, that also depends on where you're located. And if you can get gas from Russia, if you are in Texas. Also, the gas price is not that high, but it depends a lot on your location and around the world. But sort of on average, we put here that it costs $600 million to buy the gas, and then the operational cost of those type of reactors are similar to coal-fired power plant, but gas-fired power plants normally doesn't last for 50 years, like a coal-fired power plant or a nuclear power plant, so in these $50 million of operation costs, it's also the restoration or refurbishing of the plant, a gas-fired power plant to make it last for many years, so that it's comparable. And finally, you can see down at the bottom that you can build gas-fired power plant really quickly, in less than a year, and they're not very expensive. Upfront CapEx cost only $1 billion, or maybe even less. And then we come to the classical nuclear reactors, and they are crazy expensive, if you look at the orange, and they take many years to build. So of course, we've had the different examples. Down in Abu Dhabi, they were able to build these light water reactors in only four years. But for example, in Europe, we've built the Olkiluto 3 plant in Finland that took 18 years. There's the Hinkley Point C, that are currently being built. I think now the best estimate is 15 years. We also saw the Vogtle plants in Georgia in US, also took something like 15 years. Actually, don't know exactly how long they took, but it was more than 10 years. So, you can see that in the Western world, it usually takes more than 10 years to build nuclear power plants of the classical type, and they cost a lot of money. I just put $10 billion here, but some of them actually cost more than that per gigawatt, so they are crazy expensive compared to coal and gas. And then we've depicted with these orange colors that there are some people, especially the type of people who talk about small modular reactors, they believe that they can get the cost down, and also the time it takes to build these types of reactors, that's basically the small modular reactors. Like we said last time, it's a small misunderstood reactors, because it's basically just a classical reactor, but then they try to make it smaller and make it faster, but they haven't really shown yet that they can make it faster or cheaper. So, this orange part down there is still uncertain, what it's going to cost and what it's going to take. But if we look at the fuel cost and the operational cost, the fuel cost is, of course, much lower than for coal and gas, because nuclear fuel is cheaper than coal and gas, but then the operational cost is more expensive. But all in all, if you run a nuclear power plant for 60 years or more, then you can get the electricity price down to the roughly the same level as gas-fired power plants. And of course, nuclear energy, it doesn't release very much CO2, so compared to gas, it's more a clean energy source.

And then in the fourth column, we compare it to thorium breeder reactors from Copenhagen Atomics, and it has all the things you want. It has a quick deployment time. Down in the orange, it's cheap to build, it's fast to deploy, and then the operational cost is roughly the same as for gas and coal, but then the fuel cost, like we talked about in the previous slide, is almost nothing. And the reason why we put here a range between $50,000 to $300,000 is because some of the very first reactors is not going to be as great at breeding new fuel as they will eventually be. So, in the very beginning, the first 5 or 7 years or something, it will be slightly more expensive in fuel cost, and then we will get down below the $50,000 per year. So, it's only in the beginning that they're slightly more expensive. But it doesn't really matter in the bigger picture. It's a much better solution for rolling out large amount of clean energy for the whole world. And of course, Copenhagen Atomics has invented and patented a special reactor core called the Onion Core®. We will get back to that later, and that's part of the reason why we can do this. But of course, other companies could also make thorium breeder reactors with a different type of reactor, or even buy a license to the patent we have. So, it's not that just one company could do this. There's, of course, lots of companies who is eventually going to do thorium breeder reactors.

Erik: Thomas Jam, excellent job describing page 13. I'm going to play devil's advocate and say, if there was somebody here from Oklo or from one of the other companies that are working on advanced nuclear, they might say, wait a minute, you're talking your own book, because you're comparing coal, gas, classic nuclear, to your thorium breeder reactor. But what about the other advanced nuclear technologies that we talked about last week, like fast sodium reactors? Those are also a lot more efficient than classical nuclear. What I'm going to say in reaction to that is, you've got to go back to where we started this podcast, which is thinking about the big picture in the fuel cycle. Moving on to page 14, those fast sodium reactors are really cool. They run on HALEU fuel instead of the regular 5% low enriched uranium. Well, guess what? HALEU fuel costs upwards of $25,000 per kilo. The advantage of something like a sodium fast reactor is it's going to use more of the U238 so it's, first of all, it's got more of the blue U235 to burn. It's going to take the U238 which is the fertile material that's not fissile, when it starts, it's going to breed it into plutonium, and it's going to make much better use of it. So, these other advanced reactors do some really cool things too. But when you stop and think about, well, wait a minute, what if you were to not just build a few of those Oklo reactors? What if you were going to build enough of them to solve to replace all the energy we get from fossil fuels, how much HALEU, that's the very high assay, low enriched uranium, almost 20% enriched, would it take to fuel all those reactors, and what would it take in terms of enrichment facilities that we don't have today, in order to make all of that HALEU fuel? When you start to do that kind of analysis, you realize that the HALEU fueled fast spectrum advanced reactor technologies, they're really impressive. When you look at the sports car, the design of the reactor, when you look at the design of the network of gas stations we would need to fuel those reactors with, it's a very different conclusion, and that's the point that I'm trying to make on page 14 there.

The other thing that I think is really important, moving on to page 15, is the public is sick of nuclear meltdowns, fuel rod meltdowns. We've got to have reactor designs which are completely impervious to fuel rod meltdowns. Now, a lot of nuclear experts would say, well, wait a minute, with Generation III plus advanced nuclear reactors like the Westinghouse AP1000, those fuel rod meltdowns are not nearly as big of a risk as they were 30 or 40 years ago. Well, guess what? They're still possible, and the public is emotional, and they're freaked out about it. We need meltdown proof nuclear fuels that can't possibly melt down. The two big contenders are TRISO fuels, those are the ones used in the pebble bed reactors we talked about last week in the first episode of this podcast. And the other one is the fluoride and chloride fuels that are used in molten salt reactors. Thomas Jam, tell us about both of those in terms of how they work and what they do in order to prevent nuclear meltdowns.

Thomas Jam: So, it's correct that you say that the public is afraid of nuclear meltdowns, but that's sort of a little bit odd, because nobody has ever died from that. There's a guy called Bret Kugelmass who says, you know, he even put out a bit, and I think it was like $10,000 or something like that, is if anybody could show him how anybody could ever die from a meltdown. And it's true that meltdown is not dangerous. It's very expensive to clean up afterwards for the company that where it happens, but it's likely not going to kill anyone. But it's true that the general public and sort of the fear mongering, has been put around meltdown. And for that reason, there's some companies who said, okay, let's try to solve that problem, which is not really a problem, but let's try to solve it anyways. And then they came up with a different type of fuel, called tracer fuel, or pebble beds. And it is true that that they're less likely to melt down, and maybe there's a smaller risk of proliferation. So, it can also be used at military bases in the middle of a war zone. Maybe it's better for that than solid fuel reactors. So, I also say that you probably wouldn't use Molten Salt Reactors in the middle of a war zone. But apart from that, I don't see the big benefit of TRISO fuel. I know some people try to give it a big deal, but I think when you compare that to molten reactors or liquid fuels, which is listed at the bottom, you get a lot of benefits. And the TRISO fuel is super expensive. Both the enrichment is, of course, expensive, but also production of those pebbles are expensive. Of course, if we make like, a gazillion of those or a billion of those pebbles, maybe we can get the price down of the pebble production, but the enrichment is still going to be very expensive. So that's why I think liquid fuels are still much better. And I list some of the reasons down there, because you can remove fission products. That's super important, because that gives you superior fuel economy, and then also that you can refuel the reactor online. You don't have to stop the reactor. That's also very important. Of course, some of the people who make pebble beds, they will also say, you can refuel online, but it's a different type of refueling. You cannot change the fuel composition, really, in the same way you can with liquid fuel reactors or molten salt reactors. And certainly, you cannot make a breeder reactor, neither in fast spectrum or a thermal spectrum with these pebbles, but you can do that with a molten salt reactor. You can actually even do that with a fast chloride fuel molten reactor. You can also make breeder reactors, but I would contest that the fuel economy or the price of the energy would not be able to compete with the fluoride thermal breeder reactors. And then it's much easier to reuse your materials like Lithium-7 or Beryllium if you have a liquid fuel reactor. So those were some of the benefits. But I think we need to move on to the next slide.

Erik: Thomas Jam, you're exactly right. So, let's move on to page 16, where we get into spent nuclear fuel waste reprocessing. This slide came from last week's podcast. I'm going to skip most of the details and focus on the yellow highlights at that spent nuclear fuel waste. And again, it's not green slime. It's not purple slime with big bubbles coming out of it. It's these big metal fuel assemblies that look like the picture on the right side of the slide there. They're radioactive. They get stored in dry casks, which are big, vertical, cylindrical tubes. We'll show you a picture of those in just a minute. What's inside of them is some uranium that never got used, perfectly good uranium that never got used, some fission byproducts. I'll explain in just a second what that means. And then just 1% of it is the nasty stuff, the plutonium that causes all of the weapons proliferation risks and which also makes it stay radioactive for as much as 100,000 years, and causes all of the headaches associated with storage. Wouldn't it be great if we could figure out a way to recycle that spent nuclear fuel waste and get that 1% of nasty stuff separated from the 99% of good stuff that could probably be reused in order to make fuel for other nuclear reactors? That was all figured out in the 1940s but it's almost illegal today, and it's the US government that's behind it.

So, let's go into the next slide and explain. First of all, what are these fission byproducts that we talk about? Well, nuclear fission is the process that makes nuclear energy possible, of splitting heavy atoms like Uranium-235 or Uranium-233 in half. Well, when you split a big atom in half, you get two small atoms. Those two small atoms are called the fission byproducts, and there's a certain amount of randomness as to exactly what elements you're going to get. Well, you're basically taking a great big atom and you're shooting a bullet at it, a neutron, more accurately, that kind of cuts it in half. Well, exactly how big of is each half? That’s going to determine which atoms you get or which elements you get. There could be quite a few different possibilities, and some of them will have a really detrimental effect, because they absorb the neutrons that you need in order to keep that chain reaction going. So you want to be able to get rid of those fission byproducts, if you can. Moving on to page 18, let's talk about how recycling of used nuclear fuel ought to work. Then, after we've covered how it should work, I'll explain why the US government doesn't allow that to happen. Thomas Jam, this is one of your slides. Why don't you talk through of the spent fuel waste, 95% of it is perfectly good natural uranium that could and should be recycled. What's the other 5%?

Thomas Jam: Yeah, the 5% that is green on this circle in the middle is all the radioactive parts. It's sufficient products, and it's transuranic, and we have a scale up version on it upper right-hand corner, and most of it is fission products. And potentially, in the future, we could mine those fission products. But right now, it's most sensible to just store them for 300 years. And most of those, like you said, they already been stored for the first 50 years. And in those 50 years, they lost most of the radioactivity, so they’re already not that radioactive. But we should separate those out and store them for the remaining 250 years, or, up to 300 years, and after that there's so little radioactivity left that you can put them back into nature or recycle them and use them in industries. Then the last, the orange part is the 1% that's transuranics. And transuranics means all the isotopes that are higher numbers than uranium in the periodic table, uranium is the element in nature with the highest number. We humans can make other elements with even higher numbers, but they are not found in nature, any of them, and they are called transuranics. And most of that 1% is actually plutonium. So, like 90% of that 1% or 9 out of 10 atoms, is plutonium, and we can use that as the Kickstarter fuel in our reactors. And by using it as Kickstarter fuel, we convert that transuranics, all of those transuranics, into fission products, which only needs to be stored 300 years. So, it's a way to get rid of that long lived nuclear waste. It's not really waste, but the 1% is what's causing us to have to store traditional nuclear spent fuel in deep geological storage. But we don't need that if we burn that away as Kickstarter fuel in one of the thorium reactors.

Erik: So, I just want to reiterate for our listeners, everything you see on this slide here is not some brand new 2020s technology. This was all figured out 50 years ago. We're not allowed to do most of this today because of policy, and I'll explain that in just a minute, but recycling or reprocessing spent nuclear fuel waste is something France has been doing for decades, with great success, you end up with 4% of that spent nuclear fuel waste as fission byproducts that only have to be stored for a few 100 years. It's not that big of a deal. Some of those fission byproducts are actually valuable medical isotopes that once we figure out how to separate them out, you could sell them and make a profit at them. It's only that 1% that's the so-called bad stuff, but is it really bad stuff? There are some good purposes that it could be put to, and I'll say a good purpose and a really good purpose. Moving on to page 19, what it's used for today?

When they recycle it in France, is to make something called MOX fuel, or mixed oxide fuel. That's where they blend the plutonium that comes out of the reprocessing process with uranium in order to create, essentially, a high test kind of reactor fuel that contains both uranium and reprocessed plutonium that can be burned in a nuclear reactor in order to make more energy. Not a bad idea, but it's not really an extraordinarily amazing idea either. The idea that I think is absolutely fantastic is, what if you took the plutonium that comes out of the reprocessing of spent nuclear fuel waste and used it as the kindling to start a whole bunch of those thorium reactors, so that we could build enough thorium reactors to replace every bit of the energy that we get from fossil fuels today. Well, that is not allowed under current rules and is not likely to be allowed anytime soon. Why not? Let's go through the history of this on page 20.

It all started in 1946 with something called the Acheson-Lilienthal report. That was actually some very good writing. What they said back in 1946 is, look, reprocessing of spent nuclear fuel waste is obviously a really good idea. It's something that we should do. But if you think about where the risks are if rogue countries were trying to secretly start nuclear weapons programs, it would be in the enrichment of uranium in order to make reactor fuel that they could secretly keep on enriching it and get it all the way up to weapons grade. And it would also be, potentially, in the reprocessing of spent nuclear fuel waste, where you have access to plutonium coming out of reactors. Maybe somebody would figure out a way to put that to use to make a bomb, and we don't want to see that happen. Now, it turns out they weren't really understanding that problem as well as they thought they did. I'll come back to that in just a minute, but for very good reasons, they said, look, maybe it would be better if nuclear weapons states like the United States and the UK did the reprocessing and made those services available to other smaller countries, therefore, where you could say, let's not allow those smaller countries to do their own enrichment or their own reprocessing. Big countries like the US and the UK ought to offer those reprocessing services to the rest of the world, and that would allow us to control things, just to prevent smaller countries from maybe secretly developing a weapons program under everybody's noses without them noticing it. This was back in 1946 when very little was known about this. That report was where this idea of putting restrictions on reprocessing and enrichment first came from it, then morphed through several other reports, eventually found its way into the Nuclear Non-Proliferation Treaty. Now, the Nuclear Non-Proliferation Treaty, among other things, says that non weapon states can't do any enrichment or reprocessing of their spent nuclear fuel waste. The only reason that France is the one country that's been incredibly successful with reprocessing its spent nuclear fuel waste is that Charles de Gaulle famously refused to sign the Nuclear Non Proliferation Treaty back in 1968 when it was first proposed. Now, France eventually signed the NPT, but not until 1992 after France had established itself as a nuclear weapon state, thus exempting itself from those reprocessing restrictions. Today, the US government uses something called Section 123 of the Atomic Energy Act of 1954. Now, back in 1954 when Section 123 was first enacted, it made sense the US government was really the only one on Earth that had figured out all this nuclear stuff. They wanted to share it responsibly with the rest of the world for the sake of civilian nuclear energy, but they didn't want anybody to be getting their hands on nuclear bombs. So, they said, look, we're going to make a deal with other countries. If you want any cooperation at all from the United States on nuclear anything, you have to sign a treaty called a Section 123 agreement, or a 123 agreement that says you promise not to do any enrichment or reprocessing of spent nuclear fuel waste, unless the United States gives you permission to do so. Now, all of these rules actually made sense when they were adopted, because the idea was that the United States would do reprocessing and would make those services available to anyone who needed it. So, the 1940s and 1950s nuclear scientists and engineers didn't screw anything up. It took 1970s American politicians to really F things up, and boy, did they ever. What we've gotten to is a situation now where reprocessing is completely disallowed by the United States government, both inside the United States and outside, they say we're not going to do any reprocessing of spent fuel waste, even though France has been doing it successfully for decades. We're not going to do it in the good old US of A and we're going to use the leverage we have from all these Section 123 agreements to forbid any other country from reprocessing their spent nuclear fuel waste. So, we're not doing any of this reprocessing, and we're not getting that plutonium that could be serving as the kindling for Thomas Jam's reactors and for any other companies, molten salt thorium reactors that we desperately need in order to solve energy transition. Meanwhile, it's not 1954 anymore. It's not like the United States is the only country that understands nuclear engineering. So, these rules don't make any sense. And I'm going to say my strongest ask of our audience for this whole podcast is, if anyone listening has the ear of Vivek Ramaswamy or Elon Musk, please ask them to put Section 123 at the very top of their hit list for the new DOGE department, to get rid of a regulation that just doesn't make sense anymore. This is the reason that we don't have reprocessing of spent nuclear fuel waste.

So, we have to ask the question, moving on to the right column of page 20, why is it that they're so worried about this? Well, what they're afraid of is bad guys, terrorists or rogue nations getting their hands on the plutonium that's coming out of that waste and making a bomb from it. What they don't understand is that that argument just doesn't make sense. The next couple of pages are going to explain why I like to use this analogy on page 21, I call it the elevator risk analogy, suppose, and I'm recording this podcast from my home office on a high floor of a high-rise residential building. Now, if somebody wanted to kill me, it is possible that they could hijack one of Elon's rocket ships, and then a bunch of commandos could para jump from space using GPS navigation and wing suits breaking Felix Baumgartners Parachute altitude jumping, record of jumping from space, they could somehow re-enter the atmosphere at supersonic speed, navigate to my building using GPS, land on the roof, repel down the sides of the building, break through the windows and shoot me with assault weapons. But you know what, considering that there's no security in this building, it's a whole lot more likely that they would just walk through the lobby and take the elevator up to my floor, and if I wanted to think seriously about protecting myself against some kind of assassination risk, I'd start by securing the elevator before I worried too much about anybody trying to hijack one of Elon's rocket ships. What's happened is Anti-Nuclear activists latch on to these theoretically possible but completely implausible risks. And an example of that is the supposed risk of someone taking plutonium out of spent nuclear fuel waste and making a bomb from it. Why is that an unrealistic risk? Moving on to page 22, the reason is because what's in spent nuclear fuel waste is something called reactor grade plutonium, not weapons grade plutonium. Weapons grade plutonium has less than 7% Plutonium-240, and at least 93% Plutonium-239, which is the good stuff, the stuff that you could make a bomb from. Thomas Jam, please explain what this story is here on reactor grade plutonium, and why that 37% of Plutonium-240 that's in the spent nuclear fuel waste that comes out of nuclear reactors pretty much eliminates any possibility of anyone easily being able to make a bomb from it?

Thomas Jam: When you make a bomb, first of all, you want the material you're using for making the bomb, you want it to be at as least radioactive as possible, and then you don't want it sort of spontaneously start fissioning while you are assembling the bomb, or even while it's sitting there in your storage, because you want to make sure that it only fissions once you start the fission reaction, and you have already dropped the bomb over your target, and that the Plutonium-240 has sort of makes the risk of fission and also the radiation much higher during production, and that's why you don't want to make bombs out of that. So, you want to separate the Plutonium-239 and Plutonium-240 and it's not entirely impossible to do that from physics, but it's super expensive, so nobody does that, I mean, not even in labs. The way they make Plutonium-239 is a process called roasting so they roast depleted uranium into Plutonium-239 and then they take it out and do chemical separation before any large amount of Plutonium-240 and 241 has been created in the fuel. And all the countries who have made nuclear weapons so far, they have made special military reactors for this roasting process. And it's true that it could potentially be done in commercial Light Water Reactors, even the types we have today. And then if you did it there, you would have to do this chemical process of separation in order to get your bomb fuel. But when we run civil nuclear reactors, we run them for a long time, maybe two or three years. The fuel is inside the reactor. The solid fuel roaster inside the reactor for two or three years. And this means that a lot of Plutonium-240 and 241 has been created in the fuel. And that means that you would never try to use that for nuclear bombs, because it's way too expensive to use that, you would use another reactive but it's true that you cannot say that it's entirely impossible.

Erik: Well, it's exactly like someone hijacking one of Elon's rocket ships for the purpose of trying to para jump from space onto the roof of my building. You can't say it's impossible, and that's the reason the anti-nuclear activists latch onto it, but what you can say is that nobody in their right mind would do that because it's not an effective way to get your hands on weapons grade plutonium. It doesn't give you weapons grade plutonium. And there's other much easier ways that you could get your hands on plutonium if your goal was to make a bomb. Let's move on now to page 23, and here's the question I want you to ask yourself, listeners, what's better? Is it better to leave the plutonium? That's Plutonium-239 and Plutonium-240, it's all mixed together. You can't make a bomb from it. It's in spent nuclear fuel waste, and it's stacked up, as you see in the picture on the left, and these dry casks at nuclear power plants all around the world. That means somebody could go and steal it if they wanted to. I'm not sure why they would do that. There's really not much you could do from it. The alternative would be to change the rules and make it possible to recycle all of that spent nuclear fuel waste so that it's not causing the public annoyance and the upset attitude of the public who doesn't really understand what's in it. You could solve that problem and get rid of the nuclear fuel waste by burning it as kindling to start Thomas Jam’s reactors, or any other company’s molten salt reactors that run on thorium and require a Kickstarter fuel. When you do that, you're burning the plutonium up. There's no way to make a bomb out of plutonium that doesn't exist anymore. So, which one is safer? I contend the picture on the right is much safer, but we're not allowed to do that today because the US government has adopted laws in 1954 that current US government officials don't even understand, and nobody has any motivation to repeal. So again, if Elon and Vivek are listening, start with Section 123 that's what we need to reform.

I want to move on now to a series of slides that I used in another presentation recently for the Stanford Alumni Association. I want to run through these really quickly to allow Thomas Jam most of the remaining time to talk about how his reactor works. So briefly, moving on to page 24, let's talk about the challenges of scaling nuclear energy, not just to make it a little bit bigger, but to fully replace fossil fuels. Well, moving on to page 25, the Triple Nuclear Initiative is the first step in that direction that's based on conventional nuclear technology. They want to build another 742 gigawatts of electric generation capacity by 2050 that's going to cost somewhere between $4 and $11 trillion of CapEx. I want you to remember that number, $4 to $11 trillion of CapEx to triple nuclear energy, because I'm going to come back to that figure in just a couple of minutes. It's going to take 5 to 10 years to build, each one of those power plants will end up supplying, solving about 11% of the overall problem, not really solving the whole problem. What happens to Uranium demand under that scenario? Moving on to page 26, well, it goes up to about a quarter million metric tons by 2050, a lot of people think that's too ambitious. It's going to be hard to ramp uranium supply up that much. I think it is possible, especially if we can get seawater recovery working, which is an experimental technology that's not yet been proven, but is very promising. What happens, though, if you're going to triple nuclear energy is you're also going to triple nuclear waste. Moving on to page 27, you see that new spent nuclear fuel waste in storage goes up to three quarters of a million metric tons by 2050 in the triple nuclear scenario. That sounds a little bit scary. Don't worry too much, because I have a plan for what we're going to do with it. Moving on to slide 28, if you were to try to replace all of the energy that we get from fossil fuels today, that requires a 24x on nuclear, about $135 trillion of CapEx, if it costs as much as the Vogtle reactors in Georgia cost that's more than the money supply of the entire world. So obviously that's not possible. But hypothetically, if it were possible, what would it do to Uranium demand? It would push us all the way up to 1.8 million metric tons per year. That's just not possible. You can't solve this problem with conventional nuclear technology. If you could, moving on to page 30, look at what happens to spent nuclear fuel waste, almost 3 million metric tons by 2050, the public is never going to allow that, even if you educate them on why it's not as dangerous as they think it is, nobody's going to stand for 3 million metric tons of nuclear waste.

Page 31, clearly, we need a completely different approach. I propose that that approach should be to use thorium molten salt reactors as the iPhone reactor, the workhorse reactor of energy transition. Thomas Jam’s company won't be the only one to play in this space, but I think they're doing the most pioneering work, and that's why I focus on their product when I talk about this in the presentations that I give. Moving on to page 32, we need to adopt thorium as our primary source of energy going forward. 33, here's my plan for energy transition in three steps. Step number one, embrace this triple nuclear initiative. It's a good idea. Yeah, it's conventional nuclear technology, which is sub optimal in some ways, but it's technology that's here and now and available today that we can get started with. Yes, it's going to triple nuclear waste by 2050, that's okay with me. Why? Because step number two in my plan is to reprocess every single bit of nuclear waste that exists on the entire planet. Doing that would produce about 2500 metric tons of plutonium. That's enough kindling to kick start the first 12,500 thorium fueled molten salt reactors, and we need a source for that kindling fuel in order to run those reactors, the triple nuclear will then provide enough additional nuclear waste to start another 1100 or so, almost 1200 further molten salt thorium reactors per year after that. Step number three in my plan is to fully replace all of the energy we get from fossil fuels today by building one reactor per hour. Thomas Jam's plan, when I first met him, he told me he wanted to create an assembly line that would build his waste burner nuclear reactors at a rate of one per day. And I thought, this guy's crazy. He wants to build one reactor per day. This industry has only built less than 500 of them in 70 years, and this guy wants to build one a day. He's got to be off by an order of magnitude. Well, he was off by an order of magnitude. It's just in the other direction from what I thought, because one reactor per day is not enough. You need to build one reactor per hour on fully robotic assembly and test lines 24/7, 365, for 20 years straight, in order to build the 128,000 nuclear reactors at 100 megawatts thermal apiece that it would take to fully replace fossil fuels. The cost of doing that, the CapEx to do the whole thing, is somewhere between $4.5 and $7 trillion. Hey, wait a minute, what was the cost of tripling nuclear just a few minutes ago? Using conventional, somewhere between $4 and $11 trillion it's going to cost half as much to do a 24x on nuclear using Thomas Jam’s technology as it would have cost to just triple nuclear using the conventional technology. That's how much economic advantage there is to thorium molten salt energy over conventional nuclear. And I am using some numbers that assume mass production on fully robotic assembly lines. What happens, though, if you want to replace all of the energy we get from fossil fuels, well, isn't that going to create an immense amount of spent nuclear fuel waste? Moving on to page 34, no, what that's going to do is completely eliminate all spent nuclear fuel waste from existence by 2044 if we started tomorrow, because we're going to reprocess every single bit of that that requires.

Vivek, I hope you're listening. That requires a repeal of Section 123, so that we can get the whole world focused on reprocessing that spent nuclear fuel waste, turning it into kindling to run the style of nuclear reactors that Thomas Jam’s company is pioneering in Copenhagen. What does that do to Uranium demand? Well, tripling nuclear is going to create a huge amount of additional uranium demand, as you can see, taking us up to almost a quarter million metric tons, but doing almost 10 times as much, going another nine terawatts or 9000 gigawatts of thorium molten salt reactors of the type that Thomas Jam’s company is proposing only adds that tiny, little purple sliver at the top. Why is it such a small amount of uranium demand? Because all you need is the kindling, the Kickstarter fuel. We're going to have to pay for some of that Kickstarter fuel being low enriched uranium, rather than reprocess spent nuclear fuel waste, but the best source of it is spent nuclear fuel waste, and that requires regulatory reform. Okay, I had to get that off my chest. Thomas Jam, because I'm so passionate about this message I want to give you most of the rest of the time. Let's talk about why you think the thorium molten salt reactor is the iPhone reactor that's going to be the workhorse of energy transition globally, on page 36?

Thomas Jam: Yeah. So basically, it's because the economics, the price is better, the neutron economy is much better. And the classical nuclear reactors, they are so expensive that you almost always have to have some sort of government backing to build them. And also, all these rules that you talked about, the Section 123, and other crazy rules around nuclear makes it really expensive. So, it's not really the materials in the nuclear reactors that are expensive, it's all this government rules and all the lawyers and all the bankers and so on that makes nuclear energy expensive. And I think we're at a moment in time where we can actually solve that problem once and for all, and we can get to some reactors that are much cheaper to build, even cheaper than coal or gas, and they can be mass manufactured, and the energy that comes out of them is the cheapest form of energy that we've ever known. And that's going to kick start also a big economic boom in many of the Western countries. You know, right now, that Europe is sort of going in reverse and negative spiral. And so, moving on to slide 37, you can see the Onion Core®, and that's really for Copenhagen Atomics, that is the major breakthrough is that we were able to create a reactor core where we can actually make a molten salt reactor in thermal spectrum, which is quite small and therefore easy. Mass manufacturer doesn't need a lot of materials to build. It doesn't need a lot of fuel to get it started. So, it's a very, very efficient reactor, and you can be build out of existing materials. This picture on page 37, you see the Onion Core® reactor from photograph from the top. It's sort of a round ball. It's two and a half meters in diameter, and that's the main thing that is inside the reactor. Of course, there's some other pipes and pumps and tanks that are also needed. All those pipes and pumps and tanks are made out of regular stainless steel. So again, not very expensive. So, if we move on to slide 38, I will try to explain, that's a schematic of how the reactor containers that we talked about in previous slides, how they work. What's inside the reactor? How does it work? How's it different from classical nuclear reactors? So, the main difference is that it's a liquid fuel instead of a solid fuel, and that that's sort of what makes it possible. But there's also some things here that we have invented that are different from previous proposals of molten salt reactors. So, if you look at this schematic of a reactor drawing, there's sort of a wall in the middle and insulation wall, and there's a hot section to the left, and there's a cold section to the right, and the cold section holds heavy water, because you need heavy water to slow down the neutrons. That's the moderator inside the Onion Core® in the middle. And then you need the salts. The salts are the orange and red colored liquids. And then at the bottom of the container, you have some big square tanks where you have the liquids when the reactor is not running, when you want to turn on the reactor, you turn on these pumps, and the pumps pump the salts and the water around through the Onion Core®, and then magically, the nuclear reaction starts, and it creates a huge amount of energy. We can get 100 megawatts of thermal energy out of that reactor core, which is only two and a half meters in diameter. And then soon as you stop the pumps, you just cut the electricity to the pumps, then all those liquids will drain back into those tanks at the bottom, where it's safe. It cannot create a nuclear reaction when it's in those tanks. So, it's a very simple way to start and stop this reactor. You will also see that there's no control rods, because in regular old classic nuclear reactors, you need a whole control room of people controlling the reactor, because you have to adjust those control rods in order to manage the nuclear reaction. But in molten salt reactors, it's different. They manage automatically, so it will automatically find a stable temperature and a stable amount of power that comes out of the core. And this means that you don't need a whole control room of people, and you don't need to have control rods that are super safe and cannot go wrong, because these reactors are much more inherently safe. And also, these reactors run at atmospheric pressure, which means you don't need these very thick walls for high pressure containment of the radioactive materials. These are liquids, and you can pop them through regular stainless steel pipes, and as soon as you stop the pump, it drains back into a tank and it's all safe.

On page 39, we see sort of a cross section view of the Onion Core®, and you can see why it's called the Onion Core®, because there's several different layers inside the supposed onion. The outermost layer is a thorium blanket. That's a thorium breeder blanket. This is where we convert the thorium into Uranium-233 and as soon as that Uranium-233 has been created, then it's transferred into the orange channel, which is the fuel channel automatically, or it's going on while the reactor is running. So that's online refueling of the middle of the reactor. And then we need a lot of layers of water in there, and that's heavy water, and it's not under pressure, it's just a water below the boiling point, and mostly water in this core, and that's what makes it super efficient. And then, of course, there's the fuel channel. The fuel channel is sort of the orange color in the middle, and the fuel would come in at the bottom at 600 degrees, and one second later it would go out of the top at 700 degrees. And then it goes over to these heat exchangers on the previous slide, where the heat is then moved out of the reactor container. And once it's outside the reactor container, it's no longer radioactive salts. If we move on to slide 40, we try to tell you, what do those different parts inside that reactor container cost? Of course, there's the core, this Onion Core®, it's difficult to construct, and it's made out of special materials. So, it costs between $2 and $5 million, we've already ordered two of these cores from sub suppliers. So, this is not a hypothetical cost. This is actually what we paid for it. But of course, actually, we paid less because we didn't use the right materials that you would use inside a reactor. We want to test it some more before we order it out of the right materials. But we already got quotes from suppliers for the real materials that are going to use in a real reactor. So we already know what it costs to construct this one. Similar with the other things in the list below, you could say there's maybe a little bit of uncertainty on the cost the container itself. It's not a standard ISO shipping container, it is a special purpose, Nuclear Grade container. So it costs 300,000 euros plus minus whatever, 10% the tanks and pipes, similar price, 400,000 euros. Heat exchangers in between, and then you need a lot of electronics and sensors, and finally, the pumps. And if you tally all of that up, it's less than 10 million euros for each one of these units. And obviously, when we start to mass manufacture this, the price can come down further down for these components. And this is sort of what blew our mind almost 10 years ago, when we realized this, that these reactors for molten salt can be built at a completely different cost than traditional light water reactors or solid fuel reactors. The cost of each unit will be less than 10 million, and it's very likely to come down in price when we start to mass manufacture. And of course, this is what makes this big, a big opportunity to use thorium and molten salt reactors.

Erik: And I just want to add for our listeners benefit that when I did my costing, and came up with a cost of somewhere between $4.5 and $7 trillion in order to completely replace every single watt of energy that we get from fossil fuels today, that was based on a 10 million euro unit cost. You're actually saying here it could be as low as 4 million to 8 million so it could be that my numbers are high in terms of what it's really going to cost to replace every single watt of energy that we get from fossil fuels while simultaneously eliminating every single bit of spent nuclear fuel waste from existence on planet Earth, if we can just get the government out of the way to allow that to happen. I want to move on now and kind of change gears here to slide 41, Copenhagen atomics is currently in the middle of an active capital raise. They're raising another $50 million of investment capital to keep developing this technology. As I've said before, I want, in the interest of full disclosure, for everyone to know that I am an angel investor in this company. I first invested in this company in the previous investment round. I've added to my position in the current investment round. I really want to emphasize though, although I do need to say that for the sake of regulatory compliance, the reason that I'm excited to help the company to raise more capital is not because of my vested interest in the company's success, although I certainly do have that. It's because I couldn't be more passionate about this being the right technology to solve energy transition for the whole planet. So, they are involved in a capital raise, long time listeners know we normally give our guests two or three minutes at the end of each podcast to kind of pitch their wares and talk about what business they're in. I'm going to extend that for the sake of this holiday special, and give Thomas Jam a good solid 10 or 12 minutes to give the investor pitch for the capital raise. So Thomas Jam, the floor is yours.

Thomas Jam: So, if we move on to slide 42, the long term goal of Copenhagen Atomics is to mass manufacture these reactors in a giga factory, just like we talked about previously. And where we want to start is assembly line that can make one reactor today, every day. Certainly, we want to get the price down, and, of course, the volume up over the years. And if we look at slide 43, we looked at how is the total energy of the world going to develop? And clearly, thorium energy is not on the market today, so in the next 10 years, wind and solar will continue to grow, but certainly also coal and oil and gas. I know that there's a lot of people on the internet that says that we're done with coal and oil and gas, but they simply don't understand the world, if that's what they contest. This is my estimate of how much coal and oil and gas will grow over the next two or three decades, and I think thorium energy is going to grow as fast as it possibly can. And in my best estimate, by 2060, thorium entity will provide roughly the same amount of energy as gas does today. So, it's a $1.5 trillion market by 2060, this is my estimate. And of course, it can go faster or slower. But it's clear when we introduce new technologies, you can look at the past of energy technologies, it takes a number of decades before things really catch on and start to get big. I've also said many times that I think by the year 2100, more than half of all energy in the entire world will come from thorium. So, I do believe that this thorium entity is going to be the major energy source that is going to grow in the next 80 years from now. Just like we saw when we changed to the iPhone, shortly after that, we got also Android phones, and now we don't have any of those old phones that were before the smartphone. Now everything is smartphones, and I think we will see the same transition, even though, in the energy sector, it takes a little bit longer than with iPhones. But we will see a major transition in the next 20, 30, 50 years, where thorium is going to be the main growth point in energy.

So in Copenhagen Atomics, if we move to slide 44, we've already built two of these prototype reactors here in Copenhagen that we are testing. So it's not fantasy. It's actually something that has been built and tested currently, and we're currently building the third reactor for testing here. It also shows there's no other startup company anywhere in the world that is already built or almost built free test, free access in full size. So that tells you that this technology is much lower cost than traditional energy. Slide 45, we already talked about that earlier today, so I'll skip over that, but it basically shows you it's a game changer. Again, slide 46, we also talked about that earlier, so I'll move on. I want to say on slide 47 that when we put the very first reactors online, sort of the first of a kind reactor, it's going to take a little bit longer to build those units, than one year for a gigawatt power plant. So maybe it'll take two years for the very first one, but it is going to be much faster than traditional nuclear reactors, and also the fuel cost, even though it's not the breeder reactor, the very first one is probably going to come on online in 2029 or 2030 and that's not going to be a breeder reactor, but we are definitely pushing towards breeder reactor. So you can say, okay, maybe the first ones has a slightly worse…

Erik: Only 300 times better than conventional.

Thomas Jam: Only 300 times better than the solid fuel reactors. And mind you that when people talk about small modular reactors or advanced reactors, they are all down in this close to the circle called uranium in the lower right corner. So what is really going on here is that, if it goes to, slide 48, Elon Musk coined it, and he called it the Idiot Index. But there were actually people before him that called it something else. But I think I like this term, so I'm going to use that here. He says that the Idiot Index is how much you have to pay for the product versus how much the raw materials for that product cost. And you can see here that that I predict that for classical nuclear reactors, the Idiot Index is around 100, so basically, the materials cost is a tiny amount of it. The manufacturing and the lawyers and the bankers are the majority of the cost. And if you look at other industries, of course, Boeing and Airbus is also very expensive products, but if you go back to Tesla, they really try to get the price down. And Copenhagen Atomics is in the same, we also try to get the cost of nuclear energy way down. So that is our claim to fame that we bring something new to the table. A little bit about this capital raise. What are we going to use the money for? Here you can see how much money also we spent in the past on different prototypes, and we are working towards running the first test reactor in 2027 in Switzerland. We talked about that a little bit in the previous episode of the podcast, and we need almost 200 million euros in order to get to the test reactor in 2027. But right now, we are only raising the 50 million euros which we need right now for making fuel and making our Lithium-7 production. And you can sort of see here how much capsule we're going to use in the different years. We already have enough runway for the next 12 months. But of course, we need to extend that. We also need to scale up our team. I will jump past the slides 50 and 51 because we already talked about those, and we also talked about the test reactor in Switzerland.

Erik: On slide 52, you have a deal already where you're going to test this reactor. This is a picture of the facility where it's going to be tested.

Thomas Jam: Yeah. So, we are based in Europe right now, and one of the best national labs in Europe for testing nuclear technologies is called PSI, a Paul Scherrer Institute. It's located in Switzerland, close to Zurich, and this is where we've made a deal with that national lab to test our reactor in 2027. So we're already going through the approval process right now, where we planning to build a new building to host that test, and also going through all the reactor approvals. And so, the plan is to build the reactor in Copenhagen. If we move to slide 53, we will build the reactor in Copenhagen, and we will test it without a fission chain reaction here in

Copenhagen. So basically, heat it up with electricity and make sure that everything works. We will make the fuel salt here in Copenhagen as well. Then we will put all of it on trucks, drive it down to Switzerland, install it in their building, and test it. And then once the test has completed, we will drive it back to Copenhagen again.

So, I think one thing here is to show that this technology actually works. I think we've already done a huge amount of work in simulating this, so we are fairly sure that it works. But of course, we still need to show it in the real world. But another first is also that normally you build nuclear reactors on site and they are never moved. But in doing this test in Switzerland and moving the reactor on truck down there, we actually also showed to the nuclear industry that we can now move these reactors around. We can build them in one factory, move it around, set it up fairly quickly. Some of these companies that are making what they call small modular reactor, they still take 4 or 5 years on site construction to build it, but we are going to show here that in a matter of month, we can put it on a truck, move it to another country, set it up and start it running. And we can also take it down again and move it back. This has not been done before in a nuclear industry. Well, it has been done in the military, but not in the traditional commercial nuclear industry. So, this is the first time that we show that this is possible with these type of molten salt reactors or thorium reactors. And finally ending on page 54, this is a picture of the four founders. We started the company back in 2014, the current valuation of the company is roughly half a billion US dollars. And of course, the value of the company is going to grow significantly, maybe a factor of more than 100 by the time that we have commercial reactors operational. Here are some of the companies that we work with, companies and national labs around the world that are helping us prove that this technology works. And of course, feel free to contact us and get some more information about this investment round and also the exciting journey that our company is on.

Erik: So to summarize, folks, Copenhagen Atomics is raising 50 million against a pre money valuation of 500 million. The guy to contact is Mike Christiansen, their CFO. His email is invest@copenhagenatomics.com. we're going to leave it there for this episode.