[SQUEAKING] [RUSTLING] [CLICKING]

SCOTT KEMP: A week ago, we left off halfway through this section on proliferation, and this is the last of the nuclear-specific externalities, of the two main externalities that nuclear has to deal with are safety and a special kind of safety. Everything has safety issues. But there's large accident, rare event kind of safety, which we talked about, and nuclear proliferation.

And so we were talking about how might a state go about acquiring a bomb. And we went through the plutonium route. And remember, we talked about different weapon designs and how you get plutonium. And then we were about to get into the uranium route, and then we ran out of time. So here let's continue with that.

This is just to remind you that natural uranium out of the ground only has 7/10 of a percent, 235, and you have to do this process of getting rid of the 238 atoms, which is what we call enrichment, to get to something that's weapons-usable. So this is our navigation graphic that told us the different pathways to a bomb.

You could have some enrichment. You could take spent fuel and get plutonium. You could get plutonium from regularly reprocessed fuel. You could build a dedicated plutonium production facility, or you can use uranium enrichment. And you can either do it by taking it straight off the civilian fuel cycle or having a dedicated facility.

Historically, we haven't really worried too much about uranium enrichment because this was perceived to be very hard. And we're going to talk a little bit about that now. So just to talk a little bit about how much enrichment you need, this is the critical mass for an explosive quantity for standard metal density uranium with 5-centimeter beryllium reflector.

And you can see that anything basically in this red region, which is what we call HEU, everything above 20%, has reasonable critical masses. And at 20% uncompressed, it's about half a ton, but half a ton is that much uranium. And as you go to lower, yes, the number goes way up and reaches a ton of material. But a ton has 18-inch diameter sphere.

So yeah, it does have this knee in the curve, but there's a bit of a debate as to exactly where this should be. Just for reference, most reactors, in case you're not a nuclear engineer, use under 5%.

Way down here, this dashed line is 6%. There's the asymptote, the theoretical limit where you need an infinite quantity. But there are research reactors like the MIT reactor that operate up here at 90%. But the MIT reactor only has, I think, 12 kilograms in its core. So that's only about half of what you need for a critical mass at normal density.

So the idea is ideally we don't want weapon quantities of this material sitting in one place. Of course, you could go and steal the fuel from MITR and another reactor, or while the MITR was being refueled. And the old fuel was there, and the new fuel was there. You could do various things like this. So the security isn't perfect. All right.

So enrichment is in general-- in the abstract, you start with some materials, always this three-stream process. You have some. Here's a black box device. You don't really know how it works, but you put in some material that's like in this example, 1% uranium-235. And you get out a depleted stream, which we call the tails, and then an enriched stream, which we call the product.

And the key thing to note here is that the changes are very subtle. Some technologies are better than others in producing larger changes. But there's a trade-off between the amount that you can flow through. And the amount of that enrichment change. And generally, though, you wind up having to have a whole bunch of these things connected together in a cascade, if you want to get to any meaningful level, including fuel levels.

So what goes in this black box, or in this case, white box? Lots of technologies can be used. Here are some of the early ones, according to the history of the field, more or less in order of their arrival. And I just want to talk about the two that were mainstream for a while. And that is gaseous diffusion and gas centrifuge.

So gas diffusion works like this. You have a tiny membrane. This is typically made by taking a very fine nickel powder and then heating it.

So what we call centers-- so it kind of melts together but doesn't fully melt. And you get basically this sponge. You can see the scale there.

Yeah, it's really hard to read. I think that scale is 1 micron. I don't know what. Oh, it's definitely not millimeters. But yeah. So the idea is that the size is basically small compared to the mean-free path of the atoms.

So this is a uranium gas. Just in case you don't know how you turn uranium into a gas, you put six fluorines on it. You have six. And the fluorines basically create a shield around it so that there's very low Van der Waals, and so they don't stick together.

Fluorine conveniently only has one naturally occurring isotope in nature, so the mass difference of the fluorinated molecule and the unfluorinated molecule is exactly the same. And that allows you to do the separation chemistry, do the separation process. If fluorine had different fluorine isotopes, that would totally screw up your attempts to do this enrichment because you do it by weight. Conveniently, fluorine has this property.

So the idea is basically that the energy is equal to one-half mv squared. And so v is proportional to 1 over the mass, root of 1 over the mass. And that means that provided that everything has the same energy, which it does because it's constantly colliding and exchanging energy between atoms. So on average, everything is roughly the same energy. On average, the isotopes that are heavier will be traveling a little bit more slowly.

And that's just a simple idea. So if they're traveling more slowly, that means they're going to run into this membrane less often, and the light isotopes are going to run into the membrane more often. And that's it. Preferentially, because they hit the membrane more often, the light isotopes preferentially diffuse because, on average, they're going just a little bit faster. And that's how you separate atom by atom the uranium and do your enrichment.

So that's how gaseous diffusion worked. It produced these very large buildings. I think I showed you this last time, this K-25, which was built at the end of Manhattan Project, 44 acres in a single building employed 12,000 people and used in one building three times the electricity of Detroit, Michigan. When it opened, it was the largest building in the world, and it was capable of making only 20 nuclear weapons per year. The same capacity, 20 nuclear weapons per year, can now be had using roughly 2,500 of these over tubes, which are called gas centrifuges.

This is a photo of Iran's prototype facility. Such a facility might take up 25,000ft, which is about the size of a high school gymnasium. And it might consume as much electricity as, say, a typical office building at the same size. This is not hard. This is not 44 acres and 12,000 people and three times electricity of Detroit.

I dug for this photo last time. This is the diffusion process-- the old diffusion process-- and that's a person, just to give you a sense of the scale of the equipment in this facility. To do the same for centrifuges, there they are.

And there's a person. This is Iran's former president, Ahmadinejad. And you can see that there's a lot of pipework. But beyond that, this is not all that difficult by comparison. So let's just look a little bit at how the centrifuge works.

I explained how diffusion works. Centrifuge works in a very simple way that you already know that basically you have a gas. So it's again a three-stream machine. So three-stream machine-- everything has to have an inlet and outlet.

So here's the inlet right here. Can you see there's a skinny tube inside of a bigger diameter tube? And then there are two outlets-- one that takes the enriched product and one that takes the depleted product. Let me just see if I can remember which way this goes.

Yeah, so this is the enriched product down here. And this is depleted product up here. So the way this works is gas comes out of this tube. This inner tube is a rotor, this here, and it's spinning very fast.

How fast is very fast? Well, the peripheral velocity of this tube, if you put it on the ground and let it roll, is typically up to about a kilometer per second. So that's very fast. In order to spin the tube that fast, you have to evacuate all the air from around it.

Otherwise, the air friction would completely heat this thing up and be a problem. So that's why it sits in another tube. And even so, these little pipes on the outside that are wrapping around here, those pipes are there to cool off the outer casing basically through radiative coupling to control the thermal profile on the inner tube.

Then what happens is the gas comes out. And because everything is spinning it, immediately, the gas is going to the wall, like when you're spinning water in a bucket around your head, centrifugal force.

So initially, this enters in what is mostly a vacuum. And the gas basically in effect freezes as it comes out. And then it slams into the wall or into the very thin layer of gas, which is pressed against the wall. And because the heavier isotope, uranium-238 is heavier, it gets pressed against the wall a little bit further, so it tends to collect in next to the wall.

Now, if you just stop there, you can imagine having-- this is called a scoop, and it extends in, has a little arm, a little pipe that extends into the gas next to the wall. And you could imagine that you could scrape off a thin layer of the inside, and in principle, you could do that. But the problem is if you just did that, you would get very, very, very little separation, because the difference between just the gravitational separation from that is not a lot.

So what we do is we take a trick that is used in chemistry. Does anyone remember doing distillation in chemistry where you had a glass tube, and it was full of little beads? Have you seen this? No? Or if you're a chemical engineer, you may know about a separation stage that has so-called plates that look like this. No one's a chemical engineer either.

All right, so here's how it works. You boil some mix of chemicals. And let's say it's water and ethanol because we want to make alcohol. Well, some water boils off, and some ethanol boils off. Ethanol boils off preferentially. But you still got a lot of water in there too.

But then it boils off into a gas, but then it condenses here and drips onto this plate. And now, you have a little liquid of mixture. And now this is also ETOH-- methanol plus water. But it's slightly enriched in alcohol because the vapor pressure of the alcohol is a little bit lower.

And if you do it again, you boil off some stuff, and then it will condense here. And you'll have some sphere, and this will be even more enriched in ethanol, and so on and so forth as you go up the column.

So this is called a fractionating column. You can do the same thing with just with beads of glass in glass tubes. You'll see that in chem labs. We do the exact same thing here.

And the way it works is that we have-- where's my laser? This scoop is dragging into the gas. It's pressed against the wall, and therefore it's taking up some of the angular momentum. And that causes the gas to move inwards and up. It acts like a little pump. So it pumps the gas up on the edge, and then towards the center in the rarefied area, there's a countercurrent downward flow.

So you have these two streams of gas passing each other. And everywhere they are adjacent, there's this horizontal transport because of gravity. And so it's effectively acting like that fractionating column. And so at every radial coordinate, there is an enrichment.

But as you move axially along this device. The enrichment continues to increase, increase, increase, increase, increase. And so you get a massive multiplication of the enrichment through this process. And so this is why this little shield is here, to prevent the opposite effect from happening from the other scoop, which would send it down.

So that's how these things work. So they have some nice features because of this countercurrent flow inside the machine. They have a very high separation factor, which means they need fewer stages.

So to make a bomb using the old gaseous diffusion plant, this thing, you need about 1,000 of these giant things piped together in a row. To make a bomb using these, you only need order of 100 or less, 100 or fewer. They also have very low inventory. There's not a lot of gas in here. So if you have this system running and you want to change the enrichment level from low enrichment to high enrichment, you can flush it out and get the whole thing reestablished at a new enrichment level in about a day.

If you change the enrichment level in this system, it takes about a year to change the gas out. And that means that once this thing is going, you're not making LEU for reactors. You're not going to turn it into a bomb factory. It just takes too long.

Whereas this you can just after a day, you've converted the whole plant to making bombs. So it also is modular. You have a bunch of these that are all identical. Yep.

AUDIENCE: If you can use it for high energy [INAUDIBLE], what [INAUDIBLE] used to produce uranium for civil reactors, then?

SCOTT KEMP: It also uses this.

AUDIENCE: Doesn't that pose more of a risk?

SCOTT KEMP: Yes.

AUDIENCE: Is there a similar device that's is as effective, but can also be used for highly enriched uranium?

SCOTT KEMP: No. Basically, if it can physically separate isotopes, it really doesn't care what the enrichment level is. And you can think of it this way. Low-enriched uranium, which is to say uranium that has very low uranium-235, is high-enriched uranium-238. The same thing has high levels. So you're starting off at one extreme, and it can get you to the other extreme.

So yeah, it always works. No matter what, you would take one side. You would take the other side. So yeah. Yep.

AUDIENCE: Does this also apply to the separation of other isotopes like people are talking about [INAUDIBLE] and like lithium enrichment [INAUDIBLE] also then turn that into uranium enrichment technology? Or are they trying to [INAUDIBLE]?

SCOTT KEMP: So sometimes yes and sometimes no. The short answer is yes. You can always you can always do it, but it may not be the optimal technology. And so the reason is that when you're looking at enriching uranium, the difference between 238 and 235 is 3. And so it's three parts out of a roughly 238 parts. And that's a very small fraction.

Now, the difference between 6-lithium and 7-lithium is 1 out of six, or 6 and 1/2. So this is a much larger fractional mass change. So technologies that are crummier and don't work as well are fine for doing lithium.

But if you try to do it with uranium, it would just be very expensive. You could do it. It will work, but it's very inefficient.

So the most efficient technologies are preferred when doing uranium. And that's why it's all very fancy. So with this, you can do crown ethers. You can do chemical separation where there's a chemical reaction, which preferentially reacts with one or the other.

You can do all that with uranium too. It's just the amount of chemistry you need is just too much to make it economic.

AUDIENCE: 2.1505 would be very expensive.

SCOTT KEMP: Yeah.

AUDIENCE: [INAUDIBLE] lithium. If you use this lithium, then would it be two stages? You're done super cheap, or would it still be--

SCOTT KEMP: It would. They've presumably worked it all out. So to do this, you need to have the material in a gas. Most things can be converted to gas-- not everything, but I don't know if lithium can be converted to a gas. Probably, but I'm not sure. Yep.

AUDIENCE: I think you have the same separation if they were in liquid fuels. You're just exerting a centrifugal force.

SCOTT KEMP: Could you do it in a liquid? So let me think. In principle, you could. They're both fluids, but you would be dealing with a lot more heating and energy from viscosity, which might make it impossible to spin it as fast as you need to. Yeah. Yep.

AUDIENCE: Yeah, so I just looked it up. So lithium enrichment is done with chemical systems.

SCOTT KEMP: Yeah, it's usually with crown ether, or there's a cyanide process. I forget. Yeah, generally, when you're talking low-numbered isotopes, you generally favor the chemical processes. There are chemical uranium enrichment.

The Japanese were building one for a while, but they have very, very long equilibrium times because the separation stages are so weak. They take years and years and years to get those plants into equilibrium. And people have actually proposed that as a way of making uranium enrichment proliferation-resistant because it would be so inefficient to get to HEU levels. And I've always liked that idea.

But the problem is that this is cheaper, and cheaper always wins. It's the same problem with wind and solar. Cheaper always wins, no matter how good your technology is. So modular, so you can crank these things out by you have just a factory mass production of these things.

They don't really produce any emissions. They actually operate below atmospheric pressure. So oops. So if there's a leak anywhere in the system, air leaks into it rather than uranium gas leaking out. So it is almost nothing that you could sniff around and try to detect.

Like I said, you don't need a special building. You put this in a high school gymnasium. And so there's not really any signatures that you can use to detect it from satellite imagery or something-- very low energy consumption.

So again, it looks like an office building, doesn't look like a building that for some reason is using three times the electricity of Detroit. Nothing suspicious in the infrared thermal signature because of that. And so it's almost impossible to detect by technical means. The intelligence history for clandestine centrifuge programs bears that out.

So here is the list. Iraq had a program. They accidentally spilled the beans to us. It went for years undetected. We didn't know about it.

Iran's program started in '85. We found out around 1991, and we only did so because people involved in this program and Pakistan's program were being watched. And they led us to the Iranian program. But we didn't detect Iran's centrifuges directly.

Same is true of the Libyan program. We were also watching these people. Despite that, it went undetected for 16 years because the program was operating at a very low cadence. They didn't have a lot of interactions that tipped us off.

China had a program that went undetected for roughly 21 years by the United States intelligence community. The Soviet Union's program-- there's a lot of barriers between the US and Soviet Union during the Cold War. It was not easy to watch them.

At the same time, we watched no country more assiduously than we watched the Soviet Union, and we had all kinds of intelligence assessments about their nuclear weapons program because that's what we were obsessed about. Despite that, the official conclusion that the Soviets had centrifuges came 34 years after they built their first plant.

And that's because there was a lot of people in the US who were just like, now the Soviets do gaseous diffusion like we do. And there were individual analysts who were like, well, maybe they switched. But the overall community just couldn't believe it.

North Korea also started their program tinkering around 1984, and they basically revealed it to us as part of a diplomatic process 26 years later. So easy to hide these things if you're trying to hide them. And the evidence is there.

Compare these multi-decade time scales for detection to the time it has taken countries to build a facility. So these are the historical R&D times to go from nothing to a technology suitable for turning into a plant-- not building the whole plant, but that you've done all the R&D and you're ready to do the plant-- a plant good enough to make a bomb, not necessarily good enough to sell commercially viable uranium enrichment.

And so you can see the average development time, if you look at them, is about 24 months, which is frankly not that long. It's faster than building a research reactor. And the Australian program is one I like to focus on here. Does this have a [INAUDIBLE]? No, It doesn't.

The reason I like to focus on the Australian program is because it's the slowest program on record. The individuals who were involved had no prior experience in any of the relevant fields. They were not turbomachinery experts. They were not experts on uranium enrichment. They were just engineers who had general mechanical experience and were asked to build this plant.

At no point in the history of the program did they ever employ more than six people. And even so, it took them about six years to make a working technology-- very tiny program.

So the way I like to think about this is to engineer the machine, the centrifuge machine, it's like three or four PhD dissertations, and we could easily do it multiple times in this room if you wanted to do it. So it really should come as no surprise to us that countries like North Korea were able to pull this off.

So many countries have shown have pursued this technology. Not all of them continue to operate it. So here is the worldwide enrichment capability. All of this is centrifuges with actually with the exception of Argentina.

And you can just see here these in blue have very large capacities, and these in red have very small capacities. These in blue operate their programs for commercial purposes. And they sell enriched uranium to make reactor fuel.

What are these guys in red doing? Their programs are really tiny. So here the number, the size of the enrichment program is specified in bombs per year just to make it easy. And you can see here, these countries basically operate programs that are suitable for making a few weapons. But that's about it.

If they were really serious about supplying fuel for their reactor fleet, they would have much larger programs. But they don't. And you know what? We generally don't really complain about it.

Why don't we complain that Japan can make 15 bombs a year? We complain about Iran can make one bomb a year. Because Japan is our friend. Yep.

AUDIENCE: Why is Japan [INAUDIBLE]? Because they shut stuff down?

SCOTT KEMP: Yeah, no. They are bad engineers when it comes to making the centrifuges. They keep making a mistake that they haven't gotten past yet. The Brazilians are in the same camp.

There's a lot of you can make it work, but if you want to make it last a long time, there are some things you have to know. And the Japanese have not figured that out. And so they built this large capacity, and almost all of it broke after a while. So I haven't updated this number recently, so I really am not sure exactly how big their number is today.

So sometimes I get asked, well, couldn't we just build enough enrichment to support a reactor but not build a bomb? And it's the answer is no. It's the opposite.

So here's the amount of enrichment you need for a bomb per year. That's the amount you need to support one gigawatt reactor per year. And this is a typical commercial plant. And you can just see that.

AUDIENCE: [INAUDIBLE] capacity of the program [INAUDIBLE] to leave the country has nuclear or not?

SCOTT KEMP: Is there a link between the capacity of the program?

AUDIENCE: [INAUDIBLE]

SCOTT KEMP: No.

AUDIENCE: It has nuclear submarines and carriers?

SCOTT KEMP: No, because what has emerged is that some countries, in particular Holland and Germany, have a very, very good technology, and they are able to sell this at a good price. And they make money. And so they do this.

They export all this stuff despite the fact that they don't have significant nuclear establishment. Yeah, Germany used to, but they got rid of it. Holland never really did. So yeah. So it's just a business. And that's where the technology is.

The Russians just keep building capacity that they can't even use. And it seems like their strategy is to try to put these people out of business because the Russian technology is so cheap for them to build. Seems like they're hoping to take over the market, but then we put sanctions against the Russians. And so we'll see what happens.

Yeah, so basically, a full-size plant, like the ones that they operate in Holland, typically supply about 40 reactors, and they could make 800 bombs in a year. So you can just do the math in your head.

You can make 800 bombs a year. How many bombs can you make in a day? How fast could you make a bomb? It takes about a day to convert the plant or so. But you're making a bomb within about a day and a half. Your first weapon quantity.

So you could have IAEA inspectors and whatever. And they could be there, and they could actually watch all this happen. And then they could go to the United Nations and say, Holland is making a nuclear weapon. And by the time everyone showed up for the meeting, they would already have their bomb.

And this is basically the problem with these large-scale facilities is you can have safeguards, but it's not clear that it really means anything. It doesn't stop anyone. Yep.

AUDIENCE: Because [INAUDIBLE] so you can make a bomb so quickly. And it does seem like the centrifuges and enrichment process is not necessarily difficult to accomplish. Is there an estimation on nations that we say do not have a bomb, that probably do? They just don't have the delivery of it effectively?

SCOTT KEMP: So the general view is we know who has and who doesn't have nuclear weapons. And we generally think we know who has and doesn't have uranium enrichment. But in theory, it's possible that someone could have done it. Secrets tend to eventually leak-- not because they get detected technically, but because people's phones are tapped and things like this.

So I think the general view in the intelligence community is that we feel confident. We know that there are no clandestine weapons out there. Maybe there's a couple of cases where things are a little fuzzy, like South Africa, which has a uranium enrichment program, previously had nuclear weapons, supposedly got rid of their nuclear weapons, but not a lot of information was forthcoming about where everything went. Yeah.

AUDIENCE: All of this, [INAUDIBLE] for example, they produced 5% enriched uranium.

SCOTT KEMP: Yes, correct.

AUDIENCE: So why do you assume for them to be converted into facilities that can use bombs? Is it 90% of each bomb, or is it just about staggering the gas centrifuges [INAUDIBLE]?

SCOTT KEMP: Yeah, so I was going to give a special lecture on the 19th, but now because of the projector issue, I'm not sure if I'll be able to do it. But basically, what you do is you connect the output of one cascade, and you feed it into the input of another cascade of machines. And when you do that, you run the cascade outside of its design point. So there's some inefficiency in that process, but you can somewhat compensate for it. And you still eventually get there.

You basically connect all these cascades together. I didn't really tell you. I said you needed to put a bunch of units. The real way it works is that you have a bunch of units, both in parallel and in series.

These are all centrifuges. These are all operating in parallel. So you can feed material in here. And then, because of conservation of mass, if you feed some material in here, let's say one unit, then you're going to get like 0.4 out here and/or maybe 0.6 and 0.4 here. About half the material goes one way, and half goes the other way, roughly.

So this stage is only dealing with roughly half the total flow of this stage, as you know. And all the outputs like this are piped together and go to the inputs for these machines, and the same here. So you have fewer and fewer machines with every stage.

If you just threw away all your stuff, you would have a lot of waste. So the way this works is that we have a stage here, which has outputs going this way, and we have the tails, the depleted uranium, slightly depleted coming out as waste from this stage. But this stuff, even though it's depleted for this stage, it's still good relative to this stage.

So what we do is we pipe this back in up here like that. And so it cycles back through. And so this is how cascades are built.

If you do the solution, so here's a stage, and you have some product coming in. Here's the n stage. From the n minus 1 stage, you have some product which is enriched, from the n plus 1 stage, some product.

You have the tails of the waste coming in like that. Ideally, you want this enrichment coming out of this stage to be exactly the same as this waste stream. Because if they are not the same isotopic ratio, then what happens is you have a mixture two different isotopes, fractions, which is the opposite of separation. And so it's anti-enrichment.

So to make this entropy process go to 0, you design the system so that this has the exact same enrichment as this. When you switch to cascading multiples of these together to get to HEU, you lose this optimality. And so you have some losses, and you have to calculate for that. But you can still do it.

Yeah, it depends on how you build your plant. The one day is basically just flushing the gas out and moving the pipes, the output of this to something else. But yeah, I think a day is a good estimate if you've already planned it. Like you were, OK, here's what we're going to do, then a day is reasonable for the switchover. And then probably some time to get your first bomb after that.

OK. So that's uranium enrichment and bomb-making 101. So let me just review some of these pathways. So we started talking about spent fuel, and we said spent fuel. Even the stuff at regular reactors is weapons-usable. Remember?

I read you this long paragraph from the Department of Energy that said reactor-grade plutonium can be used in devices of minimal sophistication by countries with minimal experience. And it is weapons-usable. What protects us is that you have to build this facility to do this operation.

We talked a little bit about how hard that was. I talked about this quick and dirty reprocessing plant, where we use stainless steel drums that we order from the dairy industry and so on. So you can do this, but you still have to do it. You have to build a facility, test it, run it, and so on.

Some countries do this as a matter of course, and they produce separated plutonium. And that's worrisome because that's directly diverted, directly weapons-usable. We talk about dedicated plutonium production.

This is like the Iraq reactor, but you're talking from scratch. You can do this under the cover of I'm building this to train my nuclear engineers. And because I eventually won a nuclear power program, and I need to know how to operate reactors, and I need to test materials to design reactors.

And so I build my own dedicated small plant, but you're still talking 5 to 10 years to get this thing running. And so this is not exactly a fast way, but this is how most weapons programs eventually operate their weapons production material or material production because they don't want to have it connected to their civilian fuel cycle.

And then we talked about enrichment. And the nice thing is in the light-water reactors, which run off less than 5%, this is not directly weapons-usable. So you'd have to have additional enrichment facilities. And if a country doesn't have that, then they can't do it. Or you could just build a dedicated facility.

So here are some high-level conclusions. Any country with a power reactor can make plutonium weapons--period. Doesn't matter what kind of power reactor. As long as it uses uranium fuel, it's going to make plutonium. That plutonium can be used in weapons, and some people will claim it can't be, but it can.

There are, however, radiological barriers that make it hard. These are eliminated when you do the recycling and you separate the fuel. Dedicated plutonium production is ideal, but it's a decades-long process. However, if you want to take that path, it's easier to justify building these dedicated facilities if you have a nuclear power program. So you might acquire a little bit of nuclear power with the idea that you would then go build a dedicated program for producing plutonium and say it was part of our nuclear power research program.

Iran did this. Algeria did this. A bunch of other countries did this.

And then production of highly enriched uranium is becoming a proliferation pathway of choice for new states. So Iraq, Iran, Libya, Pakistan, North Korea are all countries that have shifted away from plutonium to uranium enrichment. But it's hard to justify building these facilities unless you have a nuclear power program.

So the way Iran operated its program, and when we looked at this, the situation with Iran is still not settled. But remember, they started in 1985. That's a long time ago. Why are we still talking to Iran?

Well, part of the reason is Iran has a nuclear reactor, and they assert that their enrichment program is to make peaceful civilian fuel for their reactor. And that just complicates everything, because you can't just say no, it's not and bomb it. The international community says you have to give them the benefit of the doubt. There's a bunch of debate in the United Nations, and things drag on and on and on and on. And so this connection has enabled Iran to pull this off.

So those factors in blue here are where technology affects the pathways between nuclear power and nuclear weapons. These factors in red relate to the political decisions to pursue nuclear weapons. And you can see that there's an intimate connection, which is where I started out in the previous lecture, that, yes, the decision to acquire nuclear weapons is a political choice, but the political choice is intimately dependent on the technology that you have on hand. And that is changed by having nuclear power.

So some high-level conclusions is that nuclear power will, of course, ease access to weapons materials, plutonium, or highly enriched uranium. But you can change this a little bit by trying to change the technology, but it turns out virtually all the technologies we talk about now going forward, whether they're microreactors that are fueled with HALEU or gen 4 reactor concepts, et cetera. All of these actually make it easier to get access to these weapons material relative to the ones through light-water reactor that we have today.

There's almost no idea that has been put forward that makes it harder. The one thing that kind of makes it a little bit harder are TRISO particles are a little bit harder to process than uranium oxide pellets, but is not that much harder. You can take the TRISO, and you can put it in a blender, literally. And it breaks it up enough that you can then acid leach the uranium out of it. So OK, you have to add an extra step where you're blending this stuff, but it's not a big deal.

Now, even if there were a hypothetical reactor that was more proliferation-resistant, could we build and sell that? And the answer is probably not. Because while we as reactor exporters may not care what that cost, the buyers will care.

And they are not going to buy a reactor that is bad for proliferation if it costs more. And if it costs less, we would have already invented it. We spend a lot of time trying to make nuclear power as cheap as possible.

So it's unlikely that any kind of proliferation-resistant reactors is forthcoming and competitive on the international stage. If we had a monopoly, we were the only suppliers of reactors to the world, then maybe we can force it down the throat of various countries. But we're not a monopoly. Buy reactors from Russia and from Korea, and others.

So what about number two? Number two-- you can actually change the justification through policies. And let's just have a quick look.

So it used to be people talked about doing this all the time-- closed fuel cycle, recycling. Sounds great. But under President Ford, the United States decided to make a declaratory policy that it would not allow reprocessing of its civilian uranium, or we're not supported rather, and would not allow foreign countries to reprocess US-origin fuels or fuels that touched US-origin technology, unless they had explicit permission from the United States.

And only one country has been given that permission. That is Japan. Every other country that has a nuclear agreement with the United States, Nuclear Cooperation Agreement, has basically signed away their right to do this number two. And so that is a policy that helps prevent the ready access to direct-use materials.

So people get stuck here. And then they have to build that dedicated facility to do the extraction. So that's good.

You might ask why Japan got an got an exception. That was in 1977. Prime Minister Fukuda visited President Carter and personally asked the president for an exception, and the ambassador to Japan, Ambassador Mansfield, characterized Fukuda's plea as basically telling the president, this is a matter of life or death for Japan.

And basically, that we need the ability to make a nuclear weapon in the event that our adversaries, the Soviet Union, come after us. And the US gave in and allowed Japan to do this. And that's why Japan operates the Rokkasho Reprocessing Plant today is they have that special exception.

So now Iran says we just wish to be treated the same as Japan. And I've had the ambassador to Iran personally tell me this multiple times, and it's really hard to sit there and say, oh no, sorry, you're different. We don't trust you. So keeping these red lines in the international community are really hard.

We recently produced a similar red line for-- there's our policy there. We recently produced a similar red line for enrichment. We did a deal with United Arab Emirates when they wanted to build their reactors. And we said, not only will you not reprocess, but you will also not have domestic enrichment. And they accepted that, and that has been called now the gold standard.

But unfortunately, it seems like the gold standard was a one-off. Biden, his officials started to talk to Saudi Arabia, who wants a nuclear power program for whatever reason. It's hard to imagine why because there's a lot of sun in Saudi Arabia. And Saudis kept saying they would not accept this provision. And the industry was pushing the Biden government so forcefully to do a deal with Saudi so they could export reactors to Saudi, that Biden's administration was willing to look past it.

Then the Saudis seem to have lobbied a bunch of people in Congress, and they are now expressing support for a Saudi deal that doesn't have a restriction on enrichment. And now the Trump administration is indeed negotiating that agreement right now. And from all publicly leaked information, it appears not to have any restriction limiting Saudi from doing this enrichment.

So it's a hard thing to pull off. And oh, by the way, the Emiratis who did sign up, have an escape clause that says anyone else in the region gets to have enrichment. So do we. So as soon as we do the Saudi deal, we'll destroy the Emirati deal at the same time.

So why is it hard? Well, I would say the real reason it's probably hard to get these agreements is that many of these countries want nuclear power because it gives them a nuclear weapons option. Emiratis probably wanted it principally as a matter of status, and that's why they were willing to sign that agreement.

But I think a lot of countries are willing to spend the money because it's like, well, it's expensive, but we'll be able to make nuclear weapons if we need to. And that's worth it for them. But they're not going to sign away their right to do that.

So I think that's in my opinion. And it's just an opinion-- the real reason why this is hard. But it's also logically, it should be hard because if you're going to buy a $10 billion nuclear reactor, you better have fuel to put in it because you've paid up front. And if you have to depend on a foreign country to provide that fuel to you, that is not energy security. That's the opposite of energy security.

So people talk about nuclear being good for energy security, but it is not unless you have the full front end of the fuel cycle under your control, including the fabrication of the fuel and having validated the design of the fuel that you can fabricate. And you know that fuel is safe to put in the reactor and so on.

And this is kind of the problem. This is where the evidence shows that this is not really what is behind people's motivations. Countries like Iran or Japan say we need to have this enrichment capacity because we need energy security-- sounds a valid argument.

And then you say, and do you also have the fuel fabrication? They're like, oh no. And are you pursuing it? Well, not really. So it's kind of just a fake argument, but it is a legitimate argument.

If you really care about energy security, you ought to try to have this. And so you have this issue where energy security and nonproliferation are directly at odds with each other. And if someone is advocating one for one, they must be advocating against the other. And this is a problem.

All right. So the bottom line on technology is you can make it somewhat politically more expensive. But once the state has nuclear power, it's kind of too late because you will always be able to do this pathway here. And we saw that took about six months of planning and three weeks of execution. So it's maybe not the best way to have to deal with this reactor-grade plutonium, but it's always an option once you have that reactor on site.

So what I have argued so far is that there could be a connection between nuclear power and nuclear proliferation. It's there for the taking. It's technologically there. But maybe we want to ask a different question, which is there in fact a connection historically? Is this the way countries actually pursue nuclear weapons? Bouncy, bouncy.

So this is a tricky question to answer because it always depends on which country you choose to look at. And I mentioned, for example, that-- oh, it's not on this slide. It's a much earlier slide. There are countries like France and Sweden, who specifically acquired their civilian nuclear programs in a way that gave them the ability to make nuclear weapons-- Taiwan, another one.

So here's how I propose we look at it. Here's a list of all the states that have pursued nuclear weapons. There are countries that have weapons, that had a weapon but gave it up-- South Africa, just one-- sought weapons, wanted weapons but didn't really build a program, and then didn't want weapons but wanted the option for weapons. So they wanted the capacity to build weapons, all these different countries.

And here you can see their technology, whether it was dedicated to military purposes or civilian. They are experts. Where did the people come from-- from the military program or from a civilian program? And the facilities that they actually used. So they might have used a civilian technology, but they put it into a dedicated weapons facility. So they copied the technology, but they didn't use a civilian plant kind of a thing.

So these are your configurations. And if I highlight in yellow all those that have the word civil somewhere, you see it's 70% of them. But really, we should remove these because the United States and Russia and China and United Kingdom had weapons before civilian nuclear power was a thing. So really, if you take those out, it's 80% of states.

But this is slightly the wrong question. This is answering the number of countries that have pursued weapons. How many use civilian technology?

We are interested in the opposite question. If you use civilian technology, what is the probability that you will pursue a weapon? That's what matters going forward.

But thankfully, we have Bayes' formula. So the probability of a weapons program given nuclear power is the probability of a weapons program times the probability of nuclear power given a weapons program divided by the probability of nuclear power. And so you can do this.

The problem is that we don't know how many weapons. We don't have this coefficient x, but it just cancels. And so there are 24 countries that have had weapons programs-- 25 I guess-- and 32 countries that have nuclear power programs in our sample.

So I do this, and I basically estimate that there's a 62% chance that if you build civilian nuclear power, you'll eventually decide to use it for nuclear weapons. That's the idea behind this calculation. So let's put this in perspective.

What is the arrival rate for nuclear weapon programs? Well, it depends on how you count. If you count since 1940, there's about 25 weapon programs. You get one every three years.

Nonproliferation has gotten a little bit better. Ambitions of countries that want weapons have settled down. So if you look since 1990, it's about one every six years. That depends on the stability of the international system and a whole bunch of other things. Let's just say, since the international system is getting a little less stable and it makes the math easy, let's say one program every five years is what we might expect-- one weapons program to emerge every five years.

So we have 0.2 cases per year. From the Bayes calculation, we could say 63% of those exist because of nuclear power. The others are not dependent in any way on nuclear power. So the contribution of nuclear power makes us about a tenth of a program per year, tenth of a weapons program per year.

So what does this tenth of a weapons program per year cost us? Does everyone understand this? Yeah, all right. So I don't know. Here's three ways of trying to come up with a cost of proliferation activity.

We could say, well, we're going to sanction them like we did with Iran. There's a certain cost with doing sanctions. We could go to war with them, like we did with Iraq. There's a cost associated with that. Or we could just let them have nuclear weapons and see what happens.

And so let's try to put numbers on these. This is very, very, very, very rough. But we're just trying to get a sense of whether proliferation is a big thing, a big externality on nuclear power, or not really a big externality on nuclear power. We need some notion about whether we should be worried about this.

All right. So here's the cost of Iran sanctions in 2025 dollars since they started. And it's estimated since 1995 to be about $360 billion. You can see most of it is exports, foreign direct investment, oil swaps. There are some things, which are too hard to estimate, not in here.

So $360 billion per proliferator. Now, this actually will probably continue for a while, so this number will eventually get bigger. But this is where we are today. Let's look at the cost of option two-- cost of a war.

So this is the cost of the Iraq War. Inflated it to 2025 dollars, and it cost us about $1.7 trillion, about $1 trillion direct spending to fight the war. And then the rest of this is debts, value of a life, and various other things, greenhouse gases from all the petroleum reused, things like that.

All right. What about number three? What is the cost of letting countries have nuclear weapons? So this one is very tricky.

Here's, I think, the upper bound. So has anyone seen this photo?

AUDIENCE: It's Hiroshima.

SCOTT KEMP: Yeah, it's Hiroshima. And I like to ask, did they really have just a few buildings like this? What is all this? It was made of wood, so it burned. And it created this huge megafire that injected a bunch of soot into the stratosphere, like a volcano going off. And as a result, it actually cooled the ground from a lack of sunlight hitting the ground.

And this is the principal concern of a major nuclear conflict. So this is a very much debated issue in the scientific literature. I myself worked on this, and I believe that these claims are overblown personally. But I will give you the claim that others have made.

So this is the soot. This is the consequences of injecting soot into the atmosphere from 100 Hiroshima-sized weapons. So you imagine India and Pakistan.

They both have nuclear weapons. They're constantly at each other's throats. Something happens in Kashmir, causes a conflict to erupt. A small number of nuclear weapons are used, just 100 in total. What happens?

This is the climate model prediction from these guys, Toon et Al. And they estimate cooling. And here they specify the cooling in the number of growing days reduced-- basically frost-free days where you can actually have a crop growing. And they estimate that it can be as low as, say, minus 40.

This is blue here, minus 40, minus 50 days of growing. So you might lose a month of growing, especially if this happens after your crop has already sprouted, like let's say in April. And then you get back to frost.

You're going to lose all of your crops, so you're not going to have crops for a year. So this is the concern that even a small nuclear skirmish might result in essentially a lost year of food production, in which case you're going to have massive global starvation and billions of people dying.

Now, all this depends on a lot of parameters that are very unpredictable and sensitive. Most important one is probably the particle size of the soot particles, which determine their cross-sections with the photons. And none of that has been sufficiently studied. So I think there is some serious question as to whether this is actually a true result. But if it is, it's worrisome. There could be something very serious.

So starving the planet-- I estimate the cost at infinity. And so there's your cost model. So here's our calculation. 0.13 programs per year times the cost per program. If you choose this pathway, if you choose this pathway, $47 billion per year or $220 billion per year is kind of a way to do the calculation. Yeah.

AUDIENCE: What about the cost of bringing somebody under the US nuclear umbrella?

SCOTT KEMP: Well, first, you have to convince them that it's a real thing. I have typically liked the idea of going to your adversaries and saying, OK, Iran, you shouldn't be doing this.

We're going to pay you $2 trillion, which is like 30% of your economy, and we're going to give you a whole bunch of stuff. And you're just going to stop this. And that would have been cheaper. But we can't do that politically. We're somehow unable to do this.

AUDIENCE: I think that Pakistan is actually a US ally in the area.

SCOTT KEMP: Not strongly. It's really more of a Chinese alloy.

AUDIENCE: Yeah, but historically, it has been an ally. I mean--

SCOTT KEMP: Pretty minimally.

AUDIENCE: This is what I've read, actually. And then the US, I mean, I've also read that nuclear weapons could be used as a method of nuclear deterrence in some cases. So if both countries have weapons--

SCOTT KEMP: That's the idea.

AUDIENCE: --then both countries know that the mutual self-destruction. So there was a--

SCOTT KEMP: Have I given my spiel on deterrence yet? Deterrence is an idea that works in theory but doesn't work perfectly in practice. There are all kinds of ways that it can break down. Yeah.

AUDIENCE: I mean, choices are not always rational.

SCOTT KEMP: It's more it's not only that it's not always rational. It's that for deterrence to work, you have to estimate the expectation value of your adversary's next step. You say they're going to do this escalatory path with certain probability and an expectation value that cost me x. And to me, if x is bigger than what I want y, then I'm going to stop. And the problem is you can't predict your adversary's next step.

AUDIENCE: And there's no historical data as well. The closest would be the Cuban Missile Crisis in 1960. There's no historical data to calculate those probabilities.

SCOTT KEMP: Not really. Did I tell you about the submarine people?

AUDIENCE: That's what I was about to ask about, our mistakes as well. [INAUDIBLE] false alarms.

SCOTT KEMP: Actions on false alarms. Have I not told the submarine story? All right. Everyone know what the Cuban Missile Crisis is? All right. So, yes.

So the United States was putting missiles in Europe. Russians didn't like it. So they were like, OK, we're going to put missiles outside of the United States in Cuba.

And so they had these boats bringing the missiles to Cuba. And the US had satellite imagery of these missiles being sites, missile launchers being built. And they freaked out, and they sent the US Navy to stop the missiles from being delivered to Cuba.

So this is a blockade, which technically an act of war. And they were told, don't do anything to provoke these guys. Just make sure the missiles don't land in Cuba.

Navy ships go there. Well, the Soviet ships that are carrying the missiles have an escort in the form of a submarine, and the submarines are prowling around as the surface ships have been stopped by the US Navy surface ships. And the US Navy knows that these submarines are down there and doesn't like it, because they can shoot torpedoes at their boats. So they want them to surface.

So some guy has the bright idea of dropping a depth charge off of the US surface ship to try to get the Soviet submarines to surface. So what happens is people on the Soviet submarines interpret incorrectly these depth charges as above water nuclear detonations. They're like nuclear war has started.

And the reason you have nuclear submarines is that they're survivable platforms in the event of a nuclear war. And you predelegate launch authority to the people on the submarine. And so the rule is that the captain and the executive officer have to agree, and they both have to put their keys in and turn and open the safes. And each one has a combination, and so on.

So both the captain of the submarine and the first officer, the executive officer, agreed to launch nuclear weapons at the United States. And this guy named Admiral Arkhipov, who was not the captain of the boat, but was like a fleet commander, happened to be on a joyride on this particular submarine. And although he was not in charge of the boat because he was not the captain of the boat, but he technically kind of outranked the captain.

And he was like, no, you shouldn't be launching this. And the captain's like, I am absolutely launching. This is my boat. Get out of the way.

And apparently, it got into a very heated argument where they were shouting at each other about whether they should or should not launch. And eventually, the guy managed to convince the captain to surface and just check to see if nuclear war had actually started. And lo and behold, nuclear war had not started. But if this guy had not been on the joyride, or if he had not been so hesitant to retaliate, the Soviets would have launched, and probably the US would have retaliated. And we would have had nuclear war.

And this was an era when we had tens of thousands of nuclear weapons pointed at each other. It's not hard to contrive scenarios where we would not be here. So it came down to a yelling match. So this is why nuclear deterrence is not the answer. So let me just finish this.

How much does this cost per year to nuclear power? So what I did is I take this cost per year, and I divide it against either US production or global production of nuclear energy to get a cost per kilowatt-hour or cost per megawatt-hour. It goes as low as $21 a megawatt-hour.

But when I did this calculation, I actually only assumed the cost to the United States. So really, you should only consider the cost against the US nuclear program. I didn't include the cost of sanctions to Europe, for example. So this is kind of not the correct math over here, but I put it there so you can see it.

So $59 to $275 to infinity-- so this is not a small number. This is basically doubling the cost of nuclear power. $59 a megawatt-hour is the cost of wind and solar without overbuild or storage, a lot of storage. And preventative war-- this is the cost of the most expensive nuclear today. So it's basically double. So if you believe this calculation, it turns out proliferation is a big externality.

AUDIENCE: Isn't this kind of a weird argument to be making for the US in particular, at least for US reactors? A US reactor does not necessarily mean that-- I don't know-- Brazil is going to get a nuclear weapon from that. We already have nuclear weapons. It's already a part of our nuclear fleet.

SCOTT KEMP: Yeah, the argument is more like if we decide that nuclear power is something we want to have and we want to--

AUDIENCE: Or just in the US.

SCOTT KEMP: Well, I'll get to that in a second. You're going to promote nuclear power. You have a nuclear power industry.

You're going to support your industry. You're going to have reactors in the United States, and that industry is going to want to export its reactors to other countries. And on occasion, there will be proliferation.

And so it's a surcharge that should apply to the US industry because it does promote and push for exports, as it's doing today with Saudi Arabia, which is almost certainly going to convert its civilian program into a nuclear weapons program at some point.

AUDIENCE: Well, why wouldn't you just like, add that cost to the export cost as opposed to limiting internal development?

SCOTT KEMP: So there's no export cost to the US. There's export profits.

AUDIENCE: But there's no reason you couldn't put an export cost [INAUDIBLE].

SCOTT KEMP: Then we wouldn't export. But we do. Do you see the problem is like someone-- you're paying this as an externality. So you're not paying it as an internalized cost.

So you have to attribute the cost somewhere. And it's all the benefits you get minus the cost of having that industry. If you choose to say, well, it's just going to be on the export, then that would be fine if it actually stopped the export. But it doesn't.

AUDIENCE: It feels quite dubious either way. I don't know.

SCOTT KEMP: In any way, it's an enormous number. I think that's the point. There was more questions.

AUDIENCE: That $360 billion from sanctions, that was based on Iran? Wouldn't that depend on the specific economic trade--

SCOTT KEMP: Absolutely. Yeah, absolutely.

AUDIENCE: --with a country in which we trade more with than that value would be higher or less, [INAUDIBLE]. With North Korea, it might be tiny because we don't do much trade with them.

SCOTT KEMP: Precisely. We don't do much trade with Iran either. This is the lost trade. It's estimate of the lost trade.

We would probably have done a lot of trade with North Korea, though there are other things other than its nuclear program that prevents that. But they have some of the strongest deposits of rare earths, for example. We would love to have access to North Korea. Yeah, it'd be huge, huge, hugely beneficial.

Yeah, so it does absolutely factor in. You're going to try the sanctions story on South Korea? Probably not. Trade is just way too intense. This would be way too expensive.

So you either capitulate or you do something else. So it is very case-specific, but I wanted to use real numbers. Yeah.

All this is trying to show-- these are not real costs. These are just trying to illustrate scale that this is not small. That's all I'm trying to show you. All right.

So to get to this point, can we be clever and give it only to the good guys? This always gets raised. And it's nice if this were true, but history has some warnings for us.

So who has seen this? Yeah, this is 1970. This is Iran was our ally, as evidenced by this propaganda advertisement for the Pilgrim Nuclear Plant here in Massachusetts. They were trying to build up support, and they're saying, look, the Shah wants nuclear power. Shouldn't you want nuclear power, too?

And indeed, the Shah was building a nuclear plant using US support and simultaneously harbored not-so-secret nuclear weapons ambitions almost identical to what is happening today with Saudi Arabia. And we were OK with that because the Shah gave US oil, just like Saudi Arabia gives us oil today.

And there was even a private company, and I know the head of the company, who was exporting with official US government license, uranium enrichment technology to Iran based on laser isotope separation. And they were in the process of building that facility for the Iranians when the Iranian Revolution came. And they captured the hostages at the US embassy, which led to the change in relationship with Iran.

After Iran's revolution, we found a new friend in the region. Do you know who it was? It was Iraq.

So here is former Secretary of Defense Don Rumsfeld, at that time, in his capacity as special envoy to the Middle East, shaking hands with Saddam Hussein in 1983. Saddam Hussein at this point had used mustard gas, illegal under the Geneva Conventions, and went on with US technical support to use nerve agent in 1984 against the Iranians, both of them banned under the Geneva Protocol. Eventually, we even exported the chemical precursors to help Saddam Hussein make these chemical weapons to attack the Iranians and because the Iraqis were our friends.

And then two years later, we had enough of him, and we were at war with Iraq over their invasion of Kuwait, who were also our friends. And then we learned that the Iraqis had a big hidden nuclear weapons program, including centrifuges.

And would you believe these guys? We're so friendly with them, and they go off and try to make nuclear weapons. How dare they? So, look, I don't want to belabor the point for more than it's worth, but history is full of examples where it is extremely difficult to predict the course of foreign affairs, where you're friends one day, and 10 years later, everything has changed.

So Saudi Arabia is a country that bred 15 of the 19 hijackers that flew planes during 9/11. They killed Jamal Khashoggi, the *Washington Post* journalist, very violently. And we just close our eyes to it. And all the warning signs are there.

And we say, because we want the $10 billion contract for that nuclear power plant. And then we're surprised when 10 years later, they're using it to make nuclear weapons. We really shouldn't be that surprised.

Here's a more dispassionate way to make the same argument. We are accustomed to the idea of living in a relatively stable country, but the whole world isn't like that. So here is some of the constitutional rewrites since the year 2000. And it just goes to show that countries are having major political upheaval all the time.

The average age of a constitution in the world is about 43 years. The average lifetime of a nuclear power plant is twice that. You do not know who you are giving your nuclear power plant to when you give your nuclear power plant to someone. You think you know, but you don't.

Things change. So I say, we need to be very careful about this idea that we will just give it to the good guys. And that's all I have to say. So we will put everything together in the next session and see where we stand.