[SQUEAKING]

[RUSTLING]

[CLICKING]

**PROFESSOR:** So the question before in this module is, is there really a linkage between nuclear power and nuclear proliferation? And it's inherently a question about the export of nuclear power. We're not worried that the United States might make a bomb from our civilian reactors. And most of the class has been focused on domestic policy and domestic economics for nuclear power here in the US.

But it does relate to US policy towards nuclear power because of several reasons. One is we're interested in helping other countries reduce $CO_2$. And nuclear power is actually a good technology for some countries that don't have access to cheap wind and solar. And second is that if people want to support a nuclear industry in the United States and the economics of nuclear power remain as they are today, which is to say, not competitive with wind and solar, then the export industry is the principal market for nuclear power. And so we then need to give some consideration to this question if export is really the lifeline for the US nuclear industry.

So how do we think productively about this intersection? How do we choose certain technologies to invest in? How do we make sure that whatever we're exporting isn't making the proliferation problem worse? So maybe we should say, well, why does this issue really arise at all? And maybe most of you know this, but maybe some of you don't. The issue is basically that the equipment and the materials in the nuclear fuel cycle can be repurposed for making nuclear weapons.

Now, just because there is some technical connection doesn't mean that nuclear power causes proliferation. Proliferation is a process that entails both a political decision and technical programs. So it's not surprising that there is, however, an intersection of these two things, the technical feasibility for making nuclear weapons affects the political decision to decide to pursue nuclear weapons. So if you believe that your country just would have to develop all this technology itself, your decision to pursue nuclear weapons may not even come up. You may not consider it. If, however, you have all the technology at hand, you might decide if there's a security crisis, maybe we should be using some of this nuclear stuff and build a bomb.

And there's evidence for this. So Iraq, Libya, and Iran are all countries that had nuclear weapons programs. And all of those nuclear weapons programs started after they had been offered nuclear technology on the black market. They probably, I would contend, never have thought that they could have done it, except once someone came to them-- in this case, AQ Khan-- said, would you like to buy these gas centrifuges? Then they're like, oh, we could do this, and we would have the ability to defend ourselves.

So the political science professor, Matt Fuhrman, decided to do a big regression, and he regressed over all the civilian nuclear assistance agreements assigned between 1945 and the year 2000. And you may be surprised that there are thousands of these agreements between countries between that time period.

And during that time, there are 15 countries that initiated nuclear weapons programs and a small handful that were finally successful, nine depending on how you count. And so what did he find? He found that, in fact, there are three factors that really correlate or predict whether a country will acquire nuclear weapons-- a slightly different result for start a nuclear weapons program.

And those that are significant to the 1% level have three asterisks. And you see the biggest predictors are have peaceful nuclear cooperation, have a militarized dispute, and GDP per capita. So these are correlates. That's all they are. But it kind of makes sense. The richest countries in the world decide that we're the leading countries. We ought to have nuclear weapons-- not to be surprised. Having militarized dispute-- that makes sense. But the evidence also suggests that, yeah, it also matters that you have peaceful nuclear cooperation.

So that does not necessarily mean that giving a state nuclear power will cause proliferation, but it does mean that we are increasing the probability in the future that some event might lead them to pursue weapons. Now, those charged with preventing this political decision will emphasize this role that technology seems to have, whereas those who are advocates of nuclear power will look at this and say, well, there are other factors that matter. We just should deal with these other factors and not worry about the small effect that having peaceful nuclear cooperation might have. Yeah?

**AUDIENCE:** [INAUDIBLE]

**PROFESSOR:** So the coefficients are the-- this is a probit regression. So I believe this is the number of standard deviations increased given the underlying model. It's pretty small effect, I would say, but I have to go back and double check that. I believe the result-- this is for, I believe, acquisition. And I believe the result for starting a program is a factor of 5, if my memory is correct. So you're five times more likely to start a nuclear weapons program if you have civil technology than if you don't. But the number of those programs that actually succeed to acquiring a weapon is actually small because we have a big nonproliferation effort. And we'll talk about the cost of maintaining that nonproliferation effort as kind of an externality on the cost of nuclear power.

So what I'd like to try to do is pull this apart for us and see if we can have a better understanding of how this comes about and to give you the data to make your own judgment about whether the proliferation risk is a real risk or not really a significant risk. Disco lights over here.

So let's do a thought experiment. Let's say you're a country that sees itself as a rising power on the world stage. And you can imagine a lot of countries might have that self-perception. Maybe you're already a regional power, and maybe you have some regional adversaries, and maybe some of those adversaries have nuclear ambitions, or maybe they even have nuclear weapons.

And the example I want to give is Saudi Arabia-- a very large country, a very wealthy country. It has adversaries in the form of Israel and Iran. And both of those-- Israel has nuclear weapons, and Iran has had a nuclear weapons program and potentially could make nuclear weapons. It has an ally in Pakistan. Pakistan and Saudi are kind of political sister countries. And they have nuclear weapons. And so if you're Saudi Arabia and you're like, my enemies have nuclear weapons, my friends have nuclear weapons, why don't I have nuclear weapons? I'm a very rich country. I should have these things too. So imagine this is the motivation.

And what steps would Saudi have to take? Well, first, it would have to decide what kind of nuclear weapon it wanted to build. So there are two principal types that we talk about. One is gun type, and one is implosion type. So this is the gun type. This is an illustration of the Hiroshima bomb. And the idea is that you have two chunks of fissile material, almost always highly enriched uranium, though you could, in principle, do this with uranium-233. And you shoot one down a tube into the other, and you get a nuclear explosion. It's extremely simple to make. The design of the Hiroshima weapon was so simple that we actually never bothered to test it. We just dropped the bomb on Hiroshima because there's just no way this thing was not going to work.

All of South Africa's nuclear weapons were gun type weapons. You don't need any really advanced engineering. You don't need to know any hydrodynamics. You don't need fancy equations of state. It's a very low-risk design. People even talked about there's a substantial risk. If someone puts a chunk of highly-enriched uranium on the ground and stands on a ladder and drops another chunk on top of it, you will also get a nuclear explosion. It's really that simple to make.

What you need, though, is the highly-enriched uranium. And traditionally, so highly-enriched uranium is defined as uranium enriched to more than-- just by definition enriched to more than 20%. The Hiroshima bomb used an average enrichment somewhere around 80%. Nowadays, if we were to build weapons, we would choose something like 93% or something like this because we can. It just makes it easier.

Getting this is the hard part. And one of the readings talks about whether, if we go to halo fuels that are right at 19.75 weight percent, which is 19.9 atom percent, will this actually be adequate for nuclear weapons? And there is some evidence-- actually, we should say substantial evidence, including testimony from US weapons designers, that, yes, you could make a weapon from 20%. So this is one of the concerns is that you would-- even though it's technically below the threshold of highly-enriched uranium, from a statutory perspective, if we export reactors that have large quantities of this stuff, we might be making this problem worse.

Anyway, why does it work? Basically, remember that criticality is a geometric phenomenon. And as you have small chunks, the mean-free path can be large compared to the size of the chunk, but if we just put two chunks together, then the mean-free path will be smaller than the size of the chunk. And so then, on average, more than one neutron will stay in the volume, and you'll get a runaway chain reaction. That's basically the whole scheme.

To make a nuclear-sized explosion, you need about 2 to the 8-- you need about 80 generations, so about 2 to the 80 fissions. And you can just do the calculation. 2 to the 80 fissions times however much energy-- I forget what is the immediate release. Is it 180 MeV-- it's 200 MeV per fission, but that's if you include the energy from delayed decay of stuff. So I think it's 180 or ish MeV for the prompt energy release. And so 2 to the 80 of those, and you have a bomb.

Now, all of that, the only reason that is explosive is because all of this happens in 1 microsecond. 80 generations-- the average time between one of these events is about 10 nanoseconds. That actually has a unit. Does anyone know what the name of the unit is? I'm sure someone knows here. One shake is 10 nanoseconds. That's the fast fission time constant. These are the cross section is a barn because as big as a barn, and the time scale is a shake because it's as short as the shake of a lamb's tail. They all come from farm things. There are other farm ones also. It's all because the place where we had developed nuclear weapons was Los Alamos National Lab, which was called The Ranch, and so on.

Some people will say, well, it's true that's very simple. But these weapons are heavy, and they're not practical military weapons these days. That's not true. So here is a photo of the W33. This is an artillery shell, a nuclear artillery shell that is shot out of a gun. This thing is 8 inches in diameter. It weighs 114 kilograms, which is the same weight as essentially the W80 thermonuclear warhead that we put on our ICBMs. And it's a gun type weapon. Super, super basic and simple to make. So I'm sure there are people in this class that could lift this thing and just carry it around. So yeah, these things can be small and very nasty.

Oh, and I should also mention that the yield of this weapon is, I believe-- oh, blanking on the yield. It's much larger than the Hiroshima weapon. 53 kilotons, maybe? I'd have to go back and check. We built 1,200 of these, starting in 1956. So yeah, gun type weapons are still a serious consideration.

The other type of weapon that we talk about are these implosion weapons. And the famous version is that dropped on Nagasaki, which is illustrated here. And the idea is that you compress the metal core-- in this case, you can use uranium, but why would you bother if you can do this with uranium? Just do this.

So if you want to use plutonium, it turns out plutonium releases too many neutrons just sitting around. It has spontaneous fission. And so what happens is if you try to do this design with plutonium, as this bullet is being shot down the tube, there are neutrons flying off of this chunk, and it begins having a nuclear reaction well in advance of the two chunks coming together. And at that point, K, the criticality factor, isn't high enough. And so it starts heating up.

But what it does is it runs the reaction kind of too slowly. And it makes a lot of heat, but not fast enough. And it eventually makes enough heat to push the thing apart before it runs all 80 generations. And that is called preignition. So they couldn't do this design with plutonium. And one cannot do this design with plutonium because you can't really shoot that using conventional explosives. You can't really shoot that chunk of uranium down the pipe fast enough.

So the idea instead was that we would hydrodynamically compress the plutonium. And this was a big part of the engineering of the Manhattan Project. And so what you do is you go from the environment on the left to the environment on the right. And to put this as an illustration, now the mean-free path is getting shorter because the space between the atoms is more compressed. And so we return our subcritical chunk of plutonium into a supercritical chunk by just reducing the mean-free path.

Most of the nuclear weapons in the arsenals of the world today are variations of this design. And it is more tricky. But also, countries have mostly got it right the first time they've tried. North Korea had some trouble with their first test, but it looks like, by the second test, they got it right.

But most countries are also not confident enough in their designs of these weapons to field them without testing them. So we tested this design in Alamogordo. That's the test that you see in the movie *Oppenheimer.* And most other countries have also tested these designs. Today, these designs have been miniaturized to the point where they're basically roughly this big. They're pretty small. This original thing was huge. It was about as high as a person. It was a big thing.

So those are the two basic designs. So here's Saudi Arabia. They're going to decide which design they want to use. And that will in part depend on what technologies they have. So if they just have reactors, reactors will make plutonium, and they will be forced to choose the implosion design. But if they have access to the other parts of the fuel cycle, or they have thorium, then they could potentially do the gun type design. Does anyone know what the story is with thorium, why it's a proliferation risk? Yeah?

**AUDIENCE:** [INAUDIBLE] create protactinium-233, which you can separate chemically, and then you have [INAUDIBLE].

**PROFESSOR:** Exactly. So it's just the same as making plutonium from uranium. You just you go 232 Th plus N, 233 Th-- and that decays by a beta to 233 Pa 233 U. And turns out, uranium-233 is the very best isotope there is to make a nuclear weapon. It has a smaller critical mass than uranium-235. Critical mass is similar to that of uranium-- similar to that of plutonium, but it doesn't have the big spontaneous neutron background that is a problem.

In fact, there are lots and lots of different isotopes from which you can, in principle, make nuclear weapons. And here's a list of them. So here's their half life in kilo years, the bare critical mass in kilograms. And this is the production rate and the number of kilograms per year per gigawatt of electricity that you generate. And so we can just look at these things.

There's only one that is found in nature, and that is uranium-235. Technically, uranium-234 is also found in nature, but it's pretty scarce. And the bare critical mass is pretty large, so you would never use it.

But the other ones, we can start eliminating some of them. So the curium isotopes-- they're just really not produced in any substantial quantity, especially relative to their critical masses. So this is not an efficient path to nuclear weapons. The light uranium isotopes, 233 synthesized in a reactor from uranium-235 and 238-- that's what this means. They're basically never produced because it's very rare that you get those n, 2n reactions that push the uranium isotope down in number. Same for neptunium-236-- just a very unlikely thing. So we can eliminate these.

Then some of these have obnoxiously short half-lives, like americium, plutonium-241, uranium-232. And that means that they're very hot, hard to handle. If you try to make a weapon, you're going to be giving yourself a big dose. The people who talk about the thorium fuel cycle being proliferation-resistant are talking about uranium-232. What they're saying is if you do this reaction, then while this is in the reactor, there will be an n, 2n reaction that will drive some small fraction of this to U232. And this is very spicy. You can see from the half life is very short. But as Emil pointed out, if we are clever, and we separate out this before it is turned into uranium, so it's chemically different and therefore chemically discernible, we can bypass this step and not make the 232, let this just decay outside of the reactor into 233.

So the thorium fuel cycle is predicated-- is proliferation resistant only if you have a dumb proliferator who doesn't understand things. This is really a lot of noise today.

Then there are a few others that just the critical mass is kind of large. These are also kind of uninteresting. Uranium-234-- uninteresting, critical mass is too large.

Now what is left? Well, uranium-235-- that's highly enriched uranium. We knew that. The lower plutonium isotopes, and in particular, plutonium-239, that's what we talk about. And then one that everyone kind of forgets about, which is neptunium-237, which it's not produced in very large quantities. If you're going to choose one or the other, you would choose the plutonium because you make more of it and you need less of it. You need less of it. But it's still a concern. And there are reprocessing programs that have large quantities of separated neptunium. And it actually does not fall under IAEA safeguards. It's kind of a loophole that we ought to deal with but hasn't been dealt with.

So that's why we talk about plutonium and uranium. But the key takeaway here is actually kind of subtle. All of these things are explosive in the right quantities. So if you take mostly neptune, mostly plutonium, but then you mix in some of this other stuff, it still has a critical mass. It's some superposition of these, and you can still make a bomb out of it. You can't really denature it and turn it into something that isn't usable for weapon. All you can do is slightly move the critical mass around by adding some of these things.

And that's really an important takeaway because, a lot of times, we talk about reactor-grade plutonium. Some people say reactor-grade plutonium isn't usable for weapons. Well, all reactor-grade plutonium means is it's got more of these plutonium isotopes, these higher plutonium isotopes. And yeah, what it does is it means that it's a little bit more spicy to deal with. You're not having a lot of 241, just a small amount of 241. And it changes the critical mass a little bit. So you can still use it. You just have to design the weapon a little differently. So that's an important takeaway.

So this is a summary. We talked about spontaneous neutrons, which limits your plutonium usage to just one design. The amount that you need depends on how you do the assembly. Realistically, for uranium, something of the order of 15 to 20 kilograms of uranium-235 or 3 to 8 kilograms of plutonium.

Now the IAEA has an official number for the amount that they deem to be a notional nuclear weapon. If you ask them today if it's a notional nuclear weapon, some people there will say it's not, but it absolutely is and was when it was developed. And you have the historical documents that show this very clearly. And these are the numbers that they came up with-- 25 kilograms and 8 kilograms. And this is what they want to make sure is not diverted.

And you might look at this and say, well, if you only need 3 kilograms, why are they saying the minimum acceptable quantity is 8? And yeah, people have worried about that. And their historical answer was, well, if you're in an advanced state, you need 3. But if you're not in an advanced state, you don't have a lot of knowledge, you might need 8. And also, there will be some process losses from the casting process of making the plutonium pit and so on.

And yeah, these are all true statements, but the real motivation turned out to be that they couldn't do their accounting better than these levels. That was essentially if you try to push down these numbers, it just gets too expensive to do the accounting, and it becomes more than their budget will support. In fact, they already can't do the accounting for all the programs that exist. And so what they do is they say, well, we'll discern based on other information other than the accounting of fissile materials that, for certain countries, we don't really need to check. Which is a reasonable statement to make, but it doesn't treat everyone the same.

What else can I say here? So just in case you're wondering how much 8 kilograms of plutonium is, there's a photo of the equivalent amount. Yeah, that much. It's heavy, though. It's dense stuff.

So here's where we start having the technical connections to nuclear power. Ideally, we want to use nuclear power to mitigate the effect of climate. But we don't want to make this problem any worse. We don't want people diverting plutonium from the fuel cycle, from the reactor spent fuel. We don't want people using the enrichment process to make fuel, to make highly enriched uranium. And it turns out, as I've kind of just shown that, making the weapons themselves are, in a way, not all that complicated. We did this in 1945. North Korea has done this successfully. The hard part is actually getting the plutonium or getting the highly enriched uranium. And that's where various stages of the fuel cycle really come into play.

So the once through fuel cycle is what we mostly talk about. And that's what we have in the United States. We put the uranium in the plant, we burn it, and then we just put the spent fuel in pool and call it a day. And the nice thing about that is, at no point is there any material in the fuel cycle that is directly weapons usable. So the uranium that comes out of the enrichment plant is something like up to 5%-- too low to make a bomb. Then you burn the fuel in the reactor.

And yes, there is plutonium in that spent fuel. But remember, it's got all those other fission products in there. And so it's kind of self protecting. And you would need to do that separation. And so you would have to build a reprocessing plant to get your plutonium for the weapon.

And as long as countries don't build reprocessing plants, they will not possess all of the technology needed to convert nuclear power into a nuclear weapons program, and that has been the foundation of nonproliferation since the Ford administration, which we said we will not reprocess here in the United States, and we will not support other people reprocessing because we don't want this plant to exist in any country that might convert their civil program into a weapons program.

The problem arises when these fast reactor people show up and say, well, we want to do this as a matter of course or when the nuclear waste people show up and are like, we don't know where to put our spent fuel. Therefore, let's just do some reprocessing to kick the can down the road and delay the decision of where we're going to put our geologic repository, like Japan. And so now you have the French and the Japanese doing this thing with separation plutonium as a matter of course. And that gives us this dedicated pathway in which you don't need any additional facilities to get to a bomb.

The other concern-- this is the connection to the civilian nuclear fuel cycle. But we should remember that most countries that have nuclear weapons have dedicated nuclear weapons production reactors that most countries have not used these civilian-- now, it's not true that no country has contemplated this. But this is how the United States did it, for example. So what's to stop a country like Iran building a dedicated plutonium production reactor? They had one. It was called Arak. And they could just do this on their own without civilian nuclear power.

So this is the counterargument. Well, they can just do this. Why don't they do that? And then the second thing is they could also just build a dedicated enrichment plant to enrich uranium and make a bomb. And so again, this is the other counterargument against a connection.

So let's look at these a little bit more. So who has actually done this plutonium from power reactors? Two countries, France and the United Kingdom, both made weapons using their power reactors. So yeah, it has been done. Argentina, Brazil, Sweden, and Taiwan all had programs where this was the plan. They would just divert fuel from their power program and build a bomb. And any country that has a power reactor can do this.

The Argentine and Brazilian programs were operated under military governments. Those governments collapsed before they were successful. The Swedish program has an interesting story. They designed their nuclear power program from the beginning to be dual use. Then the cost started getting out of control, and there was a lot of domestic opposition to nuclear power that was becoming a problem. But, of course, they had this hidden agenda of making nuclear weapons with the program. So they were kind of trying to advance it.

And then the United States realized what was happening. And the United States swooped in and said, you know what, Sweden, if you abandoned the reactors that you've designed for your program and instead accept light water reactor once-through fuel cycle from us, then we'll give you some discounts. Then we'll make your domestic political problem go away. And so they finally gave up their weapons ambitions. And Taiwan also tried to do this, and the United States found out and went to Taiwan and said, you know what, if you don't stop this, we're not going to defend you against Mainland China. And they went, OK, sorry.

So nonproliferation has been successful in two of these cases. And two of these cases imploded on their own accord. In case you're wondering which reactors at France-- this is the G2 and G3 reactor at Marcoule that they used.

We all know how that works. So here's how you do it. As I showed you earlier, you can use any combination of those isotopes to come up with a combination that is useful for nuclear weapons. But typically, you ideally don't want to have a lot of these isotopes, especially these even numbered isotopes, which tend to have higher spontaneous fission rates. So you would ideally not want to burn your fuel normally. We talk about burning fuel all the way up to, nowadays, 45,000-50,000 megawatt days per metric ton. So we're really over here these days. And so the plutonium is not great. It has a lot of these other isotopes. Ideally, we want just pure plutonium-239.

But if you pull out the uranium early, you get weapons-grade stuff. And so two ways you can do this. One is you could just stop the reactor. Now maybe people will be watching. Oh, why did that reactor shut down? And why are they unloading the fuel from that reactor? And so you might be tipping your hand as to what you're up to.

On the other hand, maybe you have a problem. Oh, a reactor had a leak. One of our fuel pins catastrophically failed something. We have to unload the fuel. We have to do some maintenance. And so you can come up with an excuse for doing this. But you don't really even have to do that.

The other thing you can do is when we build PWRs, the very first load that we put in the PWR has a lower enrichment and is burned much less to break in the system. And that load that is sitting in every spent fuel pool in the world. It's the first batch of fuel that we put in every reactor, and the plutonium in that first batch is pretty good. And so every reactor has this first batch sitting around that we could just reprocess and turn into fuel.

This green area is the typical fuel from CANDU reactors. So CANDU reactors, heavy water reactors, they overcome the need for enrichment by having water moderator that is already full of extra neutrons by using deuterium instead of protium light water. And so they go in with a higher concentration of uranium-238. So you have more neutron capture on 238, which makes more plutonium.

And so what you wind up with is stuff that is already not exactly weapons-grade but pretty close to it under normal operation. So CANDU reactors are particularly problematic, and a number of countries, like India and South Korea, have built CANDU reactors very early on in their nuclear programs because of this fact. It gave them a cache of spent fuel from which they could make weapons in the event they decided they needed it. And then they said, oh, they're not economic and then switched to PWRs. But yeah, this is the beginning of many countries.

Now some people-- I don't know, does anyone not believe me about the reactor-grade plutonium? Or has anyone heard that reactor-grade plutonium can't be used? I won't ask if you don't believe me. There's an official US government Department of Energy statement on this. And I think this is long, but I think it's worth me just reading it.

"Designing and building an effective nuclear weapon using reactor-grade plutonium is less convenient than using weapon-grade plutonium. The degree to which these obstacles can be overcome depends on the sophistication of the state or group attempting to produce a nuclear weapon. At the lowest level of sophistication, a potential proliferating state or subnational group--" by which they mean terrorist-- "using designs and technologies no more sophisticated than those used in first-generation nuclear weapons--" i.e. 1945-- "could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons, and probably a yield significantly higher than that.

At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium, having reliable explosive yields, weights, and other characteristics generally comparable to those of weapons from weapons-grade plutonium."

It is the case that you can take any weapon, any US weapon, and swap out the plutonium for reactor-grade plutonium, and it will work just fine.

"Proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton range possible with simple, first-generation nuclear devices. In short, reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or advanced nuclear weapon states. Theft of separated plutonium, whether weapons-grade or reactor-grade, would pose a grave security risk."

And so that is why-- do I have a photo-- I worry about these little canisters of separated plutonium.

So let's say a state has this-- yep?

**AUDIENCE:** I have a quick question. So reactor-grade plutonium is essentially almost swappable with weapons-grade plutonium? Why did we spend so much on making weapons-grade plutonium?

**PROFESSOR:** Safety. The dose rate off of reactor-grade plutonium is substantially higher. And our weapons are designed so that the people who handle those weapons in the military don't get a substantial dose. In fact, we have very special called ivory-grade plutonium, which is ivory is 99 point whatever percent pure-- you know the commercial-- that you can sleep on it so that people in submarines could literally sleep on the nuclear torpedoes, which I don't know if you've ever been in a submarine. Often, people bunk in the torpedo room next to the torpedo. So you have to be-- that's why.

So let's say you're Saudi Arabia. You've bought your nuclear reactor from the United States because the United States wants to give you a reactor. What do you really have to do? Well, you either have spent fuel like this, or you have it like this, and now you need to do the reprocessing. How hard would it be to build that reprocessing plant?

So I showed you in the last lecture, last set of slides, this $20 billion super complex reprocessing plant that looked like a large city. What if you really didn't care about high volumes and purified waste streams and vitrification and all the rest of it, and you just wanted the plutonium? How hard would it be?

Well, in 1977, Oak Ridge asked this question, and they did a study. And this is the first page of the memo from that study. And if you read it, what they propose is that, with a backhoe, you could dig a swimming pool hole, fill it with water. You would put your fuel bundle in the swimming pool because you need to protect yourself from radiation. You need to cut the fuel. So you get a carbide cutting blade, like you would use on an angle grinder. And it doesn't work under water, so you need a chain going up to a motor which is above the water. And you cut up the fuel under the water, and the fuel would fall into a basket.

And then, using a crane, you would transport that basket into a series of stainless steel tanks, and they suggest you order the tanks from the cheesemaking industry, from the dairy industry, for use as stainless steel tanks. And you just do some straightforward non purex simplified chemical precipitate lead bismuth process and precipitate out the plutonium.

And they conclude that, when you're done, it would take four to six months to build this plant that you could mail order from the dairy catalog and that, once you had it built, you could extract your first weapon quantity of plutonium in about one week. And you could potentially build this thing without anyone really noticing what you were up to. It looks like you're building a cheese factory with a swimming pool. And that's not that hard.

Are you likely to get caught? You might. It depends on how good you are at operational security and whether you go tell large parts of the government and some spy finds out. But you might not, and you might get away with this. And once this plant were built somewhere in the country, who knows where, and you divert your uranium fuel bundles from your reactor, maybe the IAEA will notice that the fuel bundles are missing. Maybe they'll notice it right away. Maybe they'll take them six months to notice it. But if they notice it right away, who's to say where they went? Where do I bomb? You've got to find that facility. So this is the concern that it's not actually all that hard.

Of course, it's much easier if you have that facility already built, and this is the other pathway that countries can take. And China, France, Germany, Japan, Russia, and the UK basically all decided this was an interesting pathway to building their bomb. So what they said is, oh, we need to do the closed fuel cycle for various reasons. It's true, for example, in Japan, the Rokkasho Plant, which cost them $20 billion, is because they don't know what to do with the spent nuclear fuel.

But actually, there was a reprocessing plant, Tokaimura, which was built before Rokkasho was built. And this was why it was like, oh, it was a research plan to see if we want to close the fuel cycle. And it made a lot of plutonium, and then they shut the plant. And so people have countries have said over time that we're going to do some research into this closed fuel cycle concept, and they build these plants. And everyone knows that these plants exist, and they operate them openly, and they say that we're just doing the fast reactor thing, and then they go, oh, it's too expensive, and they give up. But it's really been a weapons program for quite a number of these.

Pakistan and South Korea have been trying to do this. South Korea has been slowly inching along. But they don't want to irritate the US government. So there's constant negotiations about what they can and cannot do. But they are slowly moving in this direction.

So of course, you go from this situation where you have to divert the spent fuel bundle to your secret reprocessing site to this, as we've talked about, everything has been done for you basically. Fortunately, today, most of the world has been convinced that routine separation of plutonium is just not economic and doesn't make sense. Of the nonweapons states, states that don't already have nuclear weapons, Japan is the only country doing it.

And because it does it, and because it is so close to having a bomb at any given moment because it has separated plutonium, the IAEA, the International Atomic Energy Agency that inspects these facilities, last time I checked, spends about a full third of its inspection budget on this plant in Japan because it's just so close to being ready for nuclear weapons. And you can imagine, if we have the closed fuel cycle, and this is being spread all around the world, just how difficult it would be, almost impossible, to prevent some country from tipping over.

I've already talked about this, so let me talk about the dedicated pathways that countries could take, and then we'll wrap up. So this is also maybe not that difficult, but it does require building up a dedicated program. And you have to decide whether you're going to try to do it secretly or overtly. And generally, when you're building a reactor, it's too big of a construction project to keep it secret. So then you have to come up with an excuse for why you're doing this.

The excuse that many countries give is that they're interested in nuclear power, and they want to train people, and they want to test materials to design reactors. And they're just building MIT, MITR, the MIT reactor. Basically, we're just doing just doing what MIT does. But then they choose the design of their reactor, unlike the MIT reactor, to be a reactor that produces plutonium well.

So the research reactor that the Iranians designed was a natural uranium-fueled heavy water reactor, just like a CANDU reactor. It produces great-quality plutonium, and it was large enough that it would produce significant quantities in on the order of a year. So the problem is that unless you have nuclear power, even though you can do this independently of nuclear power, your excuse depends on the idea that you are building nuclear power at the same time. So it still has this connection into nuclear power.

And if instead we said, well, nuclear power is only for certain countries that don't have access to high-quality wind and solar, it would be really hard for Saudi Arabia to do this because you look at Saudi Arabia and say, what exactly is your solar shortage here? But nevertheless, some reason the US nuclear industry is very excited about giving Saudi Arabia nuclear power.

So let me just give you a sense of what this path entails. This is in 2005, is a satellite image of the Arak site in Iran. This is where they were breaking ground. They're going to build an indigenously designed, 40-megawatt, heavy water-moderated reactor. It produced about 11 kilograms of plutonium per year. So that's enough for one to two nuclear weapons, depending on how advanced your weapons are-- 2005. Here's what it looked like five years later in 2010. And it's almost complete. At this point, they were really getting ready to load fuel into the reactor. They had basically built most of this stuff.

It looks like the time scale for country to do this that has basically minimal experience in nuclear engineering is on the order of a decade, 12 years, maybe 15 years. Depends on how much money they pour into it and how sophisticated their existing engineering infrastructure is. So it is a pathway to a weapon, but it's kind of the long play. It's not the backup option in case, like, we don't need nuclear weapons, but just in case someone attacks us, we'd like to be able to make them quickly. That's how Japan thinks. And so that's why Japan wants to have the plutonium ready to go just in case.

This option doesn't give you that if you have to start building this thing from scratch. And so that's again where nuclear power changes the calculation. It says if you're not intending to pursue nuclear weapons, absolutely, but you just want to security blanket, nuclear power will get you there. And I think that's basically why Saudi Arabia wants nuclear power today. They just they want to have all this stuff just in case they need it.

Finally, let's look at uranium. Historically, this was regarded as the most difficult path to uranium enrichment. Let me see if I have-- I have some slides-- the most difficult path to a nuclear bomb. That has since changed in 1990. Pakistan broke the mold on this when they developed their own centrifuge program. And if you want, I can tell you the history of this in a separate talk. It's an interesting story.

Since then, Iraq, Iran, Libya, and North Korea have all followed suit. They all also pursued uranium enrichment, dedicated uranium enrichment, as a path to building their nuclear weapons. The reason-- it turns out that making gas centrifuges, the modern way you do enrichment, is a lot easier than the old form of enrichment, which was called gaseous diffusion. And I'll show you that in a moment.

Now, again, what happens if you get caught building this thing, as the Iranians did? Well, the Iranians said we have this power reactor we're building called [INAUDIBLE]. It's big-- it started as a German reactor design, and then was modified by the Russians as some weird hybrid reactor, but basically a big PWR.

And they said, we want to be able to make the fuel ourselves, and that's why we have enrichment program. And no one really believed them. But the fact that they had that reactor meant our hands were tied under the NPT of really accusing Iran of pursuing a weapons program. And it kind of dragged things out for decades and made the problem a lot worse. If they had just been doing this without the Bushehr reactor, we would have been-- you're guilty of trying to make nuclear weapons, and there would be no discussion. So again, you need the excuse. And that's where the connection to civilian nuclear power comes in.

So just let's look at what this entails. First, you need uranium. It's pretty common. It's more common than tin. Every country has enough uranium except for, maybe, I don't know, Monaco. Every country has enough uranium to build a bomb. Not every country has economically viable deposits that they could extract and sell uranium competitively in the market. But everyone has enough uranium sitting around to make a bomb.

And just to give you an example of that, Iraq, during its weapons program, had a phosphate mine. You mine phosphates to make soap, and it happens to be that uranium tends to coexist in phosphate ores. So they went to the phosphate mine tailing pond, where they had all this waste, and they just took that and reprocessed it to extract the uranium for their weapons program. It's around. It's not uncommon. Previously, maybe you could do that.

You could go and take the tailings out of at a phosphate mine. You could do this. We talked about this the other day is in-situ leach mining. You drill a hole in the ground, and you pump sulfuric acid down or hydrogen peroxide down, and you dissolve uranium, and then you pump it back up. And this does not look like a big-- you look at this from a satellite photo, and you have no idea what's going on here. Is this a well? You could cover this up with some sheds. This is not hard to hide.

Of course, now you have to do the enrichment. You have to go from natural uranium, which is only 0.7% uranium-235, to something up here. And so you need to build centrifuges to do that.

And here's an example of why people thought this was hard. Here's the building that the United States built at the end of the Manhattan Project to do its uranium enrichment. It's called K-25. It's 44 acres of land in a single building, employed 12,000 people, and used, in one building, three times the electricity of the entire city of Detroit, Michigan. This is a photo of a small section of the inside of the building. And you can see the size of the pipe works. And for scale, this is a person. And there were 44 acres of this stuff-- huge compressors and all of this stuff. So this is why people thought other countries can't do this.

We'll pick up on the rest of enrichment. We'll talk about centrifuges next time, Monday.