[SQUEAKING]

[RUSTLING]

[CLICKING]

R. SCOTT KEMP: Let's get started. So in the last class, we talked about accidents and, in particular, calculated the number of fatalities. And we found out that it wasn't all that bad on a per-kilowatt-hour basis.

We would like to eventually turn that number into an externality for nuclear power and compare that to the externalities from coal and everything else to see how it affects the final rankings. But before we do that, there are a couple of other externalities that are really specific to nuclear power and we need to go through them.

So one of them is nuclear waste and the other one is nuclear proliferation. So we're going to do those now. All right. So let's just talk about waste. People think waste is a big issue. Actually, if you do surveys, people are always worried about waste. How big of an issue is it?

Another interesting thing to note about this is that this concrete pad-- I'm not sure how far to the right it extends-- but this pad contains all the fuel for a single nuclear reactor over its entire 40-year lifetime. It's really not that much fuel, from a volume perspective. So these casks are pretty robust.

You can drive a train into them. You can drop them from an operational height. You can do all these things. They easily withstood the floods at Fukushima. They can withstand fires. They won't withstand armor-piercing munitions, particularly, if you really want to destroy one of these things, you can. But they're robust against accidents.

I guess one of the problems with all of this, both in the casks and in the spent fuel pool, is that we did this calculation in the last lecture about how many deaths were caused by releasing principally Cesium-137 from a reactor core. This spent fuel pool contains many, many, many reactor cores.

And while Cesium-137 has a 30-year half-life, that means in the oldest bundle, a little bit less than 1/2 of the cesium is still there. So there's a lot of potential for harm here, if either something happens that disperses the fuel from this pool or from these casks.

So it does need to be protected. The protections at this level are principally the concrete itself and this chain link fence. One could ask whether we should try to do better. This is going to be fine against some guy with a shotgun.

These are not going to be fine against someone who knows what they're doing. And that's the kind of issue here. Because of these risks, because concerns about the integrity of the fuel or-- yeah?

AUDIENCE: What counts as someone who knows what they're doing?

[LAUGHTER]

What would they do to get into it? What are we worried about?

R. SCOTT KEMP: So anything that is armor piercing, so for example, a shaped charge would be a problem. Yeah.

AUDIENCE: A shaped charge?

R. SCOTT KEMP: Should I teach shaped munitions now?

[LAUGHTER]

Let's talk after class. Yeah. So because of these potential risks-- corrosion risk, longevity risk, security risks-- nobody really wants to store the fuel indefinitely above ground. Everyone agrees we've got to get this stuff underground, ideally at 1/2 a kilometer underground or something like that, where this becomes a non-concern.

So that's called geologic disposal and that's the name of the game. But the issue is-- we are not yet there. So I'll have a little story about that a little bit later. How long do we really need to protect this stuff? Well, there are some crazy standards.

So currently, the standard-- I'll tell you the exact standard in a little bit-- but the view is the fuel should be no more toxic than natural uranium ore than you find in the ground. So here, this is all normal on natural uranium. And here's the spent fuel. And you'll see that eventually it does get down here.

Let me see. Yeah, this is all elements of the fuel cycle and this is just the fuel itself in dotted green. So eventually, it does get down here after like 250,000 years or something like that. Then, you can debate whether that's a reasonable standard. It has a certain logic to it.

But 250,000 years is a very, very long time to be trying to protect this fuel. And I just want to put that into perspective. Here is the age of one political administration, which will become relevant in a second. Here's the average age of a congressperson's tenure. Here's the age of a country.

So most countries do not live long enough to really manage this waste, which is an interesting contemplation. There's the age of the United States. Here's the age of written language, age of civilized society, the time between ice ages. Good luck managing it through several ice ages.

This is a log chart-- age of our species. So you really start to think these timescales are really big. It's easy to just say 250,000 years. And then you have to realize that there's several ice ages and longer than humans have been around. That's a scary, scary thought.

So the exact standard, if you want to know, in the United States is set by the Environmental Protection Agency, the EPA. They say that what they call a reasonably maximally exposed individual-- this is a person who lives right on top of the waste repository and drills a hole for groundwater and lives their whole life drinking water out of this well.

This is something along these lines. They want the exposure for the first 10,000 years to be no more than 1/20 of the natural background, 150 microsieverts. And then at some point after 10,000 years, there could be some event-- catastrophic tunnel collapse or corrosion of the package-- that might lead to a burst of radionuclides coming out at some future point.

And they say that that burst of nuclides cannot exceed 1 millisievert, which is about 1/3 of natural background for the next 1 million years. And the reason it is so stringent is because that's what's written into the law. And I'll tell you where it comes from in a little bit.

So this 10,000-year standard, which is the lesser of the two, that's twice the age of the pyramids. It's possible that humans can build structures in the middle of the desert out of stone that last that long, but it's really hard to start thinking about engineering on 10,000-year timescales. Yeah?

AUDIENCE: Could you explain why the green line deviates from the dotted line at 100,000 years?

R. SCOTT KEMP: Why the solid green line and the dotted line diverge? Yeah, so this has to do with, this is the total of everything from the fuel cycle. So it includes depleted uranium tailings, which, Uranium-238 has a relatively long half-life. So it does not decay as fast as all the higher-order transuranics that have shorter half-lives, which is what's in the spent fuel. Yep?

AUDIENCE: Who is it that's making these guidelines on the release?

AUDIENCE: EPA.

R. SCOTT KEMP: So EPA is the one who enforces them, but the actual guidelines originate from a report that was done in 1955, I think, at Princeton University and reviewed by the National Academies and became a recommendation. And then the law basically cites that report and says-- this should be the standard. So that's where it comes from. The EPA is the enforcer, but it's actually by law.

So these guidelines, I think they're over stringent, personally. I understand where they come from. If you want a guideline that no one can complain about, this is it. It's no worse than the uranium that came out of the ground. But it's a tough thing to manage. OK, question down there.

AUDIENCE: Yeah, so I looked into it briefly for my research. And the EPA essentially admits that it's infeasible to look at these timescales. For the 10,000, they have like, you need to monitor the site.

And they essentially say, well, but based on your monitoring, you don't have to show that you can make 10,000 years due to uncertainties involved. But then two paragraphs down in the Code of Federal Regulations, you have the line on, oh, but you also have to go for 1 million years.

R. SCOTT KEMP: Yeah.

AUDIENCE: So it's like completely inconsistent. And they seem to know it.

R. SCOTT KEMP: Yeah. So in fact, they passed a rule getting rid of the million-year timescale. And that was overturned in court because the law specifically says that in the nuclear waste policy, that it has to match what's in this original report. And the original report alludes to many hundreds of thousands of years.

They don't say a million years. So they said, at a million years, we've done many hundreds of thousands of years. This is base-10 thinking, in a sense. Yeah, it's a tough call. So I think we could work on this from a policy perspective. But this isn't really where the problem-- oh, yeah, one more question.

AUDIENCE: How is the radiotoxicity defined? Suppose for a second you took all the oxides out of depleted fuel and you mix it in with a crap ton of other non-radioactive ceramics, does that now have a lower radiotoxicity or is it just the maximum from your isotopes?

R. SCOTT KEMP: Yeah, it's a good question. I should go back and look-- is it per gram or per nuclei? I suspect it's per gram of purified radionuclides.

AUDIENCE: OK.

R. SCOTT KEMP: But that's just a suspicion.

AUDIENCE: OK.

R. SCOTT KEMP: Yeah. Yeah. I mean, given the log scale, it's not going to make a huge difference. Yeah, got one more.

AUDIENCE: I've read some articles and papers on how to effectively warn future generations about nuclear waste, like in 10,000 years in the far future. Is this something that concerns policymakers or scientists or it's just science fiction or whatever?

R. SCOTT KEMP: I don't think this is something that really concerns them.

AUDIENCE: Yeah.

R. SCOTT KEMP: But there are people, serious people, who have looked into this-- what kind of symbols do we build?

AUDIENCE: Danger symbols.

R. SCOTT KEMP: Yeah. I think the people who do it obviously take it very seriously. Yeah. But I don't think most policymakers think too hard about it. OK. So the IAEA has given these guidelines for how to find a waste repository. There should be evidence of long-term geologic stability because it would reduce probability of seismicity and volcanism over the storage time.

This should be low groundwater content and flow to prevent transport over 100,000-year timescales. This is a big one. Water, of course, contains ions. Ions means corrosion. This is how things move around. Stable chemical conditions-- mainly this means a reducing environment rather than an oxidizing environment.

Typically, for most geologies, if you are above the water table, you have water percolating through the air, then through the ground and settling in the water table, constantly bringing dissolved oxygen into that environment. So above the water table, you are typically in an oxidizing environment. Below the water table, you are typically in a reducing environment.

So this is a third one. And then you need to have some good structural properties. You don't want to build this stuff out of fluff. You want it to be granite or something that won't collapse on top of your spent fuel canister. So these are the principles and we're going to just bear these in mind when we talk about different siting locations.

So let's talk a little bit about the history of what the United States has done. The United States has done more on this than any other country. I'll talk briefly about what other countries have done. And this problem goes back to 1947. Now, in 1947, you might remember that there was no nuclear power around in 1947, but we did have nuclear waste from the nuclear weapons program.

We had fuel for these graphite reactors, which we used to make plutonium. And there are some pictures of some of these fuel bundles. And so a committee on atomic waste was established in 1955. And they held this conference that I mentioned at Princeton University. And they published a report under the guise of the National Academies in 1957.

And that report made the following recommendations, the initial report, that the waste should be isolated for 600 years, at which point, it would be approximately 300 times more toxic than yellowcake uranium, and that the ideal geology for this was salt, salt beds. Seems reasonable. Why are they interested in salt? So here's a picture of a salt mine.

Salt is very interesting stuff. A, it is typically dry for a very long time. If it weren't dry, it wouldn't still be there. These are like evaporated oceans. So another interesting element of salt-- and I wish I had a photo, but I don't-- is that it's stable on reasonably long, 100-year timescales, but on 1,000-year timescales it actually creeps.

And so what happens is these caverns will slowly close in. So you can find these really old salt mines where you have a tunnel. And you'll see these train tracks, rail tracks, going into the mine. And then they just disappear into the wall. And that's because the salt closes in and seals in whatever's in there.

And so that gave rise to the idea that salt is self-healing. So if you have a crack, like you might have a crack in granite or something, and that crack could propagate for a long distance, and it could be a vector by which rainwater or something could get in and out of the repository.

But for salt, it will anneal itself and close up. And so they saw this as basically like a naturally occurring tank. And so you would put stuff in there and then that would be safe. And because it is dry, you don't have to worry about heating up entrapped water and things like that, and causing problems. So that was the idea.

They also came up with a second plan. They said, well, if we can't put it in salt, the second choice would be to dissolve the spent fuel in glass. And as you may know, glass dissolves almost everything. So you could make these glass pucks, and they could be filled with waste, and it's pretty stable.

This is called vitrification. This idea is still around. But it turns out, it's not yet really mature. It turns out not to be as simple as it looks, because when you're dealing with fission products, you're dealing with every isotope or every element that there is. And when you have to contend with that many elements, the chemistry gets a little weird.

So it turns out some of the elements are volatile at temperatures lower than the melting point of glass. So you try to add them in and they just boil out. Other problems are certain elements actually precipitate at reasonably low concentrations in the glass. So you'll get these crusts forming on the outside.

So it's not really suspended in the glass. And some elements cause corrosion processes in certain kinds of glasses, with lots of glasses. So lots of work continues to be done on glass-based vitrification. The idea was we would make these radioactive pucks and we would basically put them in a storage warehouse and they would be chemically stable and not leach out stuff.

I think although this is still going on, I'm not exactly sure really how good this is at the end of the day, because to really get the isolation, you still need to do geologic disposal. And so it's a lot of faffing about with dissolving fuel and dealing with off-gases that are radioactive, et cetera, et cetera.

All of that just increases the risk of an event happening. And since, as we'll learn in a moment, most of it is heat limited, not volume limited, like taking a big fuel bundle and dissolving it into a puff of glass is not really a giant benefit. So the glass thing probably isn't really the answer here.

So the AEC chose salt. And so what did they do? They dutifully followed this advice, and they went and found a salt mine. And they looked in New York and they looked in Michigan, where there are some salt beds, but they eventually found an abandoned salt mine outside of the town of Lyons, Kansas, and they really liked it.

It had the right thickness, the right depth. It recently closed, which means there were a lot of unemployed people who knew how to operate the mine but were looking for jobs. And so they decided to buy this mine and reopen it for placing nuclear waste. In 1959, they began doing experiments using liquid waste.

A lot of the waste coming out of the weapons program was actually liquid waste, because we had dissolved the fuel to extract the plutonium. And in 1956, they began placing fuel elements, solid fuel elements, to measure what effect that the radiation would have on the salt. And no surprise-- ionic bonds in salts are very robust to radiation. You break them and they instantly just reform.

And so it looked like everything was going well, and they published a report. And they said the results are most encouraging. Now the problem was they basically did this in secret without telling the state of Kansas or the surrounding communities that they were storing nuclear waste in this salt mine.

And so a local newspaper got wind of what they were doing and wrote in their newspaper column, quote, "As far as we can discern, fissionable material is more dangerous than a landmine. Nobody is too wild about having atomic energy bubbling under his backyard." They didn't know what to make of this.

But despite these intrepid journalists trying to get the scoop, it turns out the citizens of Lyons, Kansas, were quite excited-- well, at least mildly optimistic about potentially being a new waste repository for the great Atomic Energy Commission, people who gave us the nuclear bomb. What was going on? Well, we didn't have general paranoia about nuclear energy. It was the atomic age. People loved the idea.

And the government, the federal government, was held in high esteem, and this was a job opportunity for a place that recently lost a lot of jobs. And people were optimistic that this was a good thing for their community. So despite these journalists, nothing negative happened. But what did happen is that the government of Kansas, the state of Kansas started to pay attention.

And so five years into the effort, the Kansas State Geological Survey-- so they're responsible for knowing where oil wells and mines are and what's going on with the geology of Kansas-- the director started to get involved. And he reviewed all the AEC studies. And the Kansas Geological Survey said the AEC has a, quote, "oversimplified view of geology."

The concern was they did not take baseline measurements of water ingress, and it had long been known since 1926 that the edges of this particular salt repository-- I have a photo, yeah-- here's the salt at different depths, and the edges of the salt repository were dissolving from water ingress. So that could potentially lead to some presence of water.

And remember the IAEA criteria? You don't want water present. He also said that they neglected to note that many vertical holes had been drilled through the salt for oil and gas exploration. So these pierced through the salt layer and then went deeper. And that provided a potential channel for the leakage of radionuclides. And so this map shows you where you have subsistence areas.

And all of these little marks are different wells and test holes that were drilled into the salt beds at various locations. And there might have even been more than were actually documented on this map. So he also said that salt, because of this flowing dynamic that I talked about that makes it a self-sealing salt, well, it also means that when you have an uneven upper crust like this, the overburden of this rock will squish the salt out this way.

So it's not actually that stable. Anybody ever heard of a salt dome? So a salt dome, we store oil and natural gas in salt domes. It's exactly this. It's a situation where, underground, you have a layer of salt and in this rock above it, you have a crack or something. And what happens is the salt plastically deforms and creates this balloon of salt that comes up closer to the surface.

And so what we do is we drill holes in here and store stuff in these. And it's a great way to build very, very, very large storage tanks. But this phenomenon of flowing salt was happening because, as you can see from this plot, it wasn't a totally flat, soft bed. So it had been cold flowing and squirting out and moving. And so you didn't really have the structural stability that you ideally wanted to have.

So these are all things that geologists know. Geologists immediately will tell you salt moves around like crazy. The AEC, which is full of nuclear engineers, did not know this stuff. They were just choosing salt because the National Academies report basically told them to. So the AEC didn't like being criticized about its programs.

And so what the state of Kansas did was to organize a conference, a scientific conference, to review all of these issues that they raised and invite a bunch of geologists to come and give papers.

And the AEC did not like the fact that the state of Kansas was getting involved in their project. And so in the middle of the conference, they held a press conference. In the middle of the scientific conference, the AEC held a press conference and announced, we're opening the repository.

No more scientific studies to be done, which was just kind of giving the finger to the state of Kansas and probably not the right thing to do. So not only did this seriously offend the scientific community, they began to write letters to political officials. So one of those officials was the governor of Kansas and another official was the representatives for Kansas in the US Congress.

So in an effort to do damage controls, the AEC went back to the National Academies and they said, will you please review our project plan and tell us that this is fine? The National Academies reviewed the project and they said, well, while your plan is likely safe, there are nevertheless a few outstanding questions that need to be answered, which is exactly the kind of scientific answer that political people find maddening.

It's like, yes, there's always more to be known. So the AEC went around saying, look, this National Academies report largely favors our project. We should move forward. And the people in the State of Kansas said, look, there are outstanding questions. And no one could agree on anything.

So all of this began to rub the Congressional representatives the wrong way. And in a letter to the Chairman of the Atomic Energy Commission, one of them wrote, quote, "This AEC campaign is a quote, 'big daddy knows best campaign' that is at best disingenuous."

He later advised the AEC that the citizens of Kansas are not, quote, "all country bumpkins." And then later in a congressional hearing, he declared that the AEC had not demonstrated that the site would be safe and suggested that they are talking about people's lives and the AEC is playing God-- not exactly the right political tenor.

So the AEC had overstepped. Congress had gotten involved. It pulled most of the funding for the project. And then an oversight committee was created, which would search for compromises. And that committee decided that whatever was done, the site should not open unless the fuel were, quote, "fully retrievable."

So this idea was that maybe we need to move forward, but if something goes wrong, we can always just pull the fuel out and deal with it later. And that sounds great. And for a moment, it gave us a political compromise that was actually operational. But it turns out that that was a really bad thing. And I'll explain why in a little bit.

So that was the plan-- open the repository, but it was going to be retrievable. And then the American Salt Corporation of Kansas City, which had owned the mine before the AEC bought it, released some technical information about previous exploratory drilling that they had done in the area. And the information said that when they had drilled into the salt, they discovered flowing water flowing in the salt.

And they didn't know where it was coming from, but they ran into it. And secondly, that they had attempted to do solution mining. Do you guys know what solution mining is? So this is actually a principal source of mining that is done for uranium extraction now. The idea is you could drill a big hole and make a bunch of tunnels to carve rock out, very expensive, remove all this rock to get to your uranium ore somewhere.

Or you could just drill a hole, pump some water or some acid down the hole, and then dissolve the uranium or dissolve the salt and pump it back up. And that's much cheaper. So this is called in-situ leach mining or solution mining. And so they wanted to do solution mining of salt with water because it was cheaper.

And they drilled the hole and they pumped the water down. And they went to pump the water back out and it was gone. So that suggested that there were some kind of fissures that connected the salt hole that they had drilled to some other place, maybe an aquifer. Who knows?

But it wasn't the idea of a natural tank in the way that everyone thought about salt. So all that was true, that salt does anneal and does self-seal, it is also not perfectly true. There are still other things that happen.

And so given this information, they realized that it was more uncertainty than they thought and that they couldn't move forward. So in 1972, the Atomic Energy Commission just gave up. They closed the project. They announced they would abandon salt and shift their focus to vitrification and glass stored in a concrete bunker.

And that was the plan, but that was hardly the end of it, because they had woken the sleeping giant of the US Congress. And so Congress started to have debates about nuclear waste, and they started to propose-- where would this waste repository be? What would be the requirements?

So retrievability became a minimum criterion for any repository. A second criterion that they implemented was that there should be deference to state governments, to state officials. So no more federal government Atomic Energy Committee riding roughshod over the state like they had done in Kansas.

Now, you had to get approval and licensing from the state. The state could require permits for transporting the fuel and so on and so forth. So state governments would have a voice.

But most of all, it basically converted the idea of a repository of something that might be good, it might give you some jobs, to something that no one really wanted. And that was the biggest problem. Everyone realized that something fishy was going on and decided that they weren't going to let the AEC do this to them.

So congressional opposition became very strong here. And let me just be clear. This is not public opposition. This is not people saying, oh, I don't want radiation around. This is congressional opposition to a federal entity essentially having political power when they want to have political power. That's really what's going on here.

So over the next 10 years, 115 pieces of legislation were put forward in Congress to figure out how to deal with the nuclear waste problem. And every one of them failed. No one could agree on what to do.

Finally, in 1982, the Nuclear Waste Policy Act became the first act to be passed by Congress to outline a solution. Now, by 1982, you may know the Atomic Energy Commission ceased to exist. It became the Department of Energy and the Nuclear Regulatory Commission. And so this all now fell to maybe two Nuclear Waste Policy Acts. DOE is to provide underground repository storage for used civilian nuclear fuel.

In other words, the federal government will solve the waste problem for the private industry, which is a remarkable statement. Back when all this started, we were just trying to deal with government waste from the weapons program. And now, as a result of this, they decided-- we don't want private companies solving their own waste problems, the federal government will just do it themselves, which was a great boon to the nuclear industry.

This meant that they just had to worry about making the power. They didn't have to deal with all the politics. And without this, it would have been potentially much more problematic. They said it should be retrievable for 100 years-- actually, I think it originally says 50 years and extendable to 100 years, but everyone treats it as 100 years-- but otherwise capable of being permanent.

This was an attempt to tamp down on the retrievability requirement. The problem with the retrievability requirement, in case it wasn't obvious, is that meant you have to keep the base repository open indefinitely. There has to be maintenance of the tunnels. There has to be ventilation systems. There has to be mechanisms that get the fuel bundles in and out.

They have to operate and you have to have a staff to maintain all of this stuff. And you can't have that indefinitely and close up the tunnel and protect the waste. These things are contradictory. So some people just didn't like the idea that it would be left there. And other people said, it's not going to work.

So this is the compromise-- 100 years retrievability. Then the law set a size limit that the first repository must not be big enough to hold the existing civilian waste. In other words, we'd have to solve this problem at least twice. They could expand the first repository after a second repository opened, but they could not expand it until the second repository was open.

So what is really going on here? Well, this is the giveaway that this is about politics. No one wanted to be the chump who got stuck with the nuclear waste dump in their state. So this was going to make sure that at least another person in Congress was also going to be the chump also-- very political situation.

And the DOE was to characterize three sites and recommend them to Congress. But Congress would choose the site, not the Department of Energy, because that's where all the scientific experts are in the Congress. And also, they decided to pay for the first bullet by implementing a tax of 1/10 of $0.01 per kilowatt hour on nuclear power. And that creates what's called the Nuclear Waste Fund.

So what did this do? This essentially creates a contract. The DOE promises to take the waste and the private companies pay a tax. So there's consideration, so it establishes a contract. And then it turns out it will matter. In a little bit, I'll explain why.

So DOE started by selecting 12 sites for technical evaluation. By 1986, they settled on their top three that they were going to recommend, and these are them. In Deaf Smith County, Texas, they chose a salt bed. Salt was still seen as good. Despite some of the issues that they discovered in Lyons, Kansas, salt was still basically good geology.

But it turns out that Texas is also the home to the Pantex Plant, the nation's nuclear weapons assembly facility, and had sent billions of dollars into the Texas economy. So they were probably sympathetic to the Department of Energy interest here and getting a solution to this problem.

The second choice was the crystalline basalt. This is a very, very hard rock. It's like the bedrock of the planet underneath the sea floor that they had a formation in Hanford, Washington-- very good geology. Also, guess what? Washington is the state that made the plutonium for nuclear weapons program.

The Department of Energy sent billions of dollars to the State of Washington. Perhaps they would be politically sympathetic to the Department of Energy's case here. And the last one was lithified volcanic ash, which is called tuff, at Yucca Mountain in Nevada. And of course, Nevada is the home to the nuclear weapons test site. And the Department of Energy has spent billions of dollars in Nevada.

And perhaps they would be sympathetic to the Department of Energy's plight. So you can see why these sites were chosen. Two of the three sites have good geology. All three sites have good politics. You would hope that given the relationship between the Department of Energy and these governments, that they would be sympathetic. Well, DOE was not immune to playing politics.

But after learning about the Department of Energy's three choices in 1986, the congressmen in these states weren't-- question?

AUDIENCE: Yes. Both basalt and tuff are indicators of volcanic activity.

R. SCOTT KEMP: Right.

AUDIENCE: Isn't it contradictory to what you said earlier, to avoid volcanic area?

R. SCOTT KEMP: Very astute observation.

[LAUGHTER]

Yes. So the congressmen in these states were not very happy to see their states on the list. They didn't want to be the sucker that got stuck with the thing. So what was the political situation in Congress at the time? So two of these states, Washington and Texas, had very powerful delegations.

The Speaker and House Majority Leader were both from Texas, and his state had 32 votes in the House. And the whip was from the state of Washington, and his state had 12 votes in the House. And Nevada had no one of particular note in Congress and only two votes in the House.

So quite literally in a back room late at night, quite literally, this delegation from Washington and the delegation from Texas got together and wrote an amendment to the 1982 Waste Policy Act, which amends the bill that says, well, yes, DOE is going to select these three sites, but DOE is prohibited now, by law, from evaluating any site other than Yucca Mountain in Nevada. This amendment is famously called the "Screw Nevada Bill."

[LAUGHTER]

And that's the law. And that Amendment to the law has neither been surpassed nor repealed and is still the law today. By law, there's only one place where you can put the nuclear waste in the United States for civilian fuel, and this is where it is. So this is a problem that we still are dealing with.

So Department of Energy went to Yucca Mountain. There it is. It's compressed volcanic ash. And they discovered that compressed volcanic ash really does not meet the EPA requirements. It is not a great barrier against the transport of radioisotopes.

So for example, in 1986, they measured groundwater and they found Chlorine-36 isotopes, which they believe are generated in the atmosphere from earlier atmospheric testing. And that indicates very rapid transit of rainwater into the groundwater there over the timescale of just a few years, maybe a few decades.

That meant it was very oxidizing environment and it meant that there was a lot of water flow going through the mountain. Not great. Didn't meet the 100,000-year guideline. It didn't meet DOE's own 1,000-year guideline. But DOE, by law, could not now choose any other site.

So what did they do? They deleted the guideline and moved forward because there's nothing else that they could do. They just said, oh, well, it doesn't meet this one. Let's just remove it. And they then learned that Yucca Mountain was an earthquake zone. It's one of the most active earthquake zones in the United States.

It has had over 600 earthquakes of magnitude 2.5 and above within 50 miles between 1975 and the year 2000. So within that 25 years, they've had 600 earthquakes. 5.6 magnitude-- I'm from California, so I know what 5.6 magnitude means intuitively. If you're not from California, you may not know what it means.

But 5.6 is a decent earthquake. 5.6 magnitude earthquake in 1992-- 1992 did tens of thousands of damage to their field office where they were running their scientific experiments. In 1999, they had an earthquake that derailed the train. It was likely the same train that would actually be bringing the spent fuel to the mountain-- problem after problem.

In 2002, they had a 4.3 magnitude earthquake in which the Department of Energy released a press release that said everything is fine, nothing was damaged. And then later it came out that they had released the press release before even checking to see if anything had got damaged.

You can see what the problem was. They were so desperate to make this site work that they started to lie and deceive the public. And that, of course, created a problem, just like it did in Lyons, Kansas. And the state of Nevada was not happy with all of this.

So in their infinite wisdom, the congressional staff, the congressional delegation selected a site in the middle of the desert, which may protect against marauding invaders, but does very little to protect us from corrosion and all the things that we really have to worry about.

There was a presentation to the presidentially appointed nuclear waste technical review board that said the following-- the mountain will provide 0.008% of the protection, and the other balance of the protection, 99-point-some-odd percent would come from engineered structures that we would build inside the mountain. In other words, we could just skip the mountain.

It's a very expensive shed. But by law, this is where the nuclear waste has to go. Meanwhile, in the City of Las Vegas, which in 1982 was a backwater full of drunks and gamblers, grew up in the '90s and 2000s to be one of the fastest growing cities in the United States with a giant economy.

And the Nevada delegation, which was two powerless people, turned out to have Harry Reid, who-- I'm blanking on his position at the moment-- became Senate Majority Leader. So he became enormously powerful figure and essentially spent his entire career making sure this place would never open and was very successful at doing that.

Roughly half of the $20 billion that we collected from this $0.001 tax, we spent like $20 billion from that tax to fund research and development of this site. $12 billion of it was spent or basically wasted characterizing a mountain. And so President Obama said we need to fix this problem. You could imagine President Obama saying this, which established a nuclear waste Blue Ribbon Commission. That's my Obama.

[LAUGHTER]

The Commission, they went back to the basics. They said, let's look at all the options. They reaffirmed the conclusion that it should be a geologic repository. They added that it should be based on consent-based siting. We shouldn't just force one of these things down the throats of some community.

We have to get people on board to do what we didn't do in Lyons, Kansas. And then we should move forward. That all sounds great, Mr Obama. But the problem is that the law still says that this is where the waste repository has to be. Until the law is changed, this is where it's going to be.

Unfortunately, we also no longer have a functional Congress, and this is not high on their list of things to deal with. And so we're not dealing with it. And it's just decades of going by and nothing is happening. And this law is a problem. So we're kind in a stalemate.

It's a stalemate that arose initially because of arrogance on the part of the nuclear engineers at the AEC, and converted an issue that could have been a scientific issue into basically a political football that, now, 70 years later, is still unresolved. It's worth noting that there is an operational nuclear waste repository in the United States called WIPP, Waste Isolation Pilot Plant.

This is not for civilian fuel. This is only for transuranic fuel that was created in the nuclear weapons program. It's 25 miles southeast of Carlsbad, New Mexico. It is a salt mine. And there is no high-level waste like spent fuel. It's all lower levels of waste.

But this shows that if you do it right, you can get something done. So the issue is basically the politics around the storage of civilian fuel. Now, if this were high-level waste, we wouldn't have it in just plastic containers and people staring at it. But other engineering and studies would have to be done to see if you could really put high-level waste in there.

But it's worth mentioning this thing does exist. It took about 20 years to get this thing going, from the initial authorization to the opening of the site. And a good chunk of that was dealing with the state of New Mexico and making sure that those approvals from the local communities and so on.

So I mentioned that we were charging $0.001 per kilowatt hour. And in exchange, the federal government promised to deal with the waste. And I said that constitutes a contract. So now we have all this waste piling up at nuclear reactors and nowhere to put it. So the US government is in breach of contract.

So what is happening? What is happening now is that if you have nuclear waste, you can do something with it. And then go sue the federal government for damages and recover your cost of managing your waste or breach of contract. And the courts will look at the lawsuit and say, yes, the federal government is in violation of its contractual agreement. Judgment in favor of the plaintiff.

And this just happens automatically, basically. And the interesting thing is that the money that is paid out from these judgments comes from a very special thing called the Judiciary Fund. The Judiciary Fund is an interesting thing. It's a permanent, unlimited allocation of money.

It ensures that the US government will always be able to pay any judgment made against it, which means that it isn't in any annual budget and no one has to put this budget up for review every year through the budgetary process. Congress never has to look at it. There's no pot of money that is running dry. The US Treasury just prints the money and they say, oh, you need more money?

We can just make it out of thin air and we pay the money. And so this is now how waste is being managed. Private industry basically does what they want to do with it. They still have to get licenses and so on to comply with NRC safety protocols. And then they just sue the federal government for their costs.

And a large industry has emerged basically ensuring that they know they have guaranteed revenues. It's a very good industry to be in because you just do whatever you want to do, and then you sue the federal government for your costs and then you recover your cost.

So it's a good business. And so far, well, as of last time I checked-- last time I had an actual number, which was 2015, which is now 10 years old-- over $5 billion had been paid out, and probably now it's in the 20s of billions of dollars or something like that, many tens of billions of dollars.

So it has created this really weird, perverse incentive to basically do nothing about this problem, because the problem is solving itself. But it can't be more than an interim solution, because officially, long-term is supposed to be a geological repository. Yep?

AUDIENCE: I'm not entirely sure where this would fall in terms of the long-term repository, but suppose you started a private corporation. Ignore how you get the funding for this. You built a long-term repository. Couldn't you then go and sue the federal government for the money to recoup your costs and just do the storage there?

R. SCOTT KEMP: So there are a couple of companies trying to do this. There's one in Texas. There's one in Canada. There may be another one somewhere in the United States, I can't remember.

And the idea is, yes, they're going to try to open a private geologic repository. The issue is that you still have to have state-level approval. And you'll have to meet all the EPA guidelines and all of these things, which are rules, which are still binding on private entities. So you still have to do everything.

But in principle, you could create a parallel structure through the federal government for solving this problem. So, yeah, that is something that's happening. They haven't made much progress. I still think states still don't want it in their state, but people are talking about it.

So what about other countries? So just let me just briefly run through some of them. The most successful so far has been Finland. They operate a repository called Onkalo. I think it's a granite bedrock. There's a documentary about the creation of this thing. It's worth watching.

It's amazing to see these Finnish people sit there on TV and say, well, we created this waste and it's our moral obligation to find a solution. And so we allowed the repository in our community because we feel that we need to do this. And it's just like, wow, you are not Americans.

[LAUGHTER]

So the operating license was, I think, supposed to be granted this year, but they've delayed it. They're trying to do more safety studies. Their protection horizon is a million years. Sweden has their own concept. They have chosen clay, bentonite clay.

They have a copper canister, which they feel the combination of copper being corrosion resistant and bentonite being something that absorbs nuclides well, which limits their transport in water. They are again looking at million-year protection timescales. Canada has selected a site at Lake Wabigoon.

And it's a granite site. I don't know what their protection timescales are, but they've simply selected the site. They aren't doing anything. France has chosen a site in clay. They are also in the regulatory phase like Canada-- no construction yet. They plan to operate the site for 150-year timescale with safety standards on hundreds of thousands of years is what they say.

The UK is trying to do a consent-based siting process where they go around to communities where they have no particular site in mind. Russia and Japan, mostly Russia, has basically said, oh, we don't need no waste depository. We're just going to do the closed fuel cycle.

So let me just tell you briefly about the closed fuel cycle. So this was originally called, for decades, reprocessing. And about 15 years ago someone got the clever idea of changing the name to recycling, which sounds better. And so this is the idea of recycling. So what is the story here?

So if we're going to look at this, it's worth thinking about-- where does the radioactivity come from? So after 10 years, it's mostly, if you see in the beginning, it's fission products. This is the solid green here. And after about 10 years, the dominant fission product is-- surprise-- Cesium-137.

And then you also have to worry about things like Strontium-90 and ytterbium and so on. And we are worried about these isotopes, particularly because, remember, strontium acts like calcium and gets in your bones. Cesium acts like potassium and is metabolically available to us. So these are the things that we really want to protect against.

And they decay away on timescales of hundreds of years. But in the first 100 years, this is what really dominates. Then, in the long run, the actinides begin to dominate after several hundred years. These are the uranium and plutonium and curium and cerium and all the rest. So you just bear this in mind how this operates.

So one of the things that you could do is you could remove these fission products, which are the dominant form for the first 100 years, and store them separately. And then you could build a long-term repository that had much lower performance standards, because you only had to deal with the actinides.

So that is the argument for reprocessing, that you would ease the requirements on the repository. Here's the problem with this argument. When you remove these and store these on the surface, you are doing exactly the opposite of what you wanted to do while you were building the repository in the first place, which is to get these things out of the biosphere where they can hurt us.

So it's a little bit of a sleight of hand and a bit of a magic trick that doesn't really have any bearing there. But this is actually the French perspective, that this is what we need to do. So they have these reprocessing plants. This is the La Hague reprocessing plant. These things are not cheap. In today's dollars, it would be like $30 to $40 billion to build.

They built one at Rokkasho. It was a decade behind schedule. And the idea is as follows. You have a thermal reactor. And then, let's see, where do I start? I'll start over here. Natural uranium comes in. You make UOX fuel, uranium fuel. You burn it in your thermal reactor. It goes to a reprocessing plant.

And then, what do you get out? You get some uranium, you get a bunch of liquid waste full of fission products that you have to deal with that you might vitrify into glass. And then you get plutonium, which you then make new fuel out of and you get what's called mixed oxide fuel. And then you put it back in the reactor.

And then people talk about burning the mixed oxide over and over. But it turns out, in reality, you can't practically usually burn it more than once. So then you get spent fuel that is spent MOX fuel out. So that is the idea. It makes better utilization of the uranium, but at the cost of having all of this additional architecture to process, dissolve the fuel, and create these different waste streams.

So this was being done. But basically, the people, the countries that were doing this, the UK and the United States and several other countries which are not on the list, decided this was too expensive. In 2011, they decided they weren't going to do this. But France, Russia, and Japan continue to engage in this plan.

The Russians, in particular, like the idea that you will have fast reactors. And you can more efficiently burn the MOX fuel in a fast reactor and burn up a lot more of the transuranics in the fast reactor. So that is kind of the idea. TerraPower is basically this concept. So this idea is back.

So the logic of this originally was-- we needed to do this because we thought there wasn't a lot of uranium in the world, so we needed to make better utilization of uranium. Then, it turned out that that was not true. Turns out uranium is more abundant than tin. There's lots of uranium in the world, but people still like the idea of efficient use.

But we should think back to the original lecture of, what does it really mean to be efficient? It basically means lowest cost. If it's cheaper to do something else, it's not efficient from a social perspective. It may be efficient from a technical perspective, but that doesn't really matter. What really matters to society is, what does it cost us to do that? Because you have to pay per unit energy.

And then it reduces the repository requirements, as I mentioned. But it's a bit of a sleight of hand. Yes, it reduces the repository requirements, but you have to then have things that are not in the repository, which is the whole point of the repository. So, tricky, so we should look at these things a little bit more carefully.

So this is just to show you about the uranium situation from Deffeyes and MacGregor, which is the most authoritative dataset on uranium availability. And we are currently mining vein deposits and some of these deposits over here that are in this light color. But you see that as we move to these other lower-grade deposits, the amount of uranium goes up by factors of 10 and factors of 10 and factors of 10.

So there's actually quite a lot of uranium in the world. And indeed, if we're talking about uranium from ocean water, there's a huge amount available. So MIT did a study in 2011 to estimate the probability that uranium would become in short supply. And let me explain this plot.

So across the left side there is the cost of the uranium relative to its current cost. So it's like twice as expensive. This is three times as expensive and so on. Now let's just put this in perspective. How much does uranium contribute to the cost of nuclear power? Does anyone know?

AUDIENCE: Very little.

AUDIENCE: Very low.

R. SCOTT KEMP: Give me a number.

AUDIENCE: 5%.

R. SCOTT KEMP: Less than 5%.

AUDIENCE: Less than that. It's like--

R. SCOTT KEMP: 3% to 5%. So if I double the cost of uranium, I've increased the cost of nuclear power by an additional 3%, something like that. It's not a big deal. So you really have to be pretty high up on this chart for it to matter. Across the bottom of the x-axis is the cumulative amount of nuclear power on a log scale.

And G1 is 100 years of operation at current installed nuclear capacity levels. G5 is 100 years, if we quintuple the amount of nuclear power in the world. And right now, nuclear power is about 20% of the United States' electricity. So quintupling US means 100% of power from the US comes from nuclear.

And this is at 10 times current production. So this is like all thermal fuels and transportation fuels also come from here for 100 years. So you have basically a fully nuclearized world, 100 years of operation-- there's a 50% chance that the price will be no more than 1, 2, 3 4-- 1.4 times the price. There's an 85% chance that the cost will be less than triple.

So it's just not a problem. Uranium's availability issue is not a serious problem. Reprocessing becomes economic when the cost of uranium exceeds roughly $300 per kilogram. Current cost of uranium, I haven't looked in the last couple of years, it used to be about $30 a kilogram. So this corresponds to about 30.

And so the cost of uranium would require a 10 on this plot. So reprocessing just doesn't make any sense if what you're worried about is uranium supply. It's way too expensive for what you're getting out of it. There's way too much uranium in the world. And that's like under very optimistic scenarios.

So in Japan, the official calculation is that the break-even happens when uranium is at $600 a kilogram. And the official French finding was that it would be at $800 a kilogram, so even higher than what I've just said.

So the optimistic reprocessing at 300 is very optimistic. In reality, once you build these things-- there's the actual price. This slide is old. Uranium is just nowhere close. Yeah, you had a question?

AUDIENCE: Does that cost take into account the increase in uranium cost that may result from having to go to mine uranium in different places? Like you mentioned granite, for example. Maybe going to different mines--

R. SCOTT KEMP: So no, it doesn't. So this is the current price. Yeah, so if we go to different mining situations, the price will go up. So the price would have to go up by quite a lot. But this prediction does take that into account. Question over there? No?

AUDIENCE: I was just following up. What does Red Book mean?

R. SCOTT KEMP: Oh, sorry. So Red Book, the IAEA and the OECD put together a book called the Red Book, which is all the known and speculative reserves of uranium in the world. And people sometimes look at the Red Book numbers, and they conclude, based on the Red Book, that there might not be enough uranium in the world.

But the problem is you have to understand how the Red Book is done. Red Book is done by sending a survey to a government and asking them to reveal what the government knows about their uranium reserves. And some governments decide to report, and some governments don't report anything. And just because the government knows about the reserve doesn't mean there aren't other reserves.

So Deffeyes and MacGregor, which is this, is actually done the correct way, which is you get a bunch of geologists and you look at all the different kind of geologies in the world, and you say, based on what we know about geology, what do we expect for the uranium concentration? That's where this plot came from. So, yeah, don't use Red Book. Use Deffeyes and MacGregor.

So there are recent reports from 10 years ago that they think that they can extract uranium from seawater for $300 a kilogram. Now, I'm skeptical of this number because biofouling is always more complex than people think it is. But if this is even remotely close, reprocessing will never be economically defensible.

I'm going to skip some of the waste storage because I only have a minute. But I wanted to show you this plot. Earlier I said that heat was the limiting factor, and that's true for the following reason. So this is basically Yucca Mountain. We have all these tunnels going into the board. This is a cross section. See this little waste package sitting on a pedestal here. And these are called drift tubes.

Here's a schematic. So you have a tunnel. And these are the drift tubes here under the mountain. And the situation is that there's rain coming in through the top of the mountain. And water has to flow down. So you need to make sure that the temperature between these drift tubes remains below 100 C, otherwise the water will no longer be liquid.

It won't be able to flow down, and then the rock above it will become saturated and very heavy and collapse the tunnels. So that is actually what sets the density of fuel that you can put into the tunnel. It's the heat. So changing the waste form to something that's smaller volume or vitrifying it, it doesn't help.

It's still the same isotopes-- same number of atoms and same amount of heat. So this is the thermal loads for Yucca Mountain. Here's the temperature of the waste package, the temperature of the wall of the tunnel, and the temperature right between the two tunnels in the middle.

And you see, initially they cool it by blowing forced air through the mountain. Then at 100 years, retrievability requirement goes away. So you no longer have to maintain this as an active site. You turn off the fans and you close it up. And then the temperature starts going up and you see the waste package gets very hot, something around 140, 150 degrees C.

And the tunnel walls slowly, slowly, slowly heat up over 1,000 years and they just kiss the boiling water and then they come back out. And that's what sets the maximum loading for Yucca Mountain. It's all about waste heat.

So in the last few seconds, I mentioned that when you use MOX fuel, you get different actinides and fission products. Well, the different higher-order actinides means that they're a little hotter. And it turns out that at about roughly at the 100-year timescale when you turn off the fans, it's about a factor of 6 hotter.

And it turns out that to make a MOX fuel bundle, you need roughly six fuel bundles to make one MOX fuel bundle. So you take six out, you put one in, but it's 6 times hotter. So it's exactly the same. So it turns out not at all to solve this problem for the heat loading. Yep?

AUDIENCE: Yeah, maybe something to add to that is in Nuclear Waste Management, the professor mentioned that the worst performer for performance assessments for those is always Iodine-129. So all of the actinides, they adsorb into the soil so they don't move much and they don't really get into the biosphere much.

So she mentioned that reprocessing, so long as you don't do anything about the iodine, there's nothing about your expected dose to individuals. Although granted, this is then playing the x 1,000-year life assessment game, which may not be very relevant in general.

But I figured I'd mention it. Actinides, they don't move. They're like the worst in activity in these parts, but they don't move.

R. SCOTT KEMP: Well, in these parts, our concern is heat.

AUDIENCE: Yeah, I know. But to add to it, it's also just, they don't--

R. SCOTT KEMP: Radiotoxicity point of view. Yeah. All right. So I'll just close with this quote from the French government-- "Spent MOX fuel will have to be stored above ground for 150 years to centuries before we put it into repository." It's just like, what's the point? OK. We'll continue this. I might have a little bit more I'll talk about next class.