[SQUEAKING]

[RUSTLING]

[CLICKING]

R. SCOTT KEMP: We're going to figure out how many people nuclear power kills. I mean, we need an answer to this. So this is part of the externalities calculation. If you recall, we spent the first major part of the class working out the explicit internalized economics.

But I said that that's not the whole story. We need also to have externalities. One externality is climate change. We talked about the difficulty of coming up with a number. So we said, well, we'll take the view that we don't know what it is, but we will be able to estimate how big it would have to be to justify things.

But the difficulty of that is that under equal decarbonization, wind and solar mostly outcompetes nuclear, except for in the thermal markets where there's potentially some opportunity. And now the question is, is there an additional safety externality associated with nuclear, or other externalities associated with wind or solar or natural gas that actually change the ordering, if you will?

We've done everything from explicit [AUDIO OUT]. Windmills are killing the birds turns out to be a big problem. So we need to get into that. But the first thing we're going to do is calculate the externality for nuclear.

So who has seen this plot? How many people feel they were-- yeah. How many people feel that this plot actually influenced their choice to become nuclear engineers? Yes? No? There's a kind of a shaky head. One half person says this plot had influence on them.

It's a nice plot. I hope it's right. We'll find out. That's what we're going to do today. We're going to figure out what this plot is. So let's go.

So I showed you this slide Wednesday. This is some of the isotopes that come out of reactor accidents which have large activity. And we mentioned that cesium-- sorry, the European spelling-- cesium-137 and also cesium-134 is significant on the early days. And these other ones, they dominate hundreds of years. But this is a log plot here. And these are the two isotopes of principal interest-- cesium-134 and cesium-137.

Iodine-131, which is not shown on this plot, is even more important. It has a very short half life. So it decays entirely in a few months, a couple of years, basically. And it gives a big dose that we also have to take into account. But it is a different dynamic because it is short-lived. It's what you eat and breathe immediately following the accident. This other stuff, cesium just hangs around for centuries and just increases slowly the background radiation dose.

So we are going to do the calculation for cesium. We'll look at some of the other isotopes. We'll add in iodine, but we won't do the calculation explicitly. And we'll just try to take into account the biggest and most important isotopes and get a measure of the dose.

Just as a mention, you've seen the periodic table before. Why is cesium-- and another one people hear about strontium-90? Why is strontium and caesium important? Well, because of the valence electrons are similar to in a case of strontium like calcium. So it sits in our bones. It's not a big beta-- it's not a big external emitter. If you're around strontium contamination, it's not a problem. But if you eat it, it's a problem because it then gets taken into your bones.

And so like the history of above ground nuclear weapons testing was that we were testing all these nuclear bombs, which are little mini fission reactors, which disperse all of their fission products into the environment. And we were just-- the US government and other governments were doing this.

And then it turned out that the strontium was emplacing itself in the teeth of babies. Instead of calcium apatite, which is the enamel coating of your teeth, it was strontium apatite. And you could measure the radioactivity of the teeth of newborn baby-- of young babies. And this fact caused essentially a political movement that forced nuclear weapons testing underground.

So, in fact, the amount of fission products released from typical nuclear weapons is actually a lot smaller than what we would get from a large accident. So strontium does matter, mainly for ingestion pathways. We're not going to talk about it. Cesium looks like potassium. And so potassium is used everywhere in your body. So it just filters through all of your organs and stays around.

So let's look at some of the source terms. We're going to look at two major accidents-- the two INES 7 events. This is an international nuclear event scale. It goes up to 7. 7 is the worst. There has only been two of these events in history-- Chernobyl and Fukushima. So let's look at those events because they dominate the source.

So Chernobyl was an RBMK-type water graphite reactor. It had no containment. They believed that it wasn't really possible. A steam explosion ejected fuel and melted the fuel and triggered fires. And the fires then helped to volatilize a lot of the fission products that were in the fuel that boil off at temperatures below the fire temperature.

So there are still 11 of these reactors operating in the world today, all in the former Soviet Union. So they continue to pose whatever threat they pose.

AUDIENCE: [INAUDIBLE] as the Soviets did actually make some changes after Chernobyl. They're not exactly the same,

R. SCOTT KEMP: Yes, but they still don't have containment. So this thing released 85 petabecquerels of cesium 137, 4,000 petabecquerels of non-noble gas activity total. But remember, petabecquerel is just decays. It doesn't tell you how bad the decays are. It doesn't tell you how much energy is in those decays. So it's not-- you can't just scale this number.

The number we want to use here is 85. This is the contamination as calculated by the French. I think this is IRSN across Europe. 75% of the total release is estimated to have been deposited on land somewhere in the world. And this is a log scale, so it's a little bit tricky to try to interpret.

Fortunately, if we wanted to measure the average contamination, say, in all of Europe, we could try to voxelize or pixelize this and figure it out. But this European Commission issued this report in 1998, and they did it for us. And their number is 7 kilobecquerels is the European spatial average contamination-- 7 kilobecquerels of cesium-137 per meter squared. So that's good to know.

Now let's make a little observation here. The first observation is that in the last class I defended the linear no threshold model. If the linear no threshold model is correct, then that means 10 millisieverts of dose to one person is the same as 1 millisieverts of dose to 10 people. And so that makes calculating the dose response really easy. We just basically need to estimate the average population times the average dose. And because it's all linear, it's roughly correct. And that's what we're going to do.

Now, what we really care about is not the average land contamination. It's the average exposure to a person. And people aren't evenly spread across all of the land. People-- like Western Europe has a higher population density than Siberia. And so we need to maybe accommodate for that.

A thing that has been raised is that Ukraine, which I've now outlined here for you in black, is sometimes called the bread bowl of Europe. A huge amount of grain is grown there, which uptakes cesium from the ground-- looks like potassium-- into the grain. And then you eat it, and you have an ingestion dose.

So arguably, the European spatial average, which includes all of uneventful space, is probably too low. Since we're really in the domain of single digits of significance here, I'm just going to round this to 10, to take into account the fact that they grow a lot of grain here, and Europe is here, and so on and so forth. Yep.

AUDIENCE: Are you taking into account that that grain still has to pass radiological standards for the European--

R. SCOTT KEMP: It will.

AUDIENCE: Say again.

R. SCOTT KEMP: It will. Yeah. It still passes the standards. It's just that it's going to be higher than it was. So that's what we're looking at. The effect is very, very small amounts of dose times very large numbers of people. And that's what we have to deal with.

Here's Fukushima. 21 petabecquerels instead of 85. It's a BWR type reactor, water moderated, high-pressure containment, much more similar to the reactors that we have operating today. There are-- I have to double-check this. I think there are 94 of these reactors in the world, but I don't think all of them are operating because a lot of them were shut down. But it's higher than 11.

The accident at Fukushima was really initiated by the tsunami that followed the earthquake. The reactors were OK. After the earthquake, one of the reactors had been-- they were already shut down because of the earthquake for about an hour. But then the cooling systems failed. And as a result, the fuel got hotter, and eventually got hot enough to boil away the water and begin to melt and release fission products.

Although the Fukushima reactor did have a small containment, hydrogen caused explosions, and that eventually, caused exposure to the spent fuel pool, which we talked about could have caught on fire. And NRC says if it had, the situation would have been 100 times worse or 25 times worse than Chernobyl. Fortunately, that didn't happen. But they still had to vent the containment, the high-pressure containment, to prevent it from rupturing. And so that's where the releases-- significant releases came from these venting events.

So the total amount released was still much smaller. And here is the situation for the releases from Fukushima. So you see these momentary pulses where they release some, and then they close the containment. Again, they release some more and so on. Let me see if I can speed this along. Yeah.

So you can see, the lucky thing about Fukushima is the winds off the Kanto plane of Japan almost always blow into the Pacific Ocean. And so we really got lucky where these very high-dose plumes that might have contaminated a large land area, basically all just got washed into the ocean.

However, a lot did get to the United States and Canada. And I'll show you-- here is the final deposited contamination. And it turns out that the United States probably got more-- I mean, the North America probably got more contamination in total than Japan from this accident.

The thing I want you to take away from this chart, again, keeping in mind linear no threshold, is that the contamination here is about, let's say, 1% of the contamination, the average contamination here-- something of order, 1%. But the land area here is roughly of order 100 times the land area that is contaminated over here.

So we could say, very roughly, since we're doing a back of the envelope calculation, that the global contamination might be like a factor of 2, higher than the local contamination. Something like that. It turns out you don't have to rely on of rough hand-waving argument. UNSCEAR has actually done a calculation I will show you later. And when they compared Europe to global, they found a factor of 1.6.

It depends where the oceans are. Depends where the winds are blowing. Depends where the reactors are. All these things matter. But there's roughly, very roughly, a factor of 2-- less than a digit of significance. So that's a good thing to keep in your mind.

So what is a, quote, "typical" major in INES 7 reactor accident? Yeah?

AUDIENCE: I have a quick question about how much is 1 kilo becquerel per square meter compared to just background radiation?

R. SCOTT KEMP: I think background contamination from nuclear weapons testing is about a third of a-- or half a kilo becquerel per square meter. I've could go look it up. If we have time, we'll do-- let me-- we'll do it at the end of class.

So here's what I propose for estimating a typical reactor accident. There's still some Chernobyl-type things around that could cause bad accidents. We have 450 reactors, but 11 of these left. Let's just weight it-- a little bit of Chernobyl in there. Not a lot of Chernobyl, but a little bit.

And then we'll have the Fukushima, accident B, which describes most reactors in the world. B is typical, but we'll divide that by 3. Because it's actually three reactor accidents-- one site accident, but three reactor accidents. So we have to make sure we do our accounting correctly.

So we'll take that release, which 21, and we'll divide that by 3. So here's the calculation. 85 becquerels times this weighting. 21 becquerels times that weighting. And it's about 9 petabecquerels for what I'm going to call a typical accident? Yep?

AUDIENCE: Where does that number 450 come from? What is it--

R. SCOTT KEMP: Oh, total number of reactors in the world. Yep. This is just my weighting. So this is per reactor accident. Now, it turns out that not all accidents are simple reactor accidents.

Some accidents are internal accidents, like at Chernobyl, and some accidents are site accidents that involve multiple reactors. So we need to figure out how to weight them. So what I'm going to do is just say, well, let's just use empirical data. Barring any better data, roughly half of them will be internal, and roughly half of them will be external.

And actually, that makes a lot of sense from a kind of statistics argument, in the sense that if it turned out internal accidents dominated tremendously, and the types of accidents of external events did not, that means you haven't done your safety well. It means you've underperformed in one area and overdone it in another area. So we expect these things to be roughly the same if we design our safety.

So here's my calculation-- 1/2 internal plus 1/2 site accident. So I'm going to put the 3 back in. I get 18 petabecquerel. And it's about 1/5 of our Chernobyl event, very roughly. That's what I'm going to argue is a typical accident. You don't have to agree with this. Do whatever you think is right and propagate your own math. But this is just like-- this is what the empirical history says.

So once we have that accident, then what happens? Well, there are lots of different pathways in which you can be irradiated. You can have stuff landing on the ground. And then it just sits there and it glows and it irradiates you. Call this ground shine.

You could inhale it because it's floating around in the air. And that inhalation can come directly because it's in the air after the accident, or you kick up some dust. Roads and stuff is constantly kicking up dust, and you Inhale it. Or it could go into the food supply, and you eat it.

So we have three different pathways here. And it turns out that these pathways are complicated by the chemistry of the isotope that is being released. Once it goes into the environment, how that isotope operates depends on all the chemical reactions that are happening out there. So as it turns out, this is not something you can do from first principles. You need to have basically experimental data that tells us, on average, what does the chemistry of the environment do to the availability of these isotopes?

So that data has been done. This is from a 1982 report by the United Nations. And they calculate that for every becquerel meter squared of contamination, there's 0.89, or 9 nanograys of contamination. We want a kilobecquerel. So we actually could state this as 9 micrograys per kilobecquerel per meter squared.

So we just go back to our situation, we have the original contamination is 20% of Chernobyl. The Chernobyl was 10 kilobecquerel per square meter. And now we have this conversion factor, which is 9 microsieverts, or 9 microgray is what it actually says-- we'll talk about that in a second-- per kilobecquerel per meter squared. Does that sound right?

And then this is all decaying. And it's only cesium-137, so we'll have some time dependency, which is the half life. And then this is 30.2 years because this is the half life of cesium-137. So this is the dose as a function of time. Does that make sense? From a typical accident?

Yes? Said a typical accident is about 1/5 fifth of Chernobyl. Chernobyl is 10 kilobecquerels per square meter of contamination for cesium. And the dose is 9 microsieverts per kilobecquerel per-- 9 microsieverts per year. I'm sorry. 9 microsieverts per year per kilobecquerel per meter squared. And then it decays, and so there's a decay factor

It turns out this number is really important. It affects the result a lot. And it is a number that is not fully agreed upon in the literature. I'll just briefly mention, we-- I just said there's a one to one conversion between grays and sieverts, which we know is the relative biological effectiveness for beta radiation. And gammas are about the same, one to one.

Technically, beta radiation is slightly higher. But if we remember the decay from cesium, most of the beta energy is carried away by the antineutrino. So for the most part, this is a gamma dose. So we really can just call sieverts and grays the same. So 9 microsieverts is basically what this says.

Now, that's only the ground shine dose. This is dose commitments due to-- see the top of the slide-- external irradiation. What about the stuff that you eat or that you breathe? Well, the UN also has data for that. They have these external radiation inhalation ingestion in total.

And so what we can do is we can just take-- we can calculate the other two by just taking the total, which is given as 220, and dividing it by the external, which is 150. And that is basically a weighting factor that converts the external only to the total dose from the other ingestion pathways.

People look confused. Who is slightly confused? You are. OK. So what we did is we-- the first thing we did is we calculated-- are we good up to here? OK, we're good up to the dose coming off the ground per unit time. And ther it decays. We're good with that.

So now, this is just the dose coming off the ground. And they have this chart that says for 150 times 10 to the 4 man sieverts from external irradiation, we would have 220 total. And basically, this is just a scaling factor. For every 150 from external, we would have 150 external plus 70 internal. 150 plus 70 is 220. So it's just a scaling factor to go up to include the effect of the internal dose. And so I just-- 220 over 150. I think I hope that gets you where we need to be.

AUDIENCE: But if it's external dose, and that comes directly from Chernobyl, then wouldn't the amount that you ingest be less, not more?

R. SCOTT KEMP: It is much less. It's about 69. But when you add 69 plus 150, you get 220.

AUDIENCE: Because that number is only external.

R. SCOTT KEMP: That number we calculated was only the ground shine dose. That's what this plot said here. This is external irradiation. You see at the top?

AUDIENCE: [INAUDIBLE]. But kilometers there. But-- sorry-- kilobecquerels there.

R. SCOTT KEMP: Yeah, so I converted-- so this would be 9.9 times 10 to the 8, which is 9 nanogray. And 9 nanogray per becquerel is the same as 9 microgray per kilobecquerel.

AUDIENCE: All right. Thanks.

R. SCOTT KEMP: Yep. Unit conversion. So this is our formula. And now we just need to say how many people were exposed. So it turns out the population of Europe has been very stable for a long time-- 730 to 750 million people. We can basically take it as a fixed value for the sake of our calculation. If you wanted to-- it's stable over the lifetime of what? Over several of these, several half lives. So 100 years. That's reasonable.

If we were doing this in Africa, we would need to have a time-dependent population, some place where the population dynamics are changing dramatically. But we just treat it as stable. So 750 times 10 to the 6 people. And then we're going to integrate that from 0 to infinity.

Now, going to infinity is not a big deal because almost all of it is decayed after some half life. It just adds little tiny bits at the end. So let's just cancel our units. Kilobecquerels cancels. Meter squares cancel. These years will cancel with these years. And what we'll be left with is something that has units of sieverts times persons, something like that, what we call person sieverts.

And so if you do the math, and you do the integral, you get 860,000 person sieverts of exposure. OK? Yep?

AUDIENCE: Sorry. What does person sievert mean?

R. SCOTT KEMP: Remember, because--

AUDIENCE: Sievert per person [INAUDIBLE].

R. SCOTT KEMP: Sieverts per person-- it's sieverts of dose times the number of people. So remember, because we're in the linear, we can use linear no threshold model. Say, a millisievert for 10 people would be 10 milli person sieverts.

AUDIENCE: If I have 10 millisieverts or whatever dose, and I have 10 people, I expect that that 10 millisievert is divided by the number.

R. SCOTT KEMP: No, no, no, no.

AUDIENCE: [INAUDIBLE]

R. SCOTT KEMP: No, because we're not taking the radiation-- That would be the case if I were taking the radiation and saying, OK, you have a little bit, and you can have a little bit, and you can have a little bit. But that's not what's happening here.

What's happening is I'm spreading the radiation everywhere. We have a background of radiation. And if I put one person there, I get one person sievert of dose. And if I put two people in that same field of radiation, unless they're standing so close that their self-shielding. But as long as I have one person here, and one person over here, and one person over here, the more people I add, the more person sieverts of dose I'm creating.

And so I give this person this 0.1% chance of cancer, and this person 0.1% chance of cancer, and this 1.1% chance of cancer. And now it's total cancers are going to be 0.1 plus 0.1 plus 0.1 total cancers.

AUDIENCE: So if I take [INAUDIBLE] millisievert, then the person next to me [INAUDIBLE].

R. SCOTT KEMP: Yes. It doesn't affect--

AUDIENCE: The more I take, the less [INAUDIBLE].

R. SCOTT KEMP: That's not-- yeah, the first description is correct. The second one is not correct. Yeah, exactly. Because it's just spread environmentally, not handed out like pieces of cake. It is not yellowcake.

So everyone good with this unit, person sievert? Now we need to convert this to cancers. So we actually know how to do this. We looked at this in class already. We can say-- if we have-- I'll go over here.

We have 860,000 person sieverts. And we saw that the excess relative risk of cancer was 0.64 per sievert. So the excess relative risk-- sorry. The excess risk is the baseline risk. Does anyone remember what the baseline risk is for cancer?

AUDIENCE: 20%.

R. SCOTT KEMP: 20% times 0.64 per sievert. And so if we take this, and we multiply it by 0.64 per sievert times 0.0.2 for 20%, this cancels. This is a m and this is cancers. 20% is cancers per person. That's the unit for the baseline risk. And so we have-- this number-- let's see-- person's cancer, and sieverts are canceled.

So we should be able to get the total number of cancers, which is 110,000 cancers. And you may not know this, but I know this. About half of cancers are fatal. So this is 55,000 deaths-- Europe only, cesium-137 only.

We don't have to take these people's word for it. We can also go to the National Academies. They have this fancy supermodel. Yes?

AUDIENCE: This is per--like this accident.

R. SCOTT KEMP: Per accident. Per typical accident. 1/5 fifth of a Chernobyl. Yes. So you don't have to use that plot and do it the way I just did it from first principles. You could look up one of these tables. They're here on page 280 of the National Academy's committee to assess the health risk from exposure to load levels of ionizing radiation, which is called BEIR VII.

They have this big 100, multipage, huge document where they try to calculate all the different risk models. And they have a relative risk model, and they have an absolute risk transport model. And they have it sex organized.

And they have it for all the different organs, and all these different things. And they can add it all up, and they give you these numbers. At the end of the day, for all solid cancers, 480 per 100,000 people exposed to 0.1 gray. So that's 480 solid cancers in-- this is for men-- per 10,000 person gray.

And here, we have the same thing. 704-- sorry, ladies. You're much more likely to die. This also is not cancers. This goes directly to mortality. You see at the top-- solid cancer mortality. So this is their statistical data on just mortality. 740 per 10,000 person gray.

And if we add averages. We say roughly, it's 50% men and women. Then 610 is the average of these two numbers. 610 deaths per 100,000 person gray. So let's do that here.

610 deaths per 100,000 person gray. And how many person gray did we have? 860,000 person gray, which is 86 times 110,000. So times 86-- 860,000 person grays. And 610 times 86 is, I think, 520 deaths. So it basically matches that calculation. That's nice to know that they both match. So pretty close.

So this is only cesium. Was this what?

AUDIENCE: [INAUDIBLE]

R. SCOTT KEMP: Oh, no. That is wrong by-- that is wrong by my math. What is 600-- they're not off by a factor of 10. What am I doing wrong?

AUDIENCE: A hundred [? thousands. ?]

R. SCOTT KEMP: Who has a calculator? 86 times 610.

AUDIENCE: [INAUDIBLE]

R. SCOTT KEMP: Typo. Yeah, they match. If they didn't match, I wouldn't have presented it. 52,000 deaths, not 500,000 deaths. 52,000 deaths. So that was only-- this is only from cesium. This is only in Europe from a typical accident.

So I mentioned that the other thing that we have to really worry about is iodine. And so let's just look at what the situation was iodine. This is from an UNSCEAR report. And what they do is they actually-- they carefully calculate all the iodine exposure out there. There's a lot of experimental assessment. And they have categories of evacuees, recovery workers, inhabitants of Belarus, Russia, and Ukraine, and inhabitants of distant countries. And they figure it all out what the dosing is.

And they have the collective thyroid dose only in 1986, because it doesn't really last that long. And they find if you add all these up, it's about 3 million person sieverts. And they have also the effective dose, not to the thyroid, to other parts of your body. And it's about 380,000 person sieverts. So this is about 3.4, Something Like 3.4 million person sieverts of dose from iodine.

And we don't have to do this whole decay thing because they've done all that. This thing is decayed all the way, and they're just giving you the final dose. So here it is. Here's the dose from Chernobyl. Here's the dose from cesium. Here's the dose from iodine. Here's some other isotopes that we could look at. And if I just rescale them all to our typical accident, here they are, rescaled.

So I can add them all up together. There are a bunch of other isotopes, and they get really tiny. So we don't have to worry about. So let's just take the top four. And it turns out 2.3 million person sieverts is the total dose instead of 860,000, which means it's about 2.7 times higher than we calculated for total deaths.

Yes? Everyone understand what's going on here? So we're just basically going from one isotope, and then I've done the same stuff for the other isotopes for you. And we can just go to the all isotope dose.

And then UNSCEAR estimates that for Chernobyl, they estimated 10 million person sieverts of dose to all Europeans, 16 million person sieverts to all the world. So their multiplier to go from Europe to the rest of the world was a factor of 1.6. I earlier made the argument using that Fukushima map that it was roughly a factor of 2. This is a little bit more conservative, so let's use this number.

So we would take our calculation of 55,000, or 52,000, deaths, and we would multiply it by 2.7, and multiply it by 1.6. So I average those together and suggested we use 53,000, and times 2.7 times 1.6, which gives us 230,000 deaths per typical major accident worldwide, all isotopes. Yes?

AUDIENCE: And then what-- are we going to multiply that by the frequency of accidents?

R. SCOTT KEMP: Correct. Yeah. So this is the basic result that you should have in your mind. The average large INES 7-- average according to this weighting that I showed you earlier-- accident kills a quarter million people from cancer and gives another quarter million people cancer that doesn't kill them.

And that's only the cancer effects. This is not the teratogenic effects and inheritable defects, the deterministic diseases, all the other stuff, heart disease, et cetera. All the other all-hazard mortality is not included. This is only cancer deaths. But it's a big source of death. So it's a good number to go on.

So quarter million people-- now, that sounds like a lot. That sounds like a lot. But you have to remember that coal is killing people all the time, and you just don't see these deaths from PM10, to PM2.5, from radiation from coal, et cetera. So we really don't know yet whether this is a big-- it's a very dramatic number, but we don't know if on average is big yet.

AUDIENCE: So what is the time frame for these deaths? Because it's not clear to me whether this means there'll be a quarter of a million deaths in month after--

R. SCOTT KEMP: No, no. They are spread out.

AUDIENCE: --20 years.

R. SCOTT KEMP: They're spread out over 100 years. Yeah. They just appear as people who just got cancer. This is your aunt who got cancer. Why did they get cancer?

And for some small fraction of the population, the reason they got cancer was radiation from cesium-137 that just happened to shoot a photon into their body and break the genome in the wrong way. And you can't tell. There's no way that you can figure it out.

And then because the background rate of cancers is already 1 in 5 persons, this is really just a tiny perturbation on that background. If you have 10 billion people, and 1/5 of them, 2 billion people, are going to get cancer, this is a tiny perturbation. You can't see it. So that's the problem, is that you can't empirically see these deaths, but they're there. They are caused by the accident. Yeah?

AUDIENCE: So how do we measure the, I guess, the frequency if the events are so sparse? [INAUDIBLE].

R. SCOTT KEMP: Well, that goes back to how did we get the dose response model? And that is basically this study, the atomic bomb survivors plus radiation workers, people who have higher doses, where we then build a model to see what those doses do. And we had this in the last class. We talked about why that model is only defensibly linear, and why we don't have a fancier model for it.

AUDIENCE: So we have the 230,000 deaths from a major accident, and I guess, how do we get that like a-- can we give that as a per year?

R. SCOTT KEMP: Well, yeah. You could assume that the deaths expose people according to the decay, so that most people are exposed right away. But then there's some time between when those people are exposed and when they become-- when they die from cancer. And that could be 10 years. So there's this smearing-- a delay and smearing.

AUDIENCE: [INAUDIBLE] get rid of. Like, if we were trying-- if we really wanted a per year [INAUDIBLE].

R. SCOTT KEMP: Order of magnitude from 1--

AUDIENCE: [INAUDIBLE] like over 100 years. But like, obviously, you can't [? divide by-- ?]

R. SCOTT KEMP: So it depends. If you're assuming there's a constant rate of accidents, or are you assuming one accident?

AUDIENCE: If we're trying to say there's a certain-- how people do [INAUDIBLE]-- totally other thing. But if you have an accident rate per year, what would that relative [INAUDIBLE]? We're trying to get that--

R. SCOTT KEMP: Then we're going to get to an accident rate per year. So maybe it will answer your question.

AUDIENCE: OK.

R. SCOTT KEMP: Yeah. Yeah?

AUDIENCE: Maybe this is a naive question. But if you can't differentiate, how do you pick a background cancer rate?

R. SCOTT KEMP: The background cancer rate is just the number of people who live-- who die versus the number of people--

AUDIENCE: [INAUDIBLE]. So it has nothing to do with how you delineate where it came from.

R. SCOTT KEMP: No. Yeah. It's just the number of people who die from cancer. Yeah. Yeah?

AUDIENCE: I guess it maybe kind of relates to previous questions, but how do we put this in perspective related to the background? Because if we look at 10 kilobecquerels per square meters times roughly 10 microsieverts per, it's like 1 millisievert per year that you get from this. I quickly looked up, what's the variation in background rate in Europe. It's anywhere between 1.5 to 5.8 millisieverts. It's like all of this disappears in the background.

R. SCOTT KEMP: That's correct.

AUDIENCE: [INAUDIBLE] doesn't show that the Netherlands, which apparently has the lowest background radiation, has significantly less cancer. So is the problem, then, that we're kind of including radiation effects in the relative risk background, and that's why everything is here?

But why don't we see in LNT a more drastic change in cancer rates than between the Czech Republic, [INAUDIBLE] is 5.8 millisieverts, and then the Netherlands is 1.5, if 0.1 millisieverts per year creates such a drastic difference [INAUDIBLE].

R. SCOTT KEMP: So I think you're asking-- regional variation and background can be, let's say, factors of 2, factors of 3. Certain very small regions are higher. And yet, you don't see factors of 2 difference in the cancer rate in those regions. That's because most cancers are not caused by radiation. Most cancers are caused by just oxidation stress in the body, by crap you're eating, by whether you're smoking cigarettes.

So already, the radiation-induced cancers are already in the noise. These are also in the noise, but they're not there. They are in the noise, but they're there. So it is incorrect to say, oh, well, lots of people die from cancer. Therefore, we should ignore this. Well, this accident did kill an additional 52,000 people. That happened.

Now, you can-- or in this case, quarter million people once we do all the calculation. Yes, the background is noisy and big, and everyone dies. But to say that it's insignificant is incorrect, if I can take that same energy source and replace it with something that doesn't cause any deaths, or many fewer deaths.

So it doesn't go away just because you can't see it. Because someone doesn't show up in the hospital, and they go, oh, this is a Chernobyl cancer. If we could do that, if we had the science-- everyone shows up at oncology, and they go, oh, yeah, this is from Fukushima, then the news reports would say, another 10,000 people died from Fukushima this year, and people would go crazy. It's the fact that we get to hide them that we don't have to take accountability for them, but they're still there.

AUDIENCE: Yeah. I mean, the question was more, why does an LNT show a difference in background between countries if it's so much smaller?

R. SCOTT KEMP: But the answer is because most of the cancers are not from radiation. Yeah.

AUDIENCE: I was just going to [INAUDIBLE]. Do you use similar models to analyze the amount of deaths related to cancer or other factors-- respiratory or cardiovascular or fossil fuels and natural gas and other types of energy sources? Or they would you use a different type of model.

R. SCOTT KEMP: You can only do such an easy model if there's a linear relationship between exposure and pathogenesis. So for a lot of diseases, which are not stochastic, which don't have a linear relationship, it will depend on thresholds, or there will be some nonlinear curvature. And that means you're going to have a much more sophisticated calculation of--

AUDIENCE: [INAUDIBLE]

R. SCOTT KEMP: Yeah, exactly. How many people from this plant, and how many people live downwind of that particular plant of coal plant or something, and breathe that PM2.5. And yeah, so it's a lot more complicated. We actually get off easy because of the LNT model in doing this calculation. Yeah.

All right. So let me keep going. So we've added the iodine, and we have this global dose, and the question is, do we believe Scott's number? I mean--

AUDIENCE: I will say no. No, I don't. But I take umbrage with the linear no-threshold model. I'm more in favor of the linear threshold model.

R. SCOTT KEMP: Did you come to class?

AUDIENCE: Yeah. Well, I wasn't there last time. I was [INAUDIBLE].

R. SCOTT KEMP: OK.

AUDIENCE: But the-- I mean, [INAUDIBLE].

R. SCOTT KEMP: Yeah. So this is where things start to go wrong. People are like, oh, I hate this number. Now I'm going to choose not to believe the linear no-threshold model because it saves me from having to deal with this number. I'm sorry. That's not scientific. You don't just get to pick a model that is not statistically defensible because you don't like the result. So I appreciate that people do this all the time, but we're not going to do that here. All right. Two more questions, then I need to move on.

AUDIENCE: I was going to say, does it really matter? If we know-- if there was some theoretical threshold, if it was really small, how much does that really affect the-- would it be magnitudes, or if it's a threshold that small--

R. SCOTT KEMP: It could have a significant effect. I don't know if magnitudes, but it could have a significant effect. But the argument, the mechanistic argument against the threshold, remember, is the fact that in low LET radiation transport, you have Compton scattering and photoelectric effect.

So you have these chains. You can create double strand breaks. Double strand breaks are basically difficult to repair. A single photon can cause a poorly repaired double strand break that then causes cancer. As long as that chain of physics is possible, there cannot be a threshold. So I don't see any basis for believing there's a threshold. It's neither empirically defensible nor mechanistically defensible. Yes?

AUDIENCE: With such a marginal change from background having [INAUDIBLE] effect, I wonder how this would stack up against other industries that cause harm, arguably. How would this compare to the increase in deaths caused by McDonald's, [INAUDIBLE]?

R. SCOTT KEMP: Oh. Probably-- yeah.

AUDIENCE: Tiny.

R. SCOTT KEMP: Tiny, yeah. No, there are-- driving your car, eating peanut butter, which contains aflatoxin, choosing to walk on the side of the road versus not walking on the side of the road, wearing a bicycle helmet-- these things have huge impacts on mortality. Yeah?

AUDIENCE: So your point isn't that this number should then be used to justify or not justify nuclear, but instead, be used for comparison.

R. SCOTT KEMP: Only that. You can only take this and compare it to other technologies which are also killing you in other ways. That's all you can use this for. Yeah. This is not-- because 250,000 feels big, it's not an argument against nuclear. Let's be really clear about that. It is not an argument against nuclear. And in the last half hour, I want to get to that comparison. Yeah?

AUDIENCE: This is really only for comparing other energy forms. We can't compare this number to--

R. SCOTT KEMP: Peanut butter. Correct. Because they're not a substitution. But we can compare it to other forms of electricity generation, and that's what we should be doing. So let's do it.

So first, I want to talk a little bit about whether we believe this number. Because how many people have heard 4,000 people died from Chernobyl? Yeah. OK. Where did that come from?

So here are the published estimates-- 4,000 deaths, 9,000 deaths, 16,000 deaths, 40,000 deaths, 60,000 deaths, 270,000 deaths. But you have to look at what is being assumed. Only the most exposed cohort of people, and only in three countries. Same people-- this is where the 4,000 deaths come from. It was a study done by the UN Chernobyl people. It was actually done pretty shortly after it was reported in 2005.

Then they said, oh, we'll look at all people, not just like the most exposed populations. And then that number went up to 9,000. Then the World Health Organization research on cancer came up with a number up until 2065. Only Europe of 16,000.

A group of independent scientists out of the UK didn't like the stuff that the UN was doing, with only reporting subsets of the population, and only the people in these three countries. And they felt this was unfair. So they produced these reports. One in 2006, and one in 2016-- 40,000 and 60,000. This one is still limited to Europe. This one is global. And then you have this Greenpeace report-- 270,000.

So all of these credible people come out less. Roughly, one fourth to one fifth of the number that I came up with. So why is that? So the answer is that they use a 1980s US Department of Energy report on the contamination to dose factor. That is, this factor. Remember this? And I said this was controversial. They used a number that reads 0.2 here.

That 1980s report doesn't have any justification for that number. They just tabulate numbers for a bunch of isotopes, and that's it. So why did I use this one? I used this one because after Fukushima, the French Institute for Radiation Protection went to the Fukushima site using an energy-resolving radiation detector, like a high purity germanium detector. And they measured the photon flux off the ground. And then they measured the contamination on the ground, and they calculated it. And the number that they got was 0.86.

It basically matches this number. And that's the most recent scientific validation of this. So I use this number because it's been validated twice, and we know how it was done. And the other number that people have been using for this report seems to come out of nowhere.

Now, here's the caveat. That measurement was done four months after the Fukushima accident. So it is possible, in fact, likely, that there is a kind of washing away effect, where stuff slowly settles into the ground and becomes less available. And therefore, the dose slowly decays from physiochemical changes in the soil. And so we would expect, actually, some kind of decay for this.

So unfortunately, there isn't any good studies, and it's all extremely dependent on the soil chemistry of where you live. But there is one datum taken six years after the Chernobyl accident where they did this dose estimation. And if I take that one datum, and I fit an exponential decay model to it, then what I would estimate is that the cesium contribution would actually be about a fifth of what we calculated, which explains exactly this differential integrated over the lifetime.

And therefore, if we go back, and we take this number and this number, and we multiply that times a fifth, you get a smaller value. Let's see if I have it in my notes here. Oh, it's about 60% total dose change, since a lot of this dose comes from iodine which doesn't have that effect.

So somewhere between 60% of a 230,000. And 230,000 is the number that I think we should go with. But that is why there's a lot of discrepancy in the literature, is about how you assume the dose response would be, or the contamination to dose would be.

So now let's put some-- let's convert this into money. So we'll have this in mind that-- I'll just write it here-- somewhere between 230,000 and 0.6 times 230,000 deaths. I'll use this number. And then at the end, I'll put this back in.

So how often do these accidents occur? So one of the problems is that we don't really know. And one way that this is often done is using PRA. And I already talked a little bit about PRA in this class. It's a bottom-up approach where you build these decision trees. And then for every kind of event you have to have some probability that you assign to it.

And one of the problems with this is that, well, you need to know a lot of things. You need to know every branching probability. And you probably have never observed most of those branches happening. And so you're kind of like guessing at it. And it's a little bit of a garbage in, garbage out model.

Plus, you have to decide which trees you're going to put on here. And one of the problems is that a lot of historical big accidents have followed paths that were not in the PRA model at the time that the accident occurred. So we don't really have a priori belief that the PRA is complete. They call this-- so one of these is-- they call that model uncertainty, and they call the uncertainty with all these branching points, epistemic uncertainty. And there's a lot of uncertainty in these models.

Nevertheless, the practitioners of PRA-- well, the careful practitioners of PRA would never say that you should take a PRA model and take the final result and use it as a measure of the safety of a reactor. All they will say is, well, if I change this thing versus changing that thing, what is my relative change in safety? And that's a totally valid and good use of PRA.

But there's unfortunately this temptation to take the final number and treat it as a true number. And the NRC has recently adopted this view when they do back fit. And it makes sense for back fit, because maybe you're looking at things which are explicitly in the model, and you're looking about, how am I going to change some piece of hardware to change this value here? So you can justify the use of PRA back fit from the perspective of relative safety change.

But you can't if you're going to do a cost-benefit analysis, which then assumes a certain absolute accident risk. That's the problem. And we have now this discussion of risk-informed licensing, where this is what people want to do is take this approach and assume it to be the true measure of safety of an accident.

And that's not a good choice because essentially, we are favoring a model that we know to be a, a model, b, incomplete, and c, full of inputs which we are highly uncertain of, in favor of empirical data. In Occam's razor, which we talk about, would say any time you have a model with enormous numbers of inputs, you should be biased against it because it's probably missing something or leading you astray.

Let's look at the results produced by these models. So here's the core damage frequency, and this is the large, early release frequency. This is the closest thing we have to a big nuclear reactor accident. And these are for results for AP 1,000, the EPR in Europe. There's the Chinese-- I'm going to put a Gen 4 reactor in there. This is HTPM from China. And then here's the models for these. These are not really widely published. You have to talk to people to get these numbers-- operating VWRs and PWRs.

And so you can see what the results are. EPR, I think they're really doing a good job. They're basically just saying, we don't really know-- something less than 10 to the minus 6. Incidentally, EPR has a lot of fancy safety systems compared to AP-1000, but it's much more expensive. But AP-1000 people-- Westinghouse is willing to put two digits of significance and claim this enormous exponent of safety. And I think that this is a pretty dubious claim. I think EPR people are doing better at it.

So if you believe these numbers are the true measure of safety-- yep?

AUDIENCE: I may have miscaught it. What's the unit frequency, from what to what?

R. SCOTT KEMP: These are events per year.

AUDIENCE: Per year. Thank you.

R. SCOTT KEMP: Yeah. So 10 to the minus events-- eight events per year. So if you assume this to be correct, we would say how many large releases would we get over 50 years? Assuming 80% of global electricity came from nuclear, and we have a linear growth from where we are now to get to that in 50 years.

And so I've done the integral for you. And look, I mean, basically not zero. You would have no accidents, even though 80% of the power in the world came from nuclear. Here is less than 0.4. Only for existing operating BWR would you have more than one accident per year. If you're in this regime, you would have a problem. Can you imagine having a large nuclear reactor accident every single year?

AUDIENCE: [INAUDIBLE] 50 years?

R. SCOTT KEMP: Oh. Yes. Yes, you're right. Yeah. So this would be-- that's right. This would be roughly one every 50 years. So that's basically where we are now. So that would be fine. That would be fine. Well, I don't know about fine, but that's--

AUDIENCE: It's not bad.

R. SCOTT KEMP: It's not bad. It's better than what we've seen historically.

AUDIENCE: [INAUDIBLE]

R. SCOTT KEMP: Yeah. So this if these models are correct, we really have nothing to fear from nuclear. But the problem is that the history is not comport with that. So these are the actual accidents, different INES scales. There's Chernobyl. There's Fukushima.

The ones that are not black, the open circles, these are nonreactor fuel cycle accidents. So they are associated with nuclear power, but they are not reactors. So this is a Soviet fuel reprocessing site. These are also such sites. And you see that they also can contribute significantly.

Another thing to see is that this basically kind of like a power law. We expect more accidents as we get to lower intensity; fewer accidents as we get to worse intensity. But it's not exactly a power law. There's only one INES 6. That's probably because of quantization noise. We're a little bit undersampling.

And the other thing to point out is that the accident rate is decreasing, at least for category 4. So maybe things are getting safer. I would argue that they have been getting safer. We're better at safety.

So what should we assume for these big accidents? So here's the thing. These large INES 7 accidents are typically what we call design beyond design basis accidents. That means we did not do things to the reactor to prevent these accidents from occurring. So although we are improving the reactor safety for small events which we are designing for, we are not doing anything to deal with these beyond design basis accidents.

AUDIENCE: Well, that goes-- doesn't go for Chernobyl, though. You can't just pull out all your [INAUDIBLE]. I get it from Fukushima, but Chernobyl, I feel like it's kind of the equivalent, from an operator standpoint, of getting blackout wasted, driving your car into an [INAUDIBLE].

R. SCOTT KEMP: Yeah. But that's-- exactly. That's why it's beyond design basis accident. It's like the operator did something stupid. And there's nothing to say that some operator of the future won't also do something stupid. There's going to be all kinds of these things that haven't happened that you can imagine-- terrorist attacks, whatever-- that could result in intentional sabotage. So there are going to be these events, and it's going to be really hard to know what their frequency is.

What I suggest is that in the absence of any good guidance about how often these things will occur, the best, most defensible thing we can do is just take the historical rate and say, that's what we've seen for these beyond design basis accidents. Anything else, you're injecting some additional information. And I don't know that we have any additional information.

So here's the history of reactor. We have 21,500 reactor years of experience, and expectation over 50 years with no growth would be about two reactor accidents, which is kind of what we've seen. But if we did-- again, here's where I was going to make that point earlier. If we did have that growth to 80% electricity, we would be at 40 INES 7 events every 50 years, which would be roughly one per year, and then we would have a problem.

So this is the problem with these events-- a major global expansion of nuclear power. Unless this beyond design basis number somehow comes down, it still presents an ongoing problem that we have to deal with that would basically kill the public acceptance of nuclear, I would argue, at roughly an accident a year-- giant accident a year. Yeah?

AUDIENCE: Could we also argue that if we saw an increase in these types of accidents that were, like you were saying, beyond design basis, human error, and we start-- if we have those more often, would we not then be, I guess, incentivized to make that more safe more quickly.

R. SCOTT KEMP: I would hope so. So we would have thought that after Fukushima, we would have made-- we would have added filter vents, and most of the world did. But the United States said no. So it depends. If it's happening every year, I think political pressure to do it would be a lot more.

AUDIENCE: [INAUDIBLE]. I guess-- I hope we did learn not to site them in places that historically have tsunamis.

R. SCOTT KEMP: Hopefully, we did. We'll find out. We'll find out.

AUDIENCE: Probably not.

R. SCOTT KEMP: This is the problem. I think memory is short. It's like there's some half life associated with learning from these events. In the immediate aftermath of Fukushima, everyone is angry at nuclear. Everyone hates it. Enrollments in nuclear engineering drop. And then three years later, everything creeps back up and people forget. So we'll see.

So we can just take these numbers, and we can calculate a large early release frequency. I guess you can't really see that this is red. So if we take that rate, and we take the existing fleet, and we take the weighted average, we would see that we would be at 4-- sorry. This is the PRA result. We are at 2 times to the minus 4. The PRA result for the existing fleet says we should be at 4.5 times 10 to the minus 6. This is the evidence that the PRA result is incomplete.

PRA has said the reactors operating today had this accident rate, and this is the rate that we've actually observed. It's a factor of 50 times difference. So the PRA is only capturing a small fraction of the total risk.

Let me see if I can blast through and finish this up. So here, we can pick-- various is the NRC safety target. Here's a historical accident rate for all events over 5 to match the safety target. Here's the true historical rate for only INES 7.

If you go back and look at this plot-- if you look at these other events, pretty tiny releases-- 0.2 petabecquerel, 0.013 petabecquerel cesium-- tiny. Only these big things beyond design basis matter. So my suggestion is we just ignore all these other accidents. They don't matter. Only things that matter are the beyond design basis accidents.

And so we'll take only the beyond design the INES 7 rate as our accident rate, and we'll ignore all these others. And that is 10 to the minus 4 per reactor year. And if we assume that every reactor is roughly a gigawatt, it's 10 to the minus 11 per megawatt hour.

And then we can take our number of deaths-- so 10-- we want terawatt hours, which is 10 to the 12 watt hours. And that is equal to 10 to the 6 megawatt hours. And we had, from the previous slide, 10 to the minus 11 per megawatt hour.

So the accident rate is 10 to the minus 11 accidents per megawatt hour times 10 to the 6 megawatt hours per terawatt hour. And that gives us-- what is it? 10 to the minus 5? 10 to the minus 5 accidents per terawatt hour. And 10 to the minus 5 accidents times 230,000 deaths per accident is equal to 2.3 deaths per terawatt hour.

So now we can put our number on the chart. There it is-- 2.3 deaths per terawatt hour. And if we assume the washing away effect of the cesium, it goes down all the way to 1.4.

So is nuclear safe? Yes. Nuclear is a pretty safe form of energy. It's not as safe as they said it was. It's a lot worse than that. But it's somewhere between hydro and natural gas. It's relatively safe. Yeah?

AUDIENCE: [INAUDIBLE] the other-- if they got nuclear wrong, what [INAUDIBLE]?

R. SCOTT KEMP: Oh, thank you. Yeah. We really shouldn't trust anything on this chart now. So what we're going to do, maybe in the next class, is we'll look at other calculations for these other factors. Yeah. And why don't I stop there. Yeah.