TEACHING ASSISTANT (TA): So if you guys don't remember me, I'm one of your TAs. I'm TA number three, that's what I call myself. I'm Ka-Yen. And I'll be teaching your lesson today because, well, Mike's in Russia. So, yeah. Yeah, so I know you guys had your first exam a couple of days ago. How did that go? OK, sounds good. All right, so we won't talk about it. But because you guys just had a super intense exam, we just want to give you guys a break. So today, I'll be teaching you guys a little bit about nuclear energy. So this lesson won't be super in-depth. There won't be a lot of crazy intense math. Actually, there won't be any crazy intense math because we just want to give you guys a break. You guys are going to be starting up full cycle on Friday with really cool topics like stopping power. So for now, we're just kind of like-- it's a refresher.

A couple of fun facts. A couple guys might already know some of the concepts that I'm mentioning, because you guys are intelligent people. But I walked into MIT not knowing a single thing about nuclear energy. I was like, I wish someone could have told me these things. So that's what I want to do for you today, OK?

So I'm going to be talking about the functionality and the benefits and the problems associated nuclear. But first let's start with a very brief history in a nutshell. So between 1895 to 1945, that's really cool people were developing nuclear science. So people like Madam Curie or like Fermi, et cetera. They were all designing this nuclear science, like they were developing it, which is pretty cool.

Most of this development happened between 1939 and 1945. Does anyone want to take a gander as to why? What?

AUDIENCE: Manhattan Project?

TA: Yeah, exactly. But what field of the Manhattan Project?

AUDIENCE: Nuclear weapons.

TA: World War two. Yeah. So World War two was happening during those times, and they were trying to develop the atom bomb, which is why the majority of nuclear science was developed between these like five or six years. Then 1945 to 1960. They've entered a phase of like, well, the war is over. Now what do we do with ourselves?

So luckily we decided to redirect this science into using it for energy and harnessing it in a controlled fashion. So mainly the focus was actually for Naval submarines, but they also realize that we can use this for energy as well, for electricity as well. So there's a lot of really cool things that happened in between these years. So in 1951, the first nuclear reactor to produce electricity was the experimental breeder reactor, the EDR1 was developed and designed and operated, and actually kind of worked. It was created by Argonne National Labs, which is in Idaho. And they actually still exist. So if you want to go work there this summer, you totally can.

And then in 1953, President Eisenhower, he created something called atoms for peace. So this is just a program that advocated using nuclear for things that were peaceful, such as electricity instead of nuclear weapons and stuff. Also 1953 was the creation of Mark 1. So Mark 1 is the first prototype Naval reactor that was created. It was created in March. And then finally in 1954, the first nuclear powered submarine, the USS Nautilus was launched, and is up and running. So lots of cool things happened between this time.

But the real heyday of nuclear was actually between 1960 to 1975. So during the span of 15 or so years, this was the real commercial energy boom. People like Westinghouse were creating nuclear reactors. I think the first one was called Yankee Rowe. It's a 250 megawatt electric nuclear power plant, which is not insignificant for a time like the 70s.

So other different companies and other different countries were doing this as well. basically, there was this huge boom in nuclear energy. So if you look at this little chart over here, this is nuclear reaction construction throughout the years. So if you look in this little chunk, you can see what a massive peak there was. This was when everyone was building nuclear reactors, people thought it was super jazzy, and everyone tried to jump on that.

Unfortunately, all good things have to come to an end, though. From 1975 to 2002, which is about this chunk over here, you can see a massive decline. And you can see that nothing really happened between the 90s and the 2000s, other than the fact that we were all born. But no new nuclear reactors were being commissioned during this time.

And then today, we're kind of-- I say we're back, but basically we're entering what people like to call a nuclear renaissance, which is between this chunk over here. You can see that there's been a slight increase in nuclear reactors being produced. But basically there's been a whole new push for creating more advanced reactors. And currently, China, India, and South Korea, they are the main players in this game. So China itself has 32 operate reactors operating at the moment, and have 20 more commissioned, like literally right now, which is kind of insane. So yeah, do you guys have any questions about this? Great.

So what causes nuclear resurgence? This is the perfect time to talk about why nuclear power's cool. Again, you guys probably know this. But the main reason is sustainability. So right now we've entered a phase in time where people are starting to realize that we've done damage to our environment, we've got to fix this. So global warming is a thing. I promise you, it's actually a thing.

And basically, we're looking for a way to produce electricity without creating such a large carbon footprint. So if you look at this chart over here, you can see that this is where nuclear lies in the amount of carbon that it produces per-- what's the unit? Per gigawatt hour of electricity. When you look at that in comparison to coal and natural gas, which is our two primary sources of energy at the moment, you can see that this is definitely more attractive. So the statistic is actually that nuclear creates 75 times less carbon emission than coal does, and 35 times less than natural gas does, which is incredible and amazing. So that's the main reason why we're going for nuclear.

But there's other kinds of really good reasons. One is the amounts of power output. You guys actually calculated this yourself in pset 1. You know just how much power or energy comes out from one fission reaction. So just so you guys can double check that you got that statistic right in your pset, it turns out that

It turns out that you get 3.5 million times more energy than burning one kilogram of coal does. So you can see that you definitely need a lot less fuel in a nuclear reactor than you do in a normal coal burning reactor. And then finally the last thing would be energy security. So one of the good things about nuclear is that it can serve as a good baseload source of energy.

So if you're working in the energy sector you probably see this chart all the time of like time versus like energy that's being consumed. And it's kind of like this fluctuating little mass that stays fairly constant, but at certain times of the day you need more energy than usual. So this is just the energy demand during the day. That's what this chart kind of crudely depicts. So nuclear power is able to provide a good baseload source.

That means it can provide conserve energy at a really high level all the time. So this is why we kind of want to replace coal and natural gas with nuclear, because it can take this role. Other alternative forms of energy might be better for the environment, it might be safer, and things like that, but it's not really able to do this. So for example, if you wanted to replace all the coal burning fire plants with solar panels, if it's not sunny that day, you're kind of out of luck, right?

Like you can't produce energy if it's not sunny outside. Similar for wind. If it's not windy outside, you're not getting any electricity. Luckily for nuclear, it doesn't have to rely on any of these factors. You can continuously produce energy. Right? So do you guys have any questions about what I've mentioned? Awesome.

So now we'll talk a little bit about reactor types. I'll just tell you guys about some of the main ones and how they work. So how people like to divide up the reactor types is in generations. So generation one, which, is all the way over there, that refers to the trial reactors. These are the ones that didn't really produce all that much electricity at all. They're more proof of concept kind of things, so that would be like the Mark I that I mentioned to you guys earlier.

Now we move on to generation two. So generation two is actually what most of US reactors-- the category that most US reactors fall into. So these were developed between the '70s and the '80s-ish, and these are the ones that are functioning mostly today. And then we have generation three, three plus, and four.

So these are the new types of reactors that people are trying to build on to create several improvements, but we'll talk about them a little bit more later. OK? So I want to start off with light water reactors, because these are the reactors that are most common in the United States. So light water reactors, or LWRs, are mostly broken up into two subcategories: boiling water reactors and pressurized water reactors.

So how you guys can think about reactors is that honestly they're just kind of glorified steam turbines. That's what they're doing. So let's start with boiling water reactors. So boiling water reactors, or BWRs, comprise about 21% of the reactors that are located and working in the United States. So it's a really, really simple mechanism and we can walk through that right now.

So over here, this little nubbin right over here, this is the fuel core. So this is what the inside of a fuel core looks like, that picture over there. So the fuel core is basically just a bunch of rods of uranium, sometimes it's clad in something like zirconium, and there's also control rods to help slow down the process. So uranium undergoes what?

AUDIENCE: Fission.

TA: Yes, fission. So what gets released during fission?

AUDIENCE: Heat.

TA: And?

AUDIENCE: Fission products.

TA: Cool. And?

AUDIENCE: Neutrons.

TA: Neutrons, awesome. So those three things are all flying around inside the reactor core at the moment as the uranium undergoes fission. So the isotopes, we just kind of let them be. Like I don't-- I'm not completely sure what we do with them. We might filter them out, but I think they just kind of hang out there. The heat obviously goes to create power. We'll talk about that in just a second.

But the neutrons come flying around. So those other neutrons can simulate other fissions, and the control rods are there to make sure that there's not too many fissions happening in the fuel core at a certain time. Anyway, going back to the heat, the heat that gets created during these nuclear fissions, that goes and heats up the water. So this is just one loop of water, basically.

So the water flows through the core and heats it up. It creates steam so the steam goes and spins a turbine. The turbine creates electricity. And it comes back and gets recondensed. That's literally it. That's all that happens during a BWR. Yeah, that's actually just it. So a cool thing about the BWR is, because it's so simple, it's also incredibly-- well, not incredibly, but it is the cheapest option out there for creating nuclear power.

One of the downsides is just that it might not be as energy efficient as it possibly could be, or not be able to create as much power as it possibly could if it was a cooler technology. But yeah. Oh, and another downside is that because we have the nuclear material interacting with the water and-- so this is a coolant pump. This is a coolant tube. This is basically connected to a lake or an ocean or some other source of cold water, and that runs through the primary loop to cool down the water and recondense it into steam.

If there ever is a breach between these two, the chances of leaking nuclear material into the environment exists. Like it's not high per se, but with BWRs there is a higher chance of leaking radioactive material into the environment. So that's one of the downsides of BWRs. Do you guys have any questions about this? Awesome.

So I just want to show you guys this picture again, because here's the underside of a BWR. I make it sound like it's super simple and like a walk in the park, but this is actually the amount of technology that goes into one of these reactors. Like look at all those wires. I don't even know what they all do. But it's kind of insane.

So the next kind of reactor that falls under the light water reactor category is the pressurized water reactors. So PWRs are actually more important, if you will, than BWRs. So remember, BWRs comprise about 21% of the reactors in the United States. PWRs comprise about 60% of the reactors the United States. But they are functionally essentially the same, and it's just slightly more complicated.

So over here we have our fuel core again, and again all it's doing is heating up water with its fission reactions. But this time this water is pressurized. So does anyone know why you would want to pressurize the water? Yeah?

AUDIENCE: So it doesn't boil?

TA: Yeah, exactly. So when you increase the pressure, you're also increasing the boiling point of the water, and that allows you to function at even higher temperatures than if you're working with a BWR, which gives you more energy efficiency. You guys will learn all about that in 2005, by the way. So yeah. It heats up this pressurized water and this pressurized water goes into a second loop which, again, just heats up water. That turns into steam, that spins a turbine that creates electricity, gets recondensed, et cetera.

And that's, again, all that there really is. So one of the upsides of using a PWR is, like I mentioned, the higher efficiency. But also the chance of leaking nuclear material into the violent becomes mitigated. Because you have two separate loops with the nuclear fuel being more isolated from the environment, if there is a breach between the condenser loop and the secondary loop, not a big deal. Nothing really bad happens. You'd have to have breaches in both the loops, which is very unlikely to happen.

Yeah. So do you guys have any questions about those two? Yeah?

AUDIENCE: What's the standard like operating temperature of these kinds of reactors?

TA: I'm not completely sure, but if you Google it you should be able to find it very easily. OK. So this next picture is, again, just to show you that like I make it sound really simple and like a walk in the park, but it's really not. There's a lot going on. So this picture over here is basically just showing that there are a lot of redundancy systems inside these reactors.

Like we don't just have one single primary loop and if it fails, it fails. We actually have four at the same time, and this is just called the n minus two redundancy, something like that. OK? So the next kind is something much cooler. It's got a heavy water reactor. Actually it's just a little bit cooler. But the main heavy water reactor that everyone can kind of think of on their minds is CANDU, which is the one that's located in Canada.

So the only difference between heavy water reactors and the light water reactors as I mentioned before is that it uses heavy water instead of light water. Does anyone know what heavy water is?

AUDIENCE: Deuterium oxide.

TA: Yeah, exactly. So it's just deuterium oxide. So remember-- I'm sorry, this might seem inane, but this is water, right? And this is heavy water, where the D is just a hydrogen with two atomic particles instead. So one proton and one neutron. So the reason why they decide to use heavy water instead of light water is because heavy water has a much lower absorption cross-section than light water does.

So what this means is that when neutrons are flying around in the reactor there is a chance of it hitting a fission product and a piece of fissionable material and undergoing fission. But there's also a chance that the water that surrounds it will absorb that neutron. So if that neutron gets pulled out of the system you're not able to create any more fissions. This is actually kind of a bad thing because the whole point of nuclear reactors is to create heat and fission. So we don't want those neutrons to be absorbed.

You can see, if you look at those statistics, you can see that the absorption cross section of H2 or deuterium is like 0.00052 barns, in comparison to H1, which is 0.332 barns. So I'm bad at math, but I think it's like 600 times less, right? Maybe? Anyway, so you can see why deuterium would be a good option for this.

So because it's absorbing less-- because it has a chance of absorbing less neutrons as it undergoes its processes, you're actually able to use a lower enriched uranium, which is really great because that lowers fuel costs. Yeah. But the main downside of this is that, even though you're lowering your fuel costs, deuterium is really expensive. It's about 1,000 or so dollars per kilogram, which is kind of ridiculous because a kilogram of water is really not much at all, you know?

So even though you're counteracting the lower fuel costs with higher water cost. Also, because you're using your reactor with lower enriched uranium, you actually have to change out your fuel more often. That fuel gets spent more quickly and I'll describe that in just a second, and therefore you just have to keep replacing it more often than you would for a normal light water reactor. Cool? Questions about this one?

Oh, I forgot to mention, but aside from that, everything else with the heavy water reactors and the PWRs, they're the same mechanisms. And finally we're going to move on to breeder reactors. So breeder reactors are a really cool idea, and they were most popular between like the '50s and the '60s-ish in the very beginning of creating nuclear reactors. So what breeder reactors are are, again, they're essentially the same thing as light water reactors I mentioned you guys before.

But instead, now there's two little chunks of extra material. So do you guys know what the difference is between fissile, fertile, and fissionable material is? Cool. All right, so all right, let's start with fissile material. So fissile material is basically just the material that is willing to undergo fission with a thermal neutron.

OK. So basically when the thermal neutron gets absorbed by this fissionable material, it's going to undergo a fission. Makes a lot of sense, right? So do you guys happen to remember what the energy of a thermal neutron is? You guys calculated this in pset 1. Huh?

AUDIENCE: 1 eV?

TA: Lower than that.

AUDIENCE: 0.025?

TA: Yeah, 0.025 eV. Like super low energy. And while we're at it, how do you calculate this? Bozeman constant times T. Cool? Whew. So main examples of fissile material would be U235 and plutonium 239. There's four in total, but those are the two most important ones. OK. So this is the main fuel that is inside a nuclear reactor, but it's not all just U235.

Like you guys have heard of-- oh, shoot, what's it called? Enrichment, right? Enrichment is basically the amount of fissile material versus the amount of other fissionable material. So moving onto fissionable material. So fissionable material is just material that is able to undergo fission after the absorption of a more energetic neutron. So that's all it is. So that's all it is.

So an example of fissionable material that's inside the other reactors at the same time is U238. So if a U238 absorbs a thermal neutron, it's not going to do much. But if it absorbs a neutron of about like, I would say, like 2 meV, then it's more willing to undergo fission. Cool? And finally we have fertile material. So fertile material is the basis for breeder reactors. But fertile material is just material that absorbs a neutron and then is able to become a piece of fissile material.

So for our purposes, the main types of fertile material we use are U238 and thorium 232. So if you look at these processes you can see that U238 absorbs a neutron, becomes U239, undergoes a beta decay to come neptunium and undergoes one more beta decay to become the beautiful plutonium 239. If we start with thorium 232 instead, absorbs a neutron, becomes thorium 233, undergoes a beta decay to become protactinium, becomes uranium 233, which is another fissile material by the way, through a series of beta decays. Cool?

So that's what breeder reactors are doing. They're adding extra chunks of uranium 238 and extra chunks of thorium 232 into the reactor. If one of the neutrons-- so imagine-- if you're looking at the little fuel core, there's a bunch of neutrons that are flying around and heat and other isotopes and things like that. So some of the neutrons will go and create other fissions with the material that's hanging out in the red. But other neutrons might escape, and when they escape, instead of going into the water dissipating and never to be seen again or being reflected, they instead create more fissile material.

So you can understand why this is a kind of an attractive idea, is that you're creating your own fuel. You're able to work at a higher fuel efficiency because you don't need to add in as much fissile materials as you would for a normal light water reactor. So people were really fascinated with this idea, like I said, in the 50s and 60s. Because back in the day they legitimately thought that we would run out of U235.

But luckily in the 60s we discovered that we have a lot more uranium ore than we thought we did. We're probably not going to run out anytime soon. And after that discovery, people were not nearly as interested in breeder reactors. The reason being is that, one, because there's just this extra material that's hanging out, this extra material could be more fissile material that creates more reactions. It's not nearly as power efficient.

And it's also slightly more expensive because you're not being able to be power efficient. And it also is better on paper than it ever is in reality. So on paper you're like, oh, this is great, because I can just create more fissile materials. I never need to add more. This is never really truly sustainable. They always have to keep adding more fissile materials, because it's not as perfect as they want it to be. Any questions about these things?

Great. Cool beans. And then finally we're going to move on to generation four reactors. So generation four reactors are all the new kind of reactors that people want to build. So the primary objective for these new designs of reactors-- like, the ones I just told you guys about, they're all good and well, but we want to make them better, right? We want to make them cleaner and safer and more cost effective. Keep them robust yet sustainable, and also make them more resistant to people being able to divert materials into creating nuclear weapons.

So yeah. Here are the six kinds of generation four reactor types that were deemed to be the most promising. So there's gas-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, sodium-cooled fast reactors, very high temperature gas reactors, and supercritical water-cooled reactors. So I'm going to be honest with you guys. I don't know all that much about these and I don't want to like spew out information that might potentially be false.

So if you guys are interested, one, you can talk to other lab members or people in this department. I know they're-- mostly Mike's group, actually. A lot of people in Mike's group are working on molten salt reactors so you guys can go ahead and ask them about that. Or if you're interested you can read more about them with this hyperlink that I included over here. Hopefully he will post the slides online and you guys just click it and there's a awesome source all about these different kinds of reactors. OK?

All right. Any questions? Hi.

AUDIENCE: Do any of these actually exist, or is it all just theory?

TA: I'm pretty sure that they were just kind of proof of concept stage right now. Like there aren't any that are producing electricity in the United States, at least. Cool. Good question. All right. So all the things that we've mentioned before like how great nuclear is and all the cool applications of it and how simple and easy reactors are, why aren't we using more of it?

So currently in the US there's only 99 operating reactors that are producing electricity, which makes up about 19% or about 20% of the total electricity output in the United States. The main players are still, you would imagine, coal and natural gas. So this is actually even worse in the rest of the world. In the rest of world, there's only about 440 reactors spread around 30 countries and produces only 14% of the global electricity.

So these proportions are pretty low. And you're wondering, like, why aren't we using more nuclear power? What exactly is holding us back? So it turns out that the main things that are holding us back is just social, economic, and therefore like government hesitance to start using nuclear power more often. So the main reason why we're a little bit hesitant to start using more nuclear power is because of safety issues.

So nuclear-- none of us can argue that nuclear is like 100% safe. It actually does have some dangers associated with it, which is why it's so important that we're doing what we're doing. But if you guys look at this chart that I showed you guys in like the first or second slide, you'll notice that there are these events listed above. What are these words? Three Mile Island, Chernobyl, Fukushima, what are they?

AUDIENCE: Nuclear accidents.

TA: Yeah, so they're some of our biggest nuclear accidents that we've experienced in history. And you can see that after a nuclear accident you can see a pretty steep decline in the amount of nuclear reactors that are being commissioned. So this is especially noticeable at Three Mile Island, which is essentially the first nuclear reactor accident that we all had to go through.

You can see that, after Three Mile Island, you can see this massive steep decline in the amount of nuclear reactors being commissioned. This is probably causational. We can pretty much assume that. And then you can see that Chernobyl-- once Chernobyl happened, you can see like this also another massive decline. And again Fukushima, once again, with the amount of reactors being commissioned after the accident just declines dramatically.

So I'm assuming you guys probably don't know exactly what happened during each of these accidents. Like you probably know that they exist, but like what happened during them? So if you do know, sorry, but if you don't know, you're about to know. So Three Mile Island, which is the first one, it happened in 1979 on March 28. So Three Mile Island reactor is a PWR located in Pennsylvania. So during this time it underwent a core meltdown.

The cause of this is just the fact that there was some kind of mechanical or electrical system that prevented coolant water from being pumped into the primary system. So because there wasn't enough water coming to cool up the core, the core began to overheat. So as the temperature of the core rises, the pressure also rises. So they notice this and they're like, oh, shoot, we got to fix that. So luckily there is like a little emergency valve that you can see in this animation gets opened up and pressure gets released.

So that's all good and well, but unfortunately after the pressure's released, you should close the valve again and continue operation. But it became stuck. So this valve became stuck and they didn't realize that it became stuck because their equipment and their instrumentation wasn't able to detect that. So they continued to operate again but this valve was open, so there was actually water that was getting leaked out of this primary loop.

So because the water was getting leaked, they noticed that, oh, shoot, the pressure is dropping. Well, what do you do when the pressure's dropping? Apparently you have to make sure that there's not too many vibrations that could damage the reactor, so they shut off the coolant pumps. Or they lower the operation of the coolant pumps. So now there's water leaking out so the core is getting hotter, but then they also took out the water that is usually used to cool the reactor core, so again it's also getting hotter.

So this combination of events led to a core meltdown. So the core melted down. That's never a good thing, by the way. Yeah. And yeah, so the core melted down, the reactor wasn't able to operate anymore. But luckily at Three Mile Island there was containment that prevented radioactive isotopes from leaving the system. So they actually took a brief survey-- or not a brief survey. That's probably a long, long experience.

But they realized that the two million people who are around Three Mile Island at the time, within like a two mile radius or like maybe a 30 mile radius or something like that, they realized that they didn't get much dose at all. They collected about a total of 1 milligram more dose than usual. So to put that in perspective, an x-ray is six milligrams. So really nothing that happened at Three Mile Island other than they had to shut it down and they had to do expensive repairs.

But people weren't hurt. The environment wasn't damaged. It wasn't that bad of a situation. I think the effect was bigger in concept than it was in actual damage. Questions about Three Mile Island accident? All righty. The next reactor accident, the big kahuna I like to call it, is Chernobyl. So on April 25, 1986 an RMBK reactor that was located in Ukraine exploded.

So what they were doing at Chernobyl during the time of this explosion is that they're actually running, ironically enough, safety tests. They were running the reactor at low power to see how it behaves. So at low power, I don't think they quite realized this, but the coolant pumps in the reactor were also powered by the nuclear reactor being generated. So if they're running this at low power, their coolant pumps weren't getting enough energy to properly cool the fuel core.

So that was unfortunate, and they realized that this is a bad thing. So the reactor starts to go supercritical. So when they realize that the reactor was creating a lot more fissions than it should have been creating, they decide to insert the control rods. So thank goodness we have these high absorption control rods to slow things down, right? For some reason, I'm not completely sure why they did this, but RBMKs, they have graphite tipped control rods.

So as they lower the control rods into the water, this graphite tip, which doesn't effectively absorb neutrons, it displaced a little bit too much water than was necessary, and that caused the first explosion. So it went super duper critical and caused the first explosion at Chernobyl. Then, for some reason like a couple of minutes later, there's a second explosion.

They're not completely sure why the second explosion happened. To this day we can't really pinpoint why. It could have been like building up helium or just a ton of other fission reactions. But there's a second explosion that actually just blew this entire core apart. So that kind of stunk, but it did stop the whole reaction. Because a super critical mass was all blown apart, it was no longer super critical. It was fine. The whole debacle stopped.

But unfortunately, there was a lot of radioactive isotopes being spread into the environment. First of all, Chernobyl didn't have the same kind of containment that Three Mile Island had, so these isotopes were just able to go everywhere. And also the second explosion had a lot of steam with it that carried these isotopes even further than they probably should have gone.

So if you're looking at the statistics of Chernobyl, it turned out that 28 highly exposed reactor staff and emergency workers die from this radiation or from thermal burns during this time. And officials also believe that there is about 7,000 cases of thyroid cancer that occurred because of Chernobyl. They're pretty sure it was Chernobyl because these are all cases that happened in people who are less than 18 years old.

So you guys know that no one really lives near Chernobyl at the moment. It's kind of been deemed unlivable because these radioactive isotopes literally went everywhere in this environment. Like it was in the water, it was in the plants. It's not safe to live there. It's a pretty radioactive environment. Luckily we see that there are animals coming back now now. If you look on NationalGeographic.com there's like little deer roaming around Chernobyl.

But it's been about-- how long has it been, like 30, 40 years? People aren't advised to live here still. So Chernobyl was terrible. Questions? Yeah?

AUDIENCE: What does it mean for a reactor to go supercritical?

TA: Oh, yeah, sorry. So you guys will learn all about criticality in a little bit, but basically when I say supercritical it just means that there's way too many fission reactions happening. Yeah?

AUDIENCE: You said it went supercritical because it wasn't being cooled enough or?

TA: I think I might have skipped a detail. It wasn't being cooled enough so the water was evaporating and then it became supercritical because there was not enough neutrons being slowed down or absorbed. My bad, I'm sorry. Good? All right. So the next reactor accident that we were alive for, which is cool, was Fukushima Daiichi.

So Fukushima Daiichi happened in 2011 on March 11, and Fukushima is in Japan. So these reactors, I think these are pressurized water reactors. Yeah, I think so. So following a major earthquake, the generators that were-- pardon. Yeah, so following a major earthquake, the things that were cooling the core, they broke. I think they're just like power generators on the side that did-- yeah. They broke the cooling pumps.

So there wasn't enough water being able to go to the fuel core. This is a very similar problem, as you can see that in all these instances of the reactor incidents, it's just kind of like the fuel core was misbehaving and we weren't able to get enough coolant water to it. So following the earthquake, these coolant pumps broke. They're like, oh, that's OK. What we can do is we have backup generators to continue running the pumps. It'll be all OK. Nothing will happen.

We're all good.

And then a tsunami hit. So it was a foot tsunami I think-- I think that-- 15 meter tsunami, oh good gosh. So a 15 meter tsunami hit and it broke the generators and then at that point they're like, oh, no. So they had no other redundancy factors to continue pumping cool water into the fuel core. So again, there wasn't enough water in the core, it became supercritical, it began to melt. So the fuel rods began to melt, but this is actually another additional bad thing.

So the water was evaporating, creating steam. The fuel rods were coated with zirconium. So what you guys might not know is that when zirconium and steam interact with each other, that's not a good thing. It starts to explode. So as you can see, the reactors at Fukushima Daiichi began to explode. There was radioactive isotopes being spread out all around the country. You guys probably saw the lovely flow charts of the radioactivity flowing out from Japan and making it to California and contaminating your fish and stuff like that.

But luckily, no one was directly hurt by burns or radioactive exposure. Cool? All right. Questions about Fukushima? Solid. So aside from these safety issues, these safety issues that happen, they get elevated in the news quite a lot. So these are mainly the things that people who don't really have any background in nuclear energy hear about nuclear energy. They're like, oh shoot, well this thing is going to explode every 20 years. Like, why do we keep using this?

Reactor accidents are actually pretty rare. If you think about it, it's been about 60 or 70 years, we have 440 reactors operating around the country. There's three main accidents that have happened. But because these are the things that people get ingrained into their mind-- thank you, news stations-- people think that nuclear reactors are incredibly dangerous. And that's why we have this social hesitance, which is why we aren't able to get enough government funding and which is why there's all these bureaucracy loopholes to jump through, which is why nuclear power isn't more of a thing. Makes sense? Yeah.

Another issue that's associated with nuclear power is nuclear waste. So what in the world do we do with it? So first of all, the main thing in nuclear waste is spent fuel. So like I mentioned to you guys, spent fuel rods are made out of uranium oxide. But after undergoing a bunch of fissions, these uranium particles get transformed into other isotopes that aren't fissionable or fertile or even remotely fissile, right?

So we eventually have to replace them and add in new rods, and this is a process that happens every 12 or so years. I'm not completely sure on that statistic. But the main issue's like, what do we do with all this material? So this material that comes out is pretty radioactive and it's also incredibly hot, so it can be dangerous if someone decides to come and eat it. So that's why we've got to figure out a way to expose it.

So the primary way of disposing of the spent fuel is putting it into spent fuel pools. So spent fuel pools are just giant tanks of water that exist at the reactor. So these tanks of water are mixed with I believe it's boron, which is a neutron absorber. They basically just put the spent fuel rods all the way at the bottom of the pool. So this pool's about like 20 meters high, I think.

This is actually a really good solution because the water in the pool, it cools down the reactor rods and also prevents a lot of neutrons from escaping because water is a really great neutron moderator. You guys all know this. It turns out it's actually fairly safe. Apparently you can go swimming on the top of the reactor spent fuel pool and you'll be OK and not be exposed to too much radiation if you want. So yeah.

So this is the main solution that people have been using for years, but they realize that this isn't super sustainable, because the amount of space that we have in these spent fuel pools is not infinite. We have way too much spent fuel to be able to just continue to store it in these spent fuel pools. So like shoot, got to find another solution. So the next solution was something called dry cask storage.

So dry cask storage is just a way to keep this spent fuel surrounded by an inert gas. And it's held inside a cask, a cask just being probably like a steel drum that's bolted and welded shut, and then there's additional pieces of shielding around it like cement and lead, et cetera. So there's just like gigantic tanks basically that are sitting outside. So they put them outside the reactor. As you can see, it looks like it's sitting in a parking lot outside the reactor.

And so this is an OK solution. So basically what they do is they take a spent fuel, let it sit in the pool for about a year or so, maybe two or three years. And then they're able to take it out because at that point it's significantly less radioactive because, you know, you guys know how to calculate this, too. You guys know like the half life of different radioisotopes. You see that the radioactivity declines at a certain point.

It's also more cool now so they put them in these tanks, so they let these tanks hang out outside. And this is an OK solution, except for the fact that, again, we just have way too much spent fuel to be able to do this. It turns out that if you were to just keep all the spent fuel that we create in fuel casks, it'd take about 300 acres of land, which is absolutely insane. And obviously no one wants to take up that.

Brief little side note, when I was googling like images of dry cask storage and I was looking for the different types, what I found particularly disturbing was that there's only two types listed: vertical storage and horizontal storage. Like there's no other solutions other than these are giant tanks. Anyway, so people realize that we need to figure out yet another way to dispose of the spent fuel, hopefully a way that doesn't get in the way of people's backyards.

So the idea was something called deep geological repositories. So deep geologic repositories literally just means that they want to bury the nuclear waste very deep into the ground and never be able to retrieve it again. So the main push for this was-- well, first of all, it's a permanent method of disposal. They hope to put it in the ground and never have to think about it again, so therefore the regions that they choose to bury in the ground have to fulfill a lot of criteria.

So this criterion includes not having a lot of seismic activity. Because we are keeping this nuclear waste underground in these casks for like thousands of years, if there is a huge earthquake, those casks break, radiation gets everywhere. That's obviously not a good thing so we want to make sure that doesn't happen. We also have to make sure that there's not a lot of water that leaks through, because the water can carry the radioisotopes and carry them into the environment, which is something else that we don't want to do.

A lot of you guys chuckled when you saw Yucca Mountain. So Yucca Mountain is the primary push by the United States to find a deep geological repository somewhere in the United States so we can deal with our spent fuel. So in 2002 the main push for this began. They spent a lot of money. They spent like billions of dollars finding the perfect location to put our spent fuel. They had like nine different locations and they finally narrowed it down to Yucca Mountain.

They're like, yes, this is the one, and they started digging down deep into Yucca Mountain and making this happen. But then things weren't as peachy keen as they hoped it would be. So Yucca Mountain is located in Nevada. People in Nevada weren't happy about this. They're like, why are we getting tossed on nuclear waste? We don't even have nuclear reactors in Nevada. This is not fair. There was a lot of opposition.

And because of the social opposition there was government opposition and many loopholes we had to jump through, and so it was just becoming a huge disaster. They also realized that it wasn't as geologically sound as they had hoped. There's a lot more groundwater running through and seeping through Yucca Mountain than they thought there would be, so it's actually not as safe as they had hoped.

So there's a huge debacle. Basically the costs are rising, nothing much was happening, there's a bunch of different things preventing progression from happening. And then 2011, under the Obama Administration, he just called it quits. There's no more government funding to Yucca Mountain. It's been abandoned, as you can see from this lovely Google picture. It's permanently closed. And you can also see that like 14 people went out of their way to review Yucca Mountain.

But we're actually doing OK. It's at like 3.6 stars, just like a normal motel or something like that, so that has been abandoned. This idea has currently been abandoned in the United States. We're kind of still looking for other solutions, but we really don't have it figured out all that well. There is one other kind of way of dealing with nuclear waste, which is repurposing. I personally think nuclear repurposing is the coolest option out there.

And basically repurposing just means you take the spent fuel and you chemically separate out any material that could be continued to be used-- any fissile material that could be continued to be used in other reactors. So basically you take the spent fuel-- and it turns out that 96% of a used fuel assembly is recyclable. So you take the spent fuel, you take out what it is useful, you throw away what's not useful, which is also still radioactive waste that has to be put in a fuel pool or something like that.

But you have this precious fuel that you can put into another reactor. So this is actually something that France and other places in Europe, and Russia and Japan, they use repurposing quite a lot. For some reason the United States doesn't do it. So the reason being is that this is a really cool idea. It's like recycling. It's like very-- it's very clever. I think I think it's personally one of the cleverer solutions, but the issue is that it's kind of a really expensive process.

So repurposing fuel takes a lot of money and it turns out that the act of repurposing fuel actually costs more than just buying a new chunk of uranium 235, which is why we don't do it. It's not economically sound. So yeah. You guys have any questions about anything I've mentioned, about deposition of nuclear waste? Almost done. OK.

So all these are issues. Like, we have a lot of nuclear waste to deal with. It is kind of-- there is an inherent danger with using nuclear power. But the real thing that holds us back from just having nuclear power everywhere and creating about 90% of our electricity as we would hope it would is economics. So in this world, money really matters a lot. The economics of nuclear power is actually a really complicated topic and it changes depending on who you talk to.

There's a lot of factors that are involved, so you can include certain factors into your calculations like, oh, the cost of building the reactor in the first place or like fuel costs or operating costs or maintenance costs or the amount of money that comes out of damaging the environment. You can weigh all these different factors in, and everyone churns out a different number.

But basically everyone you talk to, if you look at this chart, yellow is nuclear power, the gray is coal, and the blue is the natural gas. But basically, anyone you talk to, you can see that nuclear is not nearly as economic of a source of electricity generation as any other of these ones I mentioned. Unless you talk to UK. UK thinks it's OK. But everyone else is saying that it's not as money efficient.

So where are all these costs coming from? So the primary costs actually lies with something called capital costs. So capital cost is basically the sunk cost of just building the reactor. Building reactors takes billions of dollars. It also takes tons of time. And because it takes a lot of time, interest rates also jack up that price even further. So basically it's just this massive investment they have to throw in immediately, and this is where most of the issues lie.

Like it's really hard to go to an investor and be like, hey, can I have a billion dollars to build this nuclear reactor? It's going to take five years and it's going to take 20 more years for you to get your profit back. How does that sound? No investor is going to be like, yeah, that's a good idea. That's the main reason why we can't get nuclear up and running. We have a lot of plants and we have the possibility to create a lot of plants, but we just don't have the money to do so.

Because it's a huge chunk of money, like I mentioned before, it takes a while to get your profit back. And also, if for some reason something happens, you have to stop building your reactor. You just lost a billion dollars. Like, there's no turning back, right? If you look at this chart over here, which is breaking up the cost of nuclear energy per kilowatt hour, I believe-- gigawatt hour? Kilowatt hour. Kilowatt hour.

You can see nuclear, coal, and natural gas. So this giant white chunk over here refers to fuel. So if you can look at nuclear power, the majority of cost actually doesn't come from nuclear fuel at all. It's just about $0.01 per kilowatt hour, as compared to natural gas, which the majority of the costs of electricity actually come from the fuel. If you look at operation and maintenance, again it's not that large of a chunk. It's about the same as maintaining a coal power plant. But then if you look at the capital cost, which is the dark gray color, you can see how massive that is in comparison to building natural gas and coal firing plants.

So yeah, I think that's the main thing. So because it is more expensive, we can't compete with other forms of electricity. People buy the electricity that's cheapest, not necessarily the electricity that's best for our grandchildren or something like that. Yeah, so that's why nuclear power isn't more of a thing, and that ends my pretty lengthy slide show. So do you guys have any questions about anything I mentioned?

If you guys are interested about any of these topics, like if any of these things piqued your interest, I recommend going to NRC.gov. They have a lot of really cool information. Let me write that down, because I talk quickly. That's basically where I got the majority of my information for the slide show, and it is a reliable source. It might just be skewed a little bit pro nuclear, so just keep that in mind.

But there's a lot of crazy sources out there on the interwebs. Take them with a grain of salt. Take NRC.gov with less grains of salt than usual. Or if one of these things really piqued your interest, you guys can take 22.04, which is really cool class that's offered here I think this spring, and if not this spring, next spring.

But basically it's called nuclear power society. It's taught by a guy named Scott Kemp. He talks about all these things and in a lot of detail and slower. So yeah, cool. So thank you guys so much for coming. I know you guys could have slept an extra hour, but instead you heard me ramble for an hour.