[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: So this class is for people who have no background in nuclear. And I think some of you are probably here and have a background in nuclear. So I apologize if you find this boring. You don't have to stay. If you see people leaving, that might be why. But we certainly have people in this class who are lawyers, who are young undergrads who have not yet taken 22.101, people who are joining nuclear engineering as grad students, but from a different discipline and don't really know what nuclear reactors do, maybe from chemistry or from physics.

And so this class is to put everyone on the same page. The material that I'm going to cover in this class is not material that you need to know to do the rest of the class, but it's material that I hope will give you some kind of grounding so what the hell we're talking about. And so we're just going to start with how nuclear energy works and then talk a little bit about how reactors work. So we'll start with physics, reactors, and energy extraction, and fusion reactors, fission reactors, and then fusion reactors at the end.

All right. Any questions about the paper or anything else before I get started? Super. Yes.

STUDENT: Does it have to include some quantitative analysis?

PROFESSOR: It does not have to include. However, I generally encourage it to include. And the reason I encourage it is because, as engineering students, most people are comfortable with quantitative methods. And so it's a way-- it's an easy toolkit that you have access to answer a question. And often you see if you can drill down something to something where you can do a calculation, that's nice. There are other acceptable methodologies, qualitative, political science, legal. All of those are acceptable.

But if you are not well practiced in those methods, you are probably going to make a mistake. So I encourage quantitative, but it is not required. Yeah. So let's look at energy at the atomic scale. So energy is this measure of motive power that you can use to do things. If you took physics, you know of the unit of joule. But when we work at the scale of atoms, we prefer a different unit because the joule is just way too big.

So we use this unit called the electron volt. And it is defined as the energy required to move one electron up 1 volt of potential. So if you would think in your AA battery, which is a 1.5 volt, and you need to move one electron from one electrode to the other electrode, the amount of energy it would take would be 1.5 electron volts. So that is the energy. Now, to put that in context, our macroscopic unit, the joule, is the energy to move one Coulomb.

The Coulomb is a count, total number of electrons up 1 volt in potential. Wow, this thing is jiggling around. So it turns out the conversion is 1.6 times 10 to the minus 19. This is a very, very small amount of energy, and that's why we just, instead of having these huge exponents, we just use this unit. All right, so we'll talk about electron volts all the time. Electron volts, electron volts. You hear me say it a lot. This gives you a sense of the scale.

All right. So let's talk a little bit about nomenclature around the atom. Many of you who come from physics domains will, of course, know this. You know that the nucleus is made of protons, which are positively charged, neutrons, which are neutral. And we call together these things nucleons. So when we count the total number of balls in the nucleus of an atom, we say they have so many nucleons and we add them all up, neutrons plus protons. We use the letter Z for protons.

And we get a number that we call a mass number. So this is uranium 238. So named by the mass number, it means it has-- uranium means it has 92 protons. 238 means it has 238 protons and neutrons. And so what can change between other forms of uranium? The number of neutrons, this part. That can change. But we never really talk-- we never index atoms for whatever nuclei by the number of neutrons, which happens to be 146 here. But we just talk about it in terms of the number of protons, which is the element, and the number of nucleons, which gives us its weight.

Roughly, a proton and a neutron weigh the same thing. So what are the protons doing? Well, they are contributing coulombic repulsive forces. This is electrostatic forces, just like what causes your hair to stand up on end. They are contributing something called the weak force, which we're not going to talk about, but has to do with beta decay. And both of these are contributing something called the strong force. And the strong force is what is really gluing the nucleus together.

And so let's talk a little bit about the strong force. The strong force is a little weird. So this is a plot of the potential energy on the left versus distance between two nucleons. And this is a plot of the strong force. I didn't plot here the coulombic repulsion, which is also in play. Coulombic repulsion just goes as 1 over r squared. So we would see that this thing would have a kind of curve like that.

The strong nuclear force doesn't just pull or push uniformly like the coulombic force. It has this minima here. So what this is saying is there's an energy minimum, which is to say a favorable plot right here below 1 fm. Does anyone know what an fm is?

STUDENT: Femtometer?

PROFESSOR: A femtometer. 10 to the minus 15 meters. So a very tiny distance. It's the approximate distance between nucleons. So you can see that as you go to shorter distances, suddenly, this force becomes repulsive, which is to say its potential energy becomes positive. And so if you try to cram these nucleons together, they push back. If you go to longer distances, it never becomes positive, but just falls off and becomes weaker, and weaker, and weaker.

And it quickly approaches zero. It's right out here around 3 femtometers, which is not very far, smaller than the diameter of the nucleus. Already this thing is very close to zero. So typically, it falls off as 1 r to the fourth. And so the effect is that it doesn't just suck up other nucleons in the environment and build bigger and bigger molecules. It only works if you get the nucleon really, really close to another nucleon, and then it goes poof and sticks together. And that's an important feature.

So you can see here this is why the average distance between nucleons in an atom will be around 0.8 femtometers in size. Now, we can compare this. You can see this is potential energy is measured in millions of electron volts. And you can see here that it's something around minus 100 million. That's means you need to add 100 million electron volts to get it out of this well to separate the two things.

How big is the coulombic force? The coulombic force, remember, is electrostatic repulsion, say, between two protons. There's not really any more space, but you could do it. It's 1 over 4 pi epsilon naught if you remember your physics. You would integrate the force from infinity to zero as a function of the distance, where the force is equal to 1 over 4 pi epsilon naught, q1, q2, which are the charges in this case. So we can call this e2, the electron charge, over the distance squared.

And if you do this integral, you'll find out that the repulsive energy that-- actually, we don't want to integrate to zero we want to integrate to, well, 0.8 fm. 8 times 10 to the minus 60 meters. If we do this integral, we'll find out that the repulsive force is about 1.4-ish MeV, which is 1% of the attractive force from the strong force. So that's why this attractive force glues it together. It overcomes the repulsive force from electrostatic charges from the two positive charges.

So this is the picture in play for two nucleons. But it's actually a lot more complicated than this. There are a few other things that count here. There is something called spin. And these exclusion rules, which force every nucleon to have a different spin and a different energy state. But that is why nuclei have specific configurations. That's why you can't take one proton and 37 neutrons and stick them together. Despite the fact that the strong force would suggest they would all stick together, they won't because of all these other rules related to the spin.

So yes, you can't make helium 39, if you will. So this is the table of isotopes. This is showing you along the bottom the number of protons. So in other words, this is the periodic table starting over here with hydrogen and going up through all the elements. 92 of course, is uranium-- number of protons. And this is the number of neutrons. We talked about this earlier. So it's the mass minus z number.

And you'll see that these are basically the ones that are allowed by nature. They're color coded by their lifetime. So the light blue ones have lifetimes of around 10 nanoseconds, and they go all the way to black, which are stable, which means they do not radioactive decay. So this sort of suggests that these things could be created, but they would have such short lifetimes, they don't bother to color code them. They just instantly disintegrate. And then they become more and more stable as you get towards this line.

So this is all related to that color force, color charge, spin, et cetera, and so on, and so on. Now, it's some combination of these. If it takes energy to assemble all these nuclei together, it also suggests that when we disassemble them, we get some energy back. And so you could ask the question, when one of these-- when one of these atoms decays, do we get useful energy out of it. And the answer is yes. We can get useful energy out of just radioactive decay.

So here is a picture of plutonium 238, a form of plutonium that is kind of rare. But you can, through lots of effort, assemble macroscopic quantities of it. This thing has a half life of 87 years, which means half of the plutonium atoms undergo radioactive decay every 87 years. This is not in air. This is in either a vacuum environment or a low-pressure inert gas environment, because plutonium is extremely chemically reactive, thanks to its D orbitals.

But you can see that it generates so much heat that it turns red hot. The natural color of this metal is silver, but it is so hot that it is just glowing because it is self-heating. So you can take a chunk of stuff that just from radioactive decay, produces a useful amount of heat that you could then extract at that. And we indeed use this isotope, plutonium 38, to power what we call RTGS, radio isotope thermoelectric generators, which are what power spacecraft, like the Voyager spacecraft that goes into deep space.

There are also other elements that are less exotic than this one that do this. They don't typically produce as much energy. They don't necessarily glow red hot. But for example, strontium 90 and cesium 137 were isotopes that were used by the Soviet Union to make these devices. You can see they have cooling fins and they are filled with radioactive stuff that makes heat, that then drives a thermocouple. And then that produces electricity.

These were basically nuclear batteries. They had working lines of about 10 to 20 years, and they were used to power these lighthouses on the Arctic sea, where people basically couldn't live there because it was too remote. But they needed some kind of lighthouse to protect ships that were transiting in the region. The beta decay, which is the primary source of energy is, of course, all trapped by this metal casing. But it's the gammas that you have to worry about.

So I said some isotopes, those marked in black, are stable. What I mean by stable means that they just will last forever. There's no natural perturbations of their nucleus, which will lead to the elements spontaneously decaying or the isotope spontaneously decaying into another isotope. But even so, some isotopes can be said to be more stable than others, which is to say they are further down that potential energy well. They're more stable.

So they're more tightly bound together. So this gets us to this chart, which is called the curve of binding energy, which is also the name of a book by John McPhee, if you're interested, that has got interesting stuff about the history of the atomic age, if you are-- So let me just explain what this is. These are different isotopes now plotted. It's kind of mixed up because this is not element. This is now number of nucleons in the-- so you have different elements right next to each other.

But typically, the lighter elements will be over here, and the heavier elements will be over here. And on the y-axis is the binding energy, which is how deep are you into the well of stability per nucleon. So you divide by the number of nucleons in the atom. And you'll notice this overall trend. When nuclei are very light or very heavy, the binding energy per nucleon is lower. And so those isotopes are not as tightly bound, if you will, as these here in the middle.

So you see iron is basically as tight as it gets. And that's why everything decays to iron. And it's why the center of the Earth is full of iron, because there's nowhere else to go after you get iron. That is the most stable element that you can make. So for radioactive elements, the starting isotope is, of course, unstable. What does that mean? It just means that there's a simple transition. You see if I have a little-- yes, here I go.

There's a simple transition in which it can do something with a nucleon and move up to a more stable state. That is radioactive decay. It's just like going from this state into a slightly more stable state. So let's attach some numbers to this. You can see the size of the change that is on the left are in units of MeV. And you can see that this little tiny change from radioactive decay was pretty small, much less than an MeV, maybe a tenth of an MeV or something like that.

And that's kind of typical of radioactive decay. They're usually in the 100 KeV to 1 MeV range. That's, of course, per nucleon. So this tiny little change has to be multiplied by a factor of 120. So it's tiny, tiny little change, but then multiplied by-- I'm trying to get something of order MeV. Recall that 1 MeV is still 1.6 times 10 to the minus 13 joules. It's a very tiny amount of energy. You need 4 joules to heat about that much water one degree.

So this is just a teensy tiny bit of energy. You need trillions of these things to heat this a quarter of a degree, 10 trillion to heat this amount of water a quarter of a degree. But the key point is that atoms, of course, come in large numbers. So you all know from high school that Avogadro's number is 6.022 times 10 to the 23rd, so is a mole, which is kind of a reasonable number of atoms or this amount of atoms kind of thing.

And so when you have a whole lot of these things decaying, you can indeed get useful quantities like that regular electric thermal generators I showed you on the previous page. All right. The problem with using radioactive decay as a source of energy is that you wait for this process to happen on its own. And each isotope, by force of nature has some time scale called the half life, which is going to tell you how fast this happens. And that's what you've got to work with, and that's it.

So if you want to do something useful, we would like to have this happen, but we would like to stimulate it, do something to the atoms to control their release. And that gives us into these stimulated reactions, which is what nuclear engineering is about, figuring out how to make the nucleus do the things we want to do to extract this energy from the strong force. And that's what we're really going to look at.

So how do we do this? All right. So we talked in the last class about the discovery of nuclear energy being tied to the question, what makes the stars burn? And indeed, that is one of the most useful reactions that we can have. So here's a very common fusion reaction where we're going to join together two nuclei to make a new nuclei. Therefore, it's fusion. And the ones we're going to choose for this example are hydrogen 2 and hydrogen 3.

So hydrogen 2 means that it has one proton and one neutron, two nucleons, hydrogen 2. Hydrogen 3 is one proton and two neutrons. And these are also known as deuterium and tritium. Does anyone know what hydrogen 1 is called?

STUDENT: Proton? No.

PROFESSOR: You're very close. It is a proton. If it had no electron, it would just be a proton.

STUDENT: That's why I tried to guess.

PROFESSOR: You were very close. Actually, for some reason, we never tell students what hydrogen 1 is called. It's called protium. Useful to know. You'll run across it. Protium, deuterium and tritium are hydrogen 1, 2 and 3. So yes. So we won't use protium, but we'll use deuterium and tritium. Deuterium can be found in ocean water. Tritium is exotic. You have to make it in a nuclear reactor.

But this is the reaction that powers virtually all practical modern fusion concepts. So when you put these together, you get two protons and three neutrons out. And so two protons means you get helium. And one of those neutrons will not bind. It comes out as a free neutron. And so you get helium 4 and free neutron. So let's just do a little quick calculation. So beforehand, we had-- let's see. We had one.

Well, let's figure out how much energy out. So the binding energy of the final state minus the binding energy of the previous state. So the binding energy of the final state is helium 4. And if you look at the plot, it's 7 MeV per nucleon. So we have 7 times 4 because helium 4 has four nucleons. Plus what is the binding energy of a free neutron? Zero minus the input. That's not me moving. That is the projector moving. [LAUGHS]

Minus the inputs. Whoa. It only happens when I talk. So we have one deuterium, which has a binding energy of about 1 MeV per nucleon. So 1 times 2 nucleons minus helium 3, which has a binding energy of about 2.8. 2.8 times 3 nucleons. Does anyone want to run that on a calculator? 7.4. 7 times 4, minus 2, minus 3, times 2.8.

STUDENT: 17.6.

PROFESSOR: 17.6. That is indeed the amount of energy you get from DT fusion. So that's where it come from. It's just this rearranging of the nucleons along this curve of binding energy. So 17.6 MeV, compared to approximately 1/10 to 1 MeV from radioactive decay. So we get a lot more energy from this stimulated reaction than we get if we just rely on radioactive decay. And we can control the rate, whereas radioactive decay, we're sitting around and saying half of them will decay in a certain period of time. Now we can just do our thing.

So that is the magic of DT fusion. This is a reaction written out. There it is, the answer. Very good. Why is this hard? Well, remember the curve of-- remember that strong force fell to zero at around 3 Fermi? That's what has to stick these things together. In the meantime, we have the repulsive force from the protons. Like charges repel. And that is preventing this from happening. And that extends much further in space because it goes as 1 over r squared.

And so to overcome that, we have to speed these things up so fast that as the coulombic repulsion is slowing them down, it still keeps going to the point where it snaps together. And that requires temperatures of 10 million degrees. And that is why fusion is hard. We have to stably confine these molecules, get them close together, and heat them up to 10 million degrees. This is really annoying. And that is not easy to do.

All right, so that's fusion. What about fission? What can you do with heavy nuclei? Story is a little bit different. Stimulated reactions to heavy nuclei, there are lots of them that exist. This is one example of what's called the n, 2n reaction. You shoot a neutron at a nucleus and it kicks off two neutrons. And so you unbind one neutron, and you get a change and you get some energy out. The problem with this is, when you do the math, what happens is you get basically the same as radioactive decay, fractions of an MeV, typically.

So you can do this, but it's not buying you very much. And in order to make these high energy neutrons, to do this is not trivial. So it's not a net energy producer generally. However, for a few special nuclei, and indeed, only one nucleus found in nature, uranium 235, you can stimulate this weird reaction called a fission reaction, which is what is showing here. For some reason with this nucleus, when you shoot one neutron, the whole thing splits in half.

And now when you do your calculation per nucleon, it turns out you get about 200 MeV out, which is a lot more energy. And so this is the reaction on which all fission, nuclear energy, all current working nuclear energy is based. And it exists strictly because this one isotope exists in nature. You could not do it if this isotope did not exist, uranium 235. So let's just briefly look at what's happening here. We're going from over there on the right.

And the fission is random in where it lands. It breaks into different sized fragments and lands in different places, but roughly over there. And you see that the change in binding energy per nucleon is small, let's say, order 1 MeV per nucleon. But we have 200 nucleons, and so we get 200 MeV. And that's how you get a meaningful amount of energy out of fission. So a meaningful amount of energy still has quotes around it, because just to remind you, that 200 MeV is still 1/300 trillionth of what you get from burning a matchstick.

So it's tiny. So how do we get this up to macroscopic levels? Well, with a fusion reactor, we can figure out how much energy we want from our reaction, figure out how many moles of deuterium and tritium gas we need to pump into the reactor. You pump it in there, you heat it up, it goes poof, and it blows up, and it all reacts, you hope. And you get some energy out and everything is over.

But you can't really do that with uranium because it's heavy, and not a gas and not easily moved around. And so you need to build a much more complicated device to control the rate of fission, if that's what you want to do. So in the next 10 minutes, we'll talk about how we control the rate of fission in reactors. Any questions up to this point regarding where the energy comes from? It's all related to the strong force. That's what you need to take away.

So we use this concept called criticality, which I'm going to illustrate for you in a second. The key thing I want you to take away is, criticality is fundamentally a geometric consideration. We sometimes talk about a critical mass, but actually, the critical mass presumes a certain geometry. It presumes, usually, a spherical geometry. If you change the geometry or you put a neutron reflector or something else, the critical mass changes.

The foundations of criticality are geometric, and you'll see why in a second. So Szilard had this. We saw in the last class Szilard said, I imagined if I was crossing the street and somehow one neutron could be released, it would do something that would generate two neutrons in the reaction, which would be a chain reaction. And he doesn't yet identify that it was uranium that is doing that, but that's the concept of a chain reaction.

So here's how a chain reaction works. In a subcritical material, in fission-- I should probably go back here. The key feature of fission is-- we talked about this was Frederick Galileo's discovery. One neutron comes in, fissions, and more than one neutron comes out. That's what Frederick Julio published on the dawn of World War II that showed that the chain reaction was possible. So we will take-- we will watch as more than one fission-- more than one neutron comes out of fission.

So let's run the simulation. Here we go. You see a neutron flies in, it fissions, it gives three neutrons, it causes more fissions, but it stops. Because eventually, the neutrons leak out. This is the subcritical state. It means that on average, fewer than one neutrons stays within the volume, and therefore, the chain reaction cannot be sustained. So it is subcritical. So we'll do the same simulation, but we'll just choose a larger mass. And you'll see what happens. It just takes off.

And so that is the supercritical state. So in a reactor, we have to at least assemble a supercritical amount in order for the reactor to work at all. And eventually, what we want is for it to grow until we have a certain rate of fission reactions, and then we actually don't want it to keep growing. And so we're going to talk a little bit about that in a moment. You can see easily that if you don't do anything to prevent it from continuing this expansion, that the energy production just scales exponentially.

And that's how you make a nuclear bomb. It's a simple version of a reactor. And so that's why it goes boom. All right. So how fast does this process grow? So in solid uranium metal, which is an important caveat here, the time between these fissions is about 10 nanoseconds. During the Manhattan Project, they discovered all of these fundamental measures of fission, and they had to give all these things names.

And so this is called a shake. It's as long as the shake of a lamb's tail. That's where it comes from. And the probability of a certain reaction is measured by the cross section, which is a measure in units of square area. And the unit is called a barn because it's as big as a barn. It's the square area of a barn. And so all of these things are named after farm nomenclature. And the Los Alamos lab was called The Ranch. So this is all leftovers from the Manhattan Project.

All right. So we have one shake, which is 10 to the minus 8 seconds, or 10 nanoseconds is the time in between. And you can say, well, how long does it take to get to, say, 10 to the 14 neutrons fissions, at a rate of 10 to the 14 neutrons happening simultaneously, which is what you would need if you take-- the energy you require is-- I think I've skipped over something in a previous slide. The energy you would require is something like 10 to the 20, 10 to the 22 fissions per second. But every fission takes 10 nanoseconds.

So when you do the math, you want simultaneously, at any moment, there would be 10 to the approximately 14 fissions. And then if you say, I need 10 to the 14 fissions, and I go up by, let's say, 2 and 1/2 per generation, because I get about 2 and 1/2 neutrons out of the re-fission, then I can say I have 2 and 1/2 to the n. And I can say let's solve for n. And if you solve for n, you get, what, log-- what is this? You go over log of 2.5 down here. And this is log of 10 to the 14.

You can figure this out. And you find that n is about 35. So 35 generations gets you to the power of your reactor. And every generation is 10 nanoseconds. So 35 times 10 nanoseconds is about a third of a microsecond. So the reactor reaches full power in a third of a microsecond. Again, you can see why it's easy to make a bomb. And now we ask the question, how in the world do we control this thing in a practical nuclear reactor if you have a third of a microsecond to put the brakes on, to change the geometry, or do something so that this won't continue to grow?

So it's hard. And the magic comes from something called delayed neutrons. So it is true that you get 2 and 1/2 neutrons on average coming out of fission. But a very small fraction, about 0.6% of those neutrons don't come directly from the fissioning nucleus, but show up later because of radioactive decay. And let me actually be a little bit more specific. So let's go back here to the table of isotopes.

So we start here. I don't have a laser pointer, but I'll use the shadow of a shadow. So we start here around uranium is right around here, maybe that red one. And it's going to split in half. Conservation of mass requires the number of protons and neutrons to be conserved, so we wind up with some spots down here and here. Probabilistically, you're probably not going to land on these blacks. Probabilistically, you're going to land on a blue.

And that means there will be some additional radioactive decays after fission. And some of those decays will just by chance issue neutrons. And those neutrons are called delayed neutrons. So what you do is you design your reactor so it's actually subcritical. We call it prompt subcritical. It will not sustain the reaction. It's like that smaller green ball that stops, but then this radioactive decay happens because one of these fragments is on a light blue square.

And it gives another neutron, and it's been momentarily supercritical, and the reaction continues, and then it stops again. And that's actually what's controlling the rate of the reactor. It's the half life of all those little-- all these little blue squares. The half life of these things are what are controlling the speed, rather than the prompt growth of the reactor. Does that make sense to everyone? All right.

So now you say, well, what is the half life? Actually, you have no idea. You have no idea what it's going to fission into. But on average, we find certain delayed neutrons fall into certain time bins. And that gives us a kind of average behavior that we can count on. Thanks to Avogadro's number being very large, we can average over a very large number of these things, and it's relatively predictable. But fundamentally, it's still a chaotic system because it just has to statistically work out in your favor, which is why you might have a reactor start to have an energy excursion and start to take off.

And you have to do something to stop that, otherwise you have a meltdown. And so this is why reactors have to be dynamically controlled in order to prevent that from happening, because it's fundamentally still chaotic. So that's the art. You balance the neutron generation just right, so that it is, in fact, a subcritical device. But then these decayed delayed neutrons momentarily move it into supercriticality, and the reaction proceeds forward.

So how is that-- how is that done? Well, the generation rate is kind of fixed by the fuel, which is a solid amount of uranium or other fuel in there. The number of neutrons that continued to run is controlled by, principally, the loss, which we talked about here. So the loss is higher in a smaller geometry because the surface-to-volume ratio is higher than in a larger geometry. So we build the reactor so that it's called the leakage term is such that we are very close to criticality.

And then we slightly adjust, tweak the level using something that absorbs excess neutrons. So we make it so there's a little extra neutrons. And then we do some we add some additional stuff that absorbs neutrons. We call these things control rods. And a common material, for example, is boron. So there's other things you can put in control rods that have different features, but boron is the principal thing that we use, because boron has a large neutron capture cross section. It wants to suck up neutrons.

So we put that in there, and we use that to just fine tune the rate. So that brings us to the engineering of fission reactors. All right. So one of the things that we will hear about are something called thermal reactors versus fast reactors. So let me just explain what that means. As it turns out, when you fission a nucleus of uranium and it gives off of two to three neutrons, these neutrons come zipping out with a lot of speed because they are carrying the way the binding energy of the nucleus. That is part of where the energy goes.

And on average, they're born with approximately 2 MeV of kinetic energy per neutron at the time in which they are born. Oh my gosh, this projector. And so that's over here. This is a plot of the energy of the neutrons. And you can see it goes all the way up here to 10 MeV, and it goes all the way down here to 10 to the minus 5 electron volts. Very, very tiny, so many decades. This is approximately what we call thermal neutrons.

So a fast reactor operates over here, and a thermal reactor, like most of the reactors in the world, operate with neutrons in this region. Why would you build a thermal reactor? Well, the principal reason is that this is the cross section in units of barns. And you can see that it is basically a measure of the probability that a reaction will happen. And you see that the probability of-- this is the probability of fission. This is the cross section for fission of uranium.

So the probability of fission goes up by many orders of magnitude when you slow the neutron down. So that makes the reactor easier to design. But it also makes the reactor safer to design because these neutrons are born fast. But if they start colliding with things, they slow down. They transfer some kinetic energy to other atoms, and then they will slow down. And then the probability that the fission reaction happens goes up. So in order to prevent accidental fission, we actually require that they slow down.

This process is called thermalization. They slow down so much that they have the same kinetic energy on average as the average of the molecules in this table? That is 0.02 eV. That is the room temperature energy per nucleon. And so they don't get any cooler. That's just where they land. And they kind of stay in that region, and we design the reactor to operate in that region. This is the cross section for uranium. And we see it has this feature where thermal reactivity goes up. But that's actually kind of a rare thing in nature.

So just to show you how rare, here is the cross section for thorium. And you can see that it goes down as they thermalize. So you can't make a thorium reactor easily. You say, well, I've heard of thorium nuclear power. Does anyone know how thorium nuclear power works? You would change it into uranium. That's the magic of thorium. Thorium will, by itself, not actually produce a good reactor. You have to change it into uranium.

You change it into a different kind of uranium called uranium 233 instead of uranium 235, but you still have to change it into uranium first. So thorium by itself does not make a reactor. And if we did not have uranium from nature, we would not be able to ever have built these. Here's another one. This is uranium 238. This is another kind of uranium. This is in fact, 99.3% of the uranium in the Earth is uranium 238. This is only 0.7% of uranium is uranium 235.

So most of the stuff out there has this weird feature that the probability of fission is very low. It requires very high energy neutrons to do it. If the neutron is thermalized, you're out of luck. The reactor is very, very hard to build. But for 238 in particular, it has this feature where it goes in the other direction. So we can ask, well, that's great. How do we get uranium 238? Well, as I mentioned, natural uranium on Earth is only about 0.7% uranium 235.

Sorry, a moment ago, I said, how do we get uranium 238? But I meant to say, how do you get uranium 235, the stuff that has this nice feature? So we have to get rid of the extra uranium 238, which we don't want, because it's a mix of these two isotopes in nature. And the only distinguishing feature between the two are their mass. And so chemically, they're the same. They're both uranium, the same number of protons, therefore the same number of electrons, therefore the same chemistry.

So we have to find a way to, atom by atom, sort them out by their mass. And this is the process of uranium enrichment. We'll talk a little bit more about how this works in future class, and the process by which people like Iran is trying to make a nuclear bomb. They're doing something to get purified uranium 235. But the short of it is that you accelerate them. You spin them around, and the heavy ones go to the outside, and you throw that away because that's uranium 238. It's heavier, and you keep the others towards the center. Basically, that's the concept.

But this gives us some categories. If you get just rid of some of the 238 so that we can say increase the amount of 235 by a factor of 5, so we've actually gotten rid of quite a lot. The material is called low enriched uranium. This is actually most of the uranium used for reactors. This is good enough. Even though there's still a lot of 230-- even though the fuel is still 95% uranium 238 and not very useful, it doesn't matter, because this cross section goes up by so many orders of magnitude, and we have enough of it that we can get by. Yep.

STUDENT: Why is it so jagged in the middle?

PROFESSOR: Those are called the-- so that's called the resonance region. And it has to do with the fact that the nucleus has, just like the atomic states, it has these resonance energy structures in it. And if you happen to have a neutron coming in that is exactly the right energy, it can resonantly excite the process that allows for the fusion to occur. So it goes up, and then it goes down, and it goes up, and it goes down. And then actually, really, these things continue forever.

But we don't plot them because they just get to be stupidly dense. So then we stop. We just plot the average. But yeah, that is what's going on. You're seeing these resonance harmonics of the structure of the nucleus. And yeah, this really just keeps going. It's like that, then keep going. So where was I?

So 5% is enough to get by for most reactors, as long as the reactor is a thermal reactor, not a fast reactor. So right now, there's a lot of people interested in building fast reactors. Again, they want to keep the neutrons over here. They don't want to thermalize them. That means you can't make it out of 5% uranium. You need something that has either a lot more uranium 235 than 238 because this just drops to nothing. Or you need to use something else like plutonium to make it.

And so fast reactors always use fuels that are also, because they're fast, useful for making bombs. Because bombs are fast reactors. They're just run-away fast reactors. That's what nuclear bombs are. So you build a fast reactor. You have to use, basically, bomb grade material. And on top of that, if the neutrons slow down for whatever reason, the reactor becomes uncontrolled because the probability of fission goes up. So fast reactors are very hard to build and control. Thermal reactors are straightforward.

So where was I? It goes up by a factor of 1,000. So for thermal reactors, this will do just fine. As the reactor becomes smaller and smaller, leakage goes up and up, so we have to compensate for that. So we typically keep enriching. We call this stuff right here high assay low enriched uranium, right at the cutoff where it's 20% uranium 235. Most new reactor concepts are looking at this material because they want to make the cores very small. Therefore, the leakage is very high, so they compensate by upping the amount of 235.

But you can in principle go all the way to weapons grade. And in fact, our reactors that would put on submarines, which are very small, use weapons grade uranium, which is to say greater than 90% uranium 235. We'll talk about it in class, but in fact, anything above 20% can-- actually, anything above 12% can really be used to make a bomb.

So the MIT reactor runs on weapons grade 93% uranium. Just letting you know. It's over there. Yeah, get a couple of MIT reactors together and you can build a bomb pretty easy. So just briefly, for those of you who are not physicists, and I talk about thermalizing neutrons and you're like, slowing them down. I have no idea how this happens. What do you mean? This is just a little illustration.

Here's a heavy atom. Here's a neutron coming in. You can see the neutron bounced off, and this thing is like it's moving a little bit. But mostly the neutrons just bounced off at the same speed. It's like throwing a tennis ball against a wall. The wall is a lot heavier. Conservation of momentum means the tennis ball is going to bounce at roughly the same speed. If you have a light thing instead, like this molecule of-- I guess it's a molecule of helium, then you see that conservation of mass causes that thing to move off-- the neutron to move off more slowly.

And so if we want to slow things down, we want to put a lot of light atoms in there. What is the lightest atom? Hydrogen. What has a lot of hydrogen? Water. And so now you know why water is the principal so-called moderator. The moderator is the thing that is slowing down the neutrons. And that's why we built reactors out of water. You can build it out of other light stuff. You can use graphite, which is carbon, which is heavier than hydrogen, but it's still pretty light.

And a variety of other things people have-- there are other sources of hydrogen, like oils. Oils are also hydrogen-rich. And so people talk about organic reactors and things like this, but basically, kerosene in there to slow down the neutrons. Early reactors built during World War II to make plutonium used graphite, which was nice because you could just get it in these big blocks. You drill these holes. You put the fuel into the holes.

The neutrons shoot out of the fuel as they're fissioning. They travel, bounce around in the carbonaceous graphite. They slow down to the point where they can then trigger the next fission. And so the reactor proceeds. So that is how the first, what we call, production reactors were built. They would, of course, heat up. So we would flow air through them, trying to keep all this stuff cool. And I don't have a photo, unfortunately, but they would put some shielding out in front. And literally, there'd be people standing in front of the open face reactor shoveling uranium into these holes manually.

And then inside, deep inside the graphite block, there would be this reaction happening. And they ran these reactors and made a whole bunch of plutonium. We'll talk more about how plutonium was made. But this is how the early reactor is built. The water reactors, we have a couple of different concepts. So one is called the-- this is actually a later concept. The original concept was a pressurized water reactor, which we talked about briefly as being used on submarines. I'll get to that in a moment.

This is a newer concept called the boiling water reactor. So here is your uranium fuel in yellow. The neutrons come out and they hit the water. They then trigger more fissions in the rods. The rods heat up. The water happens to do two things. It's not only slowing the neutrons down. It's also cooling the rods. It absorbs so much heat that the water boils. It makes steam. You pump the steam out and you turn a generator.

It condenses on the generator blades, and then the turbine generator, and then you pump the water back in. And this is how you run your reactor. So reactors are just water boilers, basically. That's what they are. This idea was promoted by General Electric. We'll talk more about General Electric in the next class as a principal competitor to Westinghouse, who came up with the pressurized water reactor.

Approximately 20% of the world's fleet is based on this concept. A lot of the reactors in Japan, the Fukushima reactor, was of this design. Because the water is directly in contact with the fuel, one of the things that happens is the fuel corrodes and some radioactive material leaks into the water. And so this loop of water becomes contaminated with radiation, including the turbine that is producing your electricity. So you have a whole lot more radiation to deal with all throughout the plant.

If you spring a leak, the water is already radioactive. You have to deal with it. So this is a complicated issue if there's a problem. You have to worry about corrosion and things like that more because of the radiation. Here is the pressurized water reactor concept. The idea of pressurized water reactor is that you put this water in a pressure vessel, and you increase the pressure so high, the water doesn't boil, because the boiling point is a function of the pressure.

So you raise it above the vapor point. The water doesn't boil. It's just superheated water. It's like your pressure cooker at home. You're canning stuff. And instead, it sends super hot-- I'm sorry about this. I'm going to ask them about this jiggly projector. It sends super hot water into this thing called a steam generator, which is just a heat exchanger. If you look at a real one of these, it's just hundreds and hundreds of little tubes going through in a big tank.

And the super hot water that contains some of those corrosion products are confined to the tubes. And then we pump other water, which is nice and clean, around the outside of the tubes, and it exchanges the heat to the other water. And it boils the water on the outside of the tubes and makes steam. And then we use that steam, which is nice and clean, take it out of the containment, and run the turbine to make electricity.

That way, everything that contains radiation is inside this containment. And if there's a problem, everything will be contained. And that is the idea behind PWR. So in that sense, they are supposed to be, if you will, safer. So these reactors typically operate around 300 degrees C, 3 times the normal boiling point of water. But they do that because they keep the water under very high pressure. About 63% of the commercial fleet uses these designs.

Of course, there's consequences. You have very high pressures, which means that things may stress from cooling and heating, and weaken, and blow out. And so you have a different kind of safety issue to think about related to material integrity and so on. And so you overbuild these things to try to prevent that, but things can still happen. So some of the pressurized water reactors that are currently being stood up in France, what's called the EPR, and the top cap of--

Actually, I can't remember if it's the top cap or the bottom cap. One of the caps, really thick steel casting to hold all the pressure in. But it turned out when they cast it, there were some precipitates of carbon in the steel, which weakens the steel, which means that now they're not sure if that thing will last very long. So they've given it a provisional operating license, but they may have to shut the reactor down early.

And unfortunately, that cap is so ginormous that you can't actually replace it without disassembling the whole reactor building. This thing has to be built and put in place, and then you build the building around it. And so yeah, getting the material science right is really important. And this is what makes these things hard to build. All right. So I've mentioned I keep talking about the generator. What do I mean?

So again, this is a pressurized water reactor. Here's a reactor. Here's the steam generator or the heat exchanger. This is the pressurizer which keeps everything in high pressure. Here comes the steam. There's a turbine that is controlling your electric generator that is making electricity. It's making us happy. And then the cool steam comes out here, and we want to cool it down as much as possible.

So we send it to these big towers or to some other source of ultimate heat sink, where we cool the water down so we can start over and get good thermodynamic efficiency. If the water comes in too hot here, we can't run the reactor at full power. So you have to de-rate the reactor. So we have these big towers, and that's, of course, what we associate with pictures of nuclear power plants or these towers. But they are just there to cool off the water after it goes through the turbine, before it goes pumped back in.

Ideally, all this stuff that handles the radiation, the radioactive water, all of this goes in a big concrete building that is steel-reinforced. We called that the containment. And it's designed so that if this thing explodes and all this water flashes to steam, which turns it into a big hot balloon, that this thing can handle all that pressure, at least temporarily. It turns out it can't handle it forever. It can only handle it for a couple of days, and then you have to vent it. Otherwise, it will explode.

And so that in Three Mile Island accident, those vents, to keep this thing from exploding, that venting process is what led to the release of radioactivity in the Three Mile Island accident. And in fact, the same thing also occurred at Fukushima. They had to vent the-- it wasn't a PWR, but they also had to vent. And you see this little burst of radiation occurring. There are, of course, concepts that don't rely on water.

So this is called high temperature graphite reactor, HTGR. This concept, you have here these fuel pebbles, which have little grains of uranium sand in them coated with graphite. The graphite is a moderator, slows things down. And instead, you cool it with gas, usually, an inert gas like helium that doesn't chemically react. And that is nice because gas is not-- it's already gas form, so it won't undergo a phase change. If it gets too hot, it stays as gas.

So water, when it gets too hot, it boils, and the volume expands dramatically and explodes things. Here the gas just stays as gas and the pressure does go up, but you don't get the phase change, so it's a much safer device from that perspective. And so China is currently marketing a reactor of this concept called the H-- it's called the PM 10. Is that right? HTR PM? No HTR PM 10 was the prototype HTR PR I think is the current one. This is called pebble bed reactor.

It's called pebble bed because the reactors are in little pebbles. You can also build this without the fuel being-- sorry. The fuel is in little pebbles. You can also build this without the fuel being in pebbles. You can just have them as sticks instead of reactor turnout. That's a better design. But people like the pebble bed reactor because the idea is that you put the fuel in one pebble at a time, and the old fuel comes out one pebble at a time, and you can just keep the reactor running.

The problem with pebble beds is, remember, criticality is fundamentally an issue of geometry. And the geometry is always changing every time you add and remove pebble. So the criticality goes [VOCALIZING] and moves around, and you have to control it and deal with it. So there was recently a proposal to put one of these things on a boat. It's a really dumb idea because the boat goes like this and the geometry is changing, and right. So nonetheless, there's a startup company trying to do this.

Yeah, so there's some nice features. These reactors, because they don't use water, and because they don't use metal cladding but use graphite around the fuel, they can go to very, very high temperatures. So in principle, as long as the temperature stays below 1,600 degrees C, which is the temperature at which graphite begins to autocatalytically burn, this reactor is fine. So because they go to much higher temperatures, you can get better thermal efficiencies, which are a function of this delta t.

And you can do things that need a really high temperature heat, like melt steel. And so you could use these for all kinds of industrial processes in principle. We'll have a whole lecture about that. But in principle, you can use these kinds of reactors for different concepts.

STUDENT: Is it easy to change out the spent fuel container? How big is it?

PROFESSOR: It doesn't really look like this. Yeah, there's all kinds of-- it's much more complicated. Every pebble comes out and there's a radiation sensor that measures how much of the uranium is burned, and they decide either to recycle it or to dispose of it. And it's all controlled by robotics. And yeah, it is not just like this container that you take away. So this is figurative. Although these reactors are back in fashion, I just want to point out that this concept actually dates back to 1960.

We built a few of these things. They were not cost effective. They had lots and lots of problems with the fuel. The fuel, because of rubbing against each other, would abrade and create all this dust. Then it turned out that fission products would diffuse out of the fuel because the temperatures were so high, so just kinetically move around and get out of the fuel. And then you had all this dust, and so it adsorbed this radiation onto this dust. And then you had so you had all this radioactive dust floating around inside.

And if you tried to open it to service it, all this radioactive dust would come out. And so the facility in Germany, I think it was called the AVR, where they built this. It's to this day, the most strontium contaminated facility in the world, has never been disassembled, despite it being closed for decades and decades because it's just too reactive. Some of these problems have been maybe fixed. They're fixed in the lab, but whether they're fixed in real life is TBD, because it depends on engineering tolerances and getting everything just right.

And as you scale things up, things tend not to be just right. So these reactor concepts are still kind of on the edge of whether or not they're really mature enough to be deployed. But they're also more complicated because of all these pebbles, and all these pebble sorters and everything is going on. So to keep the cost down, one of the things that has been done, for example, by the Chinese, who are the only ones operating these right now, is to just get rid of the containment building.

And so they say these things, they don't have water and they don't melt down easily. So as long as nothing runs into the reactor and opens it up, or there's not some weird unexplained excursion, we deem that it is safe enough to operate these without containment, which is very questionable. That was also the case for the Chernobyl reactor. They deemed it was safe enough to operate without containment, and then there was a major accident without containment to contain new stuff.

One of the ways these reactors can fail is if there's water ingress. So you could imagine a variety of situations where, for example, you build this reactor in an area that's a flood zone, and suddenly, this reactor becomes flooded, and water then over moderates the neutrons. And suddenly, this thing explodes. There's all kinds of things you need to worry about. So every time you come up with a reactor that is different than what we've seen, there are all these wonderful features, and then there are all these other problems that people tend not to talk about.

And that's kind of an important message here. Here's another variation. What? Oh, it looks great. It looks virtually the same. Yeah. Here's what changes. The coolant goes from helium to liquid salt. Yeah, so a very high temperature salt. Usually, this is a salt called FLiBe. Fluorine, lithium, beryllium. It also has these nice features. FLiBe, I'll just write it out so you know what I'm saying. Fluorine, lithium, beryllium, FLiBe, it expands even less than helium.

One of the problems with helium is that the conductivity, the thermal conductivity of helium goes down when it gets hotter. It's weird. So the result is that in a helium version, if I get a hotspot here, the helium cools it even less, and the hotspot becomes even hotter. And then you have the fuel exceeding its design temperatures and problems. So FLiBe doesn't have that feature, and so it also expands less. And you see it's in principle, a variant on this that is more robust. So that's nice.

But of course, there are other problems with FLiBe. One is it's a salt. So if it gets cold, the whole thing congeals into an ice, a block of salt, and it's a problem. Another problem is that beryllium, which is a key component of the salt, is extremely toxic. So there's all kinds of issues again. And a third one is it turns out FLiBe, if it gets any contaminants in it, because it's an ionic material, it's really good at corrosion. It will just corrode anything very rapidly because you can just move electrons around and chemically facilitate chemical corrosion.

So these reactors are also being designed. There's a group here in our department at MIT that is a big fan of these, but again, also has issues. FLiBe is also Incidentally the coolant inside the spark fusion reactor. And all these same problems exist with FLiBe in that application as well. Here's another concept. What is this concept?

I guess this is-- oh, this is the fast reactor. So here, this reactor is a pool type reactor. I think EVR 2 was of this design. They basically have the fuel sitting in here. They have a hot liquid, non-boiling fluid circulating heat around this heat exchanger. And then they just take the heat out of this big caldron of liquid. What is the liquid? Well, it has to be something with really good thermal conductivity, and not something that absorbs neutrons or undergoes nuclear reactions.

So the coolant of choice is sodium metal, which is, of course-- has anyone thrown sodium into water? Knows that sodium spontaneously combust in air when water vapor or when you put it into water. So you have to then put a cover gas over this thing to make sure that no water vapor gets in there. Otherwise this reactor spontaneously will catch on fire.

Has anyone heard of Oklo, the startup? This is the concept that they're now going with. Of course, we built these reactors, too. The Russians are still kind of a fan of this reactor concept. They tend to have a lot of problems because of the sodium. The Russians have the highest success with it because every time their reactor catches on fire, they don't turn off the reactor. They just fight the fire while the reactor is running, which I think it's something you could only possibly do in Russia.

And they have multiple of these cooling systems. So it has to get a fire over here, and they have another one over here that they can keep running, keep cooling the reactor down. The main advantage of a fast reactor, so this is a fast reactor, so it doesn't rely on slowing down the neutrons. In fact, if the neutrons slow down, you have a problem. So you have a lot more fuel. You have the fuel closer together. You use weapons grade fuel.

But one of the features of doing it is that you then have a lot of extra neutrons, because you don't lose them to absorption in your moderator material. And so you can do things. You can put some waste or something else in here, and you can use those extra neutrons to transmute one isotope to another isotope. So one of the ways these reactors operates are they start out with weapons grade uranium.

You put low enriched uranium or natural uranium, which contains mostly uranium 238 on the outside. That's not useful as fuel, but it's absorbing the extra neutrons. And for a reaction that I will show you later on in class, that then turns into plutonium, which you then extract and use to make new plutonium fuel, which makes even more neutrons per fission. And then this thing becomes this fuel making machine, where it converts non-fuel uranium into fuel plutonium, and therefore, uses very efficiently the uranium that you pull out of the ground.

Because most of the time we're doing this-- most of the time, we were doing this-- where is it? We were doing this isotope separation, where we had to get rid of these grade 238 atoms. Now instead, we're going to convert them electronically with extra neutrons into fuel. And that means you get more uranium utilization. That would be important if the world had very little uranium in it, but it turns out not to be the case. But nevertheless, people still like the idea of efficient usage of uranium.

But it depends, of course, all on economics. If this process is not efficient, then economically, then who cares if it's efficient on a per atom basis? So we'll talk more about these reactors later on in the class. But this is also how the thorium reactors work. Thorium is this gray stuff. It's not a fuel, but you can convert it into a fuel if you stick it around the core, you absorb neutrons, and then you can get uranium 233 out of it and make fuel of that. So that's how a thorium reactor works. It's the same way as a fast reactor.

All right. So that's all I want to say on terms of fission reactors. We have only a few moments left, so let me just briefly talk about fusion. Remember, the key thing about fusion is that in order to overcome the coulombic repulsion, we have to get these atoms moving very fast. And so we need some way to heat them up and keep them contained in a space. So lots of different concepts for doing this.

One is that we could put a little pellet inside a chamber, and then we could shoot a whole bunch of laser beams at it. And if we get all the laser beams incident on it symmetrically, then it will be inertially confined, and heat up and undergo fusion. And that is what's happening at NIF, the National Ignition Facility that has operated at Lawrence Livermore National Laboratory. Doing this has taken decades of research because it turns out heating things perfectly symmetrically is not easy.

So that is NIF. There are other concepts. You can heat it using RF energy when you vibrate, and you try to contain it somehow. So one way you contain it is that you could put it in a magnetic field, so that if these are atoms are charged, then they will circle back on themselves and stay in one place. This is how tokamaks work. And then there are other concepts for heating. You can shoot neutrons and other neutral beams in there to kinetically collide with the BT gas, and try to heat them up through kinetic collision. These are very inefficient.

This is a photograph of one of the laser rooms at NIF. These are all lasers. You see a picture of a guy, and there's just lots, and lots, and lots of terawatts of laser energy going and heating these things. I don't really have time to talk about Q. I think I will wrap it up there. Maybe I'll leave it here. This just gives you a sense of what actually happens in the laser version. This is the amount of energy that goes in. Some gets scattered, some causes electrons to bounce off a material from work functions.

You get some plasmas, you get some X-rays. A lot of it just goes into heating the walls of the thing that's holding the fuel. Some of it just leaks out, and then some of it goes into actually compressing the fuel, and then you get energy. So all of these losses-- fine tuning this process so these losses are controlled are what was so hard and what took me so long to be successful at it.

And with that, I think we're out of time. So that's the 101 on how the technology works. We'll get back to policy issues next class.