MICHAEL SHORT: So today is going to be the last day of neutron physics. As promised, we're going to talk about what happens as a function of time when you perturb the reactor, like you all did about a month ago. Did any of you guys notice the old-fashioned analog panel meter that said, reactor period, when you were doing your power manipulations? We're going to do that today.

And you're going to explore that on the homework. So I'm arranging for all of your actual power manipulation traces to be sent to you. So each one, you'll have your own reactor data. You'll be able to describe the reactor period and see how well it fits our infinite medium single group equations, which it turns out is not very well. But that's OK, because you'll get to explain the differences.

First, before we get into transients I wanted to talk a bit about criticality and perturbing it. So let's say we had our old single group kit criticality relation. And I'd like to analyze, just intuitively or mentally with you guys, a few different situations. Let's say we're talking about a light water reactor or a thermal reactor, like the MIT reactor, or pretty much all the reactors we have in this country.

What sort of things could you do to perturb it? And how would that affect criticality? For example, let's say you shoved in a control rod. Let's take the simplest scenario. Control rods in. What would happen to each of the terms in the criticality condition? And then, what would happen to k effective? So let's just go one by one. Does nu ever change, ever? Actually, yeah, it does.

Over time, you'll start-- that nu right there, remember, that's a nu bar, number of neutrons produced per fission. As you start to consume U238 add neutrons. And as you guys saw through a complicated chain of events on the exam, eventually make plutonium 239, which is a fissile fuel. The nu for 238 is actually different than the nu for 239. So I don't want to say that nu never changes. It's just that shoving the control rods into the reactor is not going to change nu. But it does change slowly over time as you build up plutonium.

What about sigma fission? If this were a blended homogeneous reactor or a reactor in a blender, what would happen to sigma fission as you then shove in an absorbing material? Does it change?

AUDIENCE: No.

MICHAEL SHORT: You say, no. And I'm going to add here homogeneous. So in this case, remember if we define the average sigma fission as a sum-- I'll add bits to it-- of each material's volume fraction, or let's say atomic fraction, times each material's sigma fission, if we throw nu materials into the reactor, then this homogeneous sigma fission does change when we put materials in or take materials out. So you guys want to revise your idea?

AUDIENCE: Yes.

MICHAEL SHORT: Yes, thank you. There's only one other choice. Now the question is, by how much? If you put in a control rod where let's say the control rod's sigma fission would be equal to zero, but volume would be equal to small. Can't be any more specific than that. How much of an effect do you think you'll have on sigma fission?

AUDIENCE: Small.

MICHAEL SHORT: Very small. So let's say a little down arrow like that. What about sigma absorption? The volume is still small, but a control rod by definition sigma absorption equals huge. So what do you think?

AUDIENCE: It's going to increase.

MICHAEL SHORT: It's going to increase a little or a lot?

AUDIENCE: A lot.

MICHAEL SHORT: Quite a bit. Now let's look at the diffusion constant. And remember that the diffusion constant is 1 over 3 sigma total, minus the average cosine scattering angle sigma scattering. What do you think is going to happen to the neutron diffusion coefficient as you throw in an absorbing material? Something that's got an enormous absorption cross-section is also going to have an enormous total cross-section, because sigma total is sigma absorption plus sigma scattering.

And sigma scattering doesn't change that much. But if sigma absorption goes up, sigma total goes up. If sigma total goes up, then what happens o the diffusion coefficient?

AUDIENCE: Decrease.

MICHAEL SHORT: Yep, it's got a decrease. And how does inserting a control rod change the geometry?

AUDIENCE: It doesn't.

MICHAEL SHORT: Very, very close. Yeah, you're right. The control rod better not change the geometry, but what I do want to remind you of is that this buckling term includes-- let's say, this was a one dimensional infinite slab Cartesian reactor. That little hot over there means we have some extrapolation distance.

Remember, if we were to draw our infinite reactor with the thickness A and we wanted to draw a flux profile on top of that, it would have to be symmetric about the middle. And let's say we had our axis of this is x and this is flux. Flux can't go to zero right at the edge of the reactor, because that would mean that no neutrons were literally leaking out. So there's going to be some small extrapolation distance equal to about two times the diffusion coefficient.

So the geometric buckling is actually pi over the reactor geometry, plus 2 times the diffusion coefficient. And if the diffusion coefficient goes down, but it's also very, very small compared to the geometric buckling, how much does the buckling change and by how much? And in what direction?

AUDIENCE: It increases very slightly.

MICHAEL SHORT: Increases very slightly. So the buckling might increase very slightly. What's the overall net effect on k effective?

AUDIENCE: It goes down.

MICHAEL SHORT: Should go down, you would hope. If you put a control rod in, it should make k effective go down, because there's a little decrease here. Things kind of cancel out there. But the big one is putting an absorption material, like a control rod in, should make k effective go down. And that's the most intuitive one, but you can work out one term at a time what's generally going to happen.

So let's now look at some other scenarios for the same criticality condition. I'll just rewrite it so that we can mess it all up again. Now we want to go for the case of boil or void your coolant. And now we're getting into the concept of different feedback mechanisms.

We've already talked once about how raising the temperature of something tends to increase cross-sections in certain ways. But now let's say, what would happen if you boil your coolant? If things got really hot and the water started to boil. What do you want to happen to k effective? You want it to increase?

AUDIENCE: Decrease.

MICHAEL SHORT: Decrease, thank you. You want it to decrease, or else you'd get a Chernobyl. And we'll talk about how that happened in a week or two. So now let's reason through each one of these. Let's assume that nu doesn't change when you boil the coolant. What about sigma fission of the whole reactor?

You're taking a little bit of material out of the reactor by taking liquid water, which is fairly dense, and making it gaseous water, which is less dense. So overall, there are more fissile atoms in the reactor proportionately when the coolant is boiled away than when it's not. So what happens to sigma fission? The average sigma fission for the reactor will go up ever so slightly. Probably not enough to matter.

What about sigma absorption? If the coolant disappears.

AUDIENCE: It goes down.

MICHAEL SHORT: Yeah, water is an absorber. Hydrogen and oxygen-- really just hydrogen-- have some pretty non-negligible absorption coefficients. And if those go away, then you're losing a bit of absorber, aren't you? Actually it's interesting. Oxygen is the lowest thermal cross-section of any element. So we can treat it as pretty much transparent.

Now how about the diffusion coefficient? We've got the formula for it up there. If all of a sudden your neutrons don't have much to moderate from-- there's not much to moderate your neutrons. Yeah.

AUDIENCE: Your scattering just disappears.

MICHAEL SHORT: Your scattering just disappears, right? But so does some of your total cross-section. So chances are, those neutrons are going to go farther before they undergo any given collision because there's no water in the way. So you'd expect neutron diffusion to go up. And what about geometric buckling?

Diffusion goes up, then the geometric buckling-- I'm just going to make it really small. But the net effect here, once again, k effective goes down. We didn't talk about anything to do with the actual temperature effects on the cross-sections. This is just a density thing on the coolant itself. So let's now look at that.

What about if you have some power spike, raised fuel temperature? I'll write it again, so we can mess it up again. So let's say you raise the fuel temperature. And that's going to cause every cross-section effectively to increase if you're doing this average scenario. Let's talk a little bit about why. It's not as simple as just saying, the cross-sections go up.

So let's say we had two different temperatures, cold and hot. So this would be your sigma fission cold. And this would be your sigma fission hot. For cold, sigma fission looks something like that. And as the temperature goes up, these resonances, which I'll just label right here-- resonances being specific energy is where the absorption suddenly goes up, suddenly goes down will actually decrease in height. But they'll start to spread out more. That's about as well as I can draw it very crudely.

And same thing goes not just for sigma fission, but for sigma anything, including absorption, including total whatever you want. And so if your goal is to get your neutrons from the fast region where they're born into the thermal region where you get fission, broadening these cross-sections makes it more likely that if the neutron loses any amount of energy, it's going to hit one of these big resonance regions and get absorbed or taken away before it gets a chance to go to the fission region. So what this is really going to do-- it's kind of funny to say it in terms of a one group criticality relation, but your fission cross-section is actually going to go down.

One reason is that the fuel physically spreads out. And so just from the density modification, you're not going to get as much. But then you've also got that effect of increasing fission from these resonance regions spreading out. The question is, which one is a bigger effect? Can't answer that with a simple statement. You'll go over a lot more of that in 22.05 when you talk about what actually defines a resonance region, how do you calculate them, and how do they Doppler broaden or broaden with temperature.

How about sigma absorption?

AUDIENCE: It goes down.

MICHAEL SHORT: Yeah, sigma absorption, it's going to go down because things spread out. But it might also go up because the cross-sections spread out, or the resonances spread out. What's really going to happen though is the reactor atoms are effectively spreading themselves apart. The coolant's less dense.

The structural materials in the fuel and everything are still there. They're less dense, but there's not fewer of them in the reactor. But there is going to be less coolant in the reactor, because it has the ability to sparsify or get less dense, and kind of squeeze out the inlet and outlet of the reactor.

So what's really going to happen here is, we know diffusion is going to go up, which might cause a corresponding change in buckling. And the net effect, as we would hope, k effective would go down. And so what we've talked about now here is directly controlling reactivity with control rods, what's called a void coefficient, where you actually want to have a negative void coefficient. So if you boil your coolant too much, k effective should go down. And that's one of the mechanisms that a light water or a thermal reactor can help stabilize itself. And you can see that now from just a really simplified one group criticality relation.

And if you raise the fuel temperature, let's say the fuel gets really hot because there's been some power spike, you also want the reactor to shut itself down, which you can see that it does. Let's make things a little trickier. Let's now talk about a sodium reactor. Fast reactor. This one relies a lot more on fast fission of U238. So if we were to draw the two cross-sections of 235 sigma fission and 238 sigma fission-- remember, uranium 235 looked like the one that we drew before, whereas U238 goes something like that, with no actual scale given. I'm not going to even go there.

But uranium 238 does not need moderation for the neutrons to induce more fission. So let's now write the same criticality reaction, which, again, is a super simplified view of things, but that's OK. What would happen to each of these terms in a sodium fast reactor if you void the coolant? So nu won't change.

What about sigma fission? Well, if the coolant goes away, then on average there is fissile materials contributing more to that cross-section, but not that much. So if you want to get technical, might be the slightest of increases, but doesn't matter that much. What really matters, though, is the stuff on the bottom.

Sodium does have a low, but non-negligible absorption cross-section. So if the sodium were to boil away, then the absorption would go down by a non-negligible amount. And then what about diffusion? Well, we've got the formula for it up there. If there's not as much coolant in the way, then the neutrons are going to be able to get further on average. Let's say, they're not going to be scattering around with as much of the sodium. So there might be a small increase in diffusion and corresponding small increase in buckling. But this is where the one group kind of fails.

What the sodium is actually doing is providing a little bit of moderation, so that some of those neutrons when they bounce off of sodium leave the fast fission region and get absorbed. And that's part of the balance of the reactor. If all of the neutrons are then born fast and don't really slow down and just get absorbed, then you might have an overall positive void coefficient. So this would tell you that in a fast reactor where you're depending on your coolant not just to cool the reactor, but to absorb somewhat and to moderate somewhat, you don't want to boil the coolant in a fast reactor. And is a lot of the reason why most fast reactor coolants tend to have extremely high boiling points.

Sodium is approximately 893 Celsius. Lead bismuth is approximately 1,670 Celsius. Molten salt, about 1,400 Celsius. So all those coolant, except for the sodium one, you'll melt the steel that the reactor is made out of before your boil the coolant. So boiling the coolant is a bad day in a fast reactor, because then things will go from bad to worse, because in this case, the feedback coefficient can be positive for voiding the coolant. That's no good. So you want to keep the reactor submerged.

And that's another reason why a lot of these fast reactors are what's called, pool-type reactors. The reactor is not a vessel with a bunch of piping under it that can break and fail, but instead it's designed as a huge pool of liquid sodium. And then the core is somewhere in here with a bunch of pumps sending the coolant in and back out, or through some heat exchange or something. So there's not really any penetrations on the bottom up this pool. And you make sure that you maintain, either when you have sodium or lead bismuth eutectic, or liquid lead, or some other fast reactor coolant.

So these are some kind of interesting scenarios to think about. I think one of them that I put in the homework was imagine you have the MIT reactor and replace the coolant with molten sodium. What's going to happen? Well, let's say you got all the water out first and it wouldn't just blow up. What would actually happen to the criticality relation? That's something I want you to think about, because one of the big problems on the homework is doing exactly this for scenarios that have happened to the MIT reactor, except for the sodium one. That's never happened and hopefully never will. I can't even imagine.

But now let's talk a little bit about when you perturb a reactor by doing something to it, putting the control rods in, or pulling them out, or doing whatever you want. You're by definition going to take one of our first assumptions about how the neutron diffusion equation works and throw it out the window. So we're now moving into the transient regime.

So to study what happens in a reactor transient or when something changes as a function of time, let's first go from k effective to what we call k infinity. The multiplication factor for an infinite medium. We're only doing this because it's analytically easier to understand and still gets the point across.

So we'll say that our k infinity is still a balance between production and destruction. The difference is if we have an infinite medium, there's no leakage. You can't leak out of an infinitely sized reactor, should one ever exist. And so it just comes out as nu sigma fission over sigma absorption. A much simpler form.

And so now we can write what would happen to the flux in the reactor as a function of time. In this case, it's going to be one over velocity. I'm going to make this a very obvious wide v. That change in the reactor flux is going to just be proportional to the imbalance now in the number of neutrons produced and destroyed.

So the number of neutrons produced will be proportional to very sharp nu sigma fission minus the number of neutrons destroyed, sigma absorption, times phi is a function of t. Y'all with me so far? So this right here is a change, which is proportional to an imbalance between production and destruction, times the actual flux that you have in some given time.

So to make this simpler, let's multiply everything by v. Where's my green substitute color? Multiply everything by v. And the only unfortunate situation is we have a v and a nu next to each other. I'm going to try to keep them looking really different. Those go away.

And then we end up with, if we divide by phi, then those phi's go away. And we have phi prime over phi, equals v nu sigma fission, minus v sigma absorption. And now we can start to define things in terms of our k infinity factor and a new quantity I'd like to introduce called the prompt lifetime.

It's a measure of how long a given neutron tends to live before something happens to it. Before it's either absorbed or leaks out, well, not from our infinite reactor. And so we can define this as 1 over their neutron velocity, times sigma absorption. And just to check the units here-- velocities in meters per second. Macroscopic cross-sections are in 1 over meters. So those cancel out, and we're left with a total units of seconds. That's nice. We would want a mean neutron lifetime, or a prompt lifetime to have of seconds or time, at least. Yep.

AUDIENCE: Can you say again why the [INAUDIBLE] squared went away?

MICHAEL SHORT: Why the d phi dt squared went away?

AUDIENCE: No, the [INAUDIBLE] square.

MICHAEL SHORT: Oh, OK. So that's because we assume we're going to be analyzing an infinite medium. So right here, this to relabel these terms, this would be the total production term. That right there represents absorption. And that right there represents leakage. But if we're analyzing an infinite medium, you can't leak out, because it takes up the entire universe and beyond, depending on what you believe metaphysically. That's different costs.

So this right here, we can rewrite as 1 over lifetime. That makes it easier. And this right here, if we note that nu-- that's a nu. I'm going to be really explicit about that. Nu sigma fission over sigma absorption. This kind of looks like this is looking to be like k-- wrong color. --like our k infinity over lp. So all of a sudden we of a much simpler relation. We have 5 prime over 5 equals k infinity minus 1 over the prompt neutron lifetime. So if we solve this, this is just an exponential.

So we end up with our phi as a function of t is-- whatever flux we started at, like for your power in manipulations, it would be whatever the neutron flux was before you touch the control rod, times e to the t, or e to the that stuff, k infinity minus 1 over lp, times t, which we can rewrite as t over capital T. We're going to define this symbol as what's called the reactor period.

What the reactor period actually says is how long before the flux increases by a factor of e. And so this is actually what that meter was measuring on the reactor. It's the reactor period or the time it would then take for the reactor's power to increase by a factor of e because it's an exponential. To tell you what these typical reactor periods tend to be for a thermal reactor, t is about 0.1 seconds corresponding to an average prompt neutron lifetime of 10 to the minus 4 seconds. Seems fast, doesn't it? Like, really fast.

So the question I asked you guys is, why don't reactors just blow up?

AUDIENCE: [INAUDIBLE].

MICHAEL SHORT: Yes, there is something we've neglected from here. It's like what Sarah said. And it deserves its own board. There is a fraction of delayed neutrons. We'll give that fraction the symbol, beta. And for a uranium 235, it equals about 0.0064.

So there's less than a percent of all the neutrons coming out of a reactor have some delay to them, because they're not made directly from fission in the 10 to the minus 14 seconds that we talked about in the timeline. But they come out of radioactive decay processes with delayed lifetimes ranging from about 0.2 seconds to about 54 seconds.

This is the whole reason why reactors don't just blow up. So you can actually make a reactor go super critical. But if the k effective is less than 1 plus beta, then the reactor is not what we call prompt super critical.

And so the reason for that is, let's say you raise the reactor power by some amount and the k effective goes up to 1.005, there's still this fraction 0.0064 of the neutrons are not going to be released immediately. They're going to be released not in 10 to the minus 14 seconds, but in 10 to the 2 seconds. So a measly 15 orders of magnitude slower, meaning that there's actually some ability for this reactor to raise its power level.

And these delayed neutrons, even though that's such a small fraction, takes the reactor period from its t infinity value of about 0.1 seconds to about 100 seconds. So the same reactor when you account for the delayed neutrons increases in power by a factor of e. And it takes it about 100 seconds, which means this is totally controllable.

Now I have a question for you guys. Would you guys like me to derive this formula, or do you want to go into more of the intuitive implications of it? Because we can go either way. There is a formula that will tell you what the reactor period and time dependence will be. And you will hit it in 22.05 probably. I can't guarantee it because I'm not teaching it. Or we can talk a little bit more about some of the intuition behind delayed neutrons. So a bit of choose your own adventure. Math or intuition?

AUDIENCE: Intuition.

MICHAEL SHORT: Intuition. OK, that's fine. Good. So that was the derivation. I'll post that anyway, if you guys want to see. I think in the Yip reading it says, let's account for the delayed neutrons. Intuitively we find that the answer ends up being-- so I'll skip the derivation. And it comes out to phi naught e to the beta minus 1, times k minus 1 over lt, plus beta phi naught over beta minus 1k, minus 1, times 1 minus e to the beta minus 1k, minus 1 over l. OK, so left as an exercise to the reader--

AUDIENCE: That's intuitive.

MICHAEL SHORT: Yeah, that's intuitive. But let's actually talk about how intuitive it is. I do want to give you the starting and the ending equation. And we will not go through the rest. Yeah, Charlie?

AUDIENCE: Should we copy that down?

MICHAEL SHORT: No, you shouldn't. I'm going to scan it for you guys. So don't bother copying it down. Let's talk about where it comes from. And the answer may astound you because we're going to bring right back the idea of series radioactive decay. So let's say you want to relate the change in the number in the neutron flux to a 1 minus-- I'm going to take a quick look at the original equation because I don't want to screw that up. That's the first page, and that's the one we want.

Let's say we had some equations that looked something like this. Phi plus phi naught times beta. This is the original differential equation from whence it came. And the intuitive part that I want you to note is that the jump from changing k effective is moderated by this term right here, 1 minus beta.

So that's the fraction of prompt neutrons, that as soon as you pull the control rod out, that's your instantaneous feedback. By instantaneous, I mean on the order of, like, 10 to the minus 4 seconds, or something that you can't really control. This right here represents the delayed fraction. This is as mathy as it's going to get because you've chosen intuition. I think you have chosen wisely. It's going to be a more fun.

So what this represents right here is your kind of instant change, because whatever you change k effective to, it's going to be moderated by the prompt fraction, how long the neutrons tend to take to undergo that feedback. Yes, Sara?

AUDIENCE: Was that the average?

MICHAEL SHORT: The average what?

AUDIENCE: Average neutron lifetime.

MICHAEL SHORT: Yes, this is the average neutron lifetime. So let's define the average neutron lifetime as simply 1 minus beta times the prompt neutron lifetime, plus the beta times some delayed neutron lifetime. So what no book I've ever seen actually says, this is what's referred to as a Maxwell mixing model.

It's just the simplest thing to say, oh, if you want to get the average of some variable, take the fraction of one species times its variable, plus the fraction of the other species, times its variable. Folks do the same thing with electrical resistivity, thermal conductivity, or any sort of other material property. And it is or isn't good in some situations.

Like, if you had a piece of material made out of two different things-- let's say this had thermal conductivity k1, and it had thermal conductivity K2. Would a Maxwell mixing model be appropriate to describe the flow of heat across this thing? Probably not. But in the case of neutrons where they're flying about like crazy and their mean free path is much larger than the distance between atoms, this works great. So we can define this mean neutron lifetime and use that in this equation right here. So this term right here describes the instantaneous change. You pull the control rods out, and fraction 1 minus beta neutrons respond immediately.

What about that fraction of neutrons? Those are being produced with a fraction beta depending on what the flux was before, because they're still waiting to decay from the old power level. Does anyone notice anything suspiciously familiar about the final form of this equation for flux? You've seen it before with a couple of constants changed around. What about the form of this differential equation?

[INTERPOSING VOICES]

It is exactly the same as series radioactive decay. So the horrible derivation I was going to do for you guys and we're not anymore is, use an integrating factor. You solve it in exactly the same way. You bring everything to one side of the equation. Find some factor mu, that makes this a product rule. Do a lot of algebra. And you end up with a very suspiciously similar looking equation. So it's exactly the same posing and solution as series radioactive decay, with the difference being, that's the constant in front of everything, instead of a bunch of lambdas and fluxes.

So what this says here is that the flux as a function of time, this is the prompt feedback right here, which says that if-- let's graph it, since we're going intuitive. There's no room. Even those all boards are full. OK, here we go. If we graft time and flux right here, what that part right there says is that you're going to get some sort of instantaneous exponential feedback. But it's going to be moderated by this one minus exponential on top.

So you're going to end up with a little bit of prompt feedback, this stuff right here. And then-- have to draw longer because it's going to take forever-- you'll have some delayed feedback, because you've got to wait 100 or so seconds, or whatever that new reactor period is, for the delayed neutrons to take effect. And that's the whole reason you could pull the control rods out at almost any speed you wanted and the reactor doesn't just explode.

If you pull the control rods out fast enough, such that the change in k effective is greater than beta, then the reactor goes prompt super critical, which means you don't have any delayed neutrons slowing down the feedback. And you've kind of turned your reactor into a weapon. A very poor, terrible weapon, but a prompt super critical nuclear device, nonetheless. Did anybody pull out the control rods too fast and the controls took over for you? What about you guys in training? Did you ever do things when you watched the automatic control take over? No?

AUDIENCE: It'll just take over.

AUDIENCE: Yeah, it'll kick you off if you don't pay attention.

MICHAEL SHORT: That's what I mean. The machine takes over and it will kick you off and stop responding to you.

AUDIENCE: [INAUDIBLE] horrible noise and so we don't want that. It's more to avoid an annoying alarm.

MICHAEL SHORT: I see. But the annoying alarm is to stop you from doing something like that, like, making the reactor go prompt super critical.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: OK, so that's what I would call the machine taking over.

AUDIENCE: Oh, I see.

AUDIENCE: It'll kick you on to manual, and then [INAUDIBLE] still don't do anything [INAUDIBLE].

MICHAEL SHORT: Yeah. So if your blood alcohol level is above beta and you try and, let's say, increase the reactor reactivity too much, it will then take over, insert a control rod, make a horrible noise, and say, go home, you're drunk. Something like that. OK, that makes sense to me.

So what did your guys' reactor power traces look like? Did they look something like this, where there was an initial rise as you pulled the control right out? And then after you pulled the control rod out the power kept rising just a smidge, right? And what happened when you put the control rod back in? Let's say you put the control rod back in. You're going to get another prompt drop, not equal to the same prompt gain that you got, because now the reactor's at a different flux, and then some asymptotic feedback like that.

And so this is why to those who don't understand neutron physics, reactor feedback is very non-intuitive. It's not a linear system. You can't just pull the control right out and change the power accordingly. This is why there's automated controls in systems to stop you in case, like I said, if your blood alcohol content's above beta, which is very low, by the way. Though you shouldn't be drinking on the job, especially at a nuclear reactor. Plus, you're all under 21, so what am I even saying?

AUDIENCE: What is alcohol?

MICHAEL SHORT: That's right. Good answer. What is alcohol?

AUDIENCE: Is that going to be covered in [INAUDIBLE]

MICHAEL SHORT: That'll be on the exam, yeah.

AUDIENCE: What is alcohol?

MICHAEL SHORT: Yeah, cool. So that's all I want to go into for the intuitive stuff. And it's about 5 of 5 of. So I'd like to stop here and see if you guys have any questions on neutron physics at a whole. Noting that we're going to take Thursday's class and turn into a recitation. So I would like all of you guys to look at the problem set, because it is posted. It is hard. Trust me. This one's a doozy. So I want to warn you guys because you've got seven days to work on it.

But I want you to look at it so that we can start formulating strategies for the problems together on Thursday, because there are some tricks to it. You guys know me by now, right? There's always some sort of a trick. Like, do you have to integrate every energy to get the stopping power? No, you actually don't have to do any integrals at all. But you can if you want, and your answer will be more accurate and correct. It'll just take longer to get to.

So there's a lot of diminishing returns on these problems sets. If you're willing to take an hour and think about how can I do this simpler and with fewer decimal points, you're probably onto something. And we'll work on those strategies together.

AUDIENCE: Is this due next Monday as well?

MICHAEL SHORT: Yes. So I posted it yesterday at around noon or whatever the Stellar site says. I'll also teach you guys explicitly how to use Janus. So we got a comment in from the anonymous feedback saying, we have to use a lot of software. Can we have some sort of tutorial for dummies? Well, you guys aren't dummies, but you still deserve a tutorial. So I will show you how to export the data you'll need from this problem set for Janus. So you can focus on the intuition and the physics and not get frustrated with getting data out of a computer.

So any questions on anything from the neutron diffusion equation? Yeah, Luke.

AUDIENCE: I'm not real clear on [INAUDIBLE] neutrons are and how those are different from the prompt neutrons?

MICHAEL SHORT: The prompt neutrons come right out of fission. If we looked at that timeline of, let's say the fission event happens here. Two fission products are released in about 10 to the minus 14 seconds. They move a little further apart. And then some of them just boil off neutrons, because they're so neutron heavy, after around 10 to the minus 13 seconds or so. These right here are prop neutrons, coming directly from the immediate decay of neutron rich fission products.

Some of the delayed neutrons come from radioactive decay, but of the much later fission products with much less likely occurrences, which is why the fraction is very low. But also, because it's much longer half life, those delayed neutrons take seconds, instead of pico seconds, to show up. And that's the whole basis behind easier control and feedback a reactor.

Good question. So anything starting from neutron transport to simplifying to neutron diffusion, to getting to this criticality condition, making the two group criticality condition if you want to have fast and thermal, or any of the time dependent stuff that we intuited today. Yeah?

AUDIENCE: So for that cross-section [INAUDIBLE] you have there, so you have one for 235 and one for 238. 235, it has to be thermal neutrons [INAUDIBLE] fast?

MICHAEL SHORT: Yep.

AUDIENCE: And you said that [INAUDIBLE] different [INAUDIBLE] as well it had-- if you have [INAUDIBLE] into the--

MICHAEL SHORT: Was it on the other board or from a different day?

AUDIENCE: It was a different board.

MICHAEL SHORT: OK.

AUDIENCE: Yeah, so could you explain that graph?

MICHAEL SHORT: Yes. So in this case-- let me get a finer chalk. This blue one would be for low temperature, and this red one would be for high temperature. So this blue graph, there are resonances, which have very high values, but they're very narrow. And because the width of a resonance doesn't matter, it doesn't affect the probability that a neutron scatters up here and moves some distance down the energy spectrum. Thinner resonances tend to get passed over, especially if your reactor's full of hydrogen. Some of those neutrons will be born and immediately jump into the thermal region, where it's easy to tell how much fission they'll undergo.

As you go up in temperature, you undergo what's called Doppler broadening, which causes these resonances to spread out and also go down in value. So the actual value of the cross-section at these residences is lower, but the widths are larger. So there's a higher probability that a neutron scattering around and losing energy will hit one of these higher cross-section regions, called a resonance, at a higher temperature. That's the difference there, is these two plots show the same cross-section at low and high temperature.

These plots show the difference between uranium 235 and uranium 238. Good question. Anyone else? Cool. OK, for the first time in history, I'll let you out a minute early. Bring all your questions on Thursday. So we'll start off with a Janus tutorial. And then we'll start attacking this problem set together.