

The following content is provided under a Creative Commons license. Your support will help MIT OpenCourseWare continue to offer high-quality educational resources for free. To make a donation or to view additional materials from hundreds of MIT courses, visit MIT OpenCourseWare at ocw.mit.edu.

MICHAEL SHORT: Well, as promised, we're gonna cover no new material today. We've just hit the end of part two of the course, which I think you'll agree with me, was probably the most technically challenging part. Who would disagree, I wonder? I didn't think so. So I wanted a bit of review and help you guys out with problem set seven. Since I've got a couple of fun problems, I think they're fun because they're actually fairly realistic, like the last one, will it blend, the AP 1000 edition.

Well, you'll actually analyze if given the actual specification sheet of an AP1000 reactor, which is a modern reactor that's being built now, can you determine its k -effective using the two energy group approximation. And just to show you guys that this isn't crazy, I've got the AP1000 spec sheet up here. So who got a chance to take a look at p-set seven? Good, that's a lot of hands.

All right, I highly recommend everyone look at it ahead of time. Because it is the doozy, and it will be the last doozy of this course. So part three of the course is lighter. Because most of your other courses are going to go nuts after Thanksgiving, as far as I know, right? Yeah, this one's not. So I'm doing my best to equalize your total course load this semester by making this course crazy now and lighten up when final season comes.

AUDIENCE: The real MVP.

MICHAEL SHORT: So I've got the spec sheet for the AP1000 right here. That actually goes over a description of what the core is like, the materials that are used, how many fuel rods there are, how many assemblies there are, basically what the core is made of. And what I want to do is jump to the end where they actually talk about the analytical techniques used in the core design. And what I want to show you is for the nuclear design of the core to get axial power distributions, look at that, two-group diffusion theory. The same stuff that we just learned right here.

For axial power distribution control rod worth's one-dimensional two-group diffusion theory-- these are problems that you can solve with the stuff that we've done over the past week and a half. They have a little more complexity in that they keep all the spatial variance in there. So

probably done with computers, however they make the same equations that you do.

So Westinghouse is making the same assumptions that we made in this course. They have a lot more complexity in that they're-- you know, we just had cross sections or a macroscopic cross sections as a function of energy, but you may also think about it as a function of position and a function of temperature, since, as we started alluding to, on-- it wasn't today-- on Wednesday-- no, Tuesday. What day is it now? It's Thursday. Thank you, so it was definitely on Tuesday.

We started talking about how cross sections change with temperature. And so really if we want to go crazy on that neutron transport equation, these cross sections will be functions of energy, temperature, and position. And so that's how this reactor would have actually been designed. But you're going to do a simpler approximation and take all of the information about the core in an AP1000, blend it, so homogenize it, figure out what the average atomic fractions of all the different things in it are, and calculate its k-effective, which I think is a pretty cool problem to do.

I haven't seen it done in the courses here. But I want to see how it turns out. And you might find it's surprisingly different from one. Because we make a lot a lot of simplifications that actually matter quite a bit. But to help you parse this spec sheet, well, actually why don't I show you the problem first. And we'll go through a few of the different things that I've simplified the problem to make it not so tedious. But I also want to make sure you understand what to do.

So the simple statement is calculate k-effective of the AP1000 using two-group diffusion theory, which means you've got a criticality condition from the two-group approximation. And I'd like to go over what that is right now. So let's write out, if we had a two group-- so we have two energy group equations for gains and losses of neutrons in the fast and thermal group. What would it look like? What are the gain terms?

AUDIENCE: Sigma [INAUDIBLE] fast.

MICHAEL SHORT: Yep. There's going to be some average ν times sigma fission fast times flux fast plus sigma fission thermal times flux thermal. Any other sources of neutrons into the fast group? I don't think so. What about sinks? How do neutrons leave the fast group?

AUDIENCE: Absorption.

MICHAEL SHORT: Yep, by absorption. How else?

AUDIENCE: Scattering.

MICHAEL SHORT: Yeah, scattering from the fast to the thermal group. How else?

AUDIENCE: Leakage.

MICHAEL SHORT: Leakage. So there'll be some diffusion constant fast times some fast geometric buckling squared. And, yeah, I think that's it. No, that needs a ϕ as well fast. OK, cool. What about the thermal group? What are the sources of thermal neutrons?

AUDIENCE: Scattering.

MICHAEL SHORT: Yep, scattering from the fast group. So this same term right here. Fast to thermal times ϕ fast. And what are the losses?

AUDIENCE: Leakage and absorption.

MICHAEL SHORT: Leakage and absorption, they look pretty familiar. Thermal ϕ , thermal plus D thermal B_g squared ϕ thermal. And that's a "t." OK. The hard part in this problem is going to be doing these averages. This is the part that we haven't explicitly done on the board and I want to show you. Yeah?

AUDIENCE: Are those T_s or F_s , the first term of the second half.

MICHAEL SHORT: This one?

AUDIENCE: The top equation.

MICHAEL SHORT: The top equation.

AUDIENCE: Yeah, right there.

MICHAEL SHORT: Uh, that should be a-- I'll make the F_s really curly. Curly. And those are straight T_s . These are curly F_s . OK, great, thank you. So the hard part is going to be doing cross section averages. We've just kind of written them as, hey, they're average cross sections. And an average cross section would look something like the integral from a minimum to a maximum of the cross section as a function of energy times the flux over the same integral without the cross section. This is where I want to point out something that I want you to remember for the rest of this

course and the rest of your life. You don't have to do things analytically if you don't want to, unless it's explicitly stated that you have to. So part of this piece, that is to drill in the idea that it's the future, we have computers. And you can do numerical integration with data. Remember on one of the second problem sets, I showed you guys the web plot digitizer? How you can extract information from a printed graph?

Well, a lot of times, what you'll already have is that data. And you'll have to then integrate that numerically in something as simple as Excel or as complicated as Matlab or something worse-- whatever tool you choose to use. I'll be using Excel because it's kind of the lowest common denominator. And so to show you guys you don't need to know any fancy software to actually solve these problems. So let's go through getting some of this data right now.

Let's say that the cutoff between fast and thermal-- so if we were doing a fast cross section-- the cutoff would be at 1 eV. And our max would be, let's say, 10 MeV, which would be the top of the fission birth spectrum or the chi spectrum. 1 eV, and that would be 10 MeV. So all that's left is you need tabulated values for the cross sections and the fluxes.

And then you can perform this numerical integral. I have given you tabulated values for the fluxes, wherever that is. Yep. Use the attached AP1000 tabulated neutron flux profile, which opens, that's awesome. So I've given you the approximate neutron flux in neutrons per centimeter squared per second as a function of neutron energy. And so you can tell for low neutron energy, there aren't any ultra-cold neutrons in this problem, though there are in the problem right before. Because, remember, the "we'll see?"

AUDIENCE: Yeah.

MICHAEL SHORT: Now is when we'll see. But if we scale down, we get down to the thermal regions where it's in the eV levels. You start to see pretty significant neutron fluxes in the realm of 10 to the 14 neutrons per centimeter squared per second. So that value of 10 to the 14 for flux that we've been using in all our previous problem sets-- it's because that's what we actually get. This flux spectrum and the picture of it that we have here was taken from the MIT reactor because it's representative of a pressurized water reactor.

The only difference here is this is the spectrum from the fast flux trap. You don't usually see that fast to thermal ratio in a thermal reactor. But it's the closest spectrum that I was easily able to get my hands on. And it's not that unrepresentative. And the reaction rates for things

aren't going to be that different. Because most of the reaction rates, the cross sections down here are in the, like, thousands of barns level. And the cross sections here are in the one-barn level.

It's pretty much any fast cross section for anything it's about a barn. That's a good rule of thumb. So it's not going to change total reaction rates that much. And that's why I'm not worried about taking the fast flux spectrum from the MIT reactor and pretending like it's the AP1000's. It's not horribly that far off. And it's at the right order of magnitude, which is important.

So that data, I give you. Let's talk about how to get this data-- the macroscopic cross sections. So if you remember, a macroscopic cross section is a microscopic cross section times a number density. And that's for one single isotope. If you have a mix of isotopes, then your total averaged cross section for all different types of atoms is going to be a sum-- I'll make it very different-- over all your possible isotopes of the atom fraction of that isotope times the number density of that isotope times the microscopic cross section of that reaction for that isotope.

Or, I'm sorry, the atom fraction is included in the number density. Let's just simplify this a little bit. The total number density of that isotope-- that'll be in atoms per cubic centimeter-- times the cross section for that particular isotope, which is in centimeters squared, which leads you to a 1 over centimeter macroscopic cross section. And so let's say we were summing up something like stainless steel, which happened to be iron 18 chrome 10 nickel.

Not only would you have to then get the number densities of iron, chrome, and nickel, but you have to look at which isotopes there are. So if we wanted to get the macroscopic cross section for stainless steel, we'd have to split this into the stable isotopes of iron, the stable isotopes of chrome, and the stable isotopes of nickel and then say it's this number density times a cross section plus this number density times a cross section, and so on and so on and so on.

The easy way to get those number densities, if you take the number density of your stainless steel times the atom fraction of that isotope, that should give you the number density of that isotope. Does this make sense to everybody? Does anyone not know how to get a number density of a material from its basic chemical properties? OK.

So a number density is in atoms per cubic centimeter. And usually we would have something like its density, which would be grams per cubic centimeter. So if we take density in grams per centimeter cubed and multiply by Avogadro's number and divide by-- I'll just put a divide-by

symbol here-- the molar mass-- Avogadro's number is given in atoms per mole-- and divide by-- molar mass units are given in-- what is it-- grams per mole-- so that's going to be like moles per gram. The grams cancel, the moles cancel, and you get atoms per cubic centimeter.

So to get a number density, you can take the density of the material-- you know, for stainless steel it's like 8 grams per cubic centimeter-- times Avogadro's number-- let's say 6 times 10 to the 23rd, and this would be like 8 grams per centimeter cubed or so-- divided by the molar mass or the average molar mass of stainless steel. I'm guessing that's around 56 grams per mole.

And then you'll get a number density. And typical solid number densities tend to range from like 10 to the 26 to 10 to the 28. It'll be atoms per meter cubed. So it's going to be around, like, 21 to 23 atoms per centimeter cubed. So if you end up with something way outside those bounds, you've probably got some sort of unit or power error. So that'll help you check your math to make sure you get the number densities right.

If you get the number densities right and you know the atom fractions, then you have the number density of each isotope in the number of atoms of that isotope per cubic centimeter. And then you multiply by your microscopic cross section and you get your macroscopic cross section. Yeah?

AUDIENCE: Could you explain again what atom fraction refers to?

MICHAEL SHORT: Yeah, atom fraction is a fraction between 0 and 1 of what proportion of the atoms in your material are that isotope. So again, if your atom fractions are outside the bounds of 0 to 1, that's not physically significant. If your number densities are really far from those bounds, then they're probably not right-- unless you're talking about a gas or a neutron star. But solid matter tends to have approximately those number densities. Mm-hm?

AUDIENCE: Since we're putting this reactor in a blender [INAUDIBLE].

MICHAEL SHORT: Mm-hm.

AUDIENCE: So when we [INAUDIBLE] the atom fractions to do these calculations, how would we determine the fractions?

MICHAEL SHORT: Good question. You'll determine those fractions from the AP1000 spec sheet. So in the

AP1000 spec sheet, it tells you things like total weight of the fuel as uranium dioxide. And so you can go from total weight of the fuel to, let's say, molar or atom fraction of the fuel. If you know the weight of the fuel-- it's nice, they give you the weight of the fuel. They give you the weight of the clad.

And let's see, which materials did we say you have to think about? It said you have to talk about four materials; the coolant or the moderator-- water; the fuel-- UO₂; the cladding-- where you can assume pure zirconium, forget all the crazy zircaloids because that's just busy work; and structural materials-- assume pure iron. And so on this spec sheet, luckily, they just tell you the mass of the fuel. They tell you the mass of the clad. I do not believe they give you the mass of the water, but they do give you the volume of the core.

And so you can figure out, if you've got a core and you subtract off the volume of the fuel and the cladding and the structural materials, all you're left with is volume of the water in the core. And that'll give you your total weight of the water. And once you have all the weights, then you can go to atom fractions. And then you've got all the information you need to get the macroscopic cross sections. Is that unclear to anybody? Cool.

So we talked about how to get the N's. Let's show you how to get the sigmas. So there was a comment that came in that said please teach us how to use these databases. We just kind of throw them around. Well, I want to teach you how to use this database. Let's say we're going to get the cross sections for oxygen in uranium dioxide. That's nice and easy because there's only one stable isotope of oxygen you have to consider. It's oxygen 16.

I highly recommend using the Java version of JANIS because it is a lot easier to use, less clunky, and more intuitive. So if you don't have Java on your machine-- first of all, it runs on everything, like phones, tablets, Linux, Mac, Windows whatever. And second of all, it'll just make your life easier. So a little time investment now will make the p-set take less. So once you have Java, it should just open cleanly.

And it may show up with nothing. It may show up with something, depending on what you last looked at. In this case, it's looking at whatever last library I looked at. So let's pretend we're starting over. So sometimes you may just see this database as NEA. That's all the databases that come with JANIS. If we expand this, make sure that you go to incident neutron data. Because these are cross sections for neutron reactions that we want to go for.

And there are a lot of databases in here. And in the problem set, specifically say to use the

most recent ENDF or evaluated nuclear data file, just to make sure that we're all using the same data set. You'll notice that there are discrepancies between the data. So different groups have measured things with different uncertainties and different values. And so these cross sections aren't necessarily fundamental constants of nature. They're measurements of those constants with whatever uncertainty and error, which are two separate things, that could be in there.

So let's open up the most recent ENDF library and click on cross sections. And now whatever you see here, the green squares are the elements that have tabulated cross sections. Just to make sure that we only have to consider oxygen 16, let's go to the table of nuclides. You'll never stop using this table. It's like the most useful thing in this class. And check to make sure that there is no other stable isotopes of oxygen that we have to worry about. As long as the internet is working. Huh. Did the immigrate to Korea website crash too? Interesting.

Well, we'll let that load for a bit. And let's start looking at oxygen 16. So if you double click on the element of interest, it'll usually take a little while because its Java and it's loading cross sections. And then you can pick the nuclear reaction of choice from here. And unfortunately, I can't easily make this bigger. I will take a very quick detour and see if I can make these things a bit larger so you can see them. But if not, then whatever. No. No. Ah, oh, well.

So let's say you wanted to get the elastic scattering cross section for oxygen. The first letter before the comma is going to be the incident particle. Notice that sometimes it says N and sometimes it says Z. N specifically means neutrons. Z means whatever incident particle you chose. So we know that here Z means neutrons coming in and elastic. That's elastic scattering.

So we can then click on cross section. If you want to see what it looks like, you can check P for plot. And this will give you a logarithmic plot of the scattering cross section as a function of energy. You can see that it's pretty boring for oxygen. There aren't a lot of nucleons. There aren't a lot of different energy levels. There are not that many resonances or things going on.

So I wouldn't be that upset if you just approximated the fast scattering cross section for argon as that value, whatever it is. But let's do this completely. Let's tabulate this. So if you click on T, you actually get a table of data. And you can choose how much data you export. By default, you get, like, thousands upon thousands of entries, which is just going to make your life horrible.

So what you can do is either pick the original values starting at 1 eV. And we know we only have to go up to 10 MeV. So you can pick your bounds. And all of a sudden, there is only a few thousands worth of data. Or you can interpolate them. You can interpolate values either linearly or logarithmically-- I recommend logarithmic because this is such a large energy range-- and get maybe 5 values per decade.

So between 1 and 10 MeV, you only need five numbers. That's still pretty intense. Oh, I didn't uncheck the original values. Ah, isn't that better? So now there's only 20 or 30 entries. It glosses over the resonances. It sure does. But are they that important? That's up to you guys to decide. You can try doing one of these calculations with the original values and with the interpolated values and see just how different they really are in two-group theory. And hint is, not very much.

So then you can actually export that data. So either you can just copy-paste it. So I just highlighted, copied, start Excel, and in it comes. And right there is the data that you can start to use to do your numerical integration. And I don't want to give away how to do the numerical integration, though I kind of did, symbolically. I'd like you guys to figure out how to do this numerical integration mathematically, given that you can get the data now. So is there any step here that's unclear to anyone? Yeah?

AUDIENCE: So are we going to have to go through, like, every single material, like, all their different cross sections to, basically, sum up and average them?

MICHAEL SHORT: Yes, you are. Sounds horrible, isn't it?

AUDIENCE: Yeah.

MICHAEL SHORT: That's why I made some simplifications. So if you notice, we are simplifying the cladding as Zr. And we're simplifying stainless steel as pure iron. I don't want you guys to just do tons and tons of repetitive stuff. But I do want you to get roughly the right answer.

AUDIENCE: For Uranium, do you want us to [INAUDIBLE] U-238 versus 235?

MICHAEL SHORT: I want you to answer that question. So how would you consider the isotopes of uranium in this question?

AUDIENCE: Shouldn't it be enriched uranium?

MICHAEL SHORT: That's right. It's not the natural values, it's the enriched values. So it will say in the spec sheet--

AUDIENCE: I don't want to look up enriched uranium on Google.

MICHAEL SHORT: You don't want to be on a list? You don't have to look up enriched uranium on Google. You can look it up on JANIS. So if you go to JANIS, right, are you looking for what the enrichment level is?

AUDIENCE: Yeah.

MICHAEL SHORT: Oh, that's on the AP1000 spec sheet. Where'd it go? If we search for enrichment, fuel enrichment, first cycle weight percent. You can either average these or just pretend it's five. Because that's a pretty typical enrichment level is 5% atomic fraction U-235. Or if you want to get really technical, you can average these noting how many fuel assemblies are in each of the regions. But I don't really care if you do that.

AUDIENCE: What would be the other [INAUDIBLE]?

MICHAEL SHORT: U-238. Yeah, so there's only two isotopes of uranium, one of oxygen, however many of iron and zirconium-- hint there's not that many. And then there is H₂O. And there's only one hydrogen and one oxygen. So it's not really that much busy work. It's just enough for you to get to the right answer. So I wouldn't even call it busy work because there's a point to it.

So in that way, you can determine all of these cross sections. We give you these fluxes. These new values you can also get from JANIS. They're not labeled as new, but they are labeled as neutron multiplication factor. And they're usually way down here. And we probably need to find a physical isotope for that. So let's ditch oxygen for now, and go up to uranium. OK.

So let's do U-235. It'll pull up the data. And then near the bottom, new bar total, neutron production. Check it out. For pretty much all energies, until you get to the fast region, it's the value we talked about-- 2.44. And then in the fast region, you suddenly can get more neutrons from fission. Why do you guys think that is?

Well, what sort of additional things happen when your incident particle energy increases? Let's think back to binding energy and all the stuff at the beginning of the course. There's more different kinds of fission products that can be made. Because you're increasing the Q value of this reaction by increasing the initial kinetic energy.

So there are more fission products that can be made. And some of them, let's say, give off more neutrons than others. So you'll be able to get your new bar total from this one near the bottom. And everything else will be near the top. They'll either be a fission cross section, an absorption cross section, a scattering cross section. How do you get your diffusion coefficients? They're not tabulated, but they're close.

AUDIENCE: Yeah, isn't it based off the numbers based off the different cross sections we have [INAUDIBLE]?

MICHAEL SHORT: Yeah. Exactly. So let's render this nicely. The diffusion constant is $1 / (3 \times \text{total cross section} - \mu_0 \text{ scattering})$ average, average, average. And this average cosine is about $2/3$ times the atomic mass. So you can get these diffusion coefficients from tabulated data. The total cross section is found at the top, better known as-- well, it just says total.

So you can get total cross sections here. The only one that might be a little tricky for you to find from notation is absorption. You're not going to see something labeled absorption in this database. However, you will see this gamma reaction. Or how else do you get it? If you take the total minus fission minus scattering, you're left with absorption-- if you don't count N2N reactions or really esoteric high-energy things.

So if you can't find it, that's OK. Because you can calculate it. Because we know sigma absorption is sigma total minus sigma scattering minus sigma fission minus others that we don't care about. And since you're getting these anyway, tabulating sigma absorptions should be trivial. It's just an Excel subtraction. Yeah?

AUDIENCE: I guess U-235 doesn't have it. But last night I was looking at Pu-239. And it has N in an inelastic.

MICHAEL SHORT: Yeah.

AUDIENCE: Would that be considered absorption?

MICHAEL SHORT: Inelastic scattering is not considered absorption.

AUDIENCE: OK.

MICHAEL SHORT: So inelastic scattering means one neutron goes in, one neutron comes out, but at a very different energy level. So I guess we would also say minus sigma inelastic. And inelastic does

happen for just about every other element. But the nice thing is, those don't turn on until about 1 MeV. So it's not going to matter much. But you can quantify how much it matters, and just check.

So if you can make a justified assumption to say here's one of the calcs with and without inelastic scattering, and if they don't differ by much, then forget it, as long as you show me your math. So let's say we've got nus. We have cross sections. I give you fluxes. We have Ds. You can calculate buckling from the geometry of the reactor, which is given in the AP1000 spec sheet.

The only other trick will be what's sigma scattering from fast to thermal? So you'll have to figure out what is the cross section, not just of scattering total, but the cross section or the probability that a fast neutron enters the thermal group. And I don't want to give that away either, but it's not terribly mathematical. Yeah?

AUDIENCE: So if you only have one isotope for whatever you're analyzing, you don't have to go through the whole overall cross section. Can't you just do the number density times the number of cross sections? Yeah, you don't have to.

MICHAEL SHORT: Hm, not quite. So even if you only have one isotope for each material, if you have more than one material, you've got to average those cross sections. Because this criticality criterion is for the entire reactor and all the stuff in it. That's why it's like in a blender.

So even if iron has one isotope and zirconium has one isotope and uranium has one isotope, which wouldn't really be a reactor, then you'd still have to take atom fractions of those to get the total criticality condition. Speaking of which, I forgot to write where the K is. And since everything else here will be tabulated, you can solve for k-effective. So k-effective is the only variable unknown in this whole equation. Yeah?

AUDIENCE: But I mean, like, for one of the other questions, it's, like, oh, if you had a perfectly spherical ball of plutonium-230i, I think it is, in that situation, could you just use the cross sections from JANIS where you don't have to account for any kind of other isotope [INAUDIBLE]?

MICHAEL SHORT: That's right. So, yeah, let's go to the rest of the problem set, since you mentioned it. For one of the other questions, North Korean nuclear weapons. Why is it that just putting together a super critical mass of plutonium does not constitute an effective bomb? We're lucky for that, too, that making nuclear weapons is a lot harder than just getting nuclear material.

And this is a lot of the reason why theirs have been 500 ton yields or kiloton yields-- duds. It's really, really, really, really hard. And I want you to think about what would you need to do to turn a super critical mass of nuclear material into an effective weapon. And why is it that it's so difficult to do? I'm actually really glad it's so difficult to do. It's one of the reasons that a lot of folks don't have them.

But, yeah, if you only have one isotope like you do in this problem, you don't have to do atom fractions. You just take number density times microscopic cross section from JANIS and you get the macro cross sections. That's why it's one of the skill building problems where it shouldn't be that hard. So you'll have a criticality condition. You'll be able to get cross sections and number densities. And you'll be able to tell what that radius of the sphere is given the form of buckling for a sphere, which should be in your reading. Yeah?

AUDIENCE: Where do we get our data for power manipulation?

MICHAEL SHORT: That's being sent to you today.

AUDIENCE: OK.

MICHAEL SHORT: So you guys all did power manipulations from the reactor. I wanted to get them for Monday. The guys were busy doing an in-core experiment install. They've promised me the data today. So you guys will be able to take a look at it, and using the transient stuff that we talked about Tuesday, explain why it doesn't look linear feedback or intuitive. Yeah. So I'll be giving each of you that data today. We talked about nuclear weapons.

This top one I want you to do on your own, because it's other repetitions of the intuitive criticality examples that we did on Tuesday. The last one we haven't talked about is the ultra-cold nuclear reactor or the "we'll see" problem. So here I want you to actually get a criticality condition for the case where you can have ultra-cold neutrons. Where your moderator is, let's say, liquid hydrogen, really, really cold, way below the thermal level, and you have to split your reactor into three energy groups-- fast, thermal, and ultra cold.

And the trick to this here is somebody asked, can you ever have up-scattering? Why yes. If you have an ultra-cold moderator but you've got hot fuel, you can actually scatter up in energy where the surrounding atoms could be hotter than some of the neutrons hitting it and will impart energy to those neutrons and send it up the energy spectrum. Yeah?

AUDIENCE: Yeah, about that, it says all fission neutrons are born fast and all delayed neutrons are born thermal. Can there be no up-scattering from ultra cold?

MICHAEL SHORT: Well how do you get ultra cold neutrons?

AUDIENCE: They would scatter down.

MICHAEL SHORT: Mm-hm. But some of them might scatter up.

AUDIENCE: OK, got it.

MICHAEL SHORT: Yeah, they can scatter down by hitting something cold and scatter back up by getting knocked by a hot atom.

AUDIENCE: OK.

MICHAEL SHORT: Yeah. So it's all going to be in the formulation of the equations. For this problem, like 80% or 85% of the credit is, did you formulate the three-group equations correctly. So I want you to think about what are the actual sources and sinks in each case, what are the fractions of prompt and delayed neutrons, where did they go, and what terms matter where.

So it's doing this, but for the case that we've given you here. Solving it is a lot of algebra, and therefore not a lot of credit. So is that clear to everybody? I figured this p-set was worth explaining and not just saying, have fun. You know, I'll see you on Piazza Sunday night.

AUDIENCE: I'm there.

MICHAEL SHORT: Yeah, that's why I would check it. Yeah. Cool. I've also got problem set four for everybody here. I want to mention a couple of quick things. Please, if you hand write your p-sets, which is fine, please make sure to scan them legibly and to write legibly. We can't give partial credit for things we can't read. And so this will be a lesson to some of you guys depending on who got what grade. There are times when you may have written stuff for partial credit, but we just honestly couldn't make it out.

So please do make sure that your submissions are legible. And for things like these, these are handwritten problem sets, but they were scanned with either a scanner which does the correct contrast or writing them on one note, which apparently works pretty well, or apps like CamScanner. There's an app on your phone you can get that scans pieces of paper and automatically contrast enhances them. It knows the paper should be white and the writing

should be black.

And it also does it in color. So if you do color graphs, it recognizes that there are multiple colors and will take care of that for you. It only takes an additional minute, but it can give you double the points on a problem set because we can read stuff. So I'll give back p-set four now. We're working on five and six. The big delay in grading there was I went to Russia. And Russia doesn't have as much internet as we do, at least not where I was. And it was busy. So working on those solutions now. Yeah?

AUDIENCE: For problem one, it says throwing quarters into the reactor actually happened.

MICHAEL SHORT: Yep.

AUDIENCE: When did that happen?

MICHAEL SHORT: Oh, OK, yeah, good question. So problem 1, throwing quarters directly into the core like a wishing well. It used to be that back in the day, they would take folks on reactor tours to look down into the core. Because when the lid is off, you can see it. You can see the Cherenkov radiation, the nice blue light.

You can actually see the fuel elements because the water is sufficient shielding for you. And the distance is sufficient shielding to keep you away from the gammas, not to mention the reactor is usually off when the lid is off. So it's not that hot. The problem is you can't watch what everyone's doing all the time. And somebody dropped a quarter into the reactor. And they were like, oh, it's a wishing well. Well, it took something like six dive robots to go into the core and fish it out. Because each of those robots lasts 10 minutes before the intense radiation fries it.

And if you didn't find the quarter, you got to take him out, put down another one. And these are, like, radiation-hard, you know, narrow, whatever, diving robots. This story was relayed to me through someone that relayed it to them through whatever. So it's been through the telephone chain. But I do know that's one of the big reasons you can't look down in the core anymore. It's because folks abuse the privileges of tourists. Yeah.

AUDIENCE: JANIS 4 just doesn't work for me. Like, I have my installed Java. It's like up to date and stuff. But it just doesn't work.

MICHAEL SHORT: Interesting.

AUDIENCE: What do you think I should do?

MICHAEL SHORT: Then you could use the web version.

AUDIENCE: OK.

MICHAEL SHORT: Which is just for the browser and no plugins required. Yeah.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Cool. Any other questions about the p-set that we didn't cover together? Those looking a little more doable?

AUDIENCE: [EXHALES]