**MICHAEL SHORT:** OK. I think things have been getting pretty derivy lately, so I wanted to shift gears to something a little bit more practical. So I started alluding to this hypothetical radiation source I might have right here, and things like if you have a source of known activity, which we calculated yesterday, and you have a detector of unknown efficiency, how do you know what the efficiency is? How do you know what, let's say, your dose distance relationship is? And how do you calculate all this stuff?

So let's take the general situation that we're starting to work out. Let's say we have a Geiger counter right here. That's our GM tube. And we have a point source that's emitting things in all directions. Let's go with the stuff from yesterday. Let's say it's a cobalt 60 source. It's now 0.52 microcurie.

The question is, how many counts do you expect in this detector when it's a certain distance away? So I've actually laser-cut out a little Geiger counter jig from a previous class. And you guys can all do this too. Who here has been to the IDC before? A couple.

The international design center-- so they've got a laser cutter that you can sign up to use, which is where I did this. And it's set to just take a Geiger counter and put your sources at some fixed distance away so you can discover the dose distance relationship with things. Speaking of, does anybody know what the relationship is between dose and distance or measured activity and distance?

Yeah, Luke.

**AUDIENCE:** [INAUDIBLE] r cubed.

**MICHAEL SHORT:** Close. It's, let's say, the measured activity would be proportional to 1 over r squared. Who knows where this comes from? I'll move the source a bit away to lessen the beeping. Yeah.

**AUDIENCE:** Well, the flux of particles coming out is just [INAUDIBLE] over the surface area of [INAUDIBLE] and the [INAUDIBLE] is 4 pi r squared.

**MICHAEL SHORT:** Yeah, exactly. If you were to draw a hypothetical sphere around the source right here, then you've got, let's say, a detector that's roughly rectangular with a fixed area. Let's say it's got a half length L and a half width W. Then the area-- I'm sorry, let's just say length L, width W-- would be just L times W. And actually, what Chris mentioned as the solid angle subtended by this detector right here-- in other words, at a certain distance r away, how much of this sphere-- how much does the area of this sphere-- does this detector take up?

In other words, how many of these gamma rays are going to go in a different direction than the detector, versus how many we'll actually enter the detector? And a simple formula for the solid angle is just the surface area of whatever you've got over r squared. It's a pretty good approximation to the solid angle of something for very long distances, and it's probably the one that you'll see in the reading. But I wanted to show you the actual formula, in this case, for a rectangle-- solid angle comparison. Good, that's up there.

So let's say on the x-axis, right here, this would be distance from the source to the detector in meters. And I've said that we've got some sort of a detector that is 2.5 by 10 meters in size. That's an enormous detector. Let's actually switch it to the units right here.

So this is roughly 10 centimeters long. So let's change our length to 0.1. And what do you think the width of this Geiger counter is in meters?

**AUDIENCE:** A centimeter

**MICHAEL SHORT:** A centimeter. 0.01. We're going to have to change our axes so we can actually see the graph. So instead of looking all the way out to 15 meters away, let's look one meter away, maybe less. This whole thing is probably 50 centimeters. And we'll take a look there.

And what we notice is that except for extremely short distances, this approximate formula for the solid angle-- or in other words, if I were to draw a sphere around the source that's the radius of the distance between the source and the detector, how much of that sphere's area does the detector take up? This approximate formula-- the blue curve-- is a pretty good approximation of the red curve until you get really, really close to 5 centimeters away, or about this distance right here.

Does anyone know why this formula would break down? What happens as r goes to 0? What happens to our solid angle or our approximation for our solid angle?

**AUDIENCE:** Goes to Infinity

**MICHAEL SHORT:** It goes to infinity, right? Can a detector actually take up infinity area on, well, anything? Never mind that unit sphere. Not quite. If you were to take this detector and bring the radius down to 0 so that the source and the detector, if not counting for the thickness of the plastic, were right upside each other, if that solid angle went to, well, infinity , then the count should go to infinity, and it does not compute.

Does anyone know how many-- first of all, who here has heard of solid angle before? So a little more than half of you. That's getting clicky. I'm going to turn that off. Solid angle is kind of the analog to regular old angle, except in 3D. So instead of looking at things in radians, this has the unit of what's called steradians-- steradians-- with a full sphere taking up 4pi steradians.

Interestingly enough, 4pi is also the surface area of a unit sphere with radius of 1. So that's where this comes from. If something were to completely cover a unit sphere-- like, if you were to, let's say, encase a light source in tin foil completely, and say, how much of that solid angle does the tin foil encase? It would be 4pi steradians, regardless of the size of the sphere or how much tin foil you had to use.

So this pretty simple formula isn't the best approximation for it. And I'm not going to go through the derivation, because like I said, today is going to be a more practical nature. There is a more complex and rigorous formula for the solid angle of something, let's say, in this case, a rectangle of length L and with W, from a certain distance r, or, in this case, on our graph, x away from the sphere. And you can actually see that red curve right there. Once you get to a few centimeters away, it's pretty close.

Anyone want to guess what the maximum value of the red curve is? If I take this source and slam it right up next to the detector, how much of sphere is the detector subtending?

**AUDIENCE:** 2pi

**MICHAEL SHORT:** 2pi-- half the sphere. Because let's say this whole side of the source is completely obscured by the detector and this whole side is free to move. And if you look really closely, yep, at 0, the correct formula does give you 2pi steradians. Which is to say that half the gamma rays leaving the source would enter the detector. I didn't say anything about get counted yet.

That's where the detector efficiency comes in. And that's something we're going to be measuring today, which is why I have my big bag of burnt bananas. These are the ashes of roughly 50 pounds of bananas charred to a crisp at about 250 Fahrenheit for 12 hours in most of the dorms and a couple of the frat houses. So last year, I had the students, everyone, take home about 50 pounds of bananas or 50 bananas-- I forget which one. It was a lot. And we did some distributed labor.

So everybody peeled the bananas, put them in the oven, baked them, separated off the tin foil, baked off as much water and sugar as possible to concentrate the potassium 40 in the banana. So there's a reason I've been using potassium 40 as a lot of examples in this class, because you're full of it. That's pretty much the short answer of it. If you eat bananas-- which, I think most of you guys do-- you're intaking a fair bit of radioactive potassium, which is a positron emitter, and also it does electron capture and all that fun stuff.

So today, what we're going to be doing is calculating the activity of one banana. But that's kind of a very difficult thing to do. So anyone know how radioactive one banana actually is in any units at all? Whatever it is, it's very, very, very, very little. One banana contains a minuscule but measurable amount of radioactivity. And one of the ways to boost your confidence on any sort of radiation measurement is to boost your signal strength or to boost your counting time. And because I don't want to count for the next seven years, we've concentrated the ashes of 50 pounds of bananas in here to boost your signal strength, which is going to boost your count rate, which is the intro I want to give to statistics certainty and counting.

So let's take one of the homework problems as a motivating example. You guys, did anyone notice the extra credit problem on the homework? Let's start talking about how we'd go about that. That should motivate the rest of the day.

So I'll pull up that problem set, number 4-- which, by the way, is due Thursday, not Tuesday, because we have no class on Tuesday. That was a surprise to me, but whatever. I'll still be here. We don't get holidays-- just you guys.

So bonus question-- go do this. So we all know that smoking is a major source of radioactivity. And if you think about it, it's not just the smoke that contains those radiation particles, it's got to be the cigarettes, cigars, and other smokables themselves. And so I was thinking, there's no better concentrated source of smoking radioactivity than a smoke shop.

There's one out at [INAUDIBLE] at the end of the T. There's probably some closer to campus.

But I know there's a whole bunch that are T accessible. And so I was thinking it'd be neat for us to find out, how radioactive is it to work in a smoke shop? Because there's all these radon decay-- oh, yeah? You actually know.

**AUDIENCE:** You know you have to be 21 to go into a smoke shop?

**MICHAEL SHORT:** Are you serious? But you have to be 18 to smoke.

**AUDIENCE:** Yeah. It's a Cambridge, Boston law.

**MICHAEL SHORT:** Interesting. We may have to leave the city for this one.

[LAUGHTER]

What about Somerville? I think--

**AUDIENCE:** It's still-- you're not allowed to go into there either. It's all of Massachusetts now.

**MICHAEL SHORT:** Wow.

**AUDIENCE:** So [INAUDIBLE]

[INTERPOSING VOICES]

**AUDIENCE:** [INAUDIBLE] you can buy them. It's still late-stage. It's like town-to-town. Most of the Boston area is 21. But once you leave Boston--

**MICHAEL SHORT:** It varies.

**AUDIENCE:** Yeah.

**MICHAEL SHORT:** Yeah. I don't think it is where I'm-- from Swampscott, I don't think it's 21. But that's kind of up on the commuter rails. You don't want to go to Swampscott. At any rate, I would think that, OK, it's probably a fairly radioactive place to work. But the question is, how long would you actually have to bring a detector in and count in order to be sure that there's any sort of measurable difference?

And so, without deriving all of this stuff about binomial, Poisson, and normal statistics, I'll say, that's in the reading for today. I want to show you some practical uses and applications of this stuff. Let's say you were to measure some count rate in some experiment. And we'll put this in units of counts per minute, which would be the number of counts divided by the counting time. That's about as simple as it gets.

From Poisson statistics, you can say that the standard deviation of that count rate is actually just the square root of the count rate divided by time. And that's kind of the simple thing right here. But usually, in these sorts of experiments, if you want to know how much more radioactive is one place than another, you have to take a background count.

So if I wanted to know how much activity that source was giving off, there is lots of background radiation that we'll be going over in about a month. I would have to sit here for quite a while and wait for the slow clicks of whatever background radiation is in the room-- there we go-- to get enough of a count right going on. As you can imagine, the slower the count rate, the less certain you can be that the number that you're measuring is actually accurate.

So the idea here is that this standard deviation is a measure of confidence that your value is actually right. So the two things that you could do to decrease this standard deviation-- you could increase your counting time. Why is there a C on top? That doesn't look right. It actually is OK. Yeah. Yeah, there we go.

So by counting for longer you can decrease your standard deviation. This is going to take forever. It actually takes about 67 minutes, because we've already done this calculation, to get a 95% confidence on 5% uncertainty for this sort of background count. I mean, how many counts we have so far, like, 12? 14? Yeah, not very many.

Then you've got to be able to subtract that count rate from whatever your source actually is. And the way that you actually measure this is pretty straightforward. The way that you do error subtraction is not as straightforward. So let's say we're going to separate these two experiments into a background experiment, which we're actually going to do in an hour. When we want to count these banana ashes, we're going to have to count radiation coming from the detector itself, which will account for cosmic rays, contamination in the detector, whatever else might have been spilled in there from previous samples. And we're also going to take some sort of gross count rate, which will be our background plus the net count rate of our actual source. And that's what we're going for.

So the net count rate is pretty easy. It's just the gross count rate minus the background-- let's keep the symbols the same-- count rate. Does anyone know how to quantify the uncertainty of this net count rate? Do you just add the two?

Well, in this case, we have to account for the fact that radiation emission from anything is a truly random process. So it's actually random. There is no correlation between when one particle leaves and the next particles going to leave. And because it's a truly random process, these errors in the background rate and the gross rate could add together or could subtract from each other. In other words, one might be a little higher than it should be, one might be a little lower than it should be.

If you just add together the two standard deviations, you actually always get an overestimate of the true error, because you're not accounting for the fact that these two experiments may have partially canceling errors. So in this case, that would be your worst case scenario, which is not your most likely scenario. What you actually want is to do what's called uncertainty in quadrature, where you actually add up the sum of the square roots of those errors.

It kind of looks like the magnitude of a vector, doesn't it? It kind of looks exactly like the magnitude of a vector. So in this way, you're accounting for the fact that more error in each experiment does increase the error on whatever net experiment you're doing, but not linearly. Because sometimes you have partially canceling errors. And with enough statistics, if you count for long enough or you count enough counts, then these things, on average, are going to add in quadrature, which will come out to-- and I want to make sure we don't have any typos, so I'll just keep the notes with me-- so you'd need the background count over the background time squared, plus those. There we go.

And so, now, I'd like to pose a question to you, the same one that's here in the problem set-- how long do you have to count in the smoke shop to be 95% percent sure? So let's say your count rate's 5% uncertain. And we're going to spend the rest of today's class taking apart that statement and getting at what it should be.

So again, what we want to say is, how do you know that we're 95% confident of our count rate plus or minus 5% error? That's the main question for today. Does anyone know how we'd start? Anyone get to the reading today? I see some smiles. OK. We'll start from scratch, then.

All right, So who here has heard of a normal distribution before? A lot of you guys. Great. The idea here is that with enough counting statistics, this very rare event binomial distribution approaches a normal distribution, where you can say if you measure a certain count rate-- let's say this would be your mean count rate-- to limits of plus or minus 1 sigma or one standard deviation, 1 sigma gives you about 68% confidence in your result. Yeah, I spelled it right.

The reason for that is that if you go plus or minus 1 sigma away from your true average right here, you've filled in 68% of the area under this normal distribution. Similarly, if you go plus 2 sigma or minus 2 sigma, it's around 95% confident. 3 sigma is getting towards 99 point-- what was the number, again-- I think it's 6. Maybe it's more like 98.5%. And then so on, and so on, and so on, and so on.

There's actually societies called 6 sigma societies. And the way that they get their name is we're so confident of things we can predict them to 6 sigma, which is some 99 point a large number of nines percentage of the area under a normal distribution.

So if I ask you, how long do you have to count to be 95% confident in your result, you have to give an answer that will relate two times this standard deviation. And now we know the formula for standard deviation of this net counting experiment. So we can formulate our equation thusly-- let's say in order to be 95% confident, in other words, 2 sigma, that our counting rate is within 5% of the actual value, in other words, plus or minus 5% error, we put our error percentage here, and our true net count rate there. So this part right here tells us the 95% confidence. This part right here is our 5% error. And that part right there is our count rate.

So then we can substitute in our expression for sigma-- our uncertainty in quadrature-- and find out things like, well, it depends on what the information we're given is. Let's say before you go to the smoke shop, you take your Geiger counter, and for an extremely long time you count the background counts somewhere. So let's say in this problem the known quantities-- we know our background count rate, because you can do that at your leisure at home. And when I did this, it came out to about 25 counts per minute.

And known is the background counting time. And when I did this, to get within 95% confidence of 5% error, I had to do this for 67 minutes. And now, all that's left is we want to relate our net count rate and our gross counting time, or our gross count rate and our gross counting time, because it's the same thing.

So this is actually how you decide how long you have to sit in the smoke shop to count in order to satisfy what we asked for-- 95% confidence that your count rate is 5% error. So let's start substituting this out. That's not mine, so we can get rid of that.

So we'll take that expression and substitute in everything we can. So 0.05 C n equals 2 sigma.

And there's our sigma expression, which I'll rewrite right here. So we have see C b over t b squared plus C g over t g squared.

What's next? How do we relate t g and C g? Well, let's start with the easy stuff, right? What can we cancel, or square, or whatever? Just somebody yell it out.

**AUDIENCE:** Do we have numbers for these counts?

**MICHAEL SHORT:** Yep. So we have numbers for C b and t b, but not C g and t g. We have not yet answered the question when you go into the smoke shop and talk to the owner, and he says, fine, you're going to sit here with the radiation detector. How long do you have to be here, looking all weird? You want to have an answer. And so if you get some initial estimate of C g, you can tell him this is my approximate t g, at which point he or she will say yes or no, depending on how they're feeling.

So why don't we just start, divide by 2, right? Divide by 2. 0.025. We can square both sides. And there's a C n there. Square both sides, and we end up with 0.000625 C n squared equals C b over t b squared plus C g over t g squared.

There's lots of ways to go about it. I want to make sure I do the efficient one. Oh, I'm sorry those aren't squared. Because our standard deviations had the square root in them. There we go. That's more like it.

What's next? We've got too many variables. Yeah?

**AUDIENCE:** I think there's still a square value [INAUDIBLE]

**MICHAEL SHORT:** Isn't there still a what?

**AUDIENCE:** Isn't there a square value still under the [INAUDIBLE]?

**MICHAEL SHORT:** Because, in this case, the standard deviation is the square root of the count rate over the time. So the standard deviation squared is just count rate overtime time. Was there an earlier expression we have to correct? Yep.

[LAUGHTER]

That's where it came from. That's right. That's not. Because that's right. There we go. Good. Good, tracing out that.

OK. Now that everything is corrected here, what's next? We've got too many variables. Yeah?

**AUDIENCE:** [INAUDIBLE] the standard deviation have units of [INAUDIBLE]?

**MICHAEL SHORT:** Not quite, because there's a count rate in here. So the units of standard deviation, if this is square root of count rate over time, which is the same as number of counts times time over time, right?

**AUDIENCE:** OK.

**MICHAEL SHORT:** Yeah. Because again, a count rate is a number over-- where'd it go.

**AUDIENCE:** Number over time squared.

**MICHAEL SHORT:** Yeah. Number over time squared. That doesn't sound right though. Let's see. Hold on a sec. Although the standard deviation has got to have the same units as the count rate itself, because they're additive, right? Because they usually express some count rate plus or minus either sigma or 2 sigma, so they've got to have the same count rate. So standard deviations are expressed in counts per minute if your counts are expressed in counts per minute. OK, cool.

So we've got too many variables, but it's easy to get rid of one of them, either C n or C g. Do you a question?

**AUDIENCE:** No, I was just going to say [INAUDIBLE].

**MICHAEL SHORT:** Great. So you were going to say the same thing that I was going to do. Cool. So we'll take out our C n, and we'll stick in a C g minus C b. And we're trying to isolate t g as a function of C g or vice versa. There's a lot of C g's and not a lot of t g's, so let's just keep the t g on its own.

So we'll have 0.000625 C g minus C b squared. Then I'm going to subtract C b over t b from both sides. Minus C b over t b equals C g over t g. And do I have to go through the rest the math with you guys? I think, at this point, we've got it pretty much solved. We divide everything by C g, flip it over, and you end up with-- actually, I've already written out the expression, which I want to show you guys here.

Back to smoke shop counting time. So I want to show you some of the implications of this expression. That number right there is just a more exact part-- a bit of 2 Sigma. Instead of

0.05, we had something much, much closer.

So what I want us to look at is this graph right here. We've got a nice relation now between the count rate and counts per minute-- and it was the gross count rate and the required counting time to get to that 5% uncertainty. Well, there's a couple of interesting bits about this equation. What are some of the features you notice? Yeah.

**AUDIENCE:** The count rate is extremely low for [INAUDIBLE].

**MICHAEL SHORT:** Yes. If the count rate is extremely low, it's going to take an infinite amount of time. You're absolutely right on some level. So if we have that expression right there-- so let me just actually get it all the way out so we can see. Because I want to show you some of the math-related implications for this. So if we had our counting time-- what do we have-- C g over 0.025 C g minus C b squared, minus C b over t b, at what point is this equation undefined? Yeah, Sean.

**AUDIENCE:** [INAUDIBLE] question [INAUDIBLE], using the second one after the [INAUDIBLE].

**MICHAEL SHORT:** That's right. So like Sean said, for the condition where 0.025 C g minus C b-- let's just call it C net squared minus equals C b over t b, this equation is actually undefined. Which means that if your C b and t b-- let's say if the uncertainty from your background counting rate experiment is such that you can never get the total uncertainty down to let's say 5% error with 95% confidence, you can't actually run that experiment. Because these uncertainties are added in quadrature, if you're trying to reduce sigma down to a value below that already, how can you do that? You can't have a negative standard deviation, right?

So what this actually means is that when you're designing this experiment, even if you count for 67 minutes at 25 counts per minute, like we can now out in the air, that might not be enough to discern the activity of the smoke shop, or the source, or whatever you happen to be looking at to 95% confidence within 5% error. And so let's actually look at that on the graph. If we keep on scrolling up just by adding stuff to the y-axis, eventually we see that it gets all straight. And right here, at about 49 counts a minute, suspiciously close to the background counts, you'll never actually be able to get within this confidence and error interval.

So there's always some trade-offs you can make in your experiment. Let's see-- there it is. So sometimes, do you necessarily have to be 95% confident of your result? Depends on what you're doing. Or do you necessarily have to get within 5% error? That's probably the one you can start to sacrifice first.

So usually, you want to be confident of whatever result you're saying and be confident that you're giving acceptable bounds. So you can remain at 95% confidence, which means-- where did part go-- which means keep your 2 Sigma, but you can then increase your allowable percent error. So if you can't get within 5% error-- and I believe the homework doesn't actually say that for a reason-- yeah, we don't tell what error to choose. But we do say try to get a 95% confidence.

So then the question is, for a reasonable counting time, to what error can you get within 95% confidence? The more error you allow, the shorter time you have to count for. And I want to show you graphically how some of that stuff interplay with each other.

Let's say you were to increase your counting time, which we can do here with a slider. So for the same background counting rate, if you increase the counting time, what happens to the uncertainty on your background experiment? Does it go up, down, or nothing?

**AUDIENCE:** It goes down.

**MICHAEL SHORT:** It's going to go down. Yeah. Count for longer-- the uncertainty goes down. I'm going to have to change the bounds here to something more reasonable. So we were at 67 minutes.

And now, notice, as you increase your counting time, even though you haven't changed the counting rate, it then takes less time to distinguish whatever your source is. So let's count for less time in the background, you have to count for more time in the experiment until it just kind of explodes. Count for more time in the background, you have to count for less time in the experiment in order to get to the uncertainty and confidence you want to get to.

So if you doubled your background count time from 67 minutes to 134, then you can measure count rates as low as 42 counts per minute gross. So when you start going into the smoke shop, you can, let's say, count for a few minutes and get some very crude estimate of the counting rate and then decide how long you have to let your background accumulate so you can distinguish the activity in the smoke shop to within some confidence and some error. Yes.

**AUDIENCE:** So does the background in the case of the smoke shop just the area right outside of it? Instead of the inside?

**MICHAEL SHORT:** It's definitely location dependent. So we will get into background counts and sources of background radiation in about a month. But to give you a quick flash-forward, it depends on your elevation to say how much of the atmosphere is protecting you from cosmic rays. It definitely depends on location. So in New Hampshire, the background count's quite a bit higher, because there's a lot of granite deposits, and granite can be upwards of 52 parts per million radium. Conway granite in particular, named after Conway, New Hampshire, is pretty rich in radium ore. Oh, is that where you're from?

**AUDIENCE:** No. My last name is Conway.

**MICHAEL SHORT:** Oh, there you go. OK.

[LAUGHTER]

Yeah. It's also neat. You can use background counts as a radiation altimeter. One of my graduate students actually built a Geiger counter interface to an Arduino, where you could actually tell what the height you were flying at is by the amount of background radiation increase. So certainly it's going to depend where you are, right?

But you want to make sure that you're in an area, to answer Sean's question, representative of where the smoke shop is. So you can't go into the reactor, and drop this in the core, and say, I'm doing a background count. That's not a valid experiment. So yeah, you'd want to be, I don't know, same block. That would be a pretty good. And then go in there and see, can you measure any sort of increase, get a crude estimate of your C g-- your gross count rate. Use this formula right here to estimate how much time you'd have to wait.

So for example, let's shrink our y-axis down a little and be more optimistic than we probably should. Let's say you go in there and you get a count rate of 100 counts per minute. That would do that would surprise me. You'd only have to count for an extra 28 minutes to nail that net count rate with 95% confidence to 5% error.

Let's say now, what happens if we increase the allowable percent error? So let's say 10% error would be acceptable. We just take that number and double it. Then, all of a sudden, you don't have to count for nearly as long. So again at 5% error, which means a 0.25 here, at 100 counts per minute, you'd have to count for about 30 minutes. If you're willing to accept 10% error, it goes down to seven minutes and 18 seconds.

So do you guys see the general interplay between confidence, percent error, counting time, and counting rate? Who here is built an NSE Geiger counter before? Awesome. So this is definitely a try-it-at-home kids kind of thing. If you want to find out is something radioactive, this is what you can actually use to answer the question, is it discernibly radioactive to within some limit of error or limit of confidence? That's what we're going to be doing here with a much, much, much more sensitive detector.

So the only thing missing from our complete picture of going from the activity of a source, which we've shown you how to count, to dealing with the solid angle, which is just a simple formula, to dealing with statistics and uncertainty, is now the efficiency of this detector. Out of the number of radiation quanta or whatever that enter the detector, how many interact, and how many leave out the other side? That's we're going to be spending most of the next month on when we do ion, photon, electron, and neutron interactions with matter. So we'll find out-- what's the probability per unit length that each one undergoes an interaction, what kind of interactions do they undergo, and then we'll complete this actual picture.

So you can take a source of, let's say, unknown activity, put it a known distance away from a known detector with a known efficiency, and back out what the activity of that source is with accuracy. That's what you're going to start doing on this homework as well for the banana lab. The only thing you don't know is the activity of this bag of bananas. But we're going to give you all the information, like the efficiency of the detector and the geometry of the detector, and you're going to be able to measure the number of potassium 40 counts that the detector picks up.

So by taking-- let's see where we have some space left. We had a little bit here. So by taking that number of counts and dividing by, let's say, the efficiency of the detector, where that efficiency is going to range from 0 to 1, probably much closer to 0, and also dividing by, let's say, your solid angle over 4 pi to account for how many of the emitted potassium 40 gamma rays actually get into the detector and dividing by 2 gamma rays per disintegration-- I think that's what we had last time. Or was that cobalt 60? Yeah. We've been using cobalt 60 as an example.

So remember, we had two gamma rays emitted per cobalt 60 disintegration on average. Then you can get to the actual activity of the source. Once you know the activity of this bag of bananas, you can then divide by either the mass of one banana, or the number of bananas, or whatever to get the final answer. That's what we're going to spend the rest of today doing.

So since it's getting on five out of five of, do you guys have any questions about what we covered today or what we're about to go do?

**AUDIENCE:** You said that for solid angle you wouldn't do this.

**MICHAEL SHORT:** Yep.

**AUDIENCE:** So for solid angle, it's [INAUDIBLE] to the surface area over y squared. And in this situation, does solid angle over 4 pi mean that you can only have a maximum of half of the sphere?

**MICHAEL SHORT:** Not necessarily. Let's say you were to encase your detector in an infinite medium of radiation material. Then you could subtend 4 pi. So the idea here is that if you captured every single gamma ray, your solid angle would be 4 pi. So if your solid angle is 4 pi, then that would equal-ish the area over r squared of your thing. But this is actually not that good of an approximation when you put a source very, very up close to a detector.

So there are actual formulas for solid angle, where the real formula for a solid angle, you actually end up having to do a surface integral of the sine, which accounts for the fact that the object that you have might be, let's say, tilted towards or away from the detector, times some differential d phi d theta of this unit sphere. So you'll have to integrate to say how many of these little d phi d thetas are actually subtended by your detector. And the value of that actual surface integral gives you the real solid angle. That's the super simple one if you just know the area of something and you know that you're kind of far away.

But again, whenever possible, use the exact formula. So any other questions? Yeah, Sean.

**AUDIENCE:** You said that that expression is a true statement [INAUDIBLE] per second, right?

**MICHAEL SHORT:** The two gammas per cobalt 60? This one?

**AUDIENCE:** Yeah.

**MICHAEL SHORT:** That accounts for the fact that if you remember the decay diagram for cobalt 60, how does that decay? By beta emission. It goes to one energy level, and it tends to go down by two gamma decays to nickel 60. So each time it gives off a gamma ray to one level and a gamma ray to another level. So in this case, one becquerel of cobalt 60 would give off two gamma rays per second.

So if you're measuring a number of counts, and each count, one gamma ray was responsible, you have to then divide by the number of gamma rays per disintegration on average in order to get the actual activity of that source. Because remember, activity is measured in disintegrations, not in number of gamma rays emitted. That's the difference here.

Dose-- you'd actually care about how many gamma rays you absorb. But activity is how many atoms are disintegrating per second. Yeah.

**AUDIENCE:** What units of cobalt 60 [INAUDIBLE]?

**MICHAEL SHORT:** The units of cobalt 60?

**AUDIENCE:** It's just two gamma--

**MICHAEL SHORT:** Oh, this would be, like, atoms of cobalt 60. And those gamma rays would be gammas per atom. So in this case, it's like two gamma rays per atom of cobalt 60 disintegrating, or better yet, per disintegration. So you've got to know what material you're looking at in order to know how many gamma or how many betas or more that you're going to get per disintegration.

Who here has heard of this uncertainty in quadrature before? There's a couple folks. OK. Yeah.

The idea here is that, again, if you just add the errors up, you're probably overestimating the error and selling yourself short. Cool. In that case, if there's no questions, let's go do this. So follow me to the counting lab.

**MICHAEL AMES:** OK. So this is my counting lab. These are three high-purity germanium detectors. Have you explained high-purity germanium detectors?

**MICHAEL SHORT:** No, we haven't.

**MICHAEL AMES:** OK. Have you explained any detectors?

**MICHAEL SHORT:** Just the Geiger counter we were playing around with today.

**MICHAEL AMES:** OK. Well, here. Down in here there's a little high-purity germanium crystal with a couple thousand volts across it. When a gamma ray goes into it, it makes some electron hole pairs. Nod when I say electron hole pairs. OK, good.

And basically, you get more electron hole pairs the more energy of the gamma you have. So you collect the current from that, and you get a little pulse of current, and the height of the pulse tells you how many hole pairs you had, and then back it up to what the energy or your gamma was. That works fine if you collect all of the gamma energy. You don't always quite do that.

Anyway, so that's how-- You all can scooch up. There's not a whole lot to see in there.

**MICHAEL SHORT:** It's worth a look. If you've never seen it.

**MICHAEL AMES:** It's worth a look. You can't really see the crystal. There's just an aluminum cylinder in there. The black part is just a carbon fiber window, because you don't want to cut off the low energy gamma. So it's got a really thin carbon fiber window on it.

**MICHAEL SHORT:** What's with the hundreds of pounds of copper around the side?

**MICHAEL AMES:** What's with the hundreds of pounds of copper on the side? There's not hundreds of pounds of copper on the side. These guys are lead.

**MICHAEL SHORT:** Ah-hah!

**MICHAEL AMES:** Which does two things-- it shields the detectors from the activity out here, from you guys, from the activities coming out of here-- because sometimes I'm counting very low activity samples-- and it also, if I'm counting something that has a lot of activity, it shields us from that activity. So it kind of goes both ways.

The reason there's copper is if you get a high energy gamma ray into some lead, it makes x-rays. And it makes a very nice 75 keV-- do you guys know keV? Good.

**MICHAEL SHORT:** We've done x-rays.

**MICHAEL AMES:** Awesome. So it's a really, really nice 75 keV x-ray that interferes with trying to count things around 75 keV, because you're getting all these x-rays coming out of lead. So you line it with copper, which makes a lower energy x-ray and filters out the lead x-rays. So anyway, so this is I've got two germanium detectors. That ones also germanium, but it's a well detector. So it's got a little one-centimeter hole in so you can stick a sample right in the germanium.

They're hooked up through a little electronic box and go into the computer over there that does all the peak height analysis. Oh, yeah, liquid nitrogen [INAUDIBLE]. Thanks for pointing. Yeah, you cool the electronics and everything down so it cuts out the thermal noise. Because you're looking for really tiny little signals here, so you cool everything down. And that way, it's not too noisy.

These guys are OK warming up. It doesn't destroy the detector. The old detectors you had to keep cold all the time. And if they warmed up, then they were just paperweights.

So this is just the counting lab. I've got an actual sample counting in here right now. We'll take a look at the spectrum in a minute. Your bananas are going to go here. And let's see if we can smash it down. Yeah. Because it would be nice if I can close the lid. Oops.

**MICHAEL SHORT:** Well, almost.

**MICHAEL AMES:** Almost. Well, smash this down. Here, one you guys do this. Here, you. Smash that down until it fits in there. Although, don't break the bag. Oh! OK, we'll get another bag.

**AUDIENCE:** Oh, did I break it?

**MICHAEL AMES:** It's OK. It's just banana ash. We'll find another bag. It's OK. You know, I'm all about making mistakes.

**AUDIENCE:** [INAUDIBLE]

**MICHAEL AMES:** Yeah, yeah, yeah, just be a little more gentle. We'll throw some duct tape on it, and it'll be fine. So you're looking for potassium 40 in your bananas, correct? Where else do you think we got potassium 40? Or do you think there's any other potassium 40 in the room?

**AUDIENCE:** In us.

**MICHAEL AMES:** Yeah, right. So when you do the banana count, we frequently take a spectrum on this with the lid closed, and we always see potassium 40. There's potassium 40 everywhere. So after we get the count of the bananas, we'll take a background count. You'll want to subtract the two signals.

**MICHAEL SHORT:** We just did 15 minutes ago.

**MICHAEL AMES:** You're so ahead of me. OK, I think that's all-- Is this going to fit now?

**AUDIENCE:** [INAUDIBLE]

**MICHAEL AMES:** OK. Close enough. I've got this thing-- I've got a whole bunch of little spacers if I'm counting something that's hot. And by hot, I mean radioactive hot. I'll space it out a little further.

**AUDIENCE:** Need a little more smashing?

**MICHAEL AMES:** No, that's fine. We just got to close the lid. And if I've got something that's very radioactive, I'll just space it out away from the detector. If you've got something that's really hot, it just kind of swamps out the electronics.

**MICHAEL SHORT:** We did just go for a solid angle too, today.

**MICHAEL AMES:** There you go. Is there anything else I want to say in here? No, let's move this way.

This is the spectrum I'm collecting on MIT 1. Right now, I don't know-- how long has that been going? Half a day-- less than that. Anyway, so this is a sample of quartz that was irradiated next to the reactor. You guys are going to do shorts in like a month-- did you bring your samples?

**MICHAEL SHORT:** We're getting them.

**MICHAEL AMES:** OK, good. Anyway, this is a sample of quartz that was irradiated in the same spot you guys are going to do your irradiation, sort of in the graphite region of the reactor. The reason we're running it is the people who are looking at this quartz want to run it for 80 hours, and we'd like to know if there are any impurities in it that'll cause grief-- meaning a lot of activity when it comes out.

So we run it for a short period. I think this ran six hours. And it's just a little tiny piece. And so I can look at the gamma spectrum coming out of this. So you can see, there's a whole mess of peaks in here.

This one-- you see that? You see that lovely, little peak right there? Can you all see that? Nod. Yeah, OK. So that's the full spectrum. That's the peak. That's a tungsten 187 peak.

So I did put up one little thing right behind you. Have you all seen the chart of the nuclides? This thing?

**MICHAEL SHORT:** Every day.

**MICHAEL AMES:** Every day! Good. I've got one of these on every wall in every lab in office and a little handbook Yeah. So the tungsten 186 activates into tungsten 187. So if you've looked at the chart of the nuclides, you can tell that there's all the sort of parameters you would need to calculate how much activation you'd get based on neutron flux, and time, and cross. The 28.43, that's the abundance of that isotope. You can see the sigma gamma 38, that's the cross section for thermal neutrons. And so that's how likely you'll get from 186 to 187.

187, that's the half-life-- 23.9 hours. So with all of that-- oh, and underneath the 23.9, you've got what the gammas are-- 685, 479. it's got a whole mess of gammas. So that's a bunch of the gammas in here for that. So you could, knowing how big that peak is, what the efficiency of the detector is for collecting that peak in that geometry, the half-life, the cross set-- that whole mess of parameters-- back-calculate how much tungsten is in the sample.

So that's kind of how NAA works, which I assume you've explained.

**MICHAEL SHORT:** We have.

**MICHAEL AMES:** OK.

**MICHAEL SHORT:** Actually, the whole idea behind doing those short NAA activations is these guys are going to calculate what's in their samples.

**MICHAEL AMES:** There you go.

**MICHAEL SHORT:** Once we get the date.

**MICHAEL AMES:** But that's not how I do NAA.

**MICHAEL SHORT:** [INAUDIBLE] We're doing a simplified version.

**MICHAEL AMES:** Right, right. No, no, no. So there's two things that you could do. One of the things you could do is you take all those nuclear parameters and you calculate it just from the peak height. The other way that everybody who does NAA-- almost everybody who does NAA-- is you run a standard material. Any of you guys chemists at any point in your life? You all took some chemistry at some point? OK.

So you've run a standard, which means a material that how much tungsten is in it or how much a whole mess of other things are. So I run a bunch of different standards. So along with this piece of quartz, I ran a standard, irradiated it at the same time. I'll count the quartz and then I'll count the standard. And by comparing the peak heights and doing all the decay corrections and the weight corrections, then I calculate how much tungsten is in my sample.

So I don't actually use the cross sections, or the flux, or any of that other stuff-- all of those parameters disappear. Notably, the detector efficiency disappears out of the equation, because that's the parameter that you usually have the funniest idea about. And so you reduce the uncertainty in your concentration by doing this sort of comparative method with a standard.

That all make sense? OK. So when we run shorts, I guess, in a month, we'll take whatever your samples are. I've had feedback about, oh, God, you don't want to run that many samples. But we'll figure out how many samples we'll run.

**MICHAEL SHORT:** It's one per person. [INAUDIBLE]

**MICHAEL AMES:** That's a lot of shorts.

**MICHAEL SHORT:** In pairs, right?

**MICHAEL AMES:** Yeah. So I'll show you how the shorts get run. So when we run your shorts, we'll run your samples and we'll run standards, and then you can do the comparative method. Or, if you feel like it, you can do the other method, depending on what exercise--

**MICHAEL SHORT:** The other method.

**MICHAEL AMES:** You're going to do the other method. You don't want to do the standard method?

**MICHAEL SHORT:** Oh, no, no no. We're drilling comprehension, not [INAUDIBLE].

**MICHAEL AMES:** Not practical? Oh.

**MICHAEL SHORT:** What happens if the computer break down?

**MICHAEL AMES:** Well, if the computer goes down, you can't get any data anyway.

**MICHAEL SHORT:** Oh, [INAUDIBLE].

**MICHAEL AMES:** I can do the comparative one on an envelope. Anyway-- well, we'll run standards or not, depending on how you guys are feeling. So that's that. Oh, right. Let's count your bananas.

So this is detector 2. We did an energy calibration earlier today. So actually, I've got a couple of little button sources. Have you seen the button sources? Yeah. So that's just a couple of cobalt 60 lines and a cesium 137 line down in here. And I know where those energies are, so that just gets used to calibrate the detectors.

**MICHAEL SHORT:** We were playing around one of those cobalt 60 buttons today in class.

**MICHAEL AMES:** There you go.

**MICHAEL SHORT:** We mentioned the two gammas per disintegration, and there they are.

**MICHAEL AMES:** There they are. They're kind of small there because my buttons are probably 30 years old.

**MICHAEL SHORT:** Oh, I got some fresh ones.

**MICHAEL AMES:** Yeah. So anyway, we cleared that out. And we just hit Start. And we're not going to see anything a while. Where are we? Oh here. 14-- anyway, your banana peak will end up out in here. So it'll take a while. We're going to let this count until Tuesday. Because, why not? And I don't feel like coming in over the weekend and turning it off.

So yeah. So this is just picking up all the gammas coming out of the bananas, and everything else that happens to get through the [INAUDIBLE], and all the contamination on the inside of that. And we just let it count. And then you guys can calculate how much potassium 40 is in your ashes. You'll need to do the background subtraction. I will give you--

**MICHAEL SHORT:** Do you have background spectra?

**MICHAEL AMES:** Yeah. We collect background spectra once a month or so. So I'll give you a background spectra. I will provide the efficiency for this geometry, which is pretty poorly defined, because I've got a program that'll do that. And I can't give you the program, and it's a pain in the neck to run anyway.

If we've got a really well-defined geometry that's not a big bag, usually I try to count sort of point sources-- so I've got an efficiency standard that I can use that I know what the disintegrations in that are at a lot of energies, and I use that to do an efficiency calibration, usually. But I don't have an efficiency standard that's that big. It's just a point source.

And I think that's the practical NAA. From this end, did that all makes sense? I want you guys to nod, not him to nod. Yeah.

**MICHAEL SHORT:** Do you guys have any questions for Mike on what you've just heard? Well-timed, because we were just talking about this stuff all week.

**MICHAEL AMES:** Good deal. For neutron activation, that's kind of a real common part of the chart. So there's the manganese, iron, cobalt, nickel. One of the things-- what you'd like, usually when you're doing NAA, is you want a nice thermal neutron spectrum. You know what thermal neutron spectra means? Real slow neutrons. And they'll just give you sort of an n gamma reaction.

So on that chart, iron 58 to iron 59, that's a nice n gamma reaction. And that's the one I use to analyze for iron. If you're near the reactor, you're also getting some fast neutrons, which can give you an n p reaction. So if you're looking on the chart there, cobalt 59, if you get an n p reaction, will also make the iron 59. And that's a pain in the neck, because if you've got iron, you've always got a little cobalt floating around-- you maybe need to do a correction.

So in practical terms, when you're running NAA, you really want to avoid having all these fast reactions. There's usually an energy threshold for the fast reactions, like 1 meV or so.

**MICHAEL SHORT:** Sound familiar from the cube equation?

**MICHAEL AMES:** Yeah, OK. Right. The place where we do the irradiations is very thermal. It's got a very low, fast spectrum. So I don't usually have to worry about that. There's a couple of times I actually use the fast n p reaction. If I want to measure nickel, you can see nickel 58, an n p reaction will get cobalt 58. And since there's not a good reaction n gamma from cobalt 57, cobalt 57 isn't around usually. So that's how I measure nickel, using n p reaction.

And I need to put the rabbits into where I've got a fast flux in the reactor. Which, well, they've got a couple of spots for that. I try not to have to measure nickel, because it's pain in the neck. But sometimes people want to know nickel.

And we talked a little about what we've run in here for types of samples.

**MICHAEL SHORT:** Well, why don't you tell us?

**MICHAEL AMES:** OK, OK. So back 15, 20, 25 years ago, we did a ton of environmental samples in this lab. We had a whole three grad students, myself included, who did atmospheric particulate matter, rain water, snow, we even did some fog collection, which is kind of fun, ice cores, which are old particulate deposition. And it was all for trace elements in those kind of environmental samples-- also lake sediments. Other analytical methods have gotten a lot better, and so they've kind of caught up to NAA, and you don't need a reactor to run those. So the environmental side of this has kind of quieted down a lot.

But it's still useful for a bunch of things. And so I do some work here now. I also work in the

NCORE group. So that's a lot of my time, rather than just this lab.

Practical things-- let's go take a look at a couple other labs. You're not on wheels? You don't have a steady cam?

**MICHAEL SHORT:** I got a question.

**MICHAEL AMES:** OK. You've got a question.

**MICHAEL SHORT:** What's the weirdest thing you've ever been asked to count?

**MICHAEL AMES:** The weirdest thing I've been asked to count? That's already activated, or?

**MICHAEL SHORT:** At all.

**MICHAEL AMES:** OK. I don't know-- brain tissue. Fish samples that we actually did the fresh fish samples. And you want to kind of homogenize those. And we had this kind of titanium blender-- you remember the Bass-O-Matic? We had this titanium blender that we dropped the fish in, and you completely homogenized the fish, and then you took a little sample of it, and freeze dried it, and then analyzed it for mercury.

**MICHAEL SHORT:** [INAUDIBLE]

**MICHAEL AMES:** Yeah, right. Because, I mean guys saw, the rabbits are only this big, and the samples I want are only that big. And so to get a representative fish, you want to kind of make a fish smoothie and then take a sample out of that.

We did have a guy who came to me and was promising we were going to do this giant study using fingernails and toenails for nutritional analysis. He was working with a group that looks at zinc deficiencies, and fingernails and toenails will give you a good record of how much zinc you've had over the last week, or month, or whatever-- depend where you cut the nails.

And so I was going to get a couple of hundred African children's toenails. That didn't happen. But I did analyze my own toenails. Well, if you went to somebody who was a little suspicious of you, asking for toenails is a lot easier than asking for a blood sample. Because people would give up toenails-- it's not a big deal.

Have you ever seen the movie or read the book *Civil Action,* about the superfund site in Woburn. It was a big old superfund site, and Woburn had arsenic and chromium contamination. There used to be a lab-- I forget which building it was in-- that did a ton of research there. One of the things we did in this lab was we collected baby hair samples from people's scrapbooks. So we had baby hair going back 50-60 years-- dated, because everybody knew how old their kid was-- and we analyzed the hair samples for arsenic and chromium, and then we plotted out where they were, when the sample was taken, and how close they were to some contaminated wells.

And because we did a fairly short of radiation, after a while the activities died down and we gave the samples back. And we found that it didn't correlate with the well water or the time when the contamination was the worst, which made people happy in retrospect, that the contamination from that area didn't get into the well water. That was in the mid-90s or so.

Anyway, that was one of my samples. And the hair is a pain in the neck to work with. So I hope none of you give me hair samples. I won't run them.

So let's go down the hall, this way. You all got to follow.

And so this is just a fine powder. And it's fly ash from a coal-fired power plant. Fly ash means the ash that goes up the smokestack, as opposed to bottom ash which is what falls down. And so, they collect a whole hundreds of kilograms of fly ash, just homogenize it, sieve it, send it out to a lot of labs to analyze-- NIST is really good at this-- take all the data. And so this ash is characterized for about 20 elements or so.

So when I run my samples, if I were to run your samples with standards, I'd run a little bit of this, 5, 6, 7 milligrams. And I know what the concentrations are in this. And so that's how I do the comparative method. And so I got this.

And they all look the same. And this is some soil from Montana next to a mine, so it's nicely contaminated with some metals. This is my IAEA mercury and hair standard. But again, it's just a little powder. And this is kind of what everybody uses for standards. And you just kind of have a whole collection of them. And depending on what elements you're looking for, you try to mix and match them so you cover what you want without having to run five or six of them.

This is my hot lab, or one of my hot labs. You guys, last week, or whatever it was, I came by-- so this is the rabbit. Those you who weren't there, these are called rabbits because it's the little thing that runs through the pneumatic tube. You guys are doing [INAUDIBLE] later today? Yeah. When you're sitting at the control panel, there's a button, I think it's to the left, and it says insert rabbit. And that's what this is referring to.

For longer radiations there's a spot in the basement in the reactor where they can get these, and they send them into the irradiation location. For short irradiations, like what you guys are going to be doing in a month, I send them in from here. That's OK-- I just don't want to bump into that thing. So this is one end of the pneumatic system.

And so I can put a couple of samples in here. I stick it in that little tube there, call the control room and say, OK, turn a bunch of knobs, and switches, and whatnot. And it goes schwoonk, and in about 15 seconds it's next to the reactor to the core of the reactor in the graphite.

I usually run shorts. I'll usually irradiate for about 10 minutes. We usually let the sample sit in the reactor for a little while. So the very short half-life stuff decays away, and then it comes back out here. And the thing just kind of shoots out there and bounces into here. And then pop open the rabbit, and in that hood, pull the samples out.

I usually try to repackage the samples. So this is partly why I asked for stuff that's one or two good solid pieces. Because then I can take it out of whatever it was irradiated, put it in a clean bag or vial, and that way we don't have to do a blank subtraction for the sample. Does that make sense? Because, otherwise, if I take a little vial, irradiate it, and then count it, I'll also have whatever elements are in the vial on the thing.

For when I'm running standards-- and this is when if we're not running standards you don't have to worry about this-- that powdered standard stuff, I never get that out of a bag. Because you'd never get all of it out, and I'd have contamination everywhere if I started cutting open those bags. So I do have to do a bag correction for those. So when I do when an irradiation, I always irradiate a few empty bags, and then you do a correction for those. Because the bags have got aluminum, and antimony, and a bunch of things in them.

And so then I take a couple of samples, I throw them in a lead pig-- so I've got a whole bunch of these floating around-- and I run it down the hall, and throw it on a detector, and we count it. When we're doing shorts, I'll irradiate two samples at a time, because I have two detectors. When I used to have four detectors, I ran for samples at a time.

So you irradiate it, repackage it, count it. While those pair of samples are counting, you come down here, you irradiate the next two, so that you're just kind of always irradiating and counting. I usually do a 10-minute irradiation for shorts. I'll do a fairly quick count-- five minutes-- right after I get the sample down there, and that's looking for stuff with half-lifes under 10 minutes.

The shortest half-life I look for is for aluminum. It's 2 and 1/4 minutes. But things usually have a lot of aluminum in them, so I see aluminum pretty well.

For shorts, I'll count all the way up to about sodium, which is almost 15 hour half-life. Longer stuff, I'll do a longer irradiation to count. There's a little overlap on my shorts and longs. That helps me do QA on things. And if I run two standards, I'll check the concentrations from one standard to the other. That's another little QA thing.

What else we got?

**MICHAEL SHORT:** What question do you guys have?

**MICHAEL AMES:** Questions.

**MICHAEL SHORT:** Now that you know how this done.

**MICHAEL AMES:** It's pretty straightforward.

**MICHAEL SHORT:** What sort of things are you going to be bringing in?

**MICHAEL AMES:** Yeah, what do we got?

**AUDIENCE:** Probably middle Bronze age pottery shirts.

**MICHAEL AMES:** Oh. Yeah, yeah. OK. There is a lot of archeology that NAA got used for that a lot. I don't think we ever did it here. Fred Frey, who's a professor, retired now, from EAPs-- Earth, Atmospheric, and Planetary-- he did a lot of geological samples. And I forget where it was that they did all the archeology.

One of the things NAA is really good for is rare earth elements, which are hard to measure by other methods. I can get very low limits on that. And by picking out various rare earths and the ratios, it can help identify where things are from in the world.

**MICHAEL SHORT:** Yeah.

**AUDIENCE:** Can I use a bird as a sample?

**MICHAEL AMES:** If you give me a little, tiny piece of it.

**AUDIENCE:** OK.

**MICHAEL AMES:** I mean, you know-- I

**AUDIENCE:** Like, how small [INAUDIBLE]?

**MICHAEL AMES:** Well, see, that's the rabbit. So it's definitely got to fit in there.

**AUDIENCE:** OK.

**MICHAEL AMES:** The thing I really like-- excuse me, where's my vials? I used to have some smaller ones up here. But that should definitely fit in one of those. Like, see that guy.

**AUDIENCE:** OK

**MICHAEL AMES:** My usual description of what size sample I like is if it's a piece that you would pick up with a pair of tweezers. So not too small to pick up-- to be able to find. So no powders. And you could maybe get it with your fingers. But 20 milligrams, 50 milligrams, 100 milligrams is just in the right ballpark.

**AUDIENCE:** OK.

**MICHAEL SHORT:** What else are you guys thinking of bringing?

**MICHAEL AMES:** Doesn't matter. We'll look at what comes in, and-- yeah, I might veto some things or not. But we'll see. We'll see what we got.

**MICHAEL SHORT:** OK.

**AUDIENCE:** What are those little bricks for?

**MICHAEL AMES:** Well, we got bricks everywhere. So when I get the sample out of there, I do the repackaging in here. And so this is just shielding between the samples I'm working on and myself. I don't have my dosimeter on now, but I usually have got the symmetry and a ring badge. And then it kind of comes over here, and this is where the heat sealer is. So I can heat seal it here, and then I'll have a pig over here.

**MICHAEL SHORT:** They're just painted lead bricks?

**MICHAEL AMES:** Yeah, these are just painted lead bricks. And you know, these have been here longer than I have. And sometimes things just are somewhere, and you never move them. These, I think, are older than me too. This lab has been doing NAA since the '70s, I think. Anybody else?

**AUDIENCE:** Is there a single brick that I could just hold to see how heavy it is?

**MICHAEL AMES:** The full size bricks-- like, that size, 2 inches, by 4 inches, by 8 inches, weighs about 25 pounds. There's usually a bunch of them floating around. Here, you want this game? That one's not quite full size.

**AUDIENCE:** Wow. That's pretty heavy.

**MICHAEL AMES:** They're heavy. They're lead. Anybody else want to toss it? No, OK.

[LAUGHTER]

When people ask me-- because I work in the reactor, as well-- they say, is there anything dangerous in the reactor? The dangerous thing is dropping lead bricks on your feet. So I've got steel toast. If I miss the toe, I'd probably break my-- I don't want to think about it. And they move much bigger things in the reactor. Have you toured the reactor yet?

**AUDIENCE:** [INAUDIBLE]

**MICHAEL AMES:** So there's that giant crane there, and they move five-ton pieces a shielding. And that's the other dangerous thing in there, dropping really big things. We've never dropped anything that big. I think somebody dropped a steel plate on their foot once. That was about the worst of it.

[LAUGHTER]

You know, like, four-foot, half-inch steel-- boom.

**MICHAEL SHORT:** That's what happened to my foot.

**MICHAEL AMES:** Yeah. OK, good. And people trip and fall off ladders. And it's the usual industrial accidents.

**AUDIENCE:** [INAUDIBLE] cut off your toe.

[INTERPOSING VOICES]

**AUDIENCE:** Well, my toes are still here.

**MICHAEL AMES:** Good. Yeah. I mean, I've broken a few, but not here.

**MICHAEL SHORT:** So, cool. Thanks a ton, Mike.

**MICHAEL AMES:** Sure. And I'll see you guys in a month or something and have fun running the reactor.

**FRANK WARMSLEY:** Well, good day, folks. You guys are here to do an experiment on the reactor. It's in two parts. The first part is raising reactor power. The first is raising reactor power using a low worth absorber called a regulating rod. And then the second part will be lowering reactor power using a high worth absorber.

And the high worth absorber, things will moved much faster. And we don't want to run into a chance if you accidentally going too high, so that's why we use a low worth absorber on the way up and a high worth absorber on the way down. And I just want to show you the controls. With me today is Tim. To actually do this experiment, we need two licensed people in here, one at least has a senior reactor operator. Both Tim and I are both senior licenses, so we have that covered.

The only way you can actually do these manipulations are if you're in my training program-- I'm the training supervisor for the facility-- or you're in a program that needs you to actually operate the reactor. And the program you guys are in fits that definition.

So I just want to show you some of the controls of the reactor. First, we have our shim blade controller. This basically moves one of six shim blades at a time. The one that's selected has a slide on it. And we can change which one's selected with the shim blade selector switch.

This switch here is a regulating rod. This one will allow you to move the regulating rod up and down. Our blades our fixed speed, meaning they can only move at the exact same rate at all times. Moving the shim blade in an upward direction or the regulating rod in upwards direction, take an underhand grip and pull up or twist upwards until it stops. Moving it just a little bit doesn't move anything. You have to move all the way until it stops, and then the absorber will move in the outward direction.

If you want the blade to stop just release it. It's spring-loaded and will go back to the neutral position and stop moving. If you want to drive something in the inward position, take an overhand grip and twist downwards, and that will drive the absorber in.

Once again, let go. It'll snap back up and stop the motion of the blade or the regulating rod. The experiment we're doing is basically change reactor power by half a megawatt. And we're currently at 500 kilowatts we're going bring the reactor up to 1 megawatt and then bring it back down to 500 kilowatts.

So before we can do this, you have to log into our log book as a trainee on console. We'll show you the proper way to make the entries. As you make those entries, you'll go ahead and then do the actual movement itself.

Sp the first one is going to be using a regular rod to move the reactor power up. What's the reactor power? We have about nine different instruments that tell us what the reactor power is at all times. But the ones we're going to be paying attention to are channel seven 7 and channel 9. These two channels are what we used to basically tell us what the wrecked power is.

Channel 7 is what we control our automatic control at. If you watch the regulating rod, you'll see it move up and down on its own. That's because it's changing power based on what it sees channel 7 is doing. So if channel 7 sees that the power level's going too low, it'll cause the regulating rod to drive outwards to increase the amount of neutrons making the reactor power go up.

Channel 9 is a linear power channel, and it basically tells us what the power level is based on a chart that we create. So it's not showing you megawatts, or kilowatts, or anything like that, it's showing you a current coming from a chamber. And that current is then converted into megawatts and so forth.

So right now, we're at 500 kilowatts, 8.5 microamps, on this channel. And that's 8.5 microamps equals 550 kilowatts. You're going to be bringing a record up to 1. Megawatt and since it's linear, it'll be double that-- so 17.1.

Now, you want to be careful when you raise reactor power. So when you start to add power to the reactor by raising a regulating rod, you don't want to keep raising it until you reach your value, because you have to actually stop the power increase as well. So we have two rules that we have to follow-- one, at the power level we're at, we have period-- the reactor period. The reactor period is amount of time it takes reactor power to increase. At the power level we're at, we're not allowed to go shorter than a 100-second period.

So here is one of three periods meters-- one here, one here, which is selectable between two different meters. So as you're pulling up the regulating rod, one of the things you have to watch is to make sure that the reactor period doesn't go shorter than a 100-second period. If it does, you have to stop pulling blades.

The other thing we have to watch for is to make sure that the power level, channel 9, doesn't exceed where you're going to. Not only not exceed, but we also want to make sure that you can actually control the reactor. It's called feasibility of control. And what that means is when you get to about 80% of the power level you're going to-- since we're going up to 1 megawatt, that's about 800 kilowatts-- you want to be able to drive the absorber in and hold the absorber in. You'll drive the regulating rod inwards.

And watch that channel nine value. It'll slow until it actually starts to go down again. Once it reaches that value and you see it going down, you now know that you could control the reactor and keep it from going away-- rack power increasing continuously. So what we're going to do is have you when you reach 80% of the power level you're going to, which happens to be 800 kilowatts, you're going to start increasing or lengthening the period by driving the absorber back in the regulating rod.

And you'll keep holding it in until you see the number not only stop increasing, but actually go down a little bit. As soon as you see it going down a little bit and go of the regulating rod, You haven't stopped the power at this time, you've just decreased how fast it's going up. And then the power level will sill go up, but a much slower rate than it was before. And once it reaches the power level you want to stop at, the 1 megawatt, keep driving the regulating rod in to hold it at that power level.

Once you're at that power level, you're going to make an entry in a log book that basically says you made it to the power level you're going to. And then we'll go down in power. So once again, you make an entry in a log book that says I'm going to lower ranked power to 500 kilowatts, and then this time we'll use a shim blade. The shim blade is worth a lot more than a regulating rod-- about 10 times the regulating rod, so things will happen much faster. So you'll be able to drive this in and reactor power will change much faster than before.

Same thing-- as you get closer to the power level you start at, the 500 kilowatts, you don't want to undershoot and go too low. So right around 600 kilowatts or so, start driving or shim blade out to slow down how quickly the power level is going down. And once you get back to the place where you started it, we'll use a regulating rod to fine tune it to keep the reactor power where would want it to be. There'll be another logbook entry, and your time on the console will be completed.

So with us today we actually have two MIT students who are actually in my training program, and they've actually done a lot of these manipulations already.

**AUDIENCE:** Ladies first.

**FRANK WARMSLEY:** Sarah. Let's go.

**AUDIENCE:** [INAUDIBLE]. It's been so long since I've done one.

**FRANK WARMSLEY:** I'll take that. So, normally, we sit and watch. If, at any time, you don't feel comfortable doing something, let us know. We'll ask you just to take your hands off the console, and we'll take care of doing whatever is necessary to keep the reactor safe. But be aware, we're a factor of 10 lower than where we would automatically scram at so. So it would be very difficult for you to get to someplace where it would cause a problem without us being able to stop it.

I don't know if you want to move or anything, but the supervisor normally sits kind of right in your way so that they can keep eye on what's happening.

**AUDIENCE:** Are we doing doing any announcing for these?

**FRANK WARMSLEY:** You can go ahead and make the announcement that we're starting power manipulations, and then the last person will make an announcement that we're done with power manipulations.

**AUDIENCE:** Commencing power manipulations. Commencing power manipulations.

**FRANK WARMSLEY:** Right now, the reactor is on autocontrol. And when we do these manipulations, the reactor operator is going to take manual control. That'll cause an alarm to come in. And this will only happen for the first time. So one of the things she's going to do after she makes her logbook entry--

**AUDIENCE:** Are we filling this out?

**FRANK WARMSLEY:** No, we'll do that at the end-- is she'll take manual control of the reactor, an alarm will come in on console, and she'll answer it. And that should be the only time you hear this alarm, because we'll leave it on manual control until the final participant has done their manipulations.

**AUDIENCE:** All right. I hope to get to 1 megawatt at 17.11 [INAUDIBLE].

**FRANK WARMSLEY:** OK.

**AUDIENCE:** [INAUDIBLE]

[ELECTRONIC SOUND]

**FRANK WARMSLEY:** Now, she's pulling out the red rod all the way. You see the red rod number going up. The period is getting shorter. It's no longer at infinity. It's getting closer to 100 second. And channel 7 and channel 9 are increasing in value.

Another way you can see it is we have a display on the front the operator. Those three displays, two of them are just for evaluation only. We don't actually use those to control the reactor. They're based on a system that hasn't been approved yet. But we're testing them to see how well they work. So you can see that the power level on the far left is going up. The middle one is showing what the actual power level-- we started at 500 kilowatts. It's already up to 630 kilowatts and increasing. And the period that was at infinity is now around 160 seconds.

So she's watching, and she sees the 800 kilowatt value here on channel 7 or channel 9, and she's started to driving the regulating ride. So she's slowing down how quick the power increases going. And you see the period lengthening. It's no longer at 150-160 seconds. It's going closer to infinity again. So she's proving that she could stop the reactor power if she continued driving in this regulating rod.

**AUDIENCE:** [INAUDIBLE] back on auto?

**FRANK WARMSLEY:** No. She's closing in on the 1 megawatt. One of the things the note is that when she started, the [INAUDIBLE] was around 0300, 0310, and she's almost right back to there. When you raise reactor power, you basically open up a valve and let more neutrons in. And when you get to the place where you want to be, you basically close that valve again. So you basically add reactivity and then stop that reactivity addition by bringing the absorbers back to about where they started from.

**AUDIENCE:** We're at 17.1

**FRANK WARMSLEY:** We're at 1 megawatt?

**AUDIENCE:** Yeah.

**FRANK WARMSLEY:** Go ahead and make your log book entry. So once again, she has experience. She's been doing startups and power manipulations for a while. When the rest of you sit down here, we'll guide you through those-- the log book entries that she's making and so forth.

**AUDIENCE:** The [INAUDIBLE].

**FRANK WARMSLEY:** 30.6. OK.

**AUDIENCE:** Should [INAUDIBLE]?

**FRANK WARMSLEY:** Yep. So one of the things that could change the reactor is xenon. It's a poison that builds into the reactor while we operate. Poison in that it absorbs neutrons not leading to fission. And it has two ways of being made and two ways of having it removed. One is direct from fission and the other is decay.

That's the way it's produced. The way it goes away is basically absorbing a neutron and decaying to another isotope.

**AUDIENCE:** [INAUDIBLE] half a megawatt at 8.56 microamps.

**FRANK WARMSLEY:** OK.

**AUDIENCE:** Use the same shim blade?

**FRANK WARMSLEY:** Yep, use blade 6. And what happens is when we lower reactor power, the way we remove most of the xenon from burn up, basically the neutrons being absorbed by the fission process. The fact that we don't have the reactor at a very high power means that the amount of xenon in the core isn't being removed. So we actually start-- the power would actually want to go down on it's own. So you would have to do a lot of re-shims. And for a while, that's a very large amount of reactivity that has to be compensated for.

For this experiment, though, we actually shut down the reactor yesterday and we started up early this morning. So it's not a big factor as it normally would be after doing one of these lowering reactor power.

**AUDIENCE:** Do you want to have her do a re-shim now? Or do you want me to?

**FRANK WARMSLEY:** No. I think we'll be able to get at least one more person. So once again, she's lowering reactor power. You can see on the period meter, she's at a negative period, and the reactor power is decreasing. She's almost at 500 kilowatts. She's driving the absorber out again to slow down how quickly the power level is going down. And when she's done, the shim blade will end up about at the same point where it started, the 13.42 inches out of the bottom of the core.

**AUDIENCE:** It might not make it all the way back up to [INAUDIBLE].

**FRANK WARMSLEY:** It'll be close. Compensate with the reg rod if you need to. 30.8. OK. And that's the end of the exercise.