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PROFESSOR:

So I got much more than one request to do some stuff on nuclear materials, and I think it's just about the right time. That you guys know enough about radiation interacting with matter and everything, and stopping power, and processing, to actually make sense of nuclear materials and radiation damage. And this is my whole theme, so happy to come talk to you guys about this and show you why I think it's interesting.

Because it all goes-- this slide kind of gets onto it. It starts off with the single-atom atomic defects that make up the basic building blocks of damage and ends up with things that break in nuclear reactors under radiation. And so to understand the whole thing, you've got to know everything from the single atoms on the sort of femtosecond scale, all the way up to the engineering scale where things evolve over years or even decades.

So we'll be talking-- first, probably today, we're going to go over a material science primer. So who here has had any courses in material science? No one. That's good because I'm assuming that there is a-- see, no one knows anything here. I know there's a couple material scientists in the class, and I'll apologize ahead of time if it's a bit of a review. But we'll be going mostly through what are materials and what are the defects that change their material properties, and how do they behave. That'll take us through about today. So then tomorrow, we can see how radiation causes those defects and actually changes material properties.

So there's a whole laundry list of different ways that materials fail, and most folks are concerned with all of these-- everything from simple overload, which means you stress something too much and it just breaks, to all the different forms of corrosion. That's a whole field in itself. And then there's the things that just we have to worry about because they're only activated with radiation damage. And in this case, this isn't quite ionization by radiation, but it's actual radiation slamming into nuclei and moving atoms out of their place.

And we've got one figure that we had recently in a paper that sums up the entire multi-scale picture of radiation damage, from the femtosecond to, let's say, the megasecond scale. Or I

think it's more than that. Maybe gigasecond would be the right word for that. And all the way down from the angstrom to the meter scale. And I want to walk you through sort of a lens scale by lens scale depiction of radiation damage.

It all starts with knocking atoms out of place. We've mentioned this a little bit when we talked about nuclear stopping power, and this is where it actually comes into play. Sometimes an incoming neutron or photon or ion can displace an atom from its original site, and we call that a physical-- it's a displacement. And then that atom comes off with quite a bit of kinetic energy and can knock into a whole bunch of other atoms.

Now this loss of the solid crystalline structure, you can't really tell what the original structure looked like, right? It actually comprises a very small, localized zone of melting called a thermal spike. If you think about, all these atoms are vibrating at fractions of an eV-- at thermal energies, like the thermal neutrons we talked about in the reactor. Then you hit them with an MeV neutron. They might transfer 100 keV of energy. And a bunch of these atoms will then be moving about at, let's say, a few hundred eV. That's way beyond liquid temperature.

So actually, it's been theorized that there's a little pocket of atoms around three to five nanometers wide that reaches, like, 10,000 Kelvin for a very, very short amount of time-- less than a picosecond. Because almost instantly, those atoms knock into the ones around them, and this is how the process of heat transfer occurs. And so, very quickly, you get what's called the quench, where most of those atoms very quickly knock into other ones, slowing down, finding their equilibrium positions again, but not every one. You can see there's a few places where the atoms are still out of their original location. And it's those residual defects that actually comprise radiation damage.

And as those defects build up, they start to move. They can diffuse. They can be transported ballistically by more radiation damage. They can move by all sorts of different mechanisms and eventually find each other, forming what's called clusters. So a bunch of those missing atoms could find each other and make a hole, which we call a void. A bunch of the extra atoms shoved in between the other ones can form things called interstitial clusters. We say interstitial because it's like in the space in between where you'd normally find some atoms.

So let's say you had a whole bunch of those missing atoms come together, forming a void. This is an actual Transmission Electron Microscope, or TEM, image of a void-- pockets of vacuum in materials. Notice anything interesting about its shape?

AUDIENCE: It's, like, rounded.

PROFESSOR: It's rounded, but what's most striking to me is it isn't actually round. So you would expect a void or a bubble to be kind of spherical, right? That's the minimum energy configuration of most things. Not so when you have a little pocket of vacuum. It's where crystallinity comes into play.

And these voids can end up forming superstructures. What curious thing do you notice here?
For this whole ensemble of voids. Yeah?

AUDIENCE: It seems like they're all in line.

PROFESSOR: They are all in the same direction. Kind of funny. That's definitely not an accident, right? That's not like they're randomly aligned. There's a reason for this, that we'll go into in a couple slides. Yeah?

AUDIENCE: What's the size scale here?

PROFESSOR: The size scale? I think these are on the order of 20 nanometers or so. Yeah, I cropped these images just to get points across. Let's see if it says in the older one. Not quite. Yeah, but these voids can get upwards of tens of nanometers. As small as single atoms. Yeah?

AUDIENCE: Sorry, what is this?

PROFESSOR: This is the accumulation of radiation defects into what's called voids. Yeah. Don't worry, we'll go over it in more detail again. And if you get little pockets of vacuum in your material, you're not creating or destroying mass. You're just moving it. So those voids, where that mass was has to go somewhere else, and you actually get things that swell in the reactor on their own. They don't change mass but they change volume. They just kind of puff up like Swiss cheese, sometimes upwards of 20% or 30% changes in diameter and length for some tubing.

Now if you're depending on these fuel rods being a certain space apart in a reactor and they start to swell, squeezing out the coolant, you lose the ability to cool the reactor. Because then how can you get water around something where the tubes have then swelled together?
There's lots of other bad things that can happen, which we'll get into.

And so then that's the origin of void swelling. From single missing atoms called vacancies, they can cluster into voids which then cause physical dimensional changes of materials on the

scale of centimeters to meters. And that's why we say it's this full multi-scale picture of radiation damage. But to understand, what is damage, you have to know what is an undamaged structure to begin with. So it doesn't make sense to say, how does a structure change, if you don't know how it behaves.

So I want to give a very quick primer to material science. And apologies to any material scientists in the room because this is going to seem really basic, but this is a very quick intro to this whole field. I want to go over quickly, what is a crystalline solid? A perfectly undamaged material would be a set of atoms lined up in a very regular lattice and of regular array, where you move over a certain distance and you find another atom. And this extends forever and ever and ever, all the way out to when you reach the free surface.

And so this is what we would call an undamaged material. A pristine, perfect, single crystal. By crystal, I mean an arrangement of atoms in a certain direction. So notice here, all of the atoms are lined up in, let's say, some cubic xyz way. That's what we would call one crystal or one grain. You'll hear both of those.

And you'll notice also that the arrangement of the atoms tends to determine what the physical objects look like. Or we like to say that form follows structure in material science. So for materials like pyrite, which follows a simple cubic structure, that's the crystals you pull out of the ground. They mimic their atomic configurations in physical centimeter-sized space. For gold atoms, they adopt a slightly different structure. It's still cubic but there is atoms shoved into the cube faces. It's what we call Face-Centered Cubic, or FCC. And you start to see cube-looking structures all over single crystals of gold.

Another one, gypsum. It's got a very different type of structure called monoclinic, where none of the sides of this parallelogram are the same and there are some funny angles. But if you look at the arrangement of the atoms and the actual crystals of gypsum that grow, you see a striking similarity, which I find pretty neat.

I also want to mention, what is the absence of structure in material science? We call that something that's amorphous. Amorphous means without form. So for example, crystalline indium phosphide would have this regular structure like this. You move over a certain distance, you see another green atom, and so on and so on and so on. In an amorphous material, it can still be a solid, but there is no fixed distance between any certain types of atoms. And radiation can cause a lot of this amorphization by knocking the atoms about and having them freeze in

random configurations. This is one of the ways that radiation damage can embrittle materials because-- well, we'll get into that.

So now let's talk about the defects that can be created in a perfect crystal. The simplest ones, we call point defects. They're zero-dimensional because they're just single atoms out of place. You can have what's called a vacancy, where if you had, let's say, a face-centered cubic lattice of atoms, where you have atoms on every cube corner and every face, if you just pull one out somewhere, we refer to that as a vacancy. A missing atom. It had to go somewhere, though, and we'll get to where it is in just a second.

So it might be kind of hard to conceptualize, how do we know that there are missing atoms in all these little cubes or lattices? We do have direct evidence. They're what's called quenching studies, where you can measure the resistance or resistivity of a piece of material after heating it to a certain temperature. Because it turns out that the hotter you make something, the more of those vacancies just naturally occur. You won't actually ever find an absolutely perfect single crystal anywhere in nature, unless you go to zero Kelvin for infinite time, then the atoms arrange themselves thusly.

There's always some amount of atomic vibration going on. And there's actually some thermodynamic energy gain to having a few defects in your structure. And that number of defects increases with increasing temperature. Once you get to the melting point of a material, or like right before something melts, you can have up to 1 in 10,000 atoms just missing. Moved somewhere else. We call that the thermal equilibrium vacancy concentration.

And we can measure that using these resistivity measurements, where you heat materials up to higher and higher temperatures, cool them down suddenly in, like, liquid nitrogen or liquid helium, and measure the change in resistivity. The more defects there are, the harder it is for electrons to flow through. And the only thing that could really be responsible there in a single element would be vacancies. So we do know that these really exist.

They can also cluster up. It turns out that every time you have a vacancy in a material, the other atoms move in a little bit towards it, relaxing the pressure they feel from the atoms nearby. And one way for a whole bunch of vacancies to lower the stress of the whole atomic configuration is to cluster together. So if you have a whole bunch of vacancies, they may not allow as much stress accommodation as if they were separate, when they're together.

Now you might ask, what happened to the original atoms? You can't just take atoms away and

then go nowhere because you can't just destroy matter, right? Unless you turn it into energy, which is what we do in nuclear engineering. So in the material science world, they end up as what's called interstitials, where you kind of have a vacancy created from somewhere that knocks that atom out, and it gets stuck in the next biggest space between some other atoms. And we refer to those as interstitials.

And those can cluster up, too, to reduce their total stress in the lattice. They can cluster up into what's called split dumbbell interstitials. Instead of having one extra atom shoved in here, you might rearrange a couple so there's two atoms in the center of a cube instead of one. And that tends to be a lower energy or a more stable configuration.

So let's look a little bit at the energetics of these point defects because understanding how they move and why will tell us a lot about how radiation damage happens. So it turns out that interstitials are very hard to make. It's really hard to shove an atom where it doesn't want to be. But once you get it there, it moves very easily.

Let's draw a quick, simple cubic lattice to do a little thought experiment and explore why that might be. Let's say I want to shove an interstitial atom in here between these other atoms. Well their electron clouds are going to repel, and it's going to push all the nearby atoms away by just a little bit. And these ones might push the other atoms away by just a little bit, stretching out the lattice, or adding some compressive stress wherever that interstitial is.

But then how would it move? What's the biggest barrier it has to overcome to get to the next adjacent location? Well, which direction would it go? Would it go this way? Probably not. There's an atom in the way. So it's going to find the path of least resistance to try to get over here, because like we've talked about before, all atoms are always in motion. Vibrating. Some of them will be energetic enough to squeeze through these two atoms and get over to the next site.

And that turns out to be a pretty easy process. We can look at the energy required for an interstitial to move. We notice it's really small fractions of an electron volt, whereas creating them takes two or three electron volts. In atomic land, that's a very high energy penalty. Now let's look at vacancies. They're quite the opposite. They're rather easy to make but they're very hard to move, compared to interstitials.

Notice that the energy of movement is about the same as the energy of formation for vacancies. To take an atom out or to pluck it out, you have to break every bond between

nearby atoms. So you actually have to put energy in to break those bonds and then remove the atoms somewhere else.

Now these things are usually made in pairs, so if you think about how much energy would it take to cause a single radiation damage event where you have one vacancy, which let's say would have been right here, and one interstitial, it takes the sum of these two energies-- usually about four electron volts. That's not something that tends to happen chemically or from stress or from something like that. But radiation coming in with hundreds of keV or even MeV neutrons, anything's on the table because it's high enough energy. Yeah?

AUDIENCE: What would take about three or four eV?

PROFESSOR: So it would take about three or four eV to make a pair of a vacancy and an interstitial. If you just add these two up. It comes usually to about three or four eV, or electron volts. And that's a very difficult thing to do in sort of chemical world, where reactions might proceed with fractions of an electron volt. But when you have MeV neutrons coming in, they do whatever they want. They'll do whatever they will.

So someone actually asked me yesterday, what sort of materials can you put in the way of neutrons to stop them from doing damage? And the answer is, pretty much nothing. Fast neutrons tend to travel about 10 centimeters, even in things like steel or water, and they're going to hit what they're going to hit. There's not much you can do but put more things in the way. And we can only get to a certain density with regular matter. And I think osmium has upwards of, like, 22 grams per cubic centimeter density. That's not enough to stop neutrons, even over a considerable distance. Unless you had, like, liquid neutron star, that you could pack nuclei in at a way higher number density, not much you can do.

So moving up in the dimensions, there's another type of defect called a dislocation, where it's actually energetically favorable to slide an extra half-plane of atoms in between two sets in here in the crystal lattice, creating a sort of bulged-out structure like you see right here. And dislocations are one of the most important defects in material science and radiation damage. They're what I like to call the agents of plasticity. If you deform a material enough that it doesn't just spring back, then most likely, you were creating and moving dislocations in the material.

If you think about a couple of different ways to cause deformation-- let's bring our perfect

lattice back without all these extra notations. If you want to slide or shear two planes of atoms across, and they're all bonded to each other, what do you physically have to do? How can you get these atoms to slide across each other? What sort of energy do you have to put into it? Yeah?

AUDIENCE: [INAUDIBLE] energy.

PROFESSOR: Yep. Because all these atoms are bonded to each other, if you want them to move, you have to break every bond on that plane. That's a lot of atomic bonds to break and it's extremely unlikely that that would happen. In fact, if you broke an entire plane of bonds in some material like this, what would you physically do to it? You'd snap it in half. That would be fracture. So if you broke every bond down this plane, you would then have two pieces of this fuel rod. That's usually a pretty high-energy thing to try to do.

So instead, if you shove an extra half plane of atoms in there, and the bonds are kind of funny like so, right at that extra half-plane location, then what you can actually do is break one. Let's say you break this one, form the next one, then break this one and form the next one. And for a few atoms to move over, you only have to break a line of bonds, not a plane. So it's much less energy-intensive to get a dislocation to move than to just break something in half.

Now you might ask, well, then why do things actually break? Whether or not things deform or break is a balance between this process, which we call slip, and breaking an entire plane of atoms, which we call fracture. So this one's called slip. The other mode is fracture. We would rather materials to form in systems like reactors by slip, just moving a little bit, then just breaking altogether. Unfortunately, when enough radiation hits materials, you can fracture things in a brutal manner, and we'll see what happens then.

There's a couple kinds of dislocations. One of them is called a screw dislocation. So imagine you had a whole bunch of sheets of atoms, and you made a cut halfway through that sheet and then moved every plane up by one position. You then got what's called a screw dislocation-- kind of a spiral parking garage of atoms surrounding that core right there.

You can also have what's called an edge dislocation, which is like the one I've got here on the board right here, where you just have an extra half plane of atoms shoved in right there. So there's two types, and they move in two different ways. The edge dislocation behaves like you may physically expect. If you kind of push like this on two planes of atoms, it moves in the direction you push it. Screw dislocations are kind of screwy. If you push like this, it moves

perpendicular.

Not going to get into why, but just remember, screw dislocations are fairly screwy in the way that they behave. Not quite intuitive. But that's OK. We don't have to worry about those.

And the way that they actually move, like we showed right here, is by what's called glide, or slip, where dislocations can slide just by one plane of atoms or one atomic position in a mechanism that looks something like this. Where, as that dislocation moves, you only have to break a line of bonds and then reform a line of bonds, which is a much easier process than breaking an entire plane at once. It's like you have to break the square root of the same number of bonds.

I'm going to skip ahead through some of that. There's one other mechanism of dislocation movement that's important to us in radiation damage and that's called climb. This is when you start to think about, what happens if you have a dislocation, which we'll give this symbol right here, and you also have a vacancy, let's say created by radiation damage. If that vacancy can move, it's going to find the most stressed-out part of this lattice. Most likely, the vacancy will move here. In other words, the atom will move over there, leaving this vacancy over there.

It's kind of funny to think, like, what does it mean that a vacancy moves? Has anyone ever done anything with semiconductors and talked about electron and hole movement? OK, yeah. So what does it really mean for a hole to move, right? A hole's not a thing. A vacancy's also not a thing. It's an absence of an atom.

But here, we can say that the vacancy moves in this direction when the corresponding atom moves in the exact opposite direction. And then what you've actually done is moved your dislocation up. Instead of moving in the slip direction, you've now moved it in a perpendicular direction. This is usually not possible without things like radiation damage or very high temperature.

And then, to make things even crazier, you can also have what's called loops of dislocation, some videos of which I'll actually get to show you. You can have a dislocation that has part edge character, part screw character. If you look at how the atoms are arranged here, you're looking from sort of the top-down. You can see that there's an extra half plane of these white atoms shoved in in the black ones, and this right here would be a completely edge dislocation.

You can have a gradual transition, where about 90 degrees later, it looks like a spiral and

that's a screw dislocation. And the net effect of that is when you push in this direction on an edge dislocation, it moves that way. When you push this direction on a screw dislocation, it moves that way. So when you stress out a dislocation loop, it just grows. You're not actually creating or destroying matter, but what you're doing is causing this small loop of extra half plane of atoms to grow further and further until it actually reaches some obstacle or the outside of a crystal.

And these dislocations can actually feel the force from each other. If I draw a clean one because I think it'll be easier to see-- if I draw a small lattice of atoms here and then a dislocation core right there. So that's our dislocation core. This region of space right here is compressively stressed. There's more atoms in that space than there want to be and so it's kind of crammed in there. While this region right here is in what's called tensile stress. There's almost some space, like right here, where there's too few atoms and they kind of want there to be more.

And these dislocations can feel neighboring stress fields. Let's say there was another one right over here that had its own compressive stress field. They'll actually repel each other because you don't want to add even more compressive stress to anywhere in this group of atoms. So they'll actually repel each other to the point where, if you get two dislocations too close to each other, they'll what's called pile-up, or they'll refuse to move a bit.

So I want to show you some videos. We can actually see these dislocations. In this one, you see that faint line right there originating from this area? That's actually a dislocation loop under stress and that's actually growing. So what you're seeing here is an image of electrons passing through material and looking at regions of different contrast. So wherever there is more atoms or fewer atoms, it looks darker or lighter, and that can tell you what sort of defects there are. You guys all see that faint line right there? Notice how the loop's just growing. It's not like you're moving a line, but you're literally growing a line out of what looks like nothing.

There's another one we call a Frank-Read source. It's a source of dislocation loop. So what you're seeing here, each of these lines is a single dislocation. And then right there, you see that loop suddenly form? Let's show you that one again. I'll point on where to look. By stressing out materials, you can actually create additional dislocation loops, right around here. And there it is. You guys see that one? Yeah. Out of what looks like nothing but is actually just a couple of atomic defects, you can create a dislocation loop and allow more plastic deformation to take place, which I think is awesome.

Look at this one. Another dislocation source in germanium. It's a little easier to see, also because it's making this sort of spiral set of dislocations a little slower. So you can track its motion a little easier. Notice how they all kind of line up on certain atomic planes. Yeah?

AUDIENCE: Does the topology of these things ever change, or is it always just a slow [INAUDIBLE]

PROFESSOR: The topology will change. Let's say, if it hits another obstacle or another dislocation, yeah, they can slam into each other and change topology.

AUDIENCE: Breaking too [INAUDIBLE]

PROFESSOR: All sorts of things, yeah. That's a subject for a whole other class, I'd say. I want to skip ahead to the pile-up because I think this kind of gets the point across. But actually, we can see direct evidence that dislocations feel each other's stress fields. When you get enough of them lined up, they won't overlap. They actually push each other in a kind of dislocation traffic jam.

Because what's happening on the atomic level is, they feel each other's stress fields. There might be a source of dislocations further away, but when they get too close to each other, it literally is a dislocation traffic jam. I mean, if you try and hit the car in front of you, the repulsion of the electrons between your and their bumper will prevent the cars from getting a certain distance closer to each other. Same kind of thing here.

Moving onto grain boundaries, a two-dimensional defect. Any time you have a perfect crystal of atoms that meets another perfect crystal at a different orientation, or where the atoms are arranged in a different direction, you end up with a boundary between them that we refer to as a grain boundary. So you can actually see, this is a direct physical image of atoms of two different crystals meeting at the grain boundary. Again, taken in the transmission electron microscope.

So for those who didn't know, yes, we can see individual atoms and the defects between them. I definitely didn't know that in high school. They didn't even mention that whatsoever. Did you guys ever see images like this? Anyone? Yes? Raise your hand. Just one, OK. So yeah. It's important for you guys to know that we can have direct evidence for all this blackboard stuff because you can see atoms in the transmission electron microscope and see what happens when the two of them meet.

You see this kind of regular structure of empty space where this grain boundary meets, right?

You can actually model it as a line of 1-D dislocations, because if you take a line of 1-D lines, you end up with a 2-D boundary, which you can see very clearly here. It's almost like there's an extra half plane right there. Another one there, another one there, and another one there. And we call that a tilt grain boundary.

Grain boundaries are nice in that they can accommodate lots of these little zero-dimensional defects, moving to them without getting destroyed. So grain boundaries are one of those ways that radiation damage can be removed. And that's one of the reasons why most small-grain materials are really-- nano-grain materials are more resistant to radiation damage than large-grain ones because they act as what's called sinks or destroyers of radiation damage.

There's another kind of 2-D defect called a twin, where you can actually get a little chunk of atoms sort of switch orientation. And you can see these very clearly in, again, TEM micrographs, and the evidence actually that the twin actually is a different physical arrangement of atoms, even though you can't see the atoms in this little band right there. Look at the way the dislocations line up. Those dislocations tend to line up in energetically-favorable directions, and in this grain, they're all this way, and in the twin, they're all lined up like that.

And then finally, there's the most intuitive defect, inclusions. A 3-D piece of some other material inside what would otherwise be a pure material. This one, I actually pulled out of the rotor that powers the Alcator fusion reactor. I was asked to do some analysis to find out, is the structure of that rotor changing, because General Electric who was insuring this rotor said, we don't want to insure it anymore. Thanks for the premiums, but we're not insuring it anymore.

And we said, why? And they said, oh, it's structurally unsound. So we said, oh yeah? We'll be back in a year and we'll talk about it. And we did a lot of this work to find out that, actually, the structure hadn't really changed since 1954 when it was made. But what we did also see is we could pop out little precipitates of manganese sulfide. So there's always sulfur in iron, and sulfur tends to be a bad actor when it comes to material properties.

You throw manganese into iron to scoop up that sulfur in the form of these little precipitates or inclusions, which we were able to see perfectly when we did an x-ray map, just like the one we did after the first exam. It's like we were looking at Chris' copper silver alloy, mapping out where is the copper and silver. I made this image the same way, mapping out, where is there iron, manganese and sulfur. That's how you can tell what it is.

And so dislocations and defects can actually interact. Let's say this is the interaction of a 1-D

defect, a dislocation, with a 3-D defect, a void. If you have a material that's deforming plastically, very smoothly, and isn't going to undergo fracture, you want the dislocations to be able to move. If you put anything in their way, they tend to get stuck. It's not easy for that dislocation to shear through a whole bunch of extra atoms. And in some cases, you can stop that motion and favor fracture over slip.

So any time you make slip harder, it means that you're making fracture more likely. I didn't say you're making it easier, but you're making it more likely. And you would prefer for materials to deform a little bit by a slip than just break by fracture. So I think now is a good point to go over a few key material properties. All of these are sometimes used to describe the same thing in colloquial speech. That is wrong.

Has anyone here thought that, let's say, stiffness or toughness or strength meant the same thing? No. OK. A few people. It's OK. Because it's used wrong all the time in colloquial speech. These actually refer to different material properties with different units. And we're going to go into a little bit about what they are and then show you a few videos to test your intuition about the differences between them.

So first, I want to mention what you're seeing right here. It's called a stress-strain curve. Stress is simple. Stress is just a force divided by an area. And usually, the criterion for will a material deform or will it break is does it reach a certain stress. It doesn't matter just how much force you put on it, but it's like, how much force per atom or how much force per area determines whether bonds are going to break.

And so on the y-axis is stress. Let's say the amount of force per area we're putting in. And strain is the amount of deformation. So that's stress. And strain is, let's say, the change in length over the original length of some material in what's called the engineering or simplified notation. And so something that is stiff means you can put a lot of force into it but it won't deform very much. That's kind of the easiest property to understand.

Is something that's very stiff will have what's called a high Young's modulus, or a high slope right here. Something that's super stiff, like a ceramic, you could really push on it quite a bit, but you won't get it to deform like you would this metal. So the opposite of stiff, I would call compliant. Not soft. This is one of those tricky things right there. Something that's stiff, you try and flex it and it won't flex. Something that's compliant, you put a little bit of force into it and it undergoes some amount of strain.

And that slope right there between the stress and the strain, we call the Young's modulus. We also note that this part right here is what's called the elastic region of deformation. By elastic, we mean reversible, or it snaps right back. So right here, when I bend this bar and it snaps right back, that's called elastic deformation. And it's reversible, because you can bend one way and it snaps right back.

If I bent it more, which I don't want to do because this is a nice zirconium fuel cladding rod, you would deform it irreversibly. You'd bend it permanently. And to undergo what's called plastic deformation, when you deviate from the slope, and then a little bit more stress can cause a lot more deformation.

Have any of you guys ever tried pulling copper wire apart before? That's something I'd recommend you try, for thin wire so you don't cut your hands. What you may notice is that it's awfully hard to get the copper deforming in the first place, but as soon as it starts to stretch, it gets really easy. So this is something I recommend. Go to the electronics shop or wherever and try it out on some really thin copper wire. If it's thick, you'll slice through your fingers and you don't want to do that.

Strength, however, that's a different metric. Whereas stiffness describes the slope here, strength describes the height, or the stress at which you start to plastically deform. They're in different units. Stiffness is in stress over strain, whereas strength is given as a stress. So when you hear things like the yield stress or the ultimate tensile strength, that's referring to how strong something is, which may have nothing to do with how stiff it is.

Toughness is another property. Toughness is actually kind of like the area under this curve, because if you do a force and apply it over a distance, that's like putting work into the material and it ends up being a unit of energy. So toughness will tell you how much energy you have to put into something before creating a new free surface, otherwise known as fracture. And ductility is how much can you deform it before it breaks. So it would be like this point right here on the strain axis.

So I'll give a little bit more examples of what this is all about. Toughness, again, is actually measured as an energy required to form a free surface, or propagate a crack, let's say. Whereas something that's ductile, it doesn't necessarily mean that it's tough. Like, if you have a piece of chewed chewing gum, you can stretch it quite a lot with very little energy. And then you can say it's extremely ductile but not very strong. A piece of copper wire, you can also

stretch it an extremely far distance, but it takes more energy to do so. So that's both ductile and strong.

And then if you apply that force over a certain distance, stretching out the wire, you can also reveal some of its toughness and how much energy it takes to stretch that wire before it breaks. Hardness is the last material property I want to mention, which is not any of the ones that I showed on the stress-strain curve. Hardness is the resistance to a little bit of plastic deformation. So assuming that you're already here, how much more energy do you have to put in to get the material to deform plastic?

So very different material properties. I'll try and mention all what they are. So if we have a stress-strain curve like so, and it follows the elastic region and then deforms plastically, this point here is what we call the yield strength. Whatever that point on the stress axis is. This point right here, our strain to failure, we can use as a measure of ductility. This slope right here refers to the stiffness. And finally, this energy right here is something like the toughness. And the hardness isn't quite on this plot.

So I want to see if you guys intuitively understand this, because the next lecture, I'm going to be throwing around the words like stiffness, toughness, ductility, hardness, compliance, hard, soft, whatever, and I want to make sure that you just at least intuitively understand. There's a few videos you may have seen before. Anyone here watch the hydraulic press channel? There we go. Finally, something that half the class does. We're going to predict what's going to happen in each of these cases based on these material properties.

So in this case, this is a pressurized cylinder of CO₂. It's made of aluminum, which is a very ductile material. It's also a very tough material. How do you think it will deform when smashed? Anyone ever tried this? Squishing aluminum stuff. What happens?

AUDIENCE: You compress it.

PROFESSOR: You compress it. And then what happens?

AUDIENCE: Fracture?

PROFESSOR: Will it fracture?

AUDIENCE: After a while.

PROFESSOR: After a while, OK. If you put a lot of energy into it, eventually, when you reach this strain to failure, it should fracture. But in your personal hands-on experience, does aluminum tend to fracture when you bend it a little bit?

AUDIENCE: No.

PROFESSOR: So then what words would you use to describe it? Based on this curve right here. Yep?

AUDIENCE: Ductile.

PROFESSOR: Ductile. I would say ductile and not brittle because you can bend it quite a bit or stretch it quite a bit before it fractures. How about stiffness? Is it really hard or really easy to get aluminum bending?

AUDIENCE: It's pretty easy.

PROFESSOR: It's fairly easy. So would you call that stiff or compliant?

AUDIENCE: Compliant.

PROFESSOR: Compliant. OK. What about strength? How hard is it to start deforming aluminum irreversibly, compared to something like steel?

AUDIENCE: Not very.

PROFESSOR: Not very. Especially pure aluminum. You can chew through it. If you guys ever got a one yen coin from Japan, you can chew through it. Not very strong. Then again, your bite force is also incredibly strong. But anyway, let's see what actually happens when you compress a rather ductile, compliant, and not that strong aluminum canister. Is it actually going? Oh, it actually skipped ahead. That's what I wanted, was their sound. It was also pressurized with CO₂.

But notice what's left. So actually watch in slow-mo. Look how much you can compress that, even after the explosion. No fracture. If you had done that with, let's say, a glass canister, what do you guys think would have happened?

AUDIENCE: It would have shattered.

PROFESSOR: It would have shattered. Yeah, we'll see that in a bit with a material that may surprise you.

AUDIENCE: So it basically doesn't fracture, right?

PROFESSOR: It will fracture eventually, but the hydraulic press can't get it that far in compression. So that would be something that's extremely ductile, not that strong-- so it wasn't that hard to deform. Certainly we know it wasn't stronger than the steel base plate that they used to do the smashing. Because whatever's the softer material is going to deform more. So here he's going to have-- well I'll let him describe it, and then I'll let you guess what's going to happen.

What do you guys think is going to happen? You've got what looks like brass and copper coins on a steel base plate. Anyone have any idea?

AUDIENCE: [INAUDIBLE]

PROFESSOR: Yeah. Everyone's making this motion, which means everything's going to flatten out, right? Let's find out. Not nearly as much as you might have expected. Is anyone surprised by this? What happened there?

What actually happened there was already described up here. When you get enough dislocations piling up against each other during plastic deformation, you can undergo a process called work hardening. That process can be physically described by a lot of those dislocations piling up and making it more and more difficult to continue that deformation. So what happened here is the brass and the copper, which started out quite soft, not that hard, quite ductile, as you can see, and not that strong actually got stronger as they were deformed. Interesting, huh? Did anyone expect this to happen? OK.

Let's go to one that I think everyone can guess what's going to happen, a lead ball. So has anyone ever tried playing with lead before? Hopefully not. I have quite a-- OK good, I'm not alone. How would you describe lead in terms of the material properties here?

AUDIENCE: [INAUDIBLE]

PROFESSOR: Yep. It's not very stiff. It doesn't take much energy to start deforming it. How else? Was it hard or soft?

AUDIENCE: Soft.

PROFESSOR: OK. Do you think it's ductile or brittle? Yeah?

AUDIENCE: It's brittle.

PROFESSOR: You think it's brittle. So by that, you mean it's just going to break apart, right? If you deform it? OK, cool. And would you say it is tough or not tough? Not a lot of folks have hands-on experience with lead. It's probably good for your brains. Let's find out. Lead pancake. So what words would you use to describe what just happened?

AUDIENCE: It's ductile.

PROFESSOR: Ductile indeed. I don't know what sort of brittle lead-- was it an alloy that you had been playing with, maybe?

AUDIENCE: It was like a little sheet. It was just easy to snap.

PROFESSOR: Aha, OK. So it was a sheet of lead that was easy to snap. So I would not call lead as a very tough material because you didn't have to put a lot of energy into it, but did it deform quite a bit before you snapped it or did it just crumble apart?

AUDIENCE: Oh, it deformed.

PROFESSOR: OK. So in that case, I would call it ductile because it deformed a lot before breaking, but I would not call it tough because it took very little energy to get it to that breaking point. And it wasn't that stiff because it was quite easy to get it-- let's say it's the amount of stress you put in versus the strain. It could be quite low. And it would not be very strong because it didn't take a lot of energy or stress to get it moving. Let's look at another ball. In this case, a steel ball bearing. What do you guys think is going to happen here?

AUDIENCE: It's going to shatter.

PROFESSOR: It's going to shatter. So you're guessing that the steel is brittle, right? What else?

AUDIENCE: Probably pretty stiff and strong.

PROFESSOR: Probably quite stiff and strong, yeah. I think so, too, but I don't think the guy that did this expected that.

[INTERPOSING VOICES]

PROFESSOR: Yeah. Did that surprise anybody? Yeah. Quite a surprise, right?

So in this case, materials like hardened steel aren't necessarily that brittle. In fact, you wouldn't want a ball bearing to be brittle. If you get some small chip in it or a little bit of grit or sand in

the bearings, you would shatter the ball bearing and cause instantaneous failure of the rotating component. So what you actually want out of a high-strength ball bearing is something that's extremely hard. Resists deformation so it doesn't undergo, let's say, change of shape that would prevent it from rolling without friction or with very little friction.

You want it to be quite stiff because you don't want the load of whatever you're loading onto it to deform it, but you also don't want it to be brittle. So it's got to be somewhat tough and ductile to prevent sudden failure. You'd rather it compress a tiny bit than just cracking in half. So you can make things like ceramic ball bearings, which are very brittle, very stiff, not that tough, but also very strong, and you just have to make sure that whatever part you make is not going to reach any sort of yield strength criterion or crack or anything.

Now the last one that's probably the most surprising. They bought a \$4,000 diamond. It's a diamond like that big. What do you know about diamonds as a material in terms of these properties?

AUDIENCE: They're hard.

PROFESSOR: Yep, both is right. They're extremely stiff. It's the hardest material that we know of, almost. We've made slightly harder ones artificially. It's the hardest natural material we know of. What else? Do you know whether they're strong or tough?

AUDIENCE: They're not tough.

PROFESSOR: They're not tough. Why do you say that?

AUDIENCE: Because it will shatter.

PROFESSOR: Have you seen the video?

AUDIENCE: [INAUDIBLE]

PROFESSOR: Oh wow. OK. What else do we have? Yeah. So you're saying it's not tough.

AUDIENCE: You can cut diamonds, right?

PROFESSOR: You can cut diamonds with other diamonds. So the cutting action usually depends on the relative hardness of the material. So if you want to polish or cut something abrasively, you need to use a harder material because then the grit itself won't wear away before the material

it's trying to cut. But what's going to happen here is we're going to put a diamond and try compressing it, and we'll see what its stress-strain curve looks like.

So votes on what's going to happen. Who says, like Monica, it's going to shatter? Who thinks it's going to break the tools? Who thinks it's going to deform plastically? Yeah, I've never seen a diamond deform plastically.

AUDIENCE: They still have pretty big chunks, though.

PROFESSOR: Oh yeah, they could probably still sell those. Absolutely no deformation. It just rotates and explodes. Yeah. This would be a material that we would say has almost zero ductility. Despite being extremely hard, I don't know if there would even been enough deformation to have a slight dent in the tool itself. There's probably a little hole where the point of the diamond poked in, but once there was enough stress on that diamond, its stress-strain curve would look something like that. Maybe like that. Yeah.

So it's important that you intuitively understand the differences between strength, ductility, hardness, toughness, and stiffness, because then next class, we can explain how radiation changes them. So any questions on the materials and properties from today? Yeah?

AUDIENCE: Can you clarify why something is, for example, ductile versus brittle?

PROFESSOR: Mhm. So the reason something would be ductile versus brittle is whether or not you can plastically deform it, and that means whether or not it's more energetically favorable for dislocations to keep moving versus just breaking a plane of atoms in any irregular direction and causing fracture. So again, ductility versus embrittlement is the interplay between slip and fracture. Slip is normally done by dislocation movement. Any defects created by anything, especially radiation damage, will make slip harder so that any continued energy you put in will not move dislocations but move towards fracture.

If there's no other questions, we'll look at the stress-strain curves of some other familiar materials. It is 10:00, in case you guys have to go to other classes.

AUDIENCE: Are you taking any nuclear activation stuff today?

PROFESSOR: Yes. If you guys have things for a nuclear activation analysis, hand it in. You guys bring stuff in? We're running out of opportunities to do this. All right. In that case, the entry fee for the quiz will be your nuclear activation analysis sample.

