Particle Characterization

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Module No. # 12
Lecture No. # 39

Practical Relevance of Particle Characterization: Other Applications

Welcome to the thirty-ninth lecture in our particle characterization course. In the last few lectures, we have been discussing various applications involving particle technology and describing how particle characteristics affect their behaviour in these applications.

Today, we will continue our discussion along those lines. One of the common applications, where particulate media are used is for polishing of surfaces in order to obtain a fine finish on many types of metallic as well as ceramic materials. Particulate media are used essentially, in order to erode the surface of the material that you are trying to polish and thereby remove surface asperities. So, you can essentially take a surface which is rough, and by subjecting it to polishing using particle as media, you can reduce the surface roughness and make the surface flatter and smoother. Of course, it has to be controlled very precisely, because if you overdo the polishing, an initially smooth surface can also become rough.

So, it is a matter of managing the process in such a way, that you minimize the surface non-uniformity, unevenness and roughness. Now, when you talk about polishing of surfaces, there are really two types of polishing procedures. One is purely mechanical polishing. Now, mechanical polishing is widely used again in many industries. Lapping is a process that essentially uses embedded particle media on plates, which essentially abrade the surface that we are trying to polish and lapping is a way of removing, for example, bursts that are created during machining processes.

So, lapping is essentially a fairly gross process in the sense of removing particles and surface defects of large dimensions and providing a relatively smooth surface. Another example of such a process would be, wherever you are trying to obtain a fine finish for

mechanical dimensioning type of applications. Again, a good example is the disk drive, where you are trying to stack disks on a spindle motor and the distance between the disks must be very precisely controlled, and also, the disks must be sitting on surfaces that are perfectly flat, so that there is no wobble as the disk drive is spinning. So, the disks are separated by what are known as spacers. These spacers require a fine finish and the disk media itself also requires a fine finish.

So, these types of extremely tight mechanical tolerances are achieved using again polishing procedures involving fine particles as the media. Another example would be in the semiconductor industry, where again, high degree of surface finish and polish are required on silicon wafers, for example.

Now, when we talk about polishing in that application versus the other applications that are commonly used, the difference is that in polishing of silicon wafers, we also introduce chemistry. So, the process instead of being known as mechanical polishing is now known as chemical mechanical planarization or CMP. So, the difference between CMP and mechanical polishing is that in CMP, you also bring in chemistry as an additional factor, and the reason you want to do that, is that you want to be able to remove certain constituents preferentially from the wafer and so you want to use chemistry to make sure that some materials are left intact on the surface and only some materials are preferentially removed from the surface. So, it is selective polishing.

Selective polishing cannot be achieved strictly through mechanical polishing because by definition, mechanical polishing works uniformly on all materials regardless of their composition, whereas CMP is a process, where in addition to the particulate media, you also use additives such as PH modifiers and solvents that preferentially attack one or more chemical constituents of the surface, and therefore, you are able to do selective polishing of the surface.

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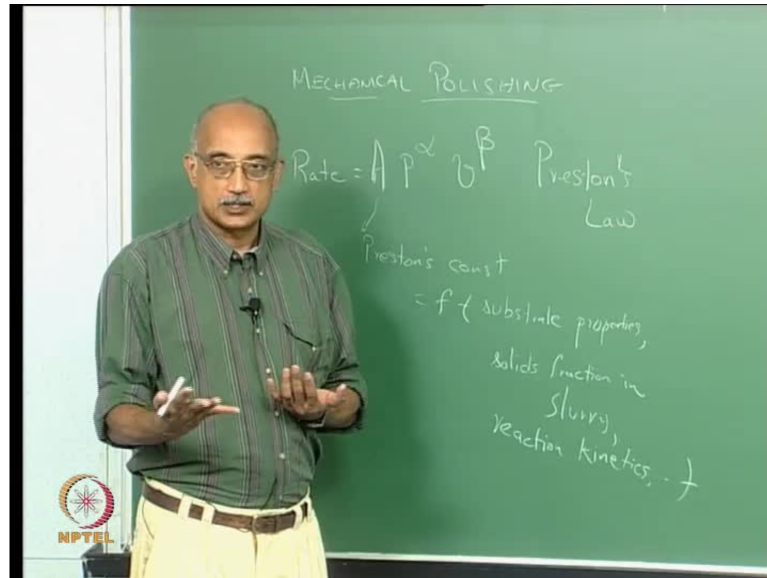

So, this is an application that involves particles. Now, if you look at the rate of removal of material from surface or the polishing rate that is obviously, a key parametric. The rate of removal of material from the surface is related to the pressure to the power alpha and velocity to the power beta times a constant, where the pressure is essentially the pressure that you are applying to bring the media in contact with the surface. So, the higher this pressure, the greater will be the removal of material from the surface. v is the relative velocity between the polishing media and the surface that is being polished.

So, for example, the surface that is being polished may be held stationary and the media may be applied to the surface in a circular motion. In fact, that is the most common way of doing polishing, where the polishing particles are actually embedded in a tape, for example or some circular disk and either the disk is held stationary and the material being processed rotates or the surface being polished is held stationary and the media rotates.

In either case, there is relative velocity being applied between the surface that is being polished and the media that is being used to do the polishing. So, this velocity v essentially, reflects the velocity difference between the surface that is being polished and the media that are being used to do the polishing.

This is actually known as Preston's law and this constant A is called the Preston's constant and this actually, incorporates many of the parameters that are crucial for the

polishing process itself. If you look at these two terms, they are essentially generic system parameters. So, there is no system specificity here. Pressure and velocity simply refer to how the polishing system is setup in terms of its operational characteristics.

This constant, on the other hand, includes in it descriptions of the substrate being polished, substrate properties, the solids fraction in the polishing slurry and reaction kinetics and so on. So, this constant actually incorporates in it all the descriptions that are specific to the system under consideration. So, for example, when we say substrate properties, one of the properties that could be of important is surface roughness; surface that is rougher polishes more easily because it has more asperities that are sticking out. So, there is more essentially, force per unit area being applied to do the polishing. Similarly, the surface that is oxidized will polish more easily compared to an un-oxidized surface because the oxide layer actually acts like a lubricant and aides the polishing process. So, the substrate properties are included in this term.

The solids fraction in the slurry is obviously an important parameter. Very simplistically, the greater the solids fraction, the higher will be the polishing rate. Although, that is not as straight forward as it sounds, there are certain subtleties involved in how you optimize the solids concentration.

Reaction kinetics is where the chemistry comes into play. So, for example, when you are trying to polish a substrate with multiple chemical constituents, the constant A may essentially be insensitive to the reaction kinetics for certain components or constituents and it may have a high dependence on reaction kinetics for other constituents or components.

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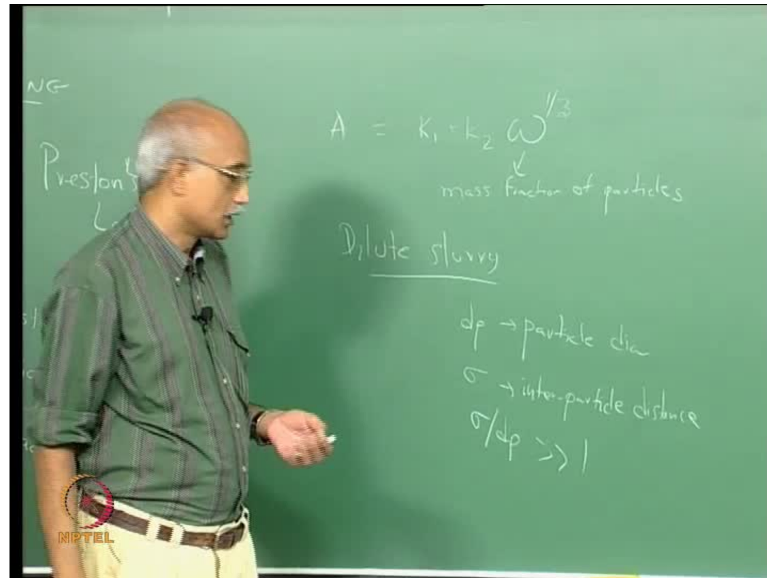

So, all of these is bundled into this constant term. So, this A parameter, the Preston's constant has been experimentally measured and related to various inherent properties of polishing systems and it turns out that for a purely physical polishing process, this can be written as a constant K 1 plus K 2 times the mass fraction of particles in the slurry to the power one-third.

So, as the mass fraction of the particles increases, the [bare] rate or the rate of material removal increases as the mass fraction to the power one-third. Now, when we talk about slurries that are used for polishing, one of the assumptions we always make in all the modeling as well as many of experimentation that we do is that it is a dilute slurry. Now, when we say dilute slurry, what we mean by that is that if you look at two relevant parameters, the first is particle diameter d p and the second is sigma, which is the mean inter-particle distance. In a dilute slurry, sigma over d p must be much greater than 1. So, the concentration must be low enough or the slurry must be dilute enough that the inter particle distance is much greater than the particle size itself. Now, there are two ways you can achieve this: one is to increase this numerator and the other is to decrease the denominator.

So, of course, to increase the numerator essentially, you have to use more and more dilute suspensions, but you can see from here that when we do that you have to deal with some loss in terms of the polishing rate itself because as you reduce the concentration of

particles, the associated polishing rate also decreases. So, the other alternative is to reduce the mean size of the particles and that is why micron size slurries behave very differently from sub-micron slurries, which behave very differently from nano size slurries.

The reason that you would like to have a dilute slurry is that its behavior is much more predictable and it is also much more measurable and quantifiable. If you have an extremely concentrated slurry, measurements and control become very difficult and the process itself becomes somewhat non-repeatable. The more dilute, if you keep the slurry, the more precisely you can define particle to surface interactions as well as particle to particle interactions and the whole system just becomes more manageable.

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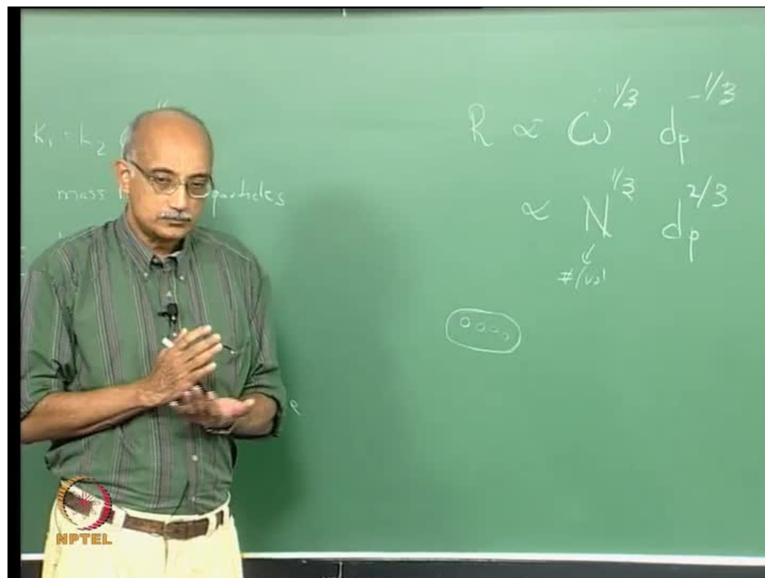

So, you want to keep this ratio much larger than 1 in any kind of polishing system, whether it is mechanical polishing or CMP - chemical mechanical polishing or planarization. Now, if you look at again the removal rate R, we said that it is proportional to the solids loading or solids mass fractions in the suspension.

Now, one way that can be expressed is to say that this is proportional to the concentration or omega to the power one-third, but the size also becomes important, the particle size and in fact, the more general expression for removal rate would say R is proportional to omega to the power one-third times particle diameter to the power minus one-third.

Now, this gives the impression, if you write it this way that there is actually an inverse dependence of polishing rate on the diameter of the particle, but that is not really true because this already has a particle size dependence built into it.

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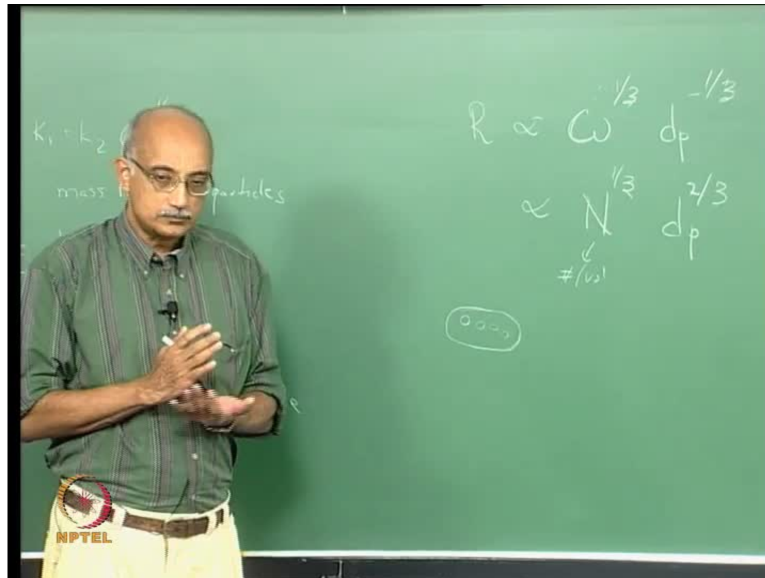

So, in fact, if you rewrite this as a number concentration, this is number per unit volume of the suspension. Then this becomes n to the power one-third times d p to the power plus two-thirds. So, this is more commonly how the polishing rate is related in terms of number concentration and particle size. This gives a better physical picture that as you increase the number concentration of the particles in the slurry, the polishing rate increases and also, as the particle size increases, so does the polishing rate.

The reason that happens is because if you actually look at polishing as a mechanism, you have a large surface which is coming in contact with smaller particles and the polishing is done by the small particles removing material from the larger surface essentially through an abrasion mechanism and any type of [bare] or abrasion mechanism is dependent on the surface area in contact.

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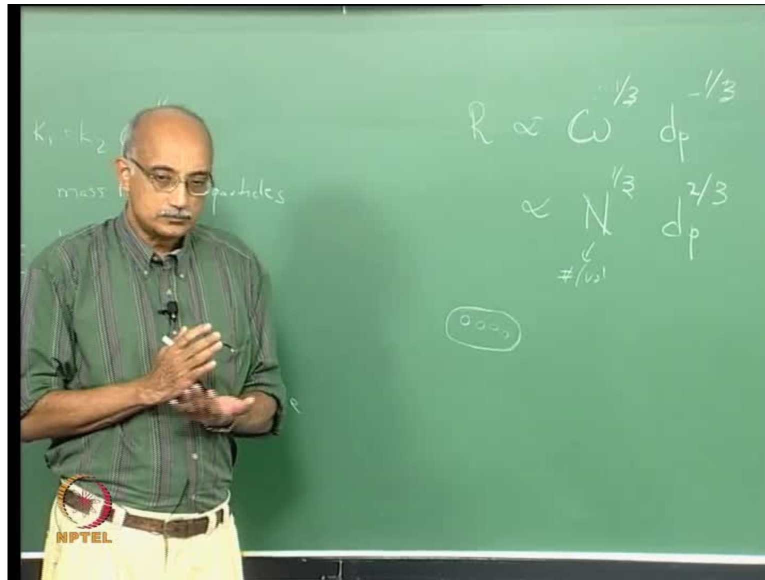

So, the critical parameter here is the total surface area of the polishing media that is in contact with the surface that is being polished and so, as the size increases, the total area of contact increases and therefore, you get more abrasion.

However, we have to be careful in that interpretation because that assumes that the total volume of material is also variable, but, if you have a given volume of material and you want to maximize the rate of abrasion or rate of polishing, then what you should try to do is make that given volume of material into as fine distribution of particle size as possible because for a given volume or mass of material, smaller particles will give you much greater surface area.

So, that is why there is essentially, something to be gained by increasing the number concentration by increasing the mean particle size in contact, but at the same time keep in mind that if you have a constraint that the total quantity of material polishing media that is available to you is a fixed value, then you get more polishing area by actually making finer particles with that material. So, the two are somewhat in conflict, but if you think about it, it is fairly straight forward.

Now, the way that of course, chemical polishing will enter into this is that the removal process in the case of CMP includes chemical reactions as well as the physical mechanism of removal and the two kind of support each other. Typically, the chemical effect will come into play first.

For example, you might have added certain chemicals into your slurry that preferentially attack one of the constituents. So, that chemical attack will proceed initially and it will have the effect of essentially dislodging that particular constituent and loosely get on the surface. When you follow that with the mechanical procedure, that will then remove the particle from the surface.

So, CMP is actually somewhat of a sequential process where the chemical polishing occurs first, followed by mechanical polishing to fully remove the material selectively from the surface. Another alternative view of CMP or mechanical polishing is to look at the indentation volume. The indentation volume refers to how much volume of material has been removed from the surface due to again the polishing procedure that is going on and this volume can again be related to parameters such as number concentration and particle diameter and so on.

But whichever way you formulate the equation, whether you look at it on a surface area view point like Preston's law does or you look at it in terms of the volume of indentation, the basic conclusion still remains that the most critical particle characteristics for surface polishing are particle concentration and particle size and the chemistry of the particle, whether there is any interaction, chemical interaction between the particle and the surface that is being polished.

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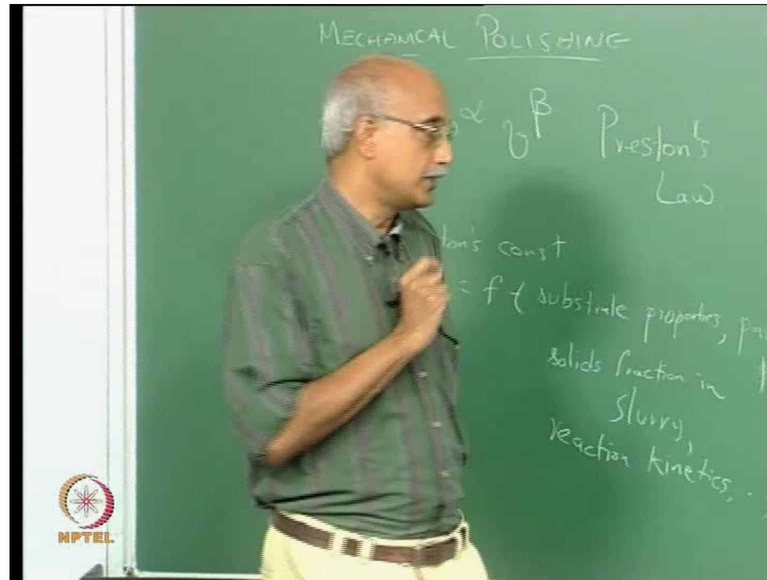

Another parameter that is of importance is hardness and by the way, that is also included in the Preston's constant, which not only includes substrate properties, but also particle physical properties. So, the hardness of the particle will also be reflected in this constant. The harder the particle, the greater will be the surface removal associated with it. Now how about shape? Does shape play a role?

As you can imagine, if you have a more crystalline particle, the tendency that it will have to abrade a surface will be greater compared to a spherical particle. By definition, a spherical particle is one that has less of an aggressive interaction mainly because it is already in its minimum free energy condition. So, it is more thermodynamically stable whereas, a non-spherical particle is always more reactive both in a physical sense as well as in a chemical sense.

So, the shape of the particle does play a role. A more crystalline particle is more likely to give you higher removal rates, but that will change over time because as you keep doing the polishing, the polishing media itself will start changing shape and so, you will start essentially truncating the elongated shape of the abrading particle and it will become more rounded. So, the kinetics of surface material removal will actually slow down, when you start using a non-spherical slurry to begin with, which through reuse becomes more and more rounded.

Now, one of the challenges in CMP or mechanical polishing is, material has to be hard and it needs to get really in close interaction with the surface in order to remove material from the surface. So, from a polishing view point, that is good. However, what can also happen is some fraction of these polishing media itself can get embedded in the surface during the polishing process; then it becomes a contaminant.

Now, you have particles that are stuck on the surface, which are foreign media that you really do not want on your product. For example, if you are using CMP on a silicon wafer, yes, you may be removing the surface roughness and also some chemical constituents, but at the same time you could be transferring alumina which may be your polishing media to the silicon wafer.

This alumina then has to be removed before the wafer can be processed further. So, again the process of particle removal that we talked about in one of the earlier modules becomes important. You have to device a mechanism by which these abrasive particles that are pressed into and lodged on the surface can be removed before the wafer gets sent for further processing.

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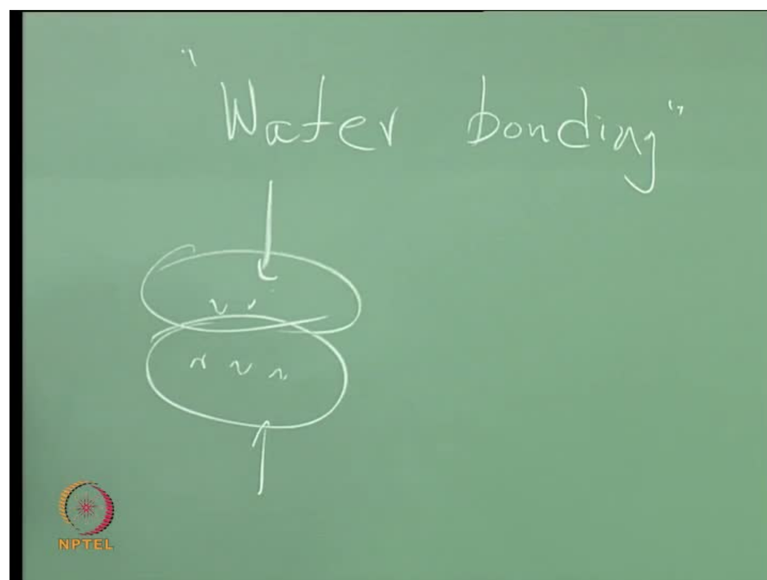

In fact, in the semiconductor industry, one of the first thing that happens after a polishing of a silicon wafer is called wafer bonding. Now, wafer bonding is a process by which two wafers are pressed together. So, you have one wafer, another wafer and you essentially, press them together so that the polished surfaces are in contact.

As you do that, what is going to happen is they are going to stick together very hard. So, if you take two smooth cleaned, polished surfaces and press them together with high force, they will tend to stick together very hard. Now, why is that advantageous? Why do you want to do that? Just two reasons: one is that once you have done that they have essentially sealed these surfaces so that they cannot get contaminated anymore; they cannot get oxidized and then essentially, you have hermetically closed these two surfaces.

So, you do not have to worry so much about keeping the environment clean and all that. The second advantage is you can now process wafers in pairs, instead of one at a time. So, from a processing view point, from a throughput view point, it is advantageous to take pairs of wafers and press their polished sides together through this wafer bonding process and then you take them through your process as a pair.

Now, obviously, this process has to be reversible because once you need to use the wafers individually, you have to be able to separate them and it turns out that as long as there is no heating involved, as long as this bonding process does not get, you know does not become a sintering process; so, to speak it is easy to remove these wafers simply by providing a tiny wedge that goes between the wafers and just prise them apart and this wedge can be applied to a non-critical area of the wafers so that you do not damage the circuitry, the electronics and so on. So, that is basically, how this process in done. You polish the wafers, stick them together in pairs, take them through the process until the time you need them to be separate and then you use this tiny wedge to separate them and process them individually.

But this requires that the surface again be kept very clean because it is not enough to just have a very smooth surface, which you may achieve by using CMP or another polishing process, but you have to make sure that the media that you used for the polishing does not itself provide contaminant that can keep this wafer bonding from happening. I mean as you can imagine, if you have particles stuck here then they are not going to get good sealing.

So, that is going to be separation between the wafers, which can then induce further contamination due to inflow and so on. So, keeping the wafers pure is also important and that again has to do with some of the characteristics, we discussed earlier about particle

adhesion to surfaces and particle removability from surfaces. As we have discussed earlier, the two cleaning methods that are particularly suitable for sub-micron and nano sized particles is ultrasonic cleaning and megasonic cleaning, which are very effective in removing particles that are embedded in the surface as well as loose on the surface, but the challenge there is, even if you have a good process for particle removal, how do you ensure that there is no recapture of these particles by the surface.

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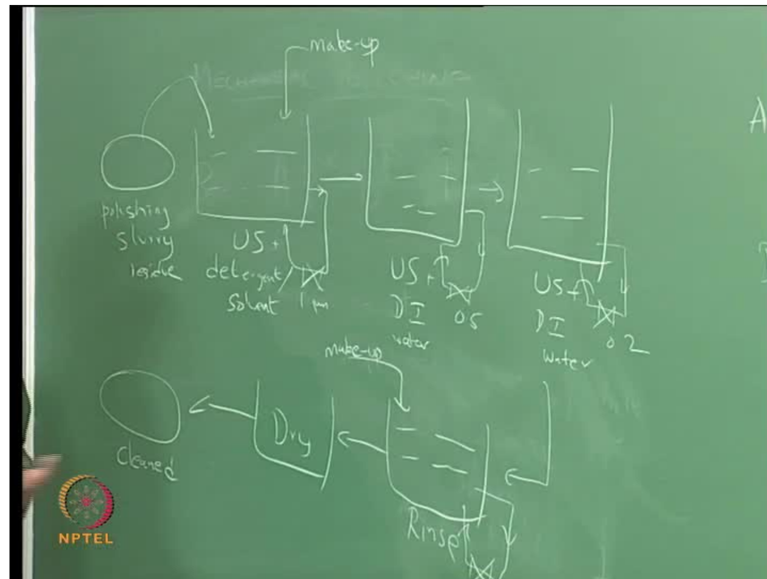

Now, what we mean by that is typically, you know once these wafers are processed, they will be taken through several stages of cleaning. So, there will be one stage of cleaning, where you will have some ultrasonics attached to the tank and then there will be some detergent or solvent and then you will go into another ultrasonic bath with just de-ionized water, for example. I think I mentioned in one of the earlier lectures that for every step of cleaning with a detergent, you need at least two steps of rinsing without the detergent. So, there may be one more stage of rinsing.

So, this again would be ultrasonic plus DI water and this may then go into another stage of rinsing without ultrasonics, just over flow rinsing or spray rinsing or something like that and then you will go through one or more stages of drying, until you recover the wafer which you know previously was contaminated. For example, this may have some polishing slurry residue, which would have hampered wafer bonding, but once you take it through this process, this will be a clean surface, which can then be used for wafer

bonding for example, but the trick here is as you run the wafer through this process, how do you make sure that for example, if you do the ultrasonic and detergent cleaning, you will remove the particles from the surface.

But the particles are not going to fly away, they are going to remain in suspension. So, there is always a potential that will redeposit on the surface. So, typically, the way that that is handled is by providing a recycle loop with filtration so that as the particles are getting dislodged and suspended in the liquid, you are constantly taking out the dirty liquid, running it through a filter and then, only feeding back the purified liquid. So, each of these stages will essentially have a recycle loop with a filtration in it and the filters will become finer and finer. For example, here you may have a 1 micron filter and here you may have a 0.5 micron filter, here you may have a 0.2 micron filter and a 0.1 micron filter because you are trying to make the solution as well as the wafer progressively cleaner.

So, this is normally how the schematic works. However, one other thing you will do is you cannot rely entirely on recycles. So, there will be some makeup water that comes in to the first cleaning tank and similarly, there will be some makeup de-ionized water that comes into the final rinse tank in order to maintain the purity of the whole system.

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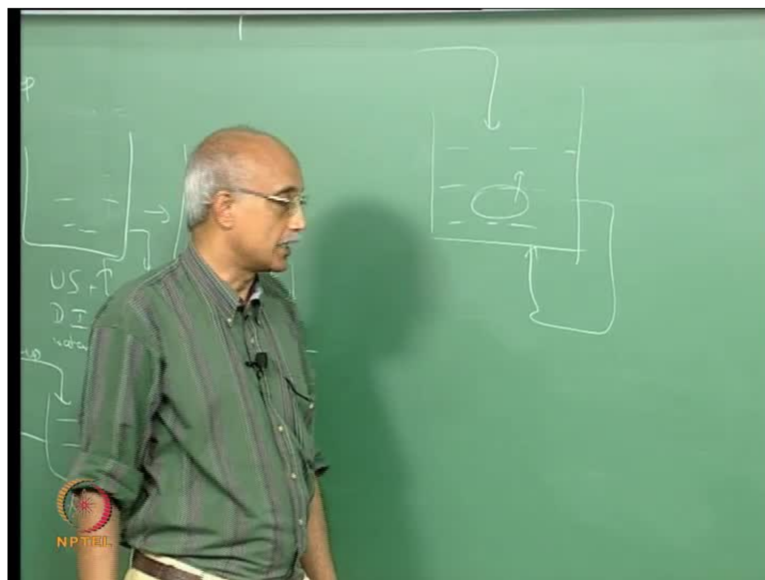

So, just like the clean room analysis that we looked at earlier, this can also be looked at in terms of mass balance. So, if you have a tank with liquid in it and let us say that it is

being recycled at a certain rate and fresh water is coming in at a certain rate and components are being cleaned inside this tank. So, these components are essentially releasing particles at a certain rate as well. So, you have an internal source.

You can see that this is very similar in principle to the clean room that we had sketched earlier, where you had fresh clean room - fresh air being taken into the clean room along with recycled air and the clean room itself had many sources of particles in it. So, very similar situation applies here as well.

Just like we were able to optimize the operation of a clean room by looking at sources inside versus sources outside and the rate of recycle, similarly, we can do an optimization algorithm here by looking at how many particles are being contributed by the wafer versus how many particles are being contributed by the cleaning medium or liquid itself and by again suitably changing the rate of the recycle.

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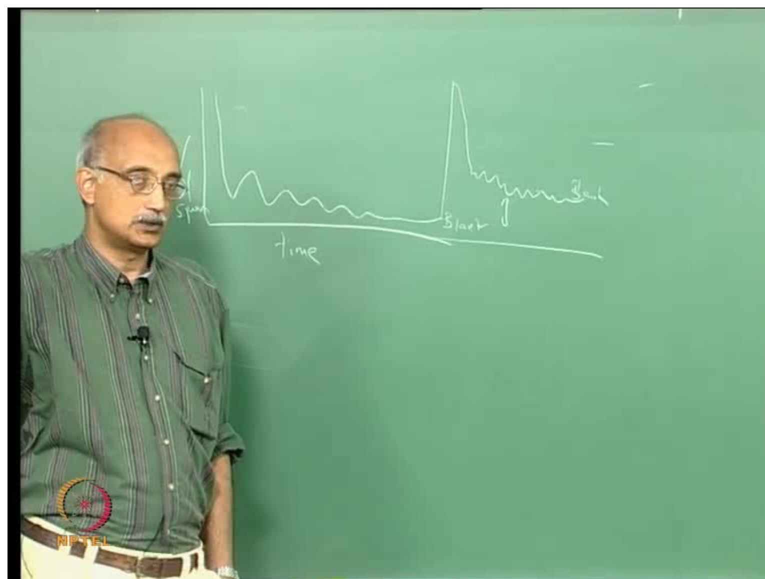

Now, when you plot the number concentration - number per unit volume of particles, let us say greater than 0.5 microns as a function of time, inside one of these tanks. Let us say that you are not running any parts through, let us say that the cleaner is ideal, you are only trying to run it without any load in order to get it to cleanup.

Then what will happen is that initially, you will have a high count and then eventually it will reach a blank value, which is very low because the system will clean itself up and

you say you should essentially drive towards zero residual particles, but now what happens is as you start cleaning wafers through this system, let us say that you have reached this value and now, you introduce a set of wafers. What is going to happen is there will be a spike in the particle count because the wafers will release particles into the tank and the numbers will go up, but then the recycle will again slowly take these numbers down. So, you will get a drop and essentially, you will reach a new blank value, but this blank value will not be as low as the blank value was, before you started running any wafers through your system. So, there will be an offset.

So, this is the steady state contamination or particles that are added by the wafer that is being cleaned through your system. So, if you keep doing this essentially, this blank value will just keep increasing in magnitude for every cycle of parts going through the system. So, eventually, you will reach such a high value that you will say I have to do something here. So, you will essentially, turnoff the system and again do not run any wafers through let it clean up let it come back down.

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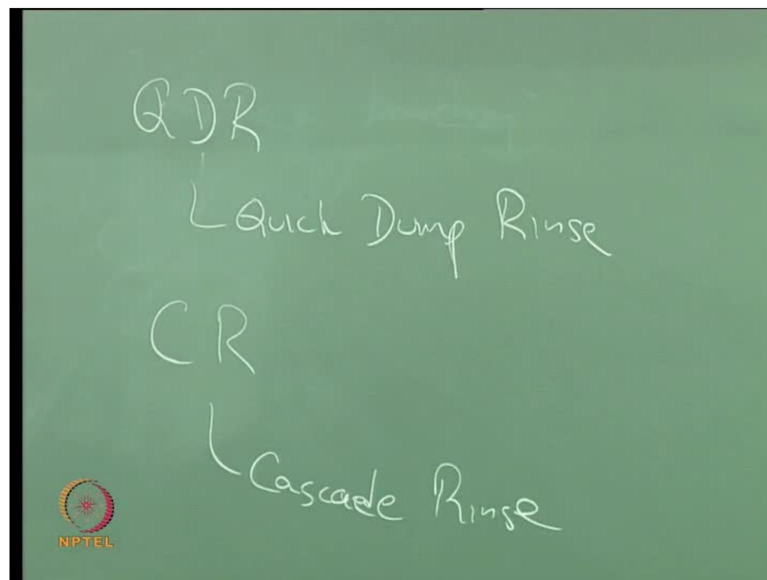

Now, one way to do push these blank values down quickly is to have an aggressive cycle of removing particles. There are two types of rinsing mechanisms that are used in the cleaning industry: one is called QDR, which stands for quick dump rinse, and the other is CR, which stands for cascade rinse.

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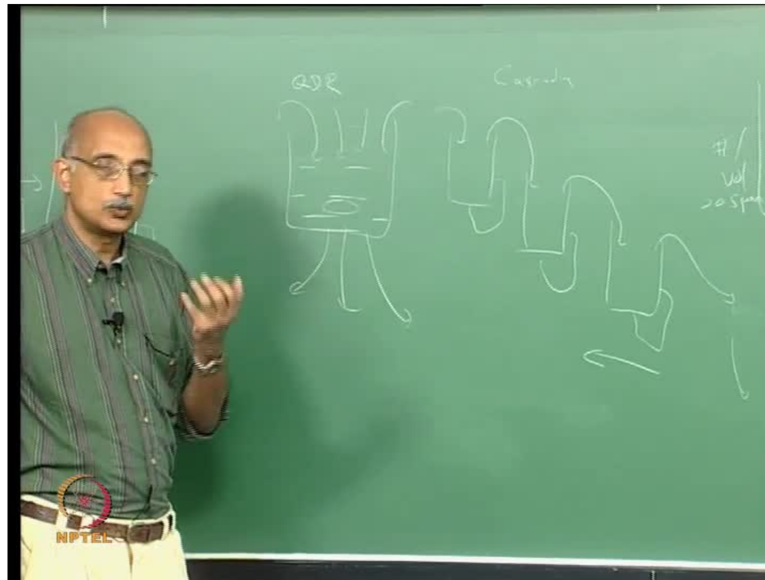

Now, the difference between these two can be sketched as follows. In the QDR, essentially what happens is, you have a tank in which wafers are being washed or rinsed. In a quick dump rinse, fresh water will flow in and discharge water will simply be taken out and discharged to the treatment system. So, instead of being recycled, this is essentially similar in concept to the vertical laminar flow clean room, if you remember.

In a vertical laminar flow clean room, you have clean air entering from the top and being discharged from the bottom. Very similar principle here, clean water comes in from the top, just goes through the component one time and gets pulled out through the bottom of the tank. This will drive down your blank values or background values very quickly, but it is somewhat inefficient in terms of water usage and therefore, you know water discharge is more, cost of operation is more. So, QDR is essentially a very pristine and pure operation, but you do not want to do it too frequently in your process. The QDR is usually done right at the end of your process, you know just before you are ready to ship your product to the customer. You do this in order to remove any remaining material on the surface.

A cascade on the other hand, as the name suggests, it is essentially a series of tanks in which pure fresh water is introduced upstream. The discharge from this goes into the next tank, the discharge from this goes into the next tank and so on and the final water is discharged, but over here, you have recycling as well. Now, in this configuration the

purest water will enter in the first tank or in a way, the last tank because the process itself will be running this way.

So, the wafers will be first taken into this tank and then into this tank and then into this tank. So, the last tank that the wafers see is the one that has the purest water in it. So, by this type of arrangement, it is possible to minimize consumption of water and at the same time achieve a high degree of cleanliness of the wafer.

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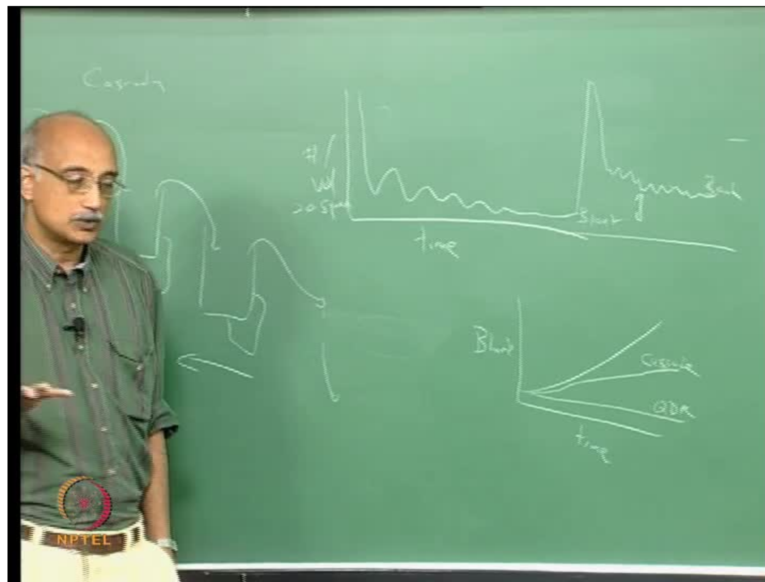

So, it is a very different concept and the thing that is different about them is the kinetics of cleanup, you know how quickly do the particles levels can drive down and can re-achieve their blank values that they had at the beginning of the process.

The QDR will give you, now, if you look at your blank count as a function of time without active rinsing, this will just keep climbing, as I mentioned, you know that is basically what we are showing here. With a good cascade rinse, you can essentially control it so that it has a behaviour that is like this. With a very effective quick temperance, you can essentially maintain your blank level at a very flat and very low value, regardless of how many wafers you are pumping through this process.

So, the kinetics of cleanup of a cleaning tank is very similar to the kinetics of how a clean room cleans up. So, you have to be able to think of both as very similar systems, who can be controlled and optimized using very similar strategies.

So, continuing in the high-tech manufacturing side, another application that is widely used particularly again in silicon manufacturing is, deposition of thin films. Thin film deposition is an essential step in order to incorporate the right type of semiconducting and non-conducting and conducting elements on a surface.

Thin film deposition is again a process that is very much dependent on particle characteristics. However, in this case, the effect of particles is somewhat indirect. Now, thin film deposition is essentially done using two different processes. One is physical vapour deposition and the other is chemical vapour deposition. The difference between the two is, in physical vapour deposition, the film that is forming on the surface is chemically the same as the material that is in the vapour phase and condensing to form the film. For example, if you are trying to form a silicon film on a surface and you do it by essentially, taking silicon vapour and causing it to condense on the substrate. That is called physical vapour deposition.

Chemical vapour deposition, on the other hand, involves a case, where the vapour phase composition may be very different from the film composition. So, for example, to make a silicon film, you may have a vapour phase that consist of various silicon containing species like silicon, silicon dioxide, silane and so on, which react on the surface to give you the film that you are looking for.

Now, in physical vapour deposition, the key step is to form the vapour. For example, if you are trying to make silicon firm in a PVD system, you have to first make silicon vapour. So, that is done essentially by either thermal methods or by using other forms of energy such as ion sputtering or plasma sputtering and so on.

Just like, I think we discussed the thing in context of making nano particles, where again the challenge was to take a solid material and converting it into a vapour phase, the difference between a nano particle synthesis reactor and a thin film deposition reactor is that in the first case, particles are desirable; you are actually trying to make nano particles by using this process.

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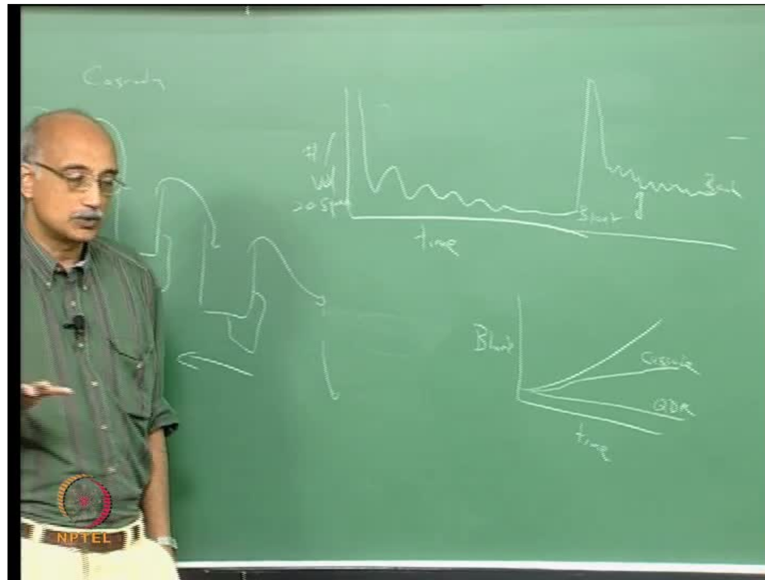

In the later case, where you are trying to make thin films, particles are a contaminant. You want to design a system so that particles do not form. So, interestingly, you can take the same reactor and by slightly altering its operating conditions, you can make it behave either like a particle synthesis reactor or as a thin film deposition reactor. The thing is in a thin film deposition reactor, you have to make sure that particles do not form and if you remember our discussion from Nano particles synthesis, particles can from by two mechanisms. One is homogeneous nucleation, where the particle forms in a gas phase and then gets transported to a surface or it can form by a heterogeneous nucleation mechanism, where the particle forms on the surface due to reactions are take place on the surface.

In a thin film deposition system, particles formed by either mechanism will be considered a contaminant because the particle formed in a gas phase, they can be transported to the substrate by the Thermophoresis or inertial impaction or other mechanisms and instead of having a nice smooth film on the surface, now, you have these isolated particles that from point defects on the film or alternatively, the particles may be forming because of reactions that are taking place on the substrate, where you are trying to form the film.

In both cases, particles in this case are considered contaminants to be avoided. So, what are the critical characteristics of particles that affect the quality of this process? It is

primarily transport phenomena as well as nucleation and growth phenomena. You have to design your reactor, if you are trying to make thin films; you have to design your reactor so that the formation of particles is thermodynamically not feasible and also kinetically constrained.

So, you have to setup the system so that all the chemical reactions as well as transport processes are such that the likelihood of particles forming and depositing on the substrate are minimized. It is again the exact opposite of what you would want to do in a particle synthesis reactor, where you would want to maximize the probability of particle formation and also optimize transport phenomena to get these particles to deposit on your substrate.

So, in the case of all, whether it is a thermal process for getting the vapour or whether it is a spattering process, where the surface is bombarded with ions or plasma to form the vapour, the key is to maintain the homogenous kinetics in such a way that particles do not form in the gas phase.

Especially, when you are using plasma to make these vapours, particles tend to charge differently from molecules. So, you will have in a plasma reactor, where there is charge being generated, the particles will be charged differently from the vapour molecules. So, their transport characteristics will be very different as well. So, that is again something you want to avoid in the design of such a reactor to form a thin films.

Another example, where particle properties play a significant role is, even things like solar energy devices. One of the key components in a solar device is the collector. You need a surface to collect the solar energy and this is usually polished glass.

Now, the challenge is how do you keep that glass clean? In fact, one of the limiting factors to the efficiency of the solar device is how do you maintain the purity of the solar collector because if you start forming dust layers on the solar collector surfaces, then the efficiency of solar energy collection begins to deteriorate.

So, the propensity of particles to deposit on highly polished surfaces is something that affects many different industries. Solar is one, but even things like aerospace. When satellites are launched for observing various things, whether they are other solar systems or the stratosphere or whatever, you are relying on certain instruments - optics to collect

the information and convey it back to you. So, here again, if these lenses that are being used to do imaging get a collection of particles on them, their functionality will be compromised and so, keeping aerospace components clean and particle free is another huge challenge, where particle characteristics in this case, particularly, particle deposition and particle adhesion play a huge role.

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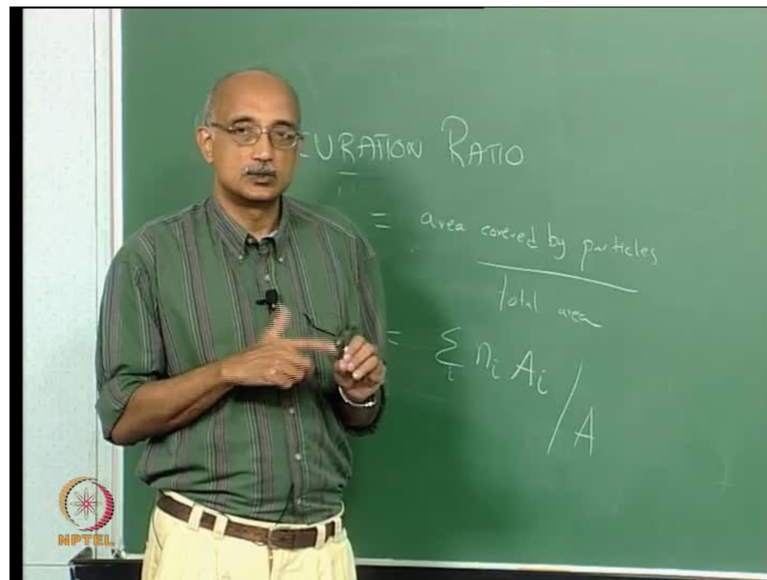

In fact, there is a parameter that is been defined in the aerospace industry which is called the obscuration ratio. Obscuration ratio is defined as the percent of a surface that is covered by particles. So, it is basically the ratio of area covered by particles to total area or which can also be written in terms of individual particle sizes, as summation i n i A i over the total area, where A i is the surface area corresponding to particles of size n i.

Now, this parameter, the obscuration ratio is again something that we have specifications for and standards for. You know just like we discussed earlier, clean room standards in term of classes, you know class hundreds and so on and surface cleanliness levels of levels, in the case of the obscuration ratio, similarly, the aerospace industries has set certain standards.

In fact, as soon as the obscuration ratio starts exceeding one percent, it is considered that the surface is too contaminated to be used any further. So, they are constantly using particle counters and other type of monitoring devices to estimate the obscuration ratio of the critical sensing and imaging devices that are used and they keep track of the

obscuration ratio as a function of time. Once it exceeds the certain critical value, they actually they take the component offline, clean the surface and here again, surface cleaning becomes an important process because they have to be able take this highly polished lenses and other optic devices and clean fine particles, which can range size from microns to nanometers and that you do it without damaging the surface.

So, you know you have to again manage the aggressiveness of your cleaning process so that you remove the particles virtually 100 percent, but you do not do anything to damage the underlying optical surface. So, the aerospace industry is again very much involved in particle characterization, particle analysis and particle control and they continue to do a lot of work in this area.

Now, other industry is that we have already touched upon in earlier lectures are pharma industry whereas, we have seen particle adhesion, particle cohesion, particle flow-ability chemical characteristics, in terms of their ability to interact with pathogens and bacteria and so on, dissolution characteristics, in the case of a tablet. There are many aspects of particle properties that are of overriding importance in the pharma industry as well.

Even things like automotive design, we know cars are designed to minimize the drag. You always talk about this aerodynamic shape that minimizes the drag that the auto, the automotive experience, but it is just as important to optimize the shape and the air flow around the automobile for minimizing particle pickup.

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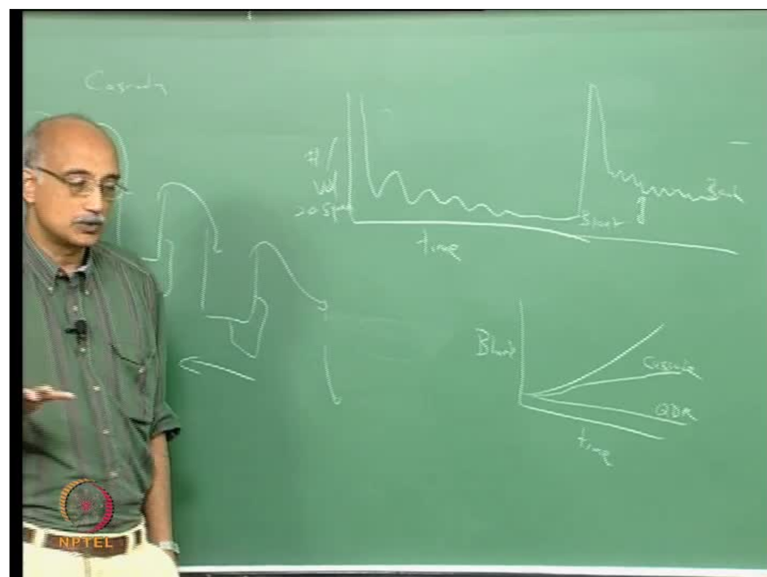

You do not want your wind shield to get too dirty, too quickly because that would mean that you have to keep cleaning it over and over and even the surface of the car, if you can keep it clean for longer, the custom is happier and it turns out that actually, there are many interesting things we can do with the physical shape of the automobile to minimize particle pickup and deposition in critical areas that the customer is very sensitive too.

So, essentially, you work with the shape of the car and the effect that it has on air flow around it, in order to push particles out of critical location towards non-critical locations. So, a lot of computational fluid dynamic modeling is resorted to in the design of automobiles, again just as much for reducing particle deposition on critical surfaces of automobiles as for minimizing drag and just as bigger a consideration for automotive design engineers. So, you know there are literally hundreds of such examples that you can think off, where particle characteristics will play a major role and it is important for us to understand, what are the critical characteristics for each application? How they can be measured? How they can be quantified? How they can be controlled? How they can be optimized and so on.

So, that is basically, what we have tried to cover in this course and hopefully, the last few applications that we have discussed have reinforced the importance that particle characteristics play in determining their end effect on the product in question. Any questions?