Particle Characterization

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Module No. # 01
Lecture No. # 01
Introduction: Why Study Particle Characterization?

Welcome to the course on particle characterization. Before you study any subject, I feel that it is important for you to understand why you are studying the subject. The question of why should be foremost in your mind. Why should you study particle characterization? Means that is a very logical, very reasonable question. Once you have answered that questions satisfactorily, then we can talk about what characteristic should you study? How should you study these characteristics? and so on. However, the why question is very important and should be answered right in the beginning. The what, how, when – all those other questions we can answer over the duration of the course. So, why is it important to study particle characteristics?

Well in a very general sense particles are the basic building blocks of life, the universe, everything. You can essentially break down our entire system, our universe into discrete particles. When we talk about particles, the size is something that is not absolute; you cannot say for example, something that measures 1 nanometer is a particle and something that measures say 1 kilometer is not, because it depends on the scale that you are referring to. For example, when physicists talk about particles and particle physics they are really talking about atoms and even subatomic dimensions. So, they are talking about angstroms or even smaller dimensions.

On the other hand, someone who is working in a process industry; let say that they are working in a power plant and they are burning coal. Then, they talk about particles; they are typically talking about these lumps of coal that need to be burnt in the boiler in order to produce energy. So, for them, a particle can be of the order of millimeters. So, they both are talking about particles; whereas, you can see the relative scale is entirely different. I mean, another way to think about it is – in a universal scale, the earth itself is like a small particle. So, just one of the key things to remember when we talk about particles is that the definition of a particle is not dependent on its size. Although people have tried to give definitions of what a particle is, on the basis of its relationship with its surroundings, for example, one of the definitions that people have given is – a particle is something that remains suspended in its environment for and observable period of time.

Now, what do we mean by that? If I take this piece of chalk, is this a particle? Or, if I drop it, it drops fairly quickly, is it observable? Is its motion, transport in this room air observable, measurable? Depends; not with naked eye, but certainly, if you have recording instruments, sure; you can study the dynamics of how it falls. However, if I want to show you this, would you say it is a particle? Probably not; on the other hand, if I just break a little chunk from it, that is a particle. So, we can see – it is a very subjective definition. That is one of the problems particularly in size analysis of particles. There is no absolute size; size is in the eyes of the beholder (( )), and something that I might call this a particle and you might not. So, how do you define a particle? A particle is a part of a whole. So, you take a big piece of something and then you fragment it; each fragment now becomes a particle. So, it is part of a whole. That is one definition of about what a particle is. A material that is large enough to be distinguishable from a cluster of atoms, but small enough to be – as we were just saying – suspended in its environment for a reasonable period of time. That is another definition of a particle.

For example, if you have a cluster of atoms that measures, let say – 10 angstroms, you probably would not call it a particle. However, if the size keeps increasing and you get to, let say – nanometer sized clusters are agglomerates, you would call that a particle. Conventionally, the definition of particle based on size, is anything that starts above roughly 0.1 nanometers. You would consider that to be a particle. So, when we talk about nanotechnology, it is really part of particle technology, except that we are dealing with particles in this specific size range of 1 to 100 nanometers. That is the range that is normally associated with nanotechnology. So, particles that are smaller than 1 nanometer are actually 0.1 nanometer – would fall into more the atom slash molecule category. Whereas, particles that are larger than 100 nanometers, that is, 0.1 microns – would fall into the coarser particle category. So, a particle has a definite shape; it has a definite size; it has a very clear interface with its surroundings, because it is a discrete entity. I mean this bench again – would we call it a particle? It all depends on the definition. However, let us say that you do not. When you do not call this a particle – about this bottle – probably do not call it a particle. However, they all have certain features – they all have a fixed shape, they all have a fixed size, and there is a clearly definable interface to its surroundings. So, from that view point, neglecting size has a parameter, you can actually call any of these particles – you can call us particle; you can call the chair, this entire building a particle. So, it is all a matter of size.

Hopefully, that gives you little bit of understanding about what constitutes a particle, but why is it important to study particle characteristics? We come back to the same question. All we have done so far is, explained what is a particle, but then, why is it important to study them? Hopefully, the discussion we have had so far already gives you some pointer as to why we should study particle characteristics. However, if you think about particles is – if you look at our everyday life, virtually, every aspect of it involves particular technology of one kind or the other. If you again look at it in a very global context, what are the chief challenges to life as we know it? You will find that everything involves particle technology in one form or the other. For example, water, energy, food, environment – these are obviously the big questions that we are all facing. Especially, as we go forward, global warming takes place, population keep increasing. We are all worried about how sustainable this whole ecosystem is. If you break it up into components, you will see that each of these aspects that really are going to determine humanity survival in future incorporate many elements of particle technology in them.

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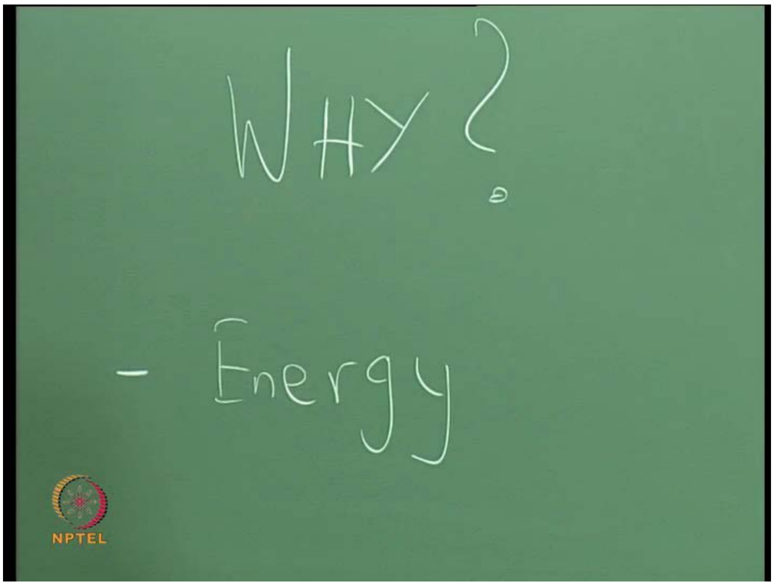

In terms of why should we study particles, the answer to the question is obviously, because particles affect every aspect of our life. So, unless you understand how particles behave, unless you know how to characterize particles on the basis of their various properties, you cannot fully control and optimize the application of these particles in your everyday processes. So, the examples that I was quoting – let us take energy (( )) Energy is predominately still being produced by means of burning hydrocarbon fuels as well as solid fuels such as, coal. Now, where is particular technology involved? Obviously, when we talk about coal, everything from the mining of coal to the transport of coal, to crushing of coal, to burning of coal, and the treatment and capture of the particular pollutants like ash that result from the burning of coal – all involve particle technology of various kinds. So, there is no question that if the energy source is a solid fuel, then unless you understand how large particles behave and how very fine particles behave, you are really not going to be able to design an efficient system to extract energy from these solid fuels.

However, when you consider even the high purity liquid fuels like petrol, jet fuel – aviation fuel is supposed to be the purest cleanest and the most efficient fuel to burn – what happens? When you take a jet aircraft that ingesting aviation fuel, do we have to worry about particles? The answer is yes in two ways. The first is when you talk about fuel and you look at the way that it is burnt, it is not burnt as a big tub of fuel; what is typically happening? You are actually spraying the fuel in to a combustor, where it is mixing with some oxidant and that is where the combustion process takes place. The process of taking a continuous plane or film of a liquid and breaking it up into fine droplets by spraying it through an atomizer involves particle technology, because particle does not mean solid particle, no. A liquid particle is just as much of particle; just called a droplet. That is the name for liquid particle.

Even the science and practice of burning liquid fuels involves particle technology, except that now, we are talking about liquid particles or droplets instead of solid particles. So, that is one way where… So, you have to understand how atomization happens; when you take a liquid and you spray it through nozzles, how does it break up into droplets, what is the distribution of sizes, what is the velocity with which these droplets emerge from the nozzle? All of these come under the characterization scope of our study. The other aspect is, there are always impurities. Even in the purest fuel, there will be some impurities. In the oxidant, which is typically just the ambient air that is being ingested into the combustor, there will be impurities as well. So, during the combustion process, what will happen is that you will form certain components or products, which are solid in nature, which represent pollutants that are resulting from this combustion process.

As an example, if you are operating a turbine or an aircraft near a marine environment, the air in a marine environment contains salt, which is you know sodium chloride. Fuels always contain sulphur as an impurity. So, what will happen is – the sodium and potassium in the air, react with the sulphur that is present in the fuel and in a highly oxidizing environment, gets converted to sodium sulphate and potassium sulphate. Now, these are called molten salts. They are actually liquid films or droplets that condense on various heat transfer surfaces and cause corrosion. These molten salts result in what is known as hot corrosion of the material. So, you can imagine that in order to characterize this whole process of how these molten salts are formed, how are they transported, how are they deposited, and then how they interact with the material that is, for example, on router blades and stator winds, and so on – again involves an understanding of particulate chemistry, particulate dynamics, particulate physics and so on.

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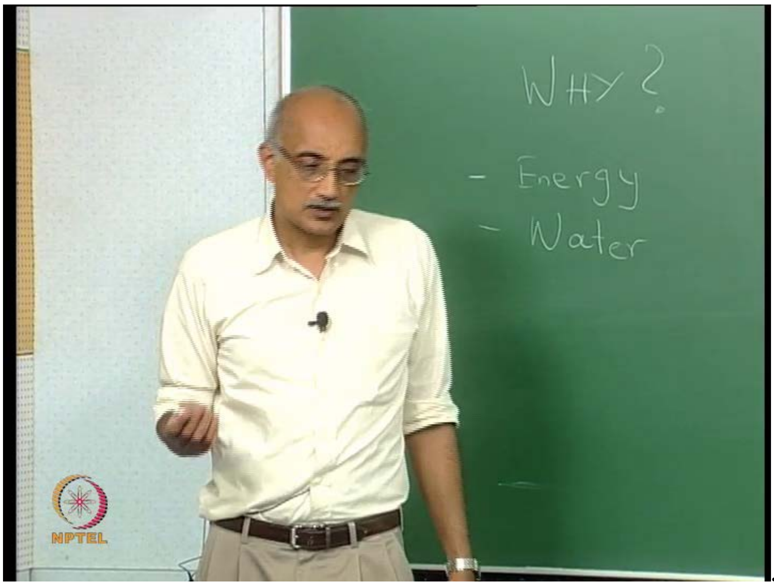

Clearly, when we talk about energy, whatever the form is, in which you are extracting energy, you always have to be concerned about particulate phenomena that are present. Another example is water. Now, how is particle science, how is particle characterization

– relevant to supply of water? In a few ways, but one that I can think of immediately is – in the case of drinking water for example, particles are typically impurities that you want to eliminate. So, the reason that we do a filtration on the water before we drink it, the reason that we have point of few filters in laboratories before we use ultra-pure water for any purpose, or the reason we use aqua guard in our homes to purify the water, is so that these particles that are present in the water supply can be extracted and removed before you actually drink the water. So, in this particular case, the most relevant particle characteristic would probably be the efficiency with which it can be filtered. That would very much depend on the shape and size of the particle as you can imagine; larger particles can be filtered using different mechanisms than smaller particles. It is going to depend on the size. Particles that are spherical in shape will have very different filtration characteristics compared to particles that are plated-like or needle-like. Also, the chemical properties of the particles can also play a role; or, we are going to rely strictly on physis option, or can we actually use chemis option to remove these particles.

We will cover all these aspects in more detail later in the course, but the thing I am trying to point out you is – even if you take the most basic technology that runs our lives like supply of water, there is a lot of particle characterization and understanding of how particles behave – that is required in order for us to design and operates such a system.

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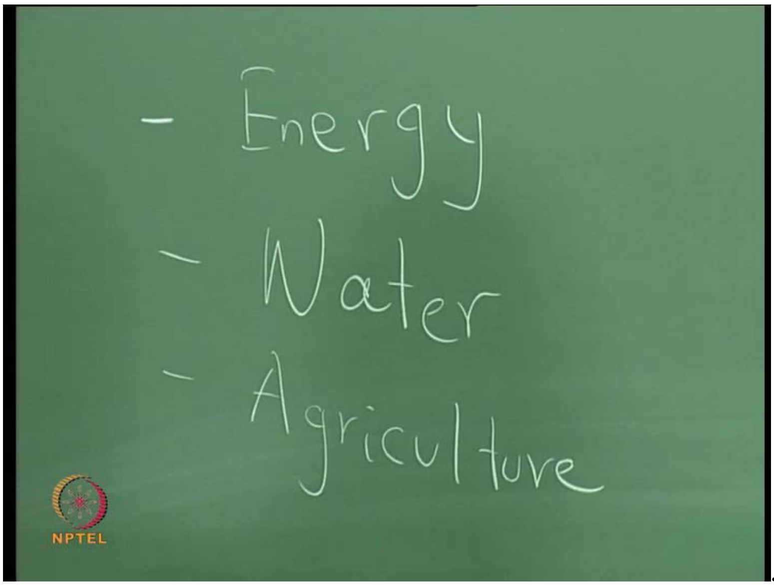

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Another one that certainly affects the lively hood of majority of our population is agriculture. When we talk about agriculture, one immediate example I can think of, where particle technology is involved is in the use of fertilizers. Fertilizers are essentially particulate in nature. They are intended to supply certain nutrients to whatever plants that you are growing, but the various characteristics of these particles play a huge role in how effective these fertilizers are. For example, the fertilizer has to be formulated in such a way that it is very stable during its supply and storage by the former, where as soon as you introduce it into the soil, it has to dissolve completely and release all the nucleons to the soil. There may even be requirements for time to release of certain components, so that you do not overwhelm the plant with a certain nutrient, which will cause run off. So, some kind of phased or time to release of nutrients may be essential also.

In some cases, there may be additives that are required. For example, Coromandel Fertilizers is now toying with the zinc oxide as an additive to those fertilizers, because our soils are all depleted in zinc. In such a case, it becomes very interesting to think about how these fertilizers with active ingredients are formulated, how are they deployed, and how are they optimized in terms of their usefulness for a crop. So, again, when you talk about agriculture in particular, about use of fertilizers, insecticides, and so on, particle characterization becomes a very important discipline.

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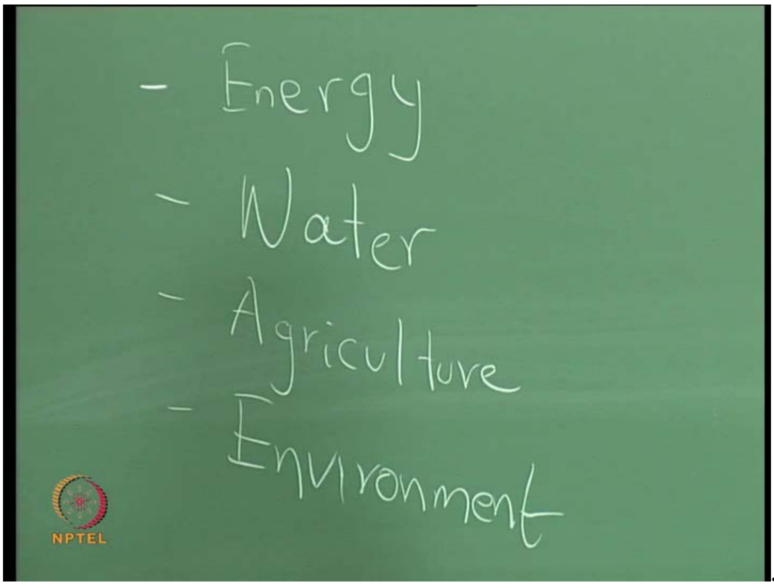

I mentioned environment. When we talk about the environment, there are two types of constituent present in the environment that we should worry about: one is the vapor phase constituents and the other is condensed phase constituents. Dust is an example of a solid particle contaminant or pollutant that is everywhere. So, when we look at for example, the ambient environment around a city and we do characterization of particles that are present in the atmosphere, the count as well as the composition of the particles are likely to be very different in an urban environment compared to a rural environment. It is very important to quantify and characterize these differences, because that will tell us a lot about – essentially, the quality of life, for example – if you are living in a very congested city with lot of automotive traffic, it is likely that the particulate levels tend to be very high in such environments, and that present certain health hazards.

Even if you are located in a rural environment, there may be situations, where some of these agriculture products will be talked about. Fertilizers and other chemicals that are used may actually emit certain chemical compounds to the environment, which can be very harmful – like there was one situation I was involved in when I was working with IBM. We had a manufacturing facility in the middle of fields in Mexico. We thought that it was a very clean environment because there was no traffic around that area. However, the discs kept corroding. When we analyzed the discs we found sulphate – sulphur deposits; turned out that there was a exactly this – some of the chemicals that the farmers were using in the farms around the plant had sulphur containing ingredients, which were essentially coming in to the clean rooms, where these products were being manufactured and depositing on these products and causing corrosion to happen.

The characterization of particulate pollutants in the atmosphere is something that is very essential just for our survival, I would say. So, this requires that we need to understand how these particles are generated, how are they transported, how are they deposited at various locations, how are they ingested through our lungs, can they actually penetrate through our skin. If the particles are really nano-dimensional in nature, there is a good possibility that they can actually…; they do not have to be ingested through our breath; they can actually penetrate through our skin. So, all these aspects of particle characteristics – in this particular case, transport characteristics become very important for us to do a risk-benefit type of an assessment. Is the risk of using for example, nano fertilizers, sufficiently high that it out phase the benefits?

These are the kinds of questions that everybody is still struggling with; there is no clear answer. We obviously, expect nano materials to be more reactive and more affective compared to coarser materials, but the risk part of it – we are not very sure about yet. There is still lot of learning that we need to go through as we start using nano technology more and more extensively. So, these are some examples of what I would call global phenomena, where particle science, particle technology, particle characterization plays an important role. However, many of you are going to go into manufacturing and process industries. Do particles play a role in industry processing in general?

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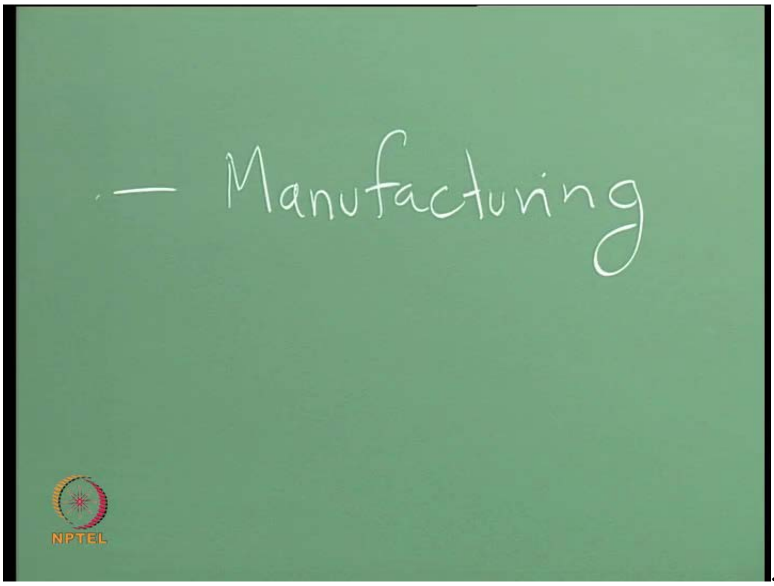

I think that is certainly true. Manufacturing processes, in general, involve extensive use of particle technology. For example, if you are running a chemical reaction, the reactants have to be introduced to the reactor in some form. They are typically introduced as vapors, or as slurries, or as dry powders. Two out of the three involve particulate processing; whether you introduce it as a slurry or whether you introducing it as a dry powder, you have to be concerned about things like flowability of the material, coagulation characteristics, cohesive behavior. All of these become very important considerations in how you design the reactor in order to minimize any impact, due to unstable or non-repeatable phenomena that may be associated with the behavior of these particulate materials. Here again it is important for us to understand the adhesion characteristics of particles, cohesion characteristics of particles, flow behavior of particulate suspensions, the viscosity and surface tension of a fluid, as it is affected by the introduction of particles. So, all of these become very important considerations.

Now, when we talk about manufacturing industries, again we can kind of split it into high-tech and low-tech. First, let us talk about high-tech industries.

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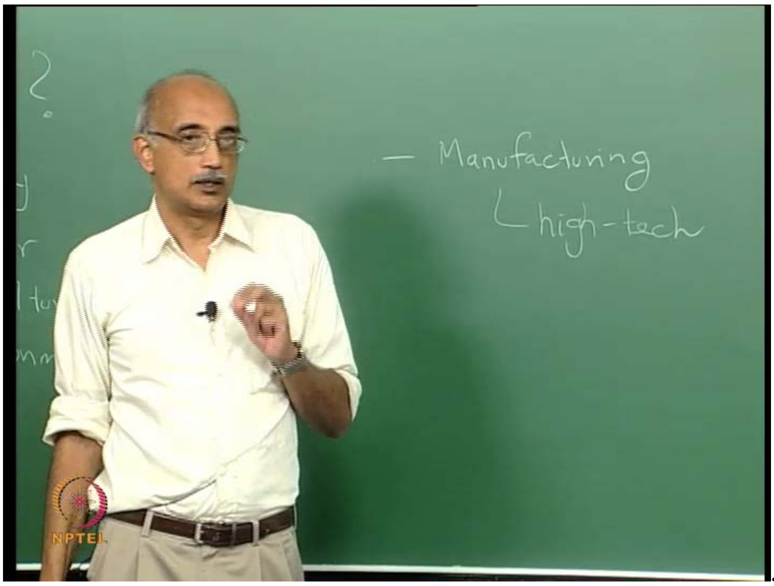

Now, what we mean by a high-tech industry is one where the technology is such that it is very sensitive to even small variations in factors they can affect these processes. A good example would be the manufacture of semiconductor vapors that are used in microelectronic products. These products are so sensitive that an excursion of one part per billion in the particle level in the surrounding air or in the surrounding fluids, can be sufficient to cause a significant reduction in process yield, as well as affect the reliability and availability of this product in the field. Another example would be hard drives; I am sure that all of you use hard drives whether consciously or not. You know that the hard drive is one of the components that is very susceptible to failure. When you look at why pc's fail or why laptops fail, hard drive failure is frequently one of the causes. Why does that happen? Do particles play a role in this?

Actually they do in two ways. One is the recording media in a hard drive, is essentially using directional magnetized particles to store data. So, the way that you actually manufacture these recording discs is very much dependent in this particular case on the magnetic properties and the orientational behavior of these magnetic particles that are stored on the discs. After you have manufactured the drive, one of the reasons that hard drive fails is because of particles. The head is flying above the disc at a distance of 10 nanometers or less. In fact, in hard drive production, we have been using nanotechnology for more than 50 years. Even though we did not call it nanotechnology, but even the first hard drives that were manufactured back in the 1950s, the head was flying roughly 80 nanometers above the disc. So, we have always been doing nanotechnology when we talk about memory storage.

What if the head is flying 10 nanometers above the disc; let say that you had 115 nanometer particles sitting on the disc, what is going to happen? The head is going to crash into it – happens frequently. That is one of the modes of failure for hard drives in the field. Particulate contaminants that are caught between the head and the disc, which cause one of two things to happen – the head can actually crash into the particle or into the disc; or, the particle can actually get captured between the head and the disc as the head is flying around. So, it will essentially put a circumferential scratch on the disc. So, in this circumferential area, data cannot be written and data cannot be read.

The third way by which particles can affect hard drives is – instead of getting caught in the interface between the head and the disc, they start accumulating on the head. Now, depending on where they accumulate, this can either cause the trajectory of the head to move downwards, so that it eventually hits the disc; or, sometimes, it causes the head to move upwards, so that it flies farther away from the disc than it was designed to do. That is the problem, because as the head flies above its design height, the sensitivity to recording and reading data decreases. So, you start getting what are known as soft errors. If the head flies closer to the disc, you get a hard error; if it starts flying farther away from the disc, you get a soft error. However, either case, you are not happy as a user. So, in the case of hard drives, in the case of silicon vapors integrated circuits – in all these cases, the presence of a particle in the wrong place at the wrong time can have hugely disastrous consequences for the product, for the user, and ultimately for the manufacturer. So, it is very important in such industries to completely understand what all the sources of particles in the process are, what the magnitudes of the sources are, and how these can be controlled.

Particles when they are contaminant can never be completely eliminated. So, people do not even talk about particle elimination; what they talk about is particle control. You try to maintain and manage the particles at a level, where the product can still function with acceptable reliability and yield. You just cannot try for… You can try for 0, but you will never achieve it. However, it is clear that in order to have a profitable high-tech manufacturing process, characterizing particles and controlling them is a very important requirement.

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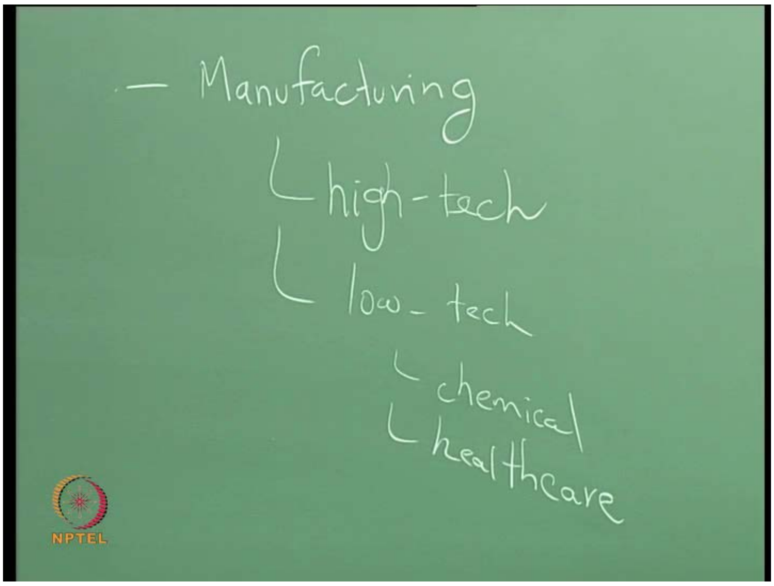

When we talk about what I would call low-tech processes, these are what I would tell the more conventional manufacturing processes that we see all around us. This could include things like chemical manufacturing. Particularly as chemical engineers and chemist, we use a lot of chemicals in our work. When we manufacture these chemicals, again the particles can get involved in two ways: one is as a contaminant and the other is as an essential constituent. So, if it is a solid chemical that you are manufacturing, then the ability to again manufacture it as per some specifications – store it, transport it, and deliver it to the consumer as desired by the consumer – all depend very much on your ability to characterize and control the behavior of particles in these chemicals.

Another example is health care products in general. Although I am not sure if I would characterize health care products as low-tech necessarily, some of them do involve high technology these days. For example, manufacture of medical devices – many of these devices are to be used in sterile clean rooms like operating rooms. So, there is a requirement on how clean these devices must be. That again comes back to particle technology. We have to have a way of removing even very fine sub-micron particles from these medical devices before you can take them into an operating theater for example, and start using patient. So, the manufacture of medical devices involves many aspects of particle characterization and control.

Also, in general, medical products for example, tablets that you consume; when you think about it, it is hugely challenging to make these – even the commonest medication like Crocin for example. Crocin; you get it as a solid tablet. As soon as you put it in your mouth, you want it to dissolve, but you do not want it to dissolve; you want it to be stable; you want to swallow it; as soon as you swallow it, you want to see an effect immediately; you do not want to wait for 20 minutes to see if your headache goes down or your fever goes down. If you look at the demands on the manufacture of something as simple as Crocin tablet, the company has to first make the tablet and it has to be structurally stable, so that they can package it, they can put it in some container, then they can ship it to a store. The store needs to keep it for some time, then you buy it from them and you bring it your home. You keep it for some time and then you use it whenever…

Usually, the shelf life on these are like 2 years, 3 years. So, these tablets, capsules have to be stable for a long period of time under normal storage conditions and transport conditions. However, as soon as I encounter your gastric juices, they must immediately dissolve and must be immediately transported in your blood to all the necessary places. So, there are very conflicting requirements, because you require high stability at one point in the process, but you require almost instantaneous instability at other points in the process. So, the selection of binders to hold these particles together in a compact formulation, and then release them later as per the requirements of the patient – again involves a lot of investigation and understanding of particle characteristics. So, in general, medicine is a field that is very dependent on particle characterization and management. Another example would be plastics.

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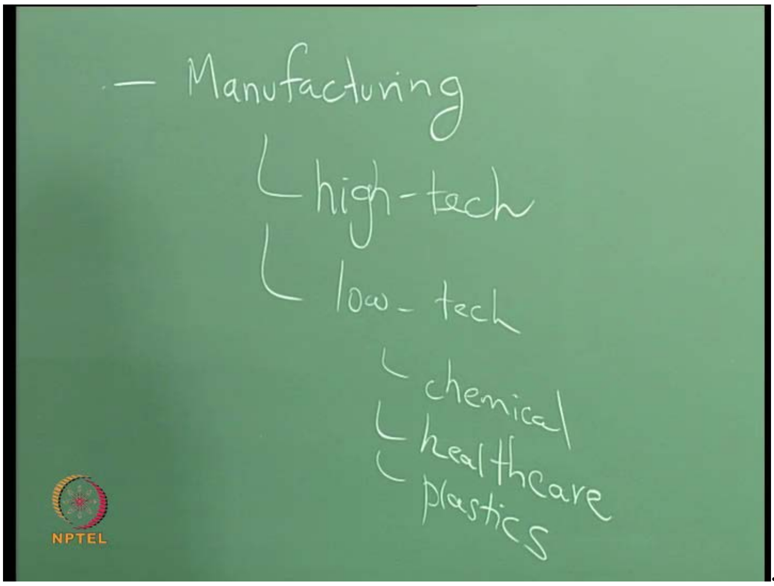

Now, plastic materials are used all over. In the old days, we use to get by which using virgin plastic. So, you take a pure plastic material, mold it, machine it, and use it. However, plastics are very limited in many of their properties. Plastics are obviously wonderful for many things, but they have limitations on their hardness, their toughness, thermal conductivity, electrical conductivity, scratch resistance, bad resistance. So, in order to improve these characteristics, people started using fillers. What is a filler? It is a particle material.

Now, if you look at where this composite technology has evolved, in the very early days, the filler materials used to be large in size – typically of the order of sometimes even millimeters. They would be added as powder. For example, carbon powder was a very popular filler material for many plastics. However, the problem with such large quantities of material is, as the material becomes more expensive, it becomes less and less cost effective to use large quantities of these materials. So, the plastic industries started thinking about how they can minimize the quantity of these materials, but still obtain the functional enhancement that they are looking for. It turned out that one way to do that was to reduce the size of these filler materials, because for the same quantity or volume of the material, if you make the powder into finer particles, you get much more surface area. So, the effectiveness increases greatly. So, the industry evolved from using essentially coarse fibers or coarse powder and other filler materials to using micro fibers to now using nano fibers, nano tubes, nano sheets and so on.

Now, any time you start talking about size reduction, and you start talking about nanotechnology, you are getting into the meet of particle characterization and particle technology. In order to formulate these composites in an effective manner, one of the key requirements is uniformity of the dispersion. It is not enough to have… In our overall concentration of let say 5 percent by filler volume, for example, it has to be very uniformly dispersed in the polymer in order for you to get the functional enhancement that you are looking for. So, enhancement of the filler material in a plastic is now a huge consideration for plastics and polymer processing industries. Again, particle characterization starts to play an increasingly important role in such cases.

You can think of many more examples of this kind. There are limitless numbers of processes that run on the basis of particular technologies and particular processes that you need to have a clear understanding of. Take something as simple as brushing your teeth; does that involve particle technology? In the old days, people used to actually brush their teeth with powder. Clearly, that involves particle technology. However, nowadays, we used paste, but if you look at the paste closely, there are many ingredients in the paste that are intended to remove black, all the types of bad things from your teeth. So, the formulation of tooth paste actually does involve many aspects of particle technology.

How about detergents? Again, we use every day; at least, somebody in our house uses them. Again, the whole formulation of a detergent powder involves so many aspects of particles that… Their list is endless. For example, the way that most detergent powders are made is using spray dry. So, essentially take a slurry of the detergent materials, spray it through a nozzle, and you simultaneously blow hot air either in co-current fashion or counter current fashion. As these detergent liquid droplets dry, they get converted to powder form. That is how powder detergents are made. There is lot of interest on how to optimize the operation of these spray dryers in order to have maximum throughput at minimum cost; also, have optimized properties of these detergents. When you talk about a detergent, detergency is obviously the most critical parameter. It has to have sufficient detergency to be able to remove dirt from clothes, but that is not the only consideration. The amount of material that you need to use to remove a certain amount of dirt is of great interest to the manufacturers, because again they are trying to minimize their cost. So, they want to do maximized removal of dirt with minimized use of active ingredients.

So, the manufacture of detergent powders again involves so many aspects of particle characterization.

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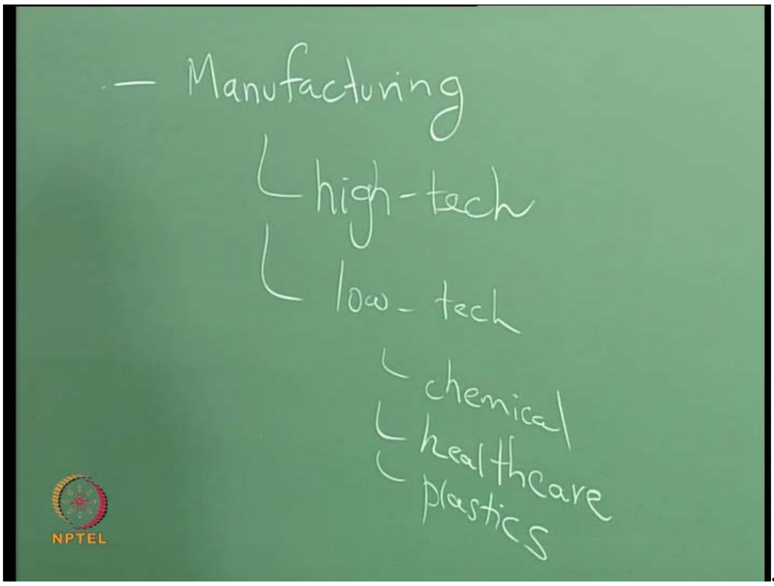

Food processing is an industry that relies hugely on particle characterization. When we talk about food in general, you have… The kind of food that you make at home, which I think is certainly… If you talk to your people who do the cooking in your house, you will see that it has many aspects of particle characterization. They do it somewhat unconsciously, but when you make rice, the finish that you get on the rice – how soft it is, how hard it is, what is the average grain size of the rice that you cook – all of these have a huge influence on your ability to eat and enjoy the food that you make.

However, how about purchased products? You will get a lot of packaged foods now for eating. Microwavable products, re-heatable products – all of them involve packaging technology. They are trying to take a certain dish that you would want to eat and package it in such a way that it can be conveniently cooked and eaten in as short the time as possible. Here again, many aspects of particle technology get involved, because what they are really trying to do is – take these discrete materials that make up the dish that you are trying to prepare, consume, and package them in such a way that they are very compact. However, as soon as you start preparing, they essentially release their full flavor and rechange the characteristics that make them edible in the first place. So, food technology is another area where particles play a huge role. Here again, the particle can be contaminant as well. You certainly do not want to have any food products contaminated with particulate material. So, understanding particle characteristic and controlling them becomes very important in this case as well. So, examples abound everyday around us, where particles are important.

Now, having said that particles are important; does it mean that it is as important for us to be able to characterize them? What do you mean by characterization? What do you see? Suppose that this is a particle. What are its characteristics that you observe immediately? what jumps out at you? Shape, size, color; is that enough? Is that sufficient for us to characterize a particle? I guess so; for everyday use, even when you see people, those are the things you look at – shape, size and color. So, I guess that the most natural human reaction. That is a way our eyes are tuned to looking at shapes of objects first, then the size, then the color and so on, but what registers immediately on our mind is the shape. However, obviously, that is not enough if you are trying to run a process using particles, where many different characteristics of the particle may become important. Any examples that you can think of? Besides these three, what are the other characteristics of a particle may be important?

Reactivity; suppose you are trying to use a particle for its ability to react with its environment or with other materials that are present, the chemical reactivity is obviously important. Surface area; if you are trying use a particle as a catalyst, the surface area of the catalyst is the most important factor. The point is… We will discuss this in more detail in the next class. The characteristics of a particle that are relevant – it is again a very large list; I can easily list 100 particles of particles, properties of particles that different people may be interested in for different applications. So, the point is not to be able to characterize every characteristics of a particle, but identify the most critical characteristics that are truly relevant for the process that you are trying to run.

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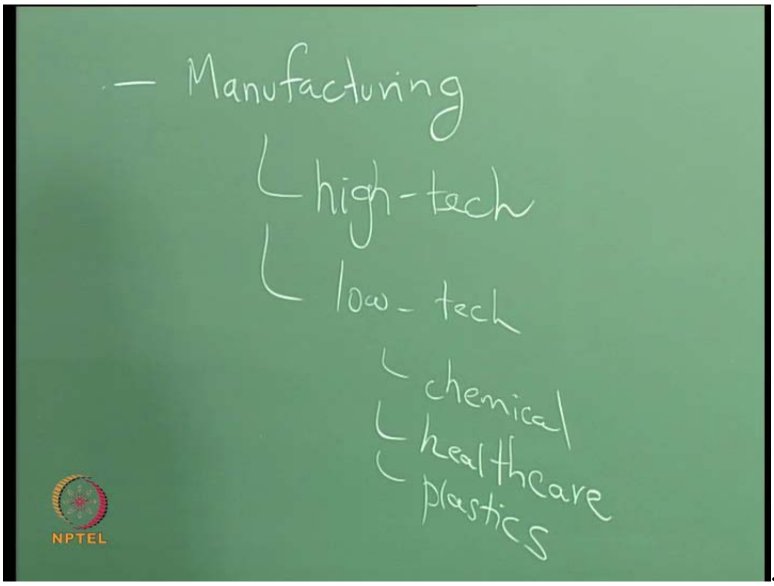

Just as an example, if you are running a chemical reaction using a catalyst, then the most important property or characteristic of the particle that you should try to measure and control, would be the active surface area of the particle. You would not really care so much about the crystal structure of the particle, for example. On the other hand, if your purpose is to use particles as a way to provide a protective coating like a powder coating on a surface, then the characteristic that you should be most interested in is – the protective property that it yields; how hard is it; how porous is it; how adherent is it on the surface. So, the relevant properties are a small subset of all the possible properties or characteristics of a particle. Once you have decided which are the critical characteristics, the next judgment call that you would have to make is, how do I characterize this characteristic? Do I use the most sophisticated tools that is available to be, or do I use a simplest tool?

What do I loose from either approach? Where is the optimum point? How much characterization is enough? Should I try to characterize as well as I can, or should I characterize as well as I need to? That is a very important question if you are in business, because if you are in business, you do not want to do anything more than you have to. So, finding that speech part of – what are the important characteristics and what is an optimum way to characterize them? That becomes to me an overriding concern of a process engineer.

In the next lecture, what we will do is, we will describe a fairly comprehensive list of particle characteristics and I will identify a subset of those characteristics that we will deal with, in more detail, in this course. We will also outline some of the methods of characterization that we will be adopting or discussing as we go forward in this course. Let us stop at that point in this lecture. Any questions? See you in the next lecture.