Plant Design and Economics
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Lecture No -55
Inherently Safer Design

Welcome to lecture 55 of plant design and economics. In this last lecture of module 11, we will talk about inherently safer design and then we will follow it up with the Bhopal gas tragedy. We will take Bhopal gas tragedy as a case study and will try to highlight certain points related to inherently safer design.

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There are 4 categories of process safety strategies; inherent category, then passive strategy, then active and then procedural. The inherent category of process strategy wants us to identify and implement ways to completely eliminate or significantly reduce hazards. So instead of developing protective systems and procedures, let us try to identify the hazards and let us try to implement ways to completely eliminate the hazards or significantly reduce the hazards.

In case of passive category we add safety features that do not require action by any device. For example dikes which are basically barrier walls that prevent say hazardous liquid from moving from one place to another. Passive flame arrester and the use of welded fittings in place of flanges and threaded connections. So such passive safety strategies do not require any action by any other device.

Active safety strategy, add safety shutdown systems to prevent accidents. This will include process control system, safety interlocks, automatic shutdown system and automatic mitigation system. Procedural strategy; this will include the standard operating procedures are followed, safety rules be kept in place and we follow it strictly. There will be operators training, emergency response procedure should be in place and management techniques to ensure safety at workplace in general.

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Inherently safer design is the fundamentally different way of thinking about the design of chemical process. As we just discussed, the inherently separate design focuses on the complete elimination or significant reduction of hazards instead of managing and controlling the hazards. We can apparently think such design processes will lead to very expensive plants. But on the contrary it is generally believed that this approach will result in economical processes, it will be safer and more robust.

That is why industries, chemical process industries have recognized the importance of inherently safer design and has attempted to adopt the principles of inherent safety.

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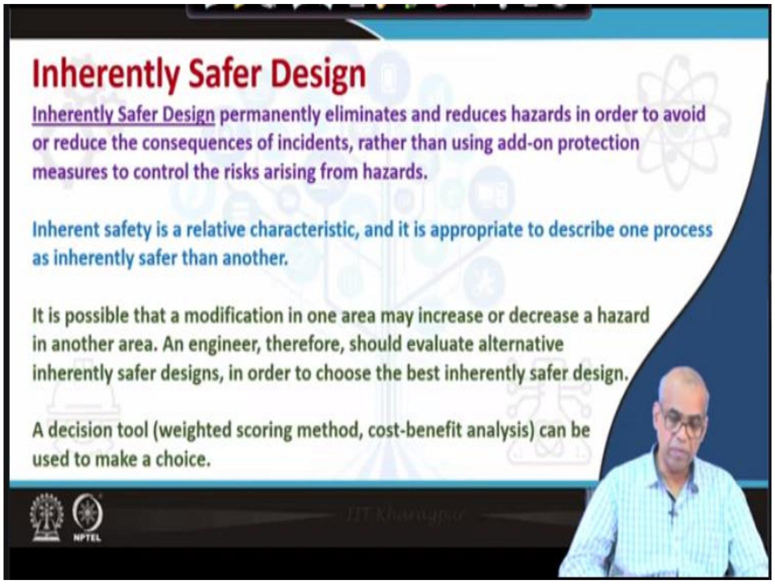

Inherently safer design permanently eliminates and reduces hazards in order to avoid or reduce the consequences of incidence rather than using add-on protection measures to control the risk arising from hazards. Inherent safety is the relative characteristic and it is appropriate to describe one process as inherently safer than another. It is possible that a modification in 1 area may increase the hazard in another area or it may also decrease hazard in another area.

So as the design engineer, we should evaluate alternative inherently safer designs and then only we should choose the best inherently safer design. So there is nothing like unique inherently safer design. Because a chemical process has several areas and different areas will be associated with different degrees of hazards, different hazards to different extent. So it is quite possible that modification in 1 area in order to reduce the hazards may actually increase hazard in another area.

So as a design engineer, we must evaluate various alternative inherently safer designs and then choose the best inherently safer design for the design case at hand. So, one can use decision tools to make an appropriate choice. Decision tool such as weighted scoring method, cost benefit analysis or even voting procedure can be used to make a choice.

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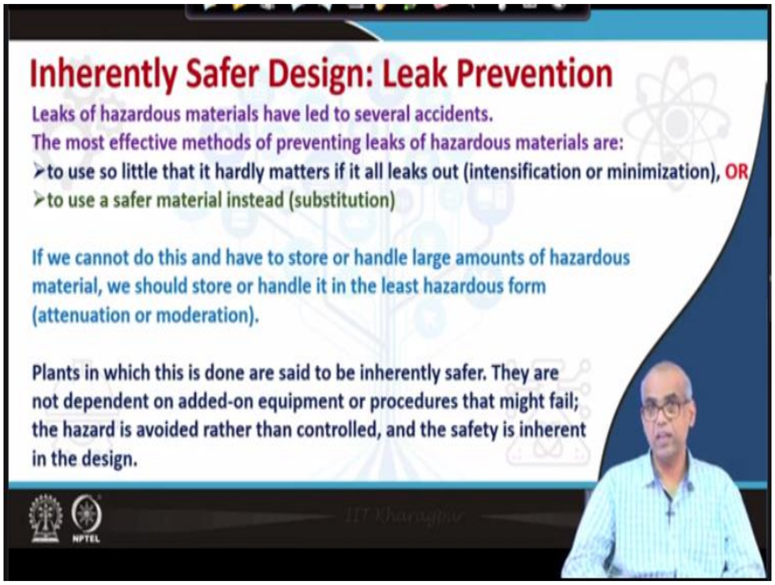

Now, let us try to understand the basics of inherently separate design by taking an example of leak prevention. Note that leaks of hazardous materials have led to several accidents. The most effective method of preventing leaks of hazardous materials are to use so little of the hazardous material that it will not matter at all if everything leaks out. Everything in the sense the if all the hazardous materials leaks out then also perhaps it will not cause a disaster.

This principle is known as intensification or minimization. That means that we are using the hazardous material to the minimum extent possible. Still better will be to use a safer material. So use a safer material or less hazardous material in place of hazardous material. This principle is known as substitution. Note that one of the greatest disaster in the history of chemical process industries happen in Bhopal.

So that also happened due to leak of gas, a deadly gas known as methyl isocyanade. We will talk more about it later when we talk about a case study. Now, it may not be possible for us, say to use a safer material or use so little that it will not matter if it leaks out. That means, we have to store and handle large amounts of hazardous material. Then we should store or handle the hazardous material in the least hazardous form.

This is known as moderation or attenuation. The plant which does this are said to be inherently safer plants because they are not dependent on the add-on equipment or procedures which might fail, but the hazard is avoided here instead of controlling the hazard. So the safety is inherently present in the design of the plant.

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Inherently safer design can actually lead to lower capital cost for the plant. It can also lead to lower operating cost, greater reliability and quicker start-up times. Plants with inherently safer technologies tend to be simpler, easier and friendlier to operate and more tolerant of errors. Because hazards are always avoided or significantly reduced, there is less need to add on protective equipment such as interlocks, alarms, emergency isolation valves, fire insulation, water sprays and similar protective equipment.

Then the plants become usually cheaper as well as safer. And this is what the industries have realized. The potential of inherently safer design and have started adopting it.

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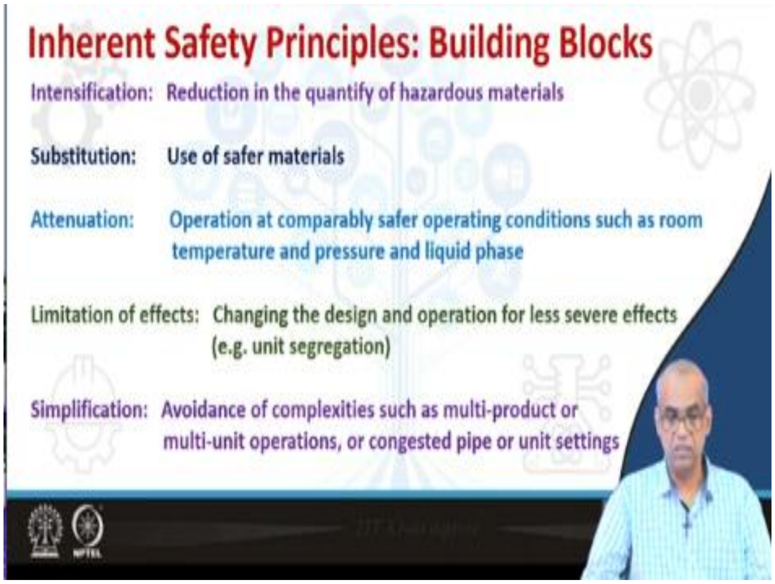

Now, apart from intensification, substitution, attenuation we have several principles that are used in inherently safer design. So, you can call them inherent safety principles or building blocks of the inherently safer design. For example, intensification means reduction in the quantity of hazardous materials, substitution means use of separate materials. We show these when we talk about leak prevention example.

Attenuation operation at comparably safer operating conditions such as room temperature, pressure and liquid phase. Limitation of effects: changing the design and operation for less severe effects. Simplification will mean avoidance of complexities such as multi-product or multi-unit operations or congestive pipe or unit settings. Note that simple processes are generally safer processes. They are more friendlier processes.

So simplicity in the plant design enhances inherent safety in the design. So apart from these inherent safety principles or building blocks, there are other building blocks as well.

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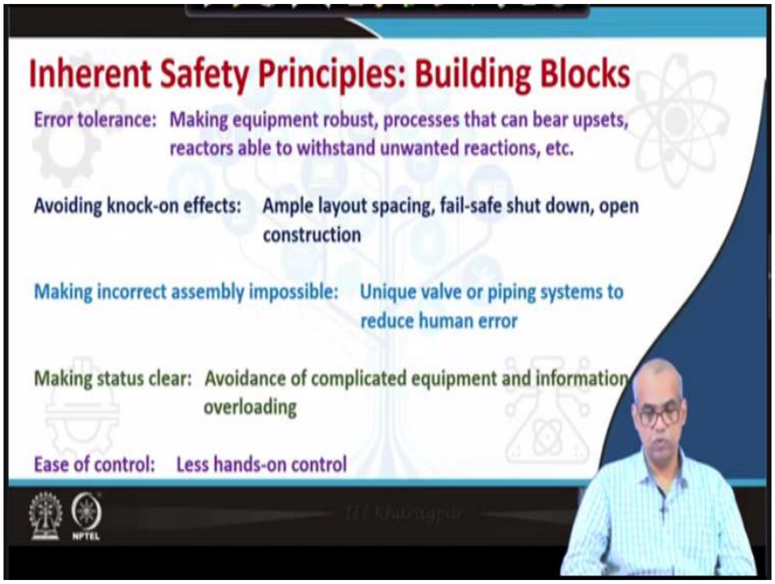

For example error tolerance, avoiding knock-on effects like fail-safe-shutdown, open construction so more layout spacing. Making incorrect assembly impossible by unique valve or piping systems to reduce human error. Ease of control, so that you need less hands on control.

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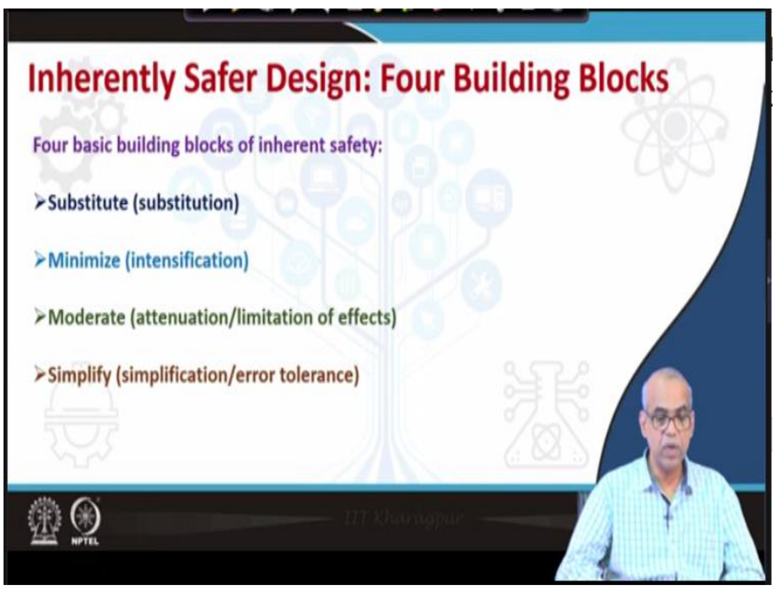

Now among these various inherent safety principles 4 building blocks are very, very important. Those four basic building blocks of inherent safety are substitution, intensification, attenuation or moderation and simplification. And we can also consider that this is the hierarchy in which we should approach inherently safer design. For example, we should look at the principle of substitution first, then intensification, then moderation and then simplification.

So these 4 building blocks are the most important building blocks or inherent safety principles towards inherently safer design of a plant; substitution, intensification, attenuation or moderation, and then simplification.

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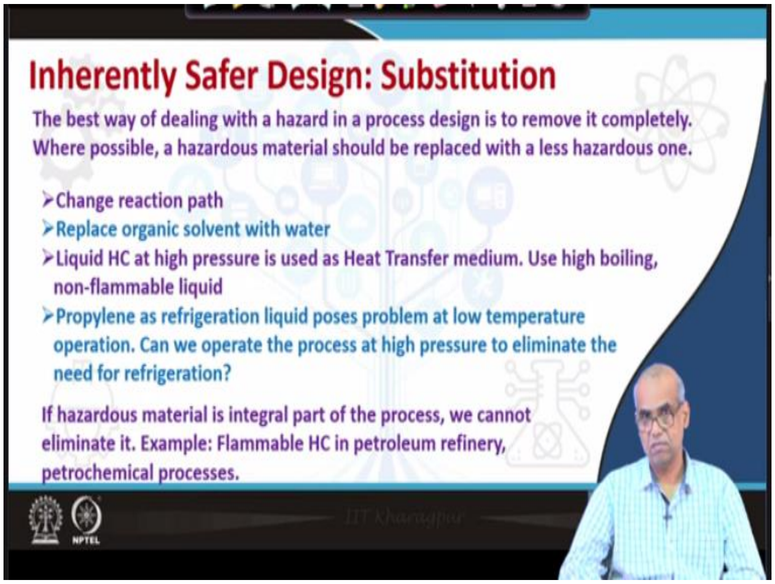

Let us now look at these 4 building blocks in some details. The best way of billing with the hazard in a process design is to remove it completely. So wherever possible a hazardous material should be replaced with a less hazardous material. So you will notice that such principles are very common principles often times, it is common sense principles. But even then it has taken a very long period of time and also several disasters in chemical process industries to actually implement these in designs.

So here are some examples of principles of substitutions in design. Change reaction path. So if, your process involves a hazardous material, maybe as an intermediate, think of a different reaction path or different chemistry and avoid the use of hazardous material. If possible replace organic solvents with water; water is a much safer solvent. Oftentimes liquid hydrocarbons are used at high pressure as heat transfer medium. Hydrocarbons are flammable.

To enhance safety use high boiling liquid, even better use non-flammable liquid. Propylene is used as refrigeration liquid for some low temperature operations. And use of propylene is a hazard. Let us ask ourselves, can we operate the process at high pressure so that we can eliminate the need for refrigeration or the operation at high pressure allows us to use a different less hazardous refrigeration liquid.

Please note that it may not always be possible to eliminate the hazardous material, particularly when it is an integral part of the process. For example, flammable hydrocarbon and petroleum refinery or in petrochemical processes, you will not be able to eliminate such flammable hydrocarbons where they are integral part of the process.

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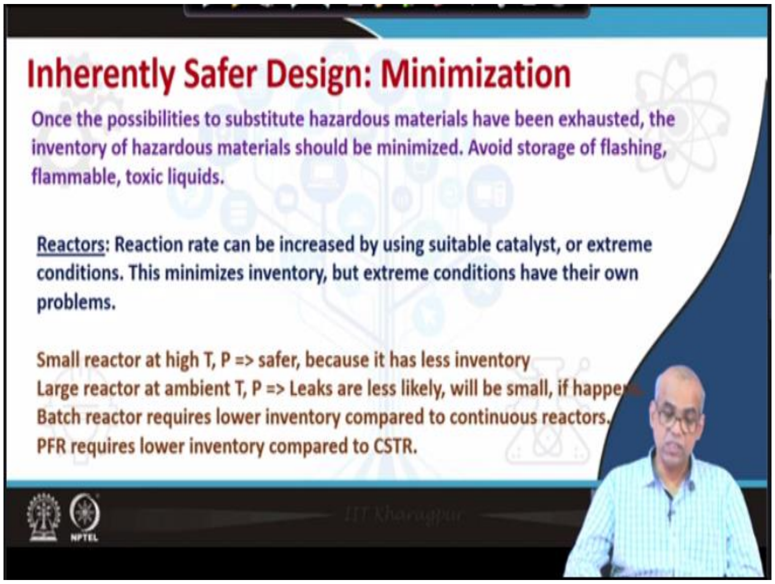

After we have followed the principle of substitution will go to the next principle according to the hierarchy which is minimization or intensification. Once the possibilities to substitute hazardous materials have been exhausted, the inventory of hazardous materials should be minimized. So if we must use hazardous material because substitution was not possible, we must minimize the inventory of hazardous material. Particularly the inventory of flashing, flammable and toxic liquids should be as minimum as possible.

Let us now look at the application of this minimization principle in say chemical reactors, distillation columns etcetera. We know that the reaction rate can be increased by using a suitable catalyst. Reaction rate can also be increased by using extreme conditions. When the reaction rate is increased, it will lead to minimization of inventory because they are able to process more. So if you are using extreme conditions to increase reaction rate that will definitely minimize inventory.

But extreme conditions will bring in their own problems. So the designer engineer must judge both the options carefully and then take the appropriate decision. If a small scale reactor is operating at high temperature and high pressure, it is inherently safer because it has lower amount of inventory compared to a large scale reactor operating at ambient temperature and pressure. Note that the large scale reactor will have more amount of inventory, more amount of hazardous material.

So small scale reactor operating at high temperature and pressure is inherently safer compared to large scale reactor operating at ambient temperature and pressure. But large scale reactor operating at ambient temperature and pressure is safer for different reasons. For example, the leaks are less likely in a large reactor operating at high, lower temperature or ambient temperature and pressure. And even if leak happens, the leak will be small because of low pressure.

Also it is operating at lower temperature, so the formation of the vapour will also be low. If I compare a batch reactor and a continuous reactor, the batch reactor requires lower inventory compared to continuous reactors. Plug flow reactors requires lower inventory compared to CSTR. Note that for the same conversion, the PFR volume is less than CSTR usually.

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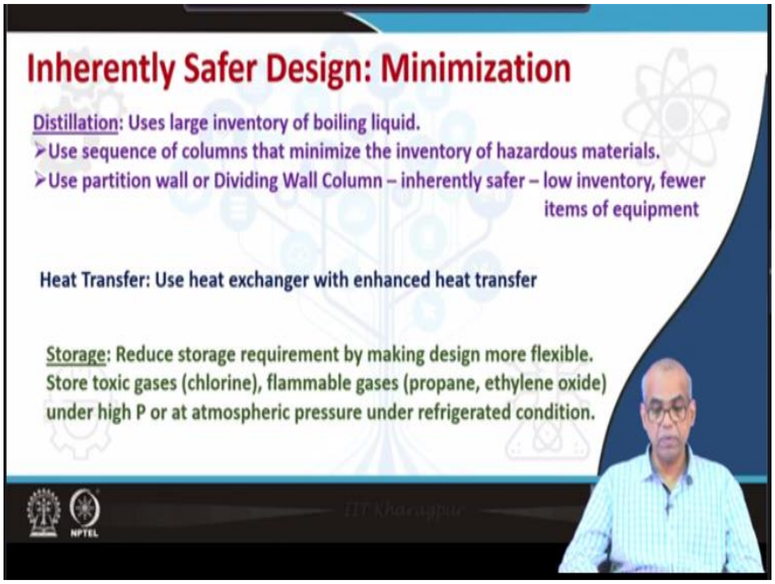

Distillation column uses large inventory or boiling liquids. So when you are using a sequence of distillation columns to perform the separation of multi component mixtures, let us use sequence of columns that minimize the inventory of hazardous materials. So these objectives can be included in the design of distillation sequence. We can use partition wall or dividing wall column.

Dividing wall column is inherently safer compared to ordinary distillation columns because it has lower inventory and not only that it is a case of, it is an example of process intensification. So when if you are using dividing wall column you can perform, say the role of 2 distillation columns or 2 ordinary distillation columns by using a single dividing wall column. So we are using fewer items of equipment.

When you are using fewer items as equipment, there are chances of leakage less. So safety factor increases. In case of heat transfer operations, use heat exchanger with enhance heat transfer that will reduce inventory. We must reduce storage requirement by making design more flexible. Store toxic gases such as chlorine, flammable gases such as; propane, ethylene oxide under high pressure or at atmospheric pressure under refrigerated condition. That leads to enhanced safety.

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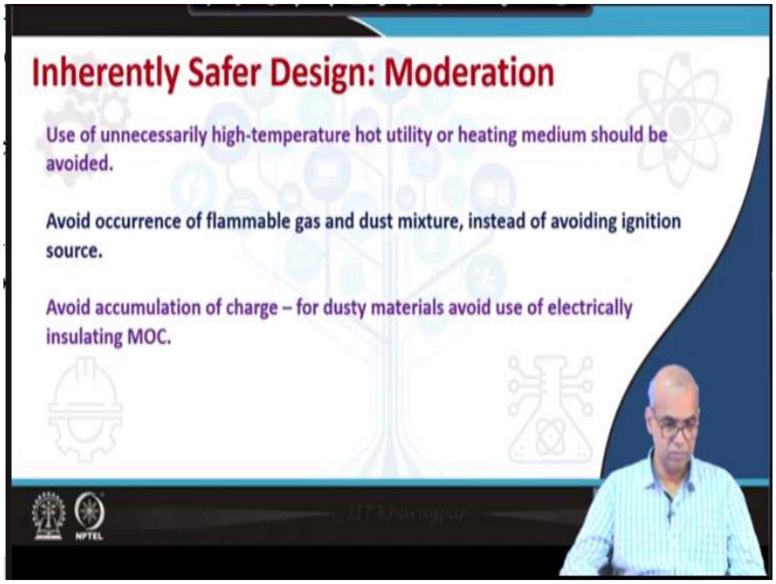

Next principle in the hierarchies moderation or attenuation. Use of unnecessarily high temperature hot utility or heating medium should be avoided. Avoid occurrence of flammable gas and dust mixture instead of avoiding ignition sources. There are large numbers of ignition sources, so you should more rely on avoiding occurrence of flammable gas and dust mixtures. Avoid accumulation of charge.

For dusty materials we should avoid use of electrically insulating material of construction because such material of constructions will allow accumulation of charge.

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Finally, the last principle is simplification. Simpler processes are always safer. For processes containing hazardous material, let us minimize the following to minimize leaks. Number of equipment items, pipe lengths, pipe joints and use of intrusive instruments, we should use non-intrusive instruments, non-contacting instruments, non-intrusive instruments. So such points will lead to minimization of leaks and will lead to safer process.

Consider a pressure relief system which is required for say pressure results. Pressure relief systems are expensive and also bring considerable environmental problem. Now if it is possible replace the pressure relief system by using thick walled pressure vessel. It can be even an economic option. Both are safer and economic option. So you must judge that.

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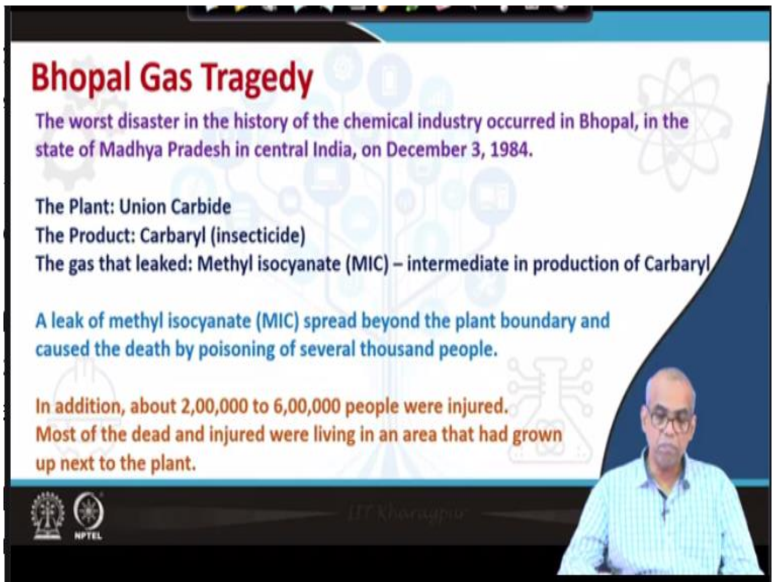

Now we will take a case study and I will take the example of Bhopal gas strategy. The worst disaster in the history of chemical process industries occurred, unfortunately in our own country in Bhopal in the state of Central India on December 3, 1984. It was a plant by Union Carbide. The product was an insecticide named carbaryl and the gas that leaked from union carbide's plant was methyl isocyanate.

Methyl isocyanate was not the product, the product was the insecticide Carbaryl. Methyl isocyanate, a deadly gas was an intermediate in the production of carbaryl. A leak of methyl isocyanate spread beyond the plant boundary and cause the death by poisoning of several thousand people. Some reports say that the numbers was as high as 25,000 people. In addition about 2,00,000 to 6,00,000 people were injured, most of the dead and injured were living in an area that had grown up next to the plant.

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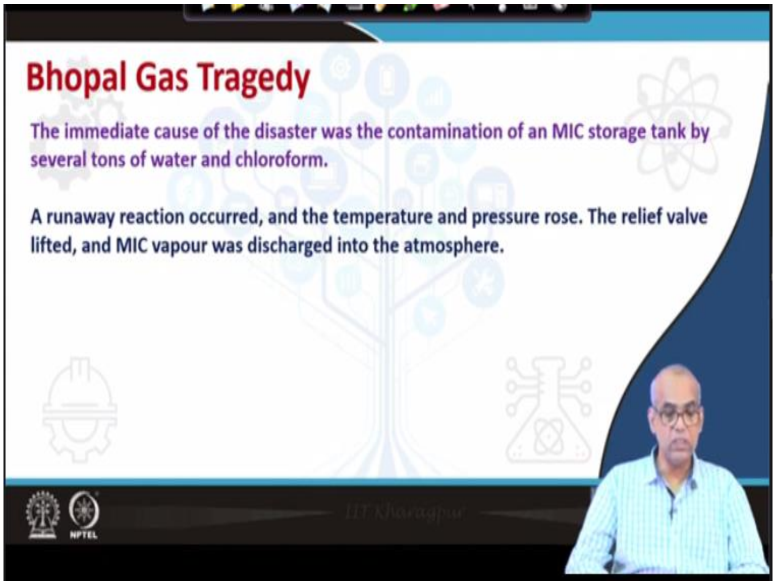

The immediate cause of the disaster was the contamination of an methyl isocyanate storage tank by several tons of water and chloroform. A runaway reaction occurred and the temperature and pressure rose. They rose to very high extent. The relief valve lifted and the methyl isocyanate vapour was discharged into the atmosphere. Unfortunately, the protective equipments were either absent or was not in full working order.

The consequences of the accident could have been much less serious if less methyl isocyanate had been stored, if the temporary dwellings had not grown up close to the plant and if the protective equipment had been kept in full working order. Now, let us see how this protective working order fails, what went wrong with those.

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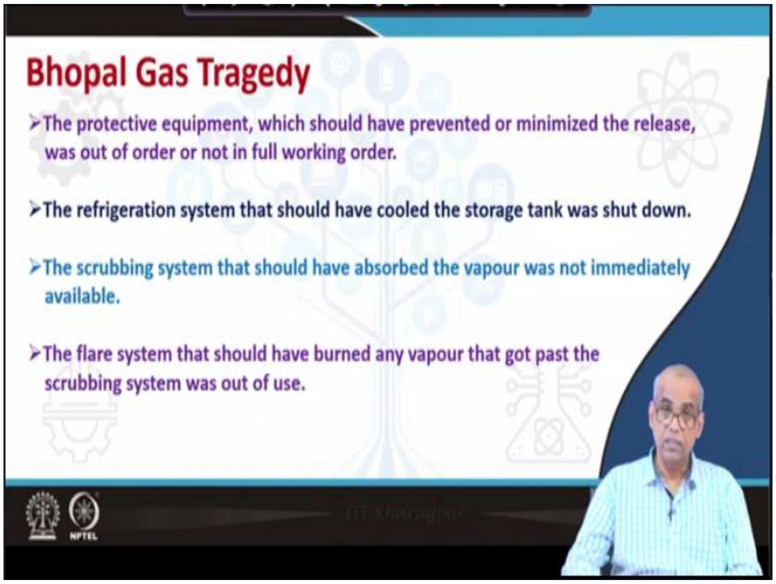

The protective equipment which should have prevented or minimized the release or methyl isocyanate was out of order or not in full working order. The refrigeration system that should have cooled the storage tank was shut down. A serious lapse of safety measure. The scrubbing system that should have absorbed the vapour was not immediately available. Another lapse of safety measure.

The flare system that should have burned away vapour that got past the scrubbing system was out of use. So this is another major lapse of safety measure.

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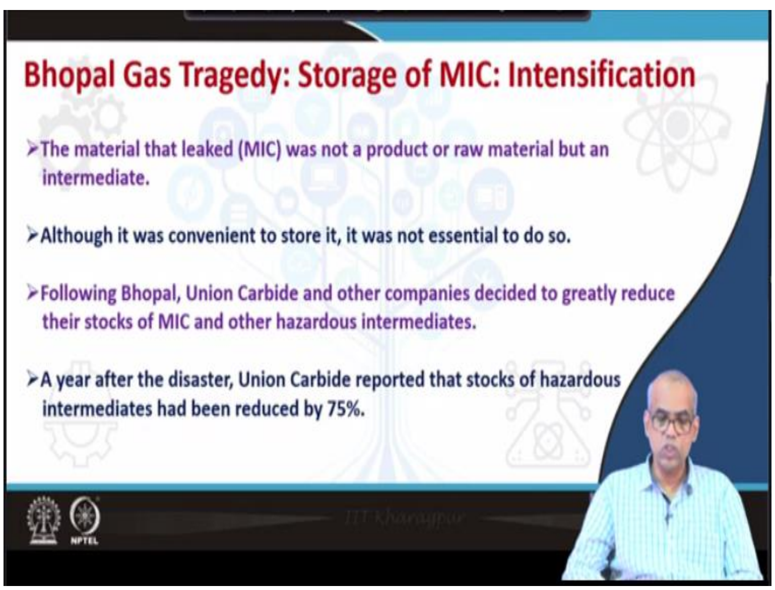

Now, let us see how these principles of inherently safer design could have been adopted. First, let us look at intensification. The material that leaked, methyl isocyanate, was not a product or a raw material, but an intermediate although it was convenient to store it, but it was not essential to store it. Following the Bhopal disaster, Union Carbide and other companies decided to greatly reduce their stock of methyl isocyanate and other hazardous intermediates.

A year after the disaster, Union Carbide reported that stocks of hazardous intermediates had been reduced by 75%. So it was actually not necessary to store huge amount of methyl isocyanate. So the principle of intensification was not followed.

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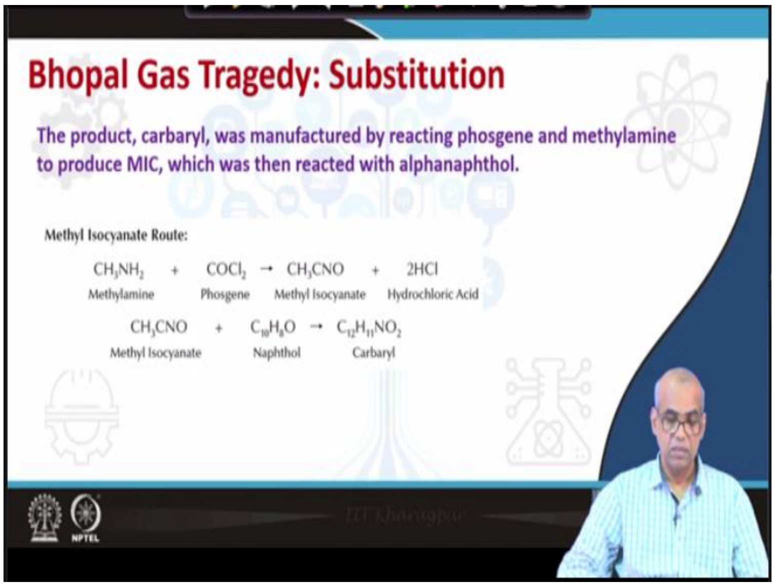

Substitution; the product carbaryl which is an insecticide was manufactured by reacting phosgene and methylamine. So, methylamine and phosgene were reacted to produce methyl isocyanate and hydrochloric acid. Methyl isocyanate is the intermediate which is a deadly gas. So methyl isocyanate was reacted in the next step with alpha naphthol to produce the product carbaryl which is used as insecticide.

Now, this is the route which uses methyl isocyanate and this was followed there in the plant of union carbide at Bhopal. Now using the principle of substitution, we could have thought about another reaction path where methyl isocyanate was absent.

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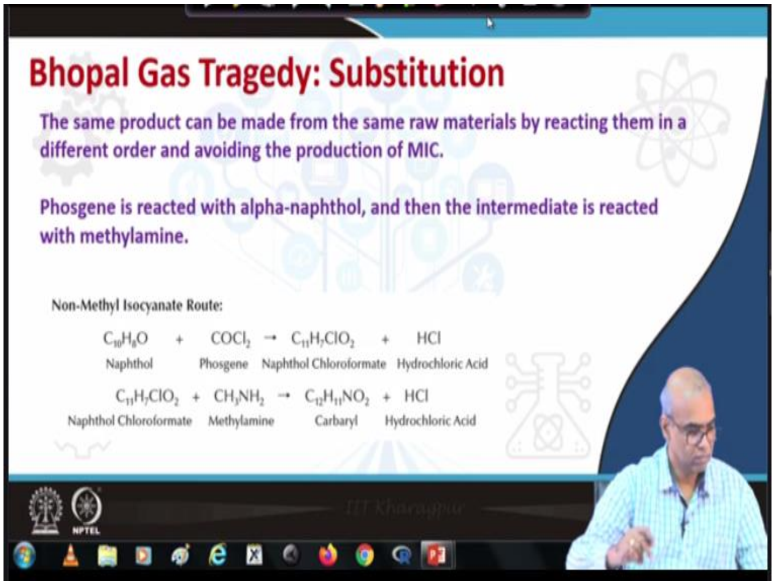

So non-methyl isocyanate route. The same product carbaryl can be made from the same raw materials, phosgene and methylamine. By reacting them in a different order. And thereby avoiding the production of methyl isocyanate, how? So this is the non-methyl, non-methyl isocyanate route. So in this case phosgene is first reacted with alpha-naphthol. Look at the reaction is now being carried out in a different order.

So, phosgene is first reacted with to produce naphthol chloroformate and hydrochloric acid. This naphthol chloroformate is the intermediate which is unless dangerous intermediate compared to methyl isocyanate. In the second step naphthol chloroformate is reacted with methylamine to produce the product carbaryl. So this principle of substitution was followed. The production of methyl isocyanate could have been avoided completely.

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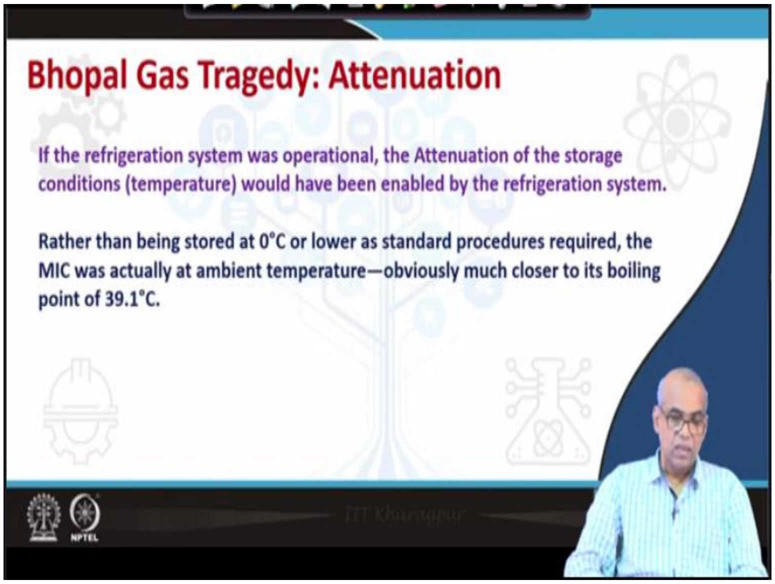

Next attenuation or moderation: If the refrigeration system was operational, the attenuation or moderation of the storage conditions that means the temperature of the storage tank would have been enabled by the refrigeration system. Note that it is a standard procedure to store such liquid at 0 degree Celsius or even at lower temperature. But the methyl isocyanate was actually stored at ambient temperature. And the ambient temperature was much closer to its boiling point of 39.1 degree Celsius.

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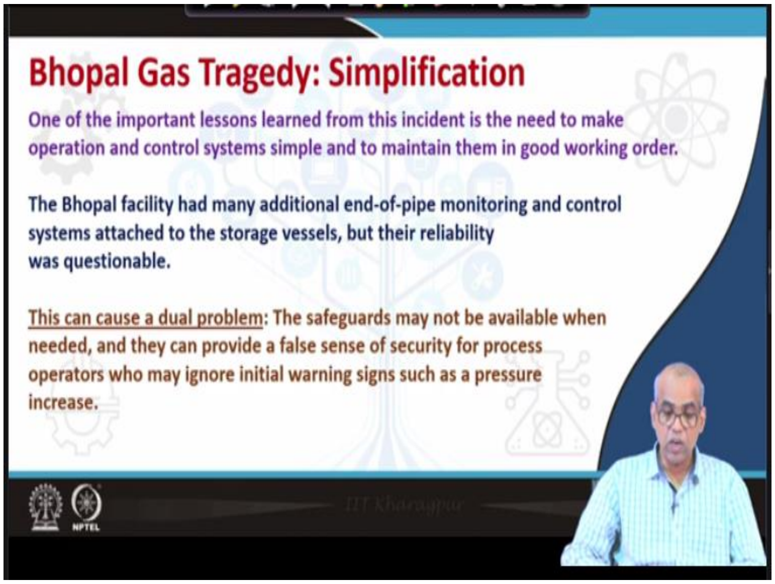

Next simplification: Let us look at the process of simplification and its relation with the Bhopal gas tragedy. One of the important relations learned from this incident is the need to make operations and control systems simple and to maintain them in good working order. The Bhopal facility had many additional end-of-pipe monitoring and control systems attached to the storage vessels.

But they are reliability was questionable. So this cause a dual problem. The safeguards may not be available when needed that means it actually does not give you required safety when it is actually needed. And this also provides a false sense of security for process operators. So there are several monitoring and controlling system attached to the storage vessel but their reliability is under doubt, their reliability is questionable.

So the safeguard is not available when it is required, number one and second the operators gets a false sense of security, that ok, we are secured but actually not. And in that case, the operators will tend to ignore the initial warning signs such as pressure increase. So simplification is necessary for the inherently safer design.

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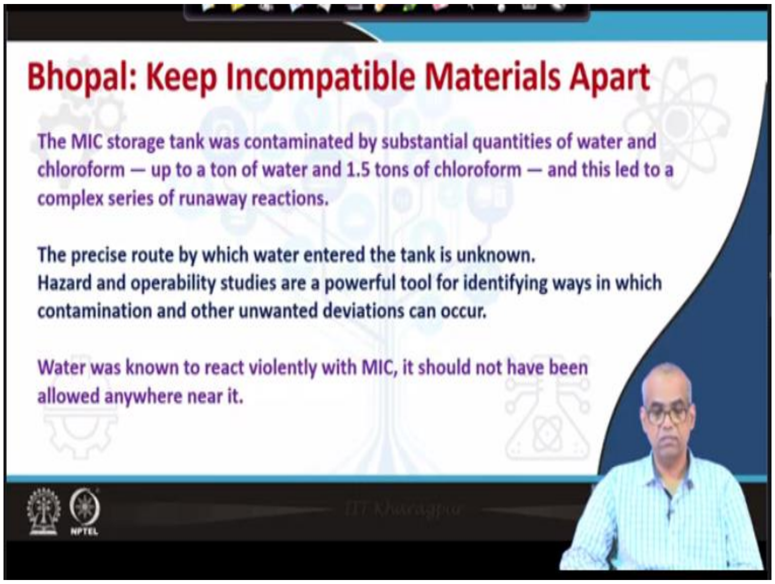

We should keep incompatible material apart. The methyl isocyanate storage tank was contaminated by substantial quantities of water and chloroform. It is estimated that a ton of water and one and half ton of chloroform was mixed with methyl isocyanate storage tank. And this led to a complex series of runaway reaction. The precise route by which water entered the tank is unknown.

Hazard and operability studies are a powerful tool for identifying ways in which contamination and other unwanted deviations can occur. It is known that water reacts violently with methyl isocyanate. So water should not have been allowed anywhere near the methyl isocyanate storage tank. The hazard and operability studies would have revealed that clearly to the workers and the management.

So we see that a series of safety measure was complete either was lacking or there was laps. There was complete either there was complete laps or such safety measures were not in full force. And that caused a disaster of this extent which is certainly the largest disaster that has ever happened in any in chemical process industries anywhere in the globe. This particular Bhopal gas strategy has forced us to take safety very religiously in chemical process industries day to day operations.

And also we should all adapt to the extent possible inherently safer design to avoid repetition of any such disaster. With this we stop our discussion here.