Indian Institute of Technology Madras
Present

NPTEL
NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

NUCLEAR REACTOR AND SAFETY
AN INTRODUCTORY COURSE
Module 03 Lecture 02
Reactors Generations

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Good morning, students.

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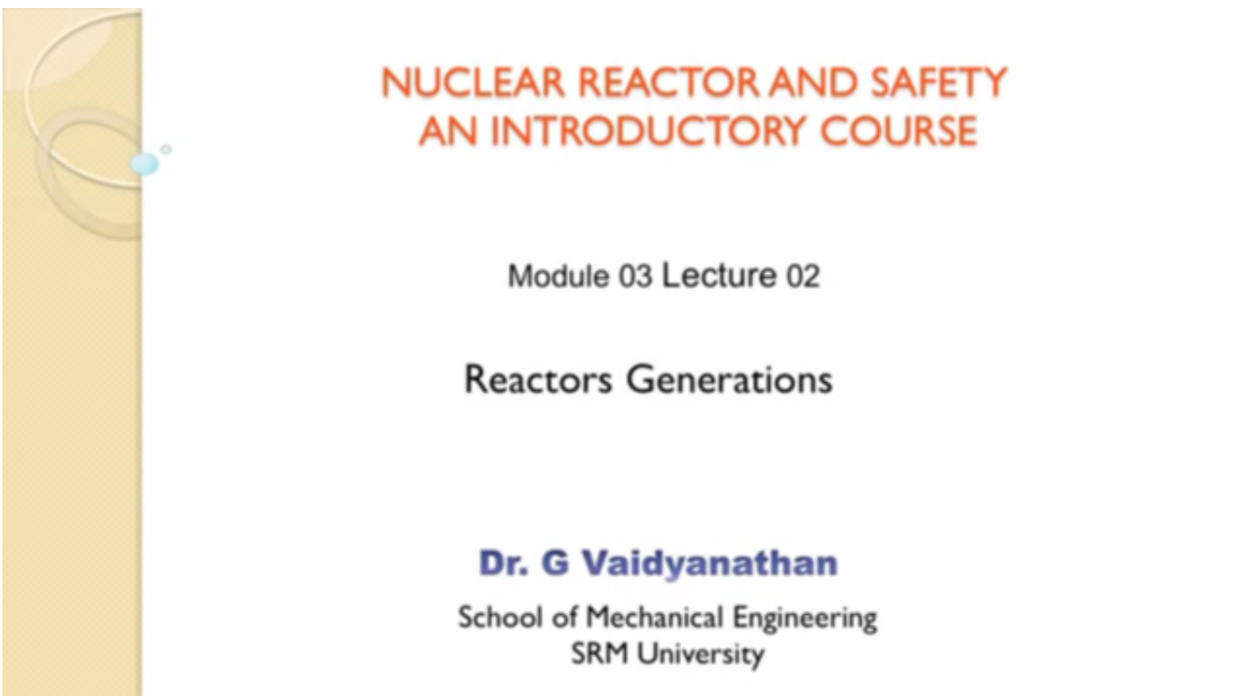

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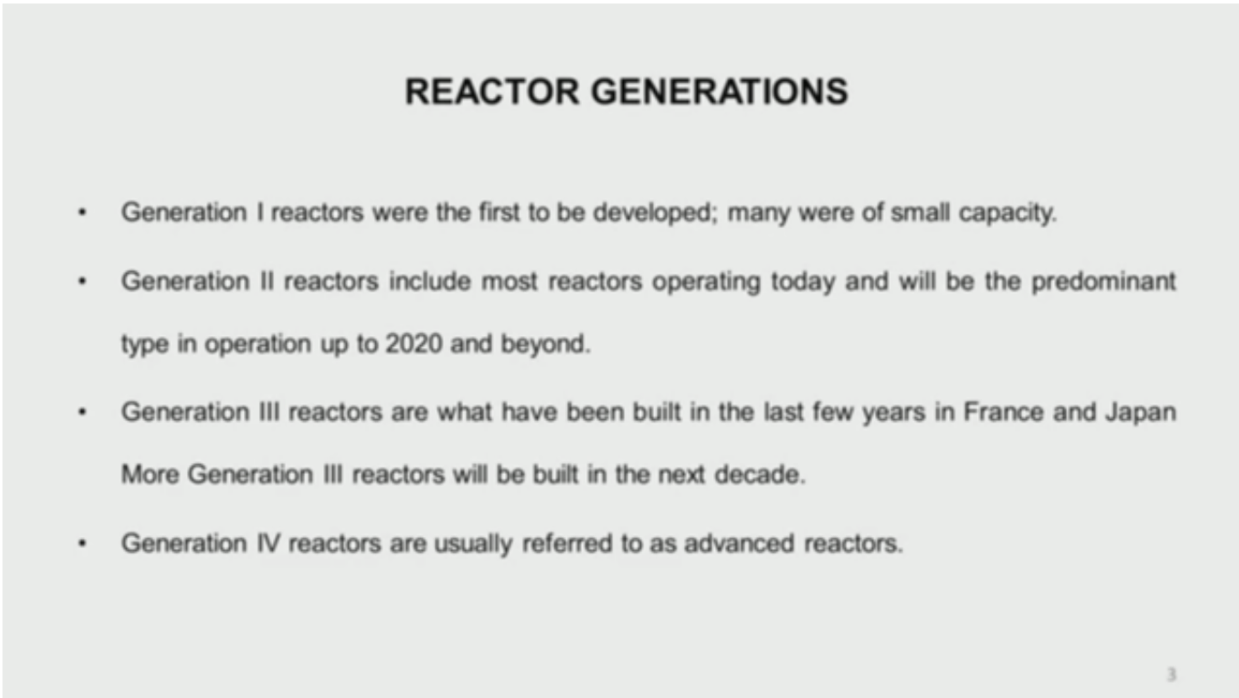

Last lecture we had a look at the first reactor in the world, the Chicago pile, which is made by Fermi and his colleagues in Chicago. Then we had a look at the constituents of a nuclear reactor. We look -- it has -- should have a core. It -- whether it needs a moderator, then the control rods, then you had the reactor vessel and so on. We also had a look at the different types of reactors: the pressurized water reactor, the boiling water reactor, the fast reactor, sodium cooled fast reactors, the gas cooled reactors, which are not now present in big numbers.

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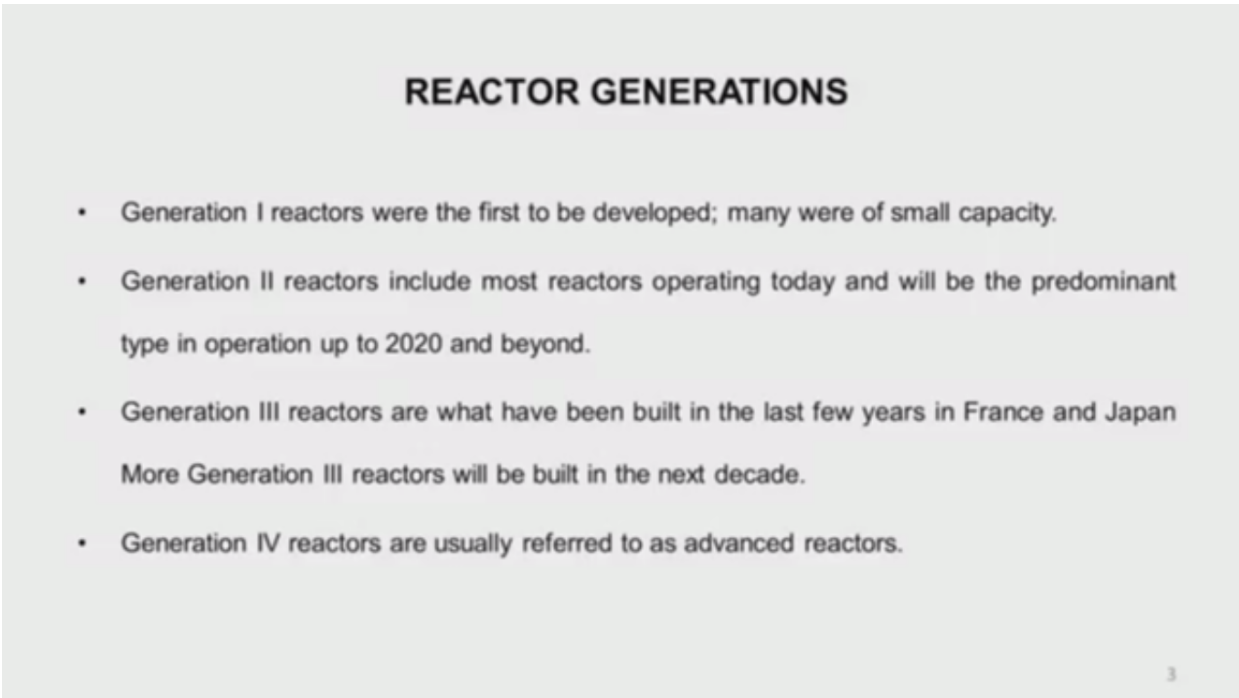

But then just as we call different generations, even these reactors have now been tagged with generation numbers. Luckily, the generations are not very many. The Generation I reactors were those reactors which are developed in the very initial days like maybe the Chicago pile, the shipping port reactor in the USA and some of the initial reactors -- test reactors in the different countries.

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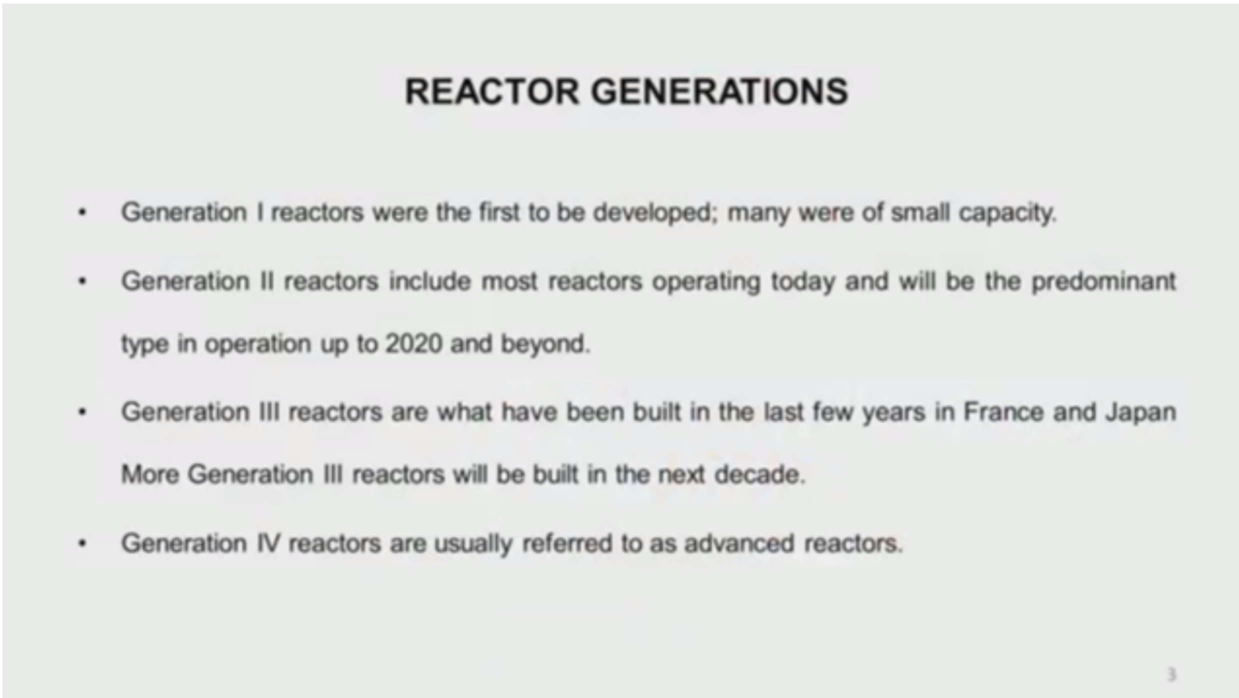

Then came the Generation II reactors: the PWR, the BWR, which are mostly in operation.

Then the Generation III reactors with some advanced features over the Generation II reactors have been built in France and Japan. Still many are going to be built in the next decade, but now all the countries have felt that there is a very imperative need to consolidate the efforts of the research towards particular designs instead of focusing on many, many, many designs, which have been reported, why not to come to particular designs and then do more research on them, so it economics also would be nice, you know, people could contribute to the same.

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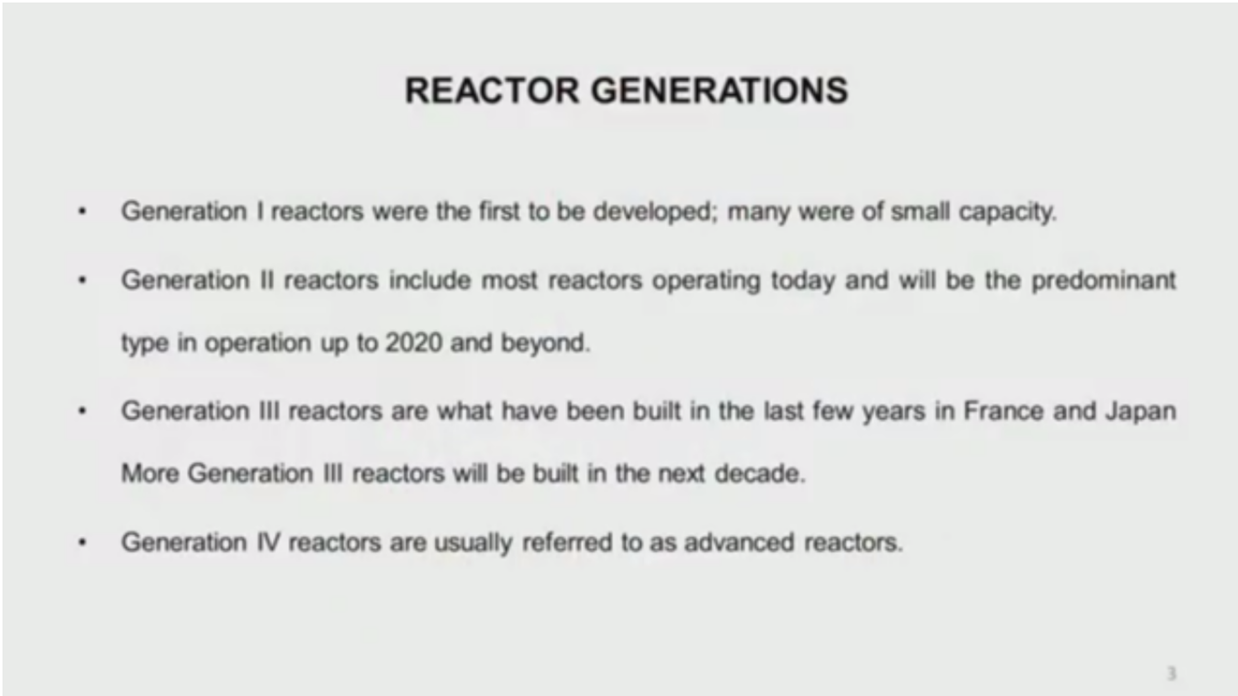

So that is called as the Generation IV reactor, which also called the Gen IV and is having different member countries in this Gen IV reactor forum.

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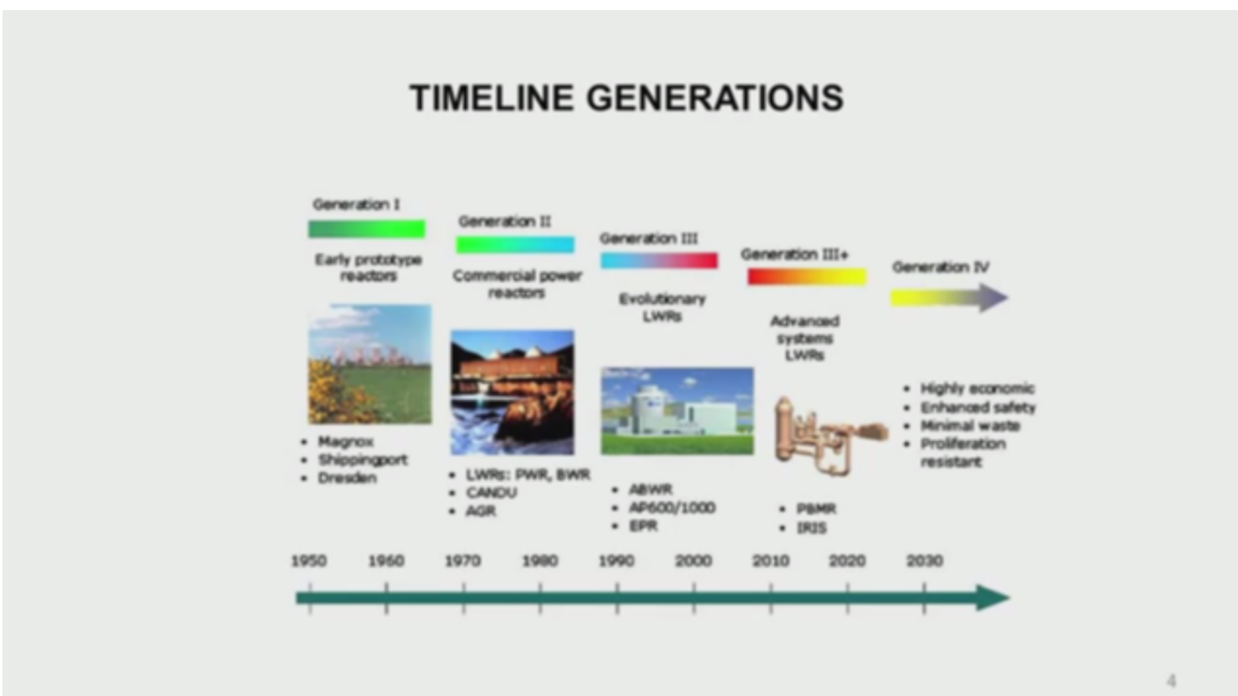

Pictorially, I was showing you the different generations. Generation I as I mentioned include the gas cooled Magnox reactors, the advanced gas cooled reactors, then the shipping port reactor, which is also a pressurized water reactor. Then the Dresden reactor is a boiling water reactor. Then you see in the beyond the 60s, you had the Generation II, most of them pressurized water reactors and boiling water reactors. These two are generally also called as Light Water reactors because they use light water, ordinary water as the coolant and the moderator.

Of course, then comes the CANDU reactor or the heavy water reactors. As I mentioned in my last lecture, heavy water reactors are cooled by heavy water and moderated by heavy water. Main advantage of heavy water is you can use natural Uranium with heavy water, but if you want to use light -- light water, you have to go with enriched Uranium.

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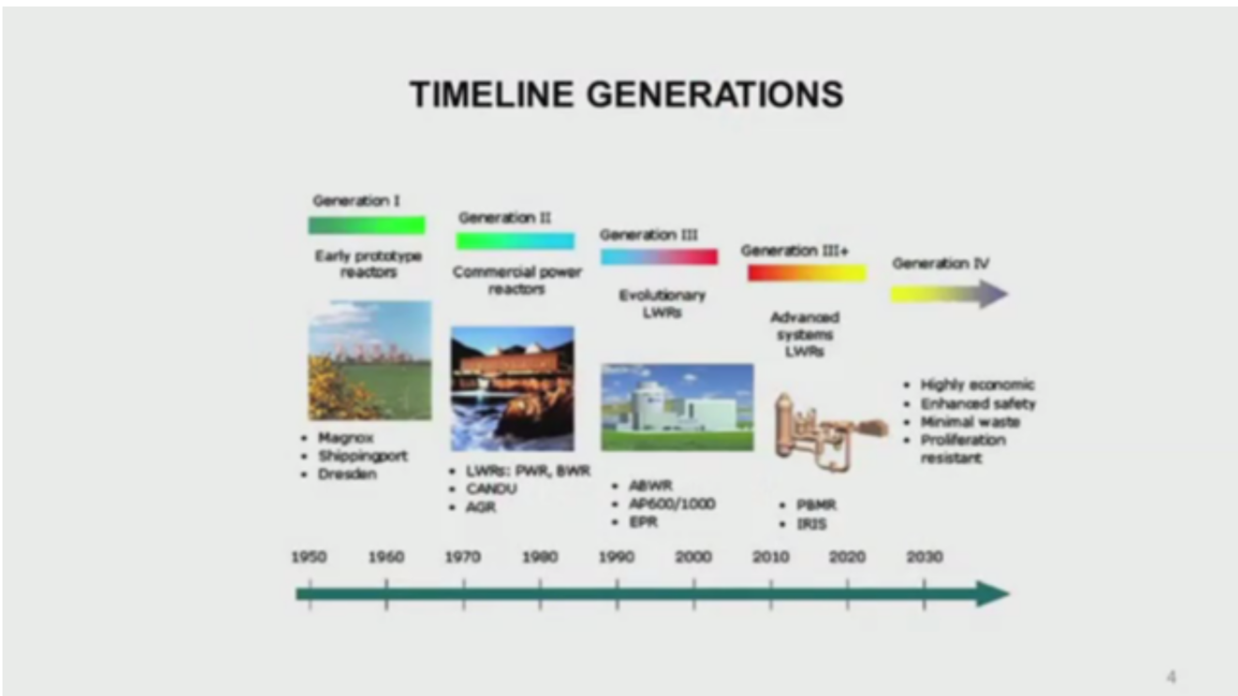

Then the advanced gas cooled reactors, which were improvement over the Magnox reactors. Then there have been some evolutionary designs which have called as the Generation III which took place in the 1990s, the advanced port reactor. Then the AP600 and 1000 reactor designs and of course the European pressurized reactor, which is again was a evolutionary design. It is supposed to be about 1600 megawatt electrical and one of them is under construction in Europe.

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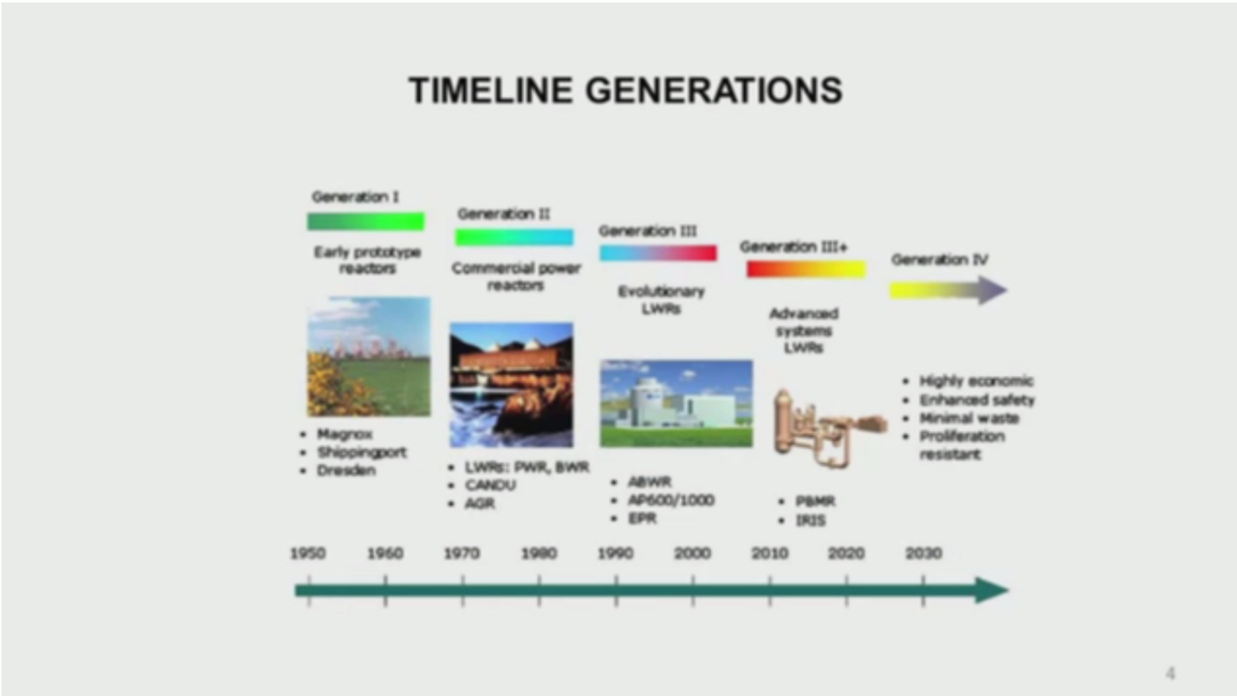

Then, of course, here some more technology developments have taken place. So we have a sub-module Generation III plus. They've got the Pebble Bed, Pebble Bed Modular Reactor development in Africa and then IRIS is another type of reactor design, which has been developed and what is the focus of this Generation IV reactors? Main thing is economics, but enhance the safety. Of course, two objectives. Not that safety is not costly, but safety need not be made excessively costly.

Then what else? You must have minimum waste production. That is another requirement of this Gen IV. Then this proliferation. You always hear about this word proliferation. We have talked about oh, proliferation of nuclear weapons, proliferation. What is proliferation? The fear is that some of the radioactive material or Plutonium could be taken out and people could make bombs with that. So proliferation of nuclear weapons is one which is not desired so that it should be proliferation resistant. So the how the -- how you design?

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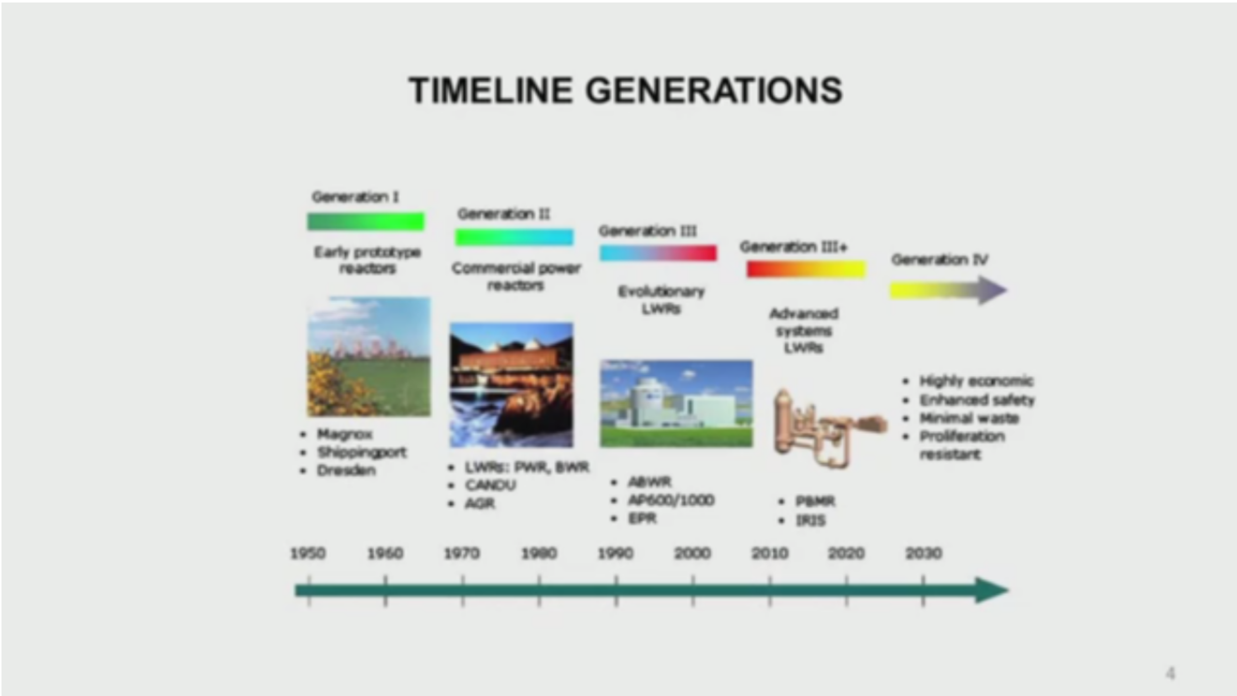

Then the main thing is how do you go with the proliferation resistance is not that you don't build reactors. Of course, you build reactors. You will generate Plutonium. But you see that there is minimal transport. Anything can happen when it is getting transported from one place to another. So this Generation IV reactors aim at a site in which you have the reactor, you have the reprocessing plant, you have the fuel fabrication plant, you have the waste treatment plant. The fabricated fuel again goes into the reactor, so it is in a single place. So that is one type of proliferation resistance.

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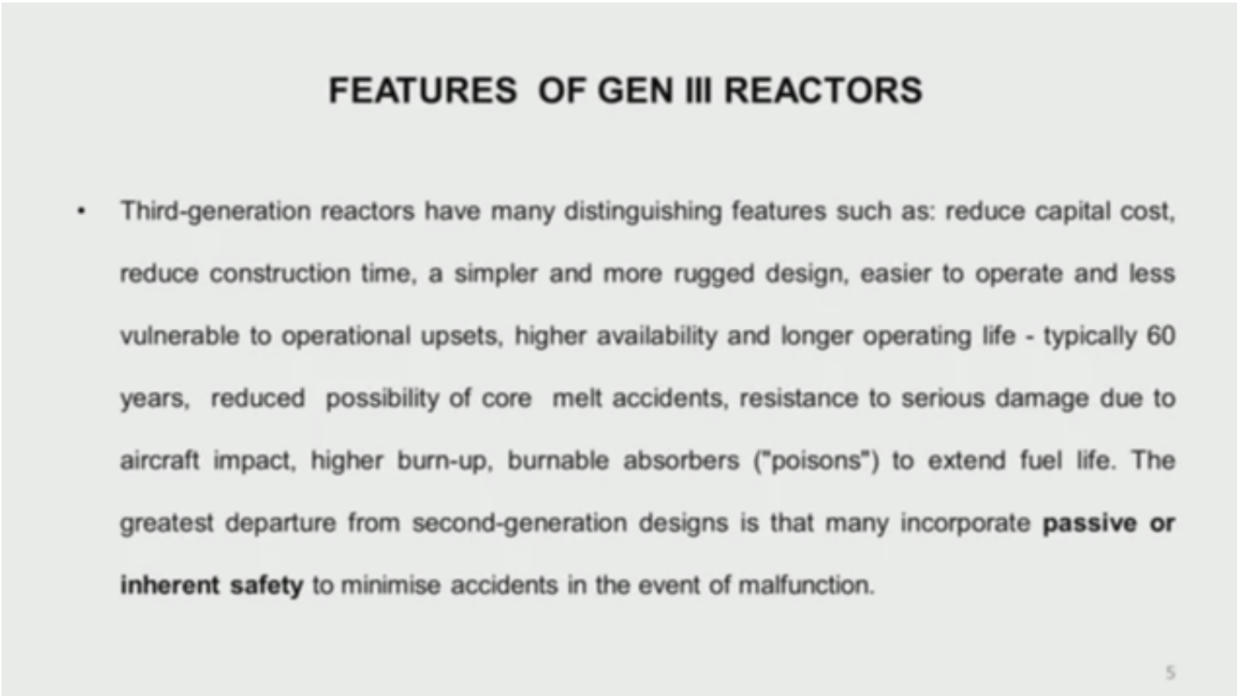

Now let us look at the Generation III reactors, which are mostly present today, the PWR, the BWR and the CANDU PHWRs. What are the main features of this third-generation? Again, to reduce capital cost has been one approach and reduce construction time. This construction time has a very important economic aspect. You might be aware that when you build a plant you take money from the consortium or the government.

In India the government makes the money and this money you have to pay interest. If suppose you build a reactor in about 10 or 15 years, it have to pay the interest on that amount, so that will surely reflect on your cost of the electrical power that you are going to generate. So what? So it has an impact on the interest during construction, normally called as IDC. So this IDC is a very important factor to be considered in the economics and that is the reason why we are looking for short construction times. Of course, not losing the quality in the construction, but still you take approaches such that the construction time is less. So this requires a very good planning. The procurement activity should be such so that the equipments arrive at the right time so that your construction time, erection time, everything is well matched.

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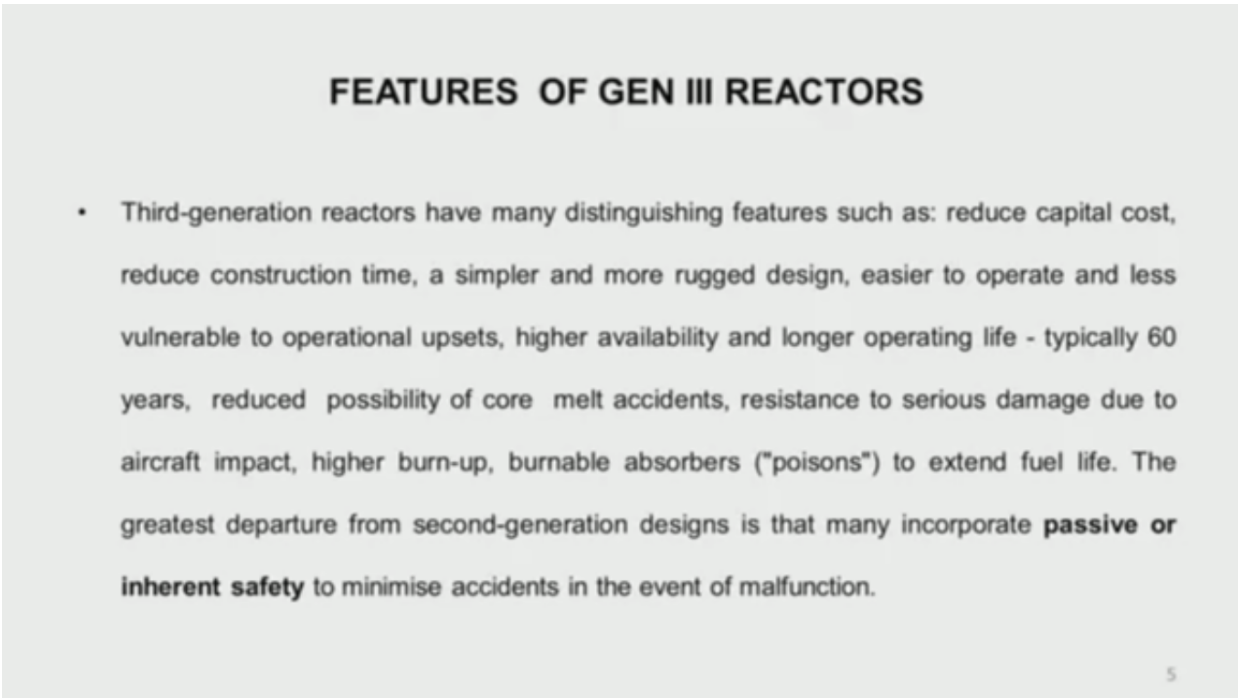

Then more rugged design. The rugged design means it should be able to withstand the effect of different events. Let us say we have a power failure, or a loss of coolant, or a leak. In all such conditions, it must be able first this should not happen. The event should not happen and should an event happen, they should be easily, you know, hand -- it can be easily handled. So the main thing is minimize the number of incidents so that they are not -- the design should be such that they are not vulnerable to such things and another thing is which we look forward is whether we can increase the life to a larger number of years.

Now if you look at the present reactors, we had operating history of about 30 to 40 years. Now during this period, we do have come about the effect of radiation on materials. So how it affects and the radiation does produce voids in the material and that can make the material weak. So there is need to develop new materials. All these things have taken place in the last two, three decades. So the idea is that if I can use materials which can have long life under irradiation atmosphere, whether I can use fuel again which has a longer life like that all these aspects we should -- we are bringing in into the designs. So the present designs with these improved features is still going on.

Then other things we talk about -- we talked about internal events like pump trip etc. There could be external events like a bomb or an aircraft crash. So all these things do have an impact on the safety. So, basically, the present directions in the Generation III reactors has been to improve all these factors and they already have some sort of passive features, or inherent, or intrinsic safety features to minimize the accidents, which can happen due to malfunction. Now what is this passive or inherent safety? This requires a bit of clarification.

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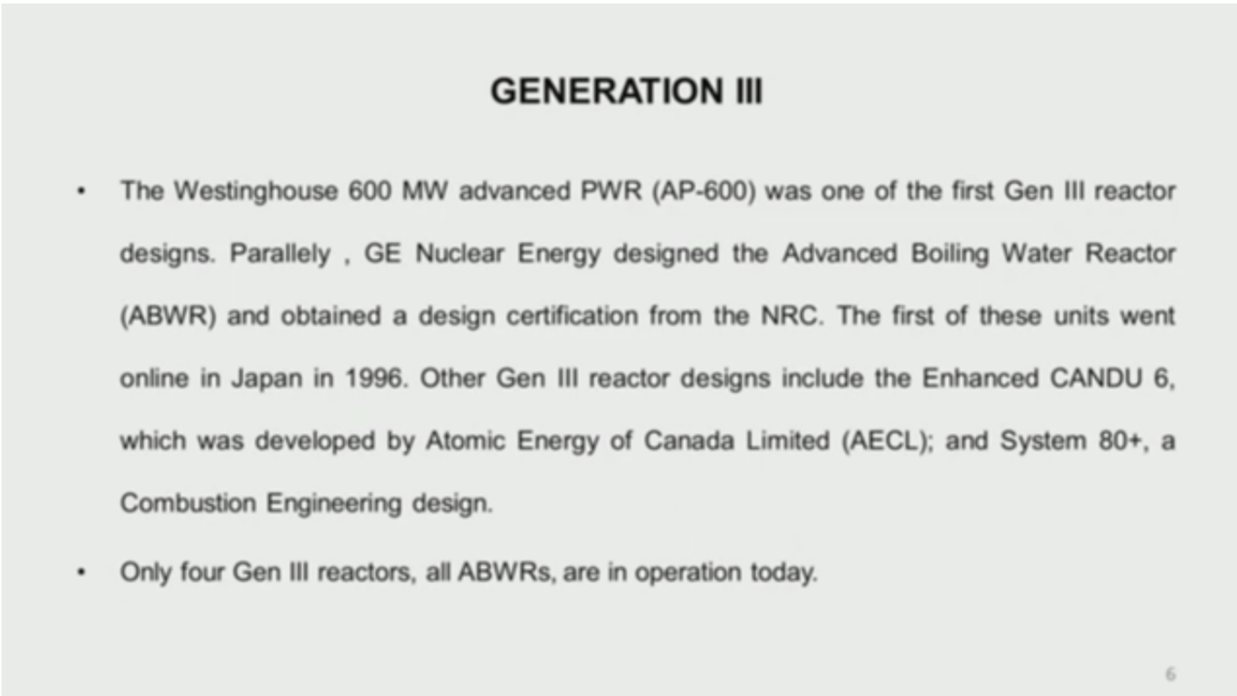

Now examples of the Generation III, the Westinghouse not Generation III to Generation III plus the Westinghouse AP-600 600 megawatts, then the advanced boiling water reactor by General Electric. General Electric and Westinghouse are the big companies in USA. Then the EPR, EPR is by the French Areva. So they are supplying and you might recall that the Jaitapur reactor is basically a European pressurized reactor and to be supplied by Areva. That was -- is proposed to be built in the -- in Maharashtra. Jaitapur is in Maharashtra.

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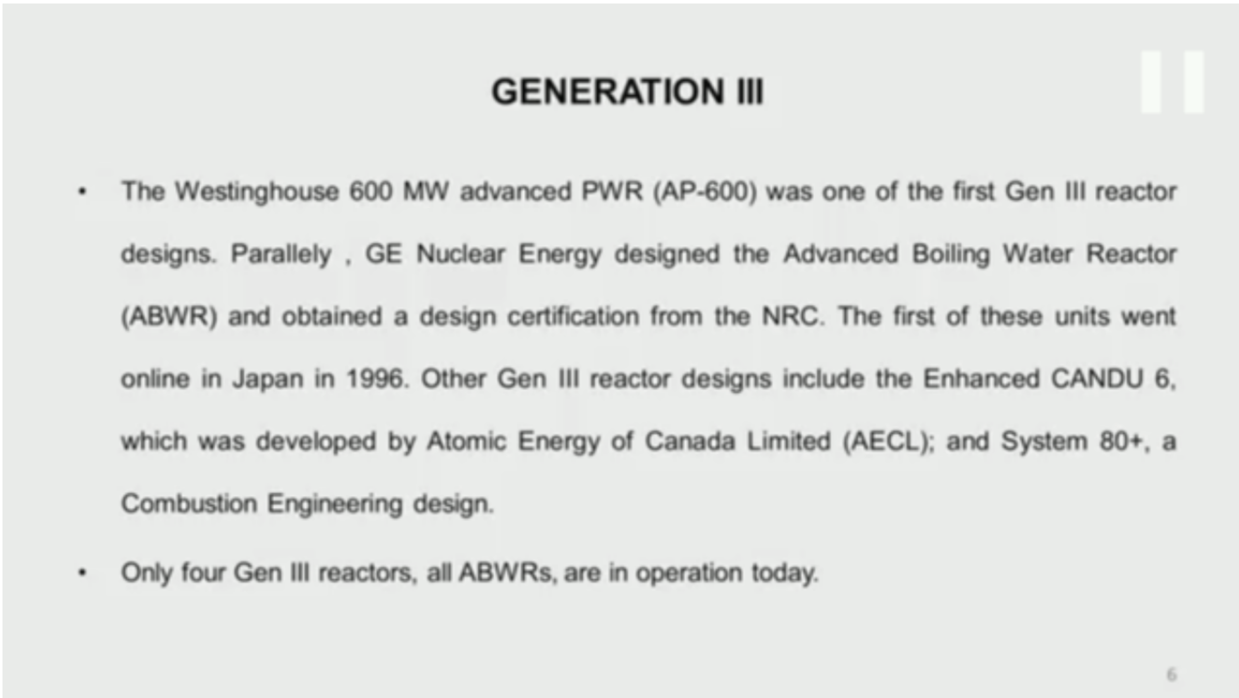

Now the CANDU group or the Canadian Atomic Energy of Canada Limited, they have developed another reactor design, CANDU 6. This is also having a good number of features. Then, but out of all this ABWR is in now operation today mostly in Japan there is a -- so that is what is the status of the Generation III plus.

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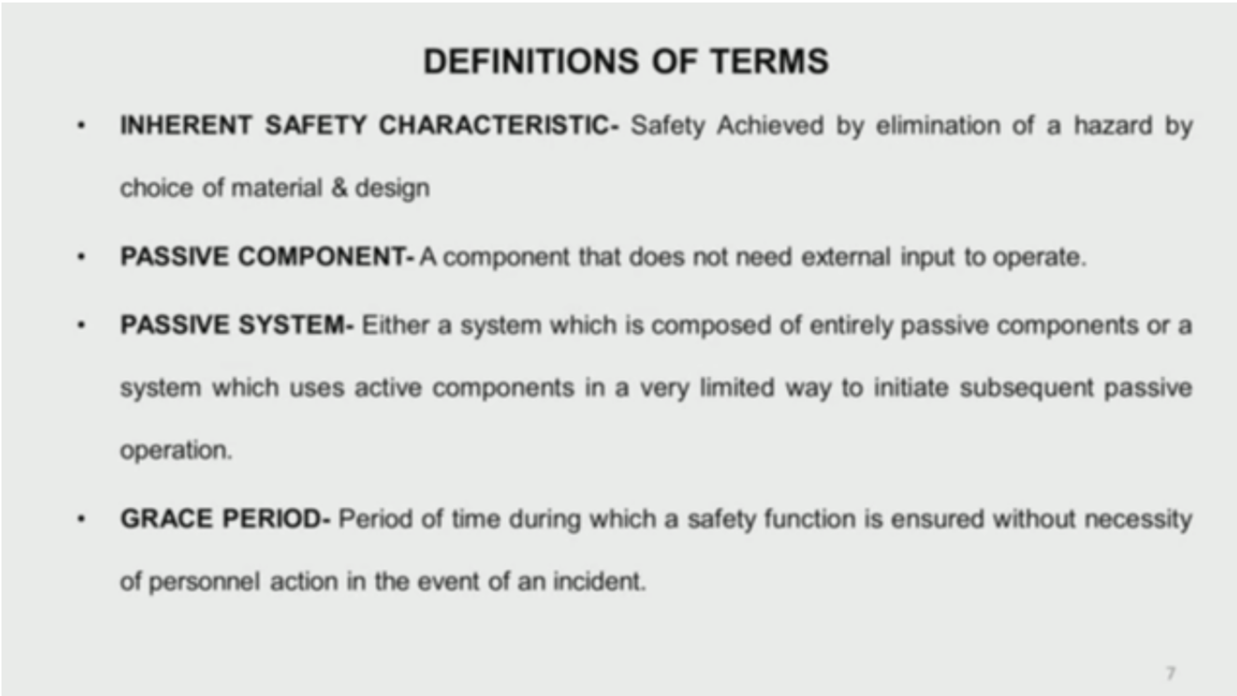

As I mentioned the word passive, safety, inherent safety needs some clarification because unfortunately they have been used too much without the correct meaning and to be frank with you, when people are talking this is inherently safe, nothing is inherently safe for everything. It is not that okay, suppose say inherently safe I will walk in the middle of the road when the car comes, no, nothing can be made inherently safe. So this International Atomic Energy Agency, the main body, which makes the rules for design and safety of nuclear reactors, they had a meeting just to clarify what are all these. So I have just taken these from there.

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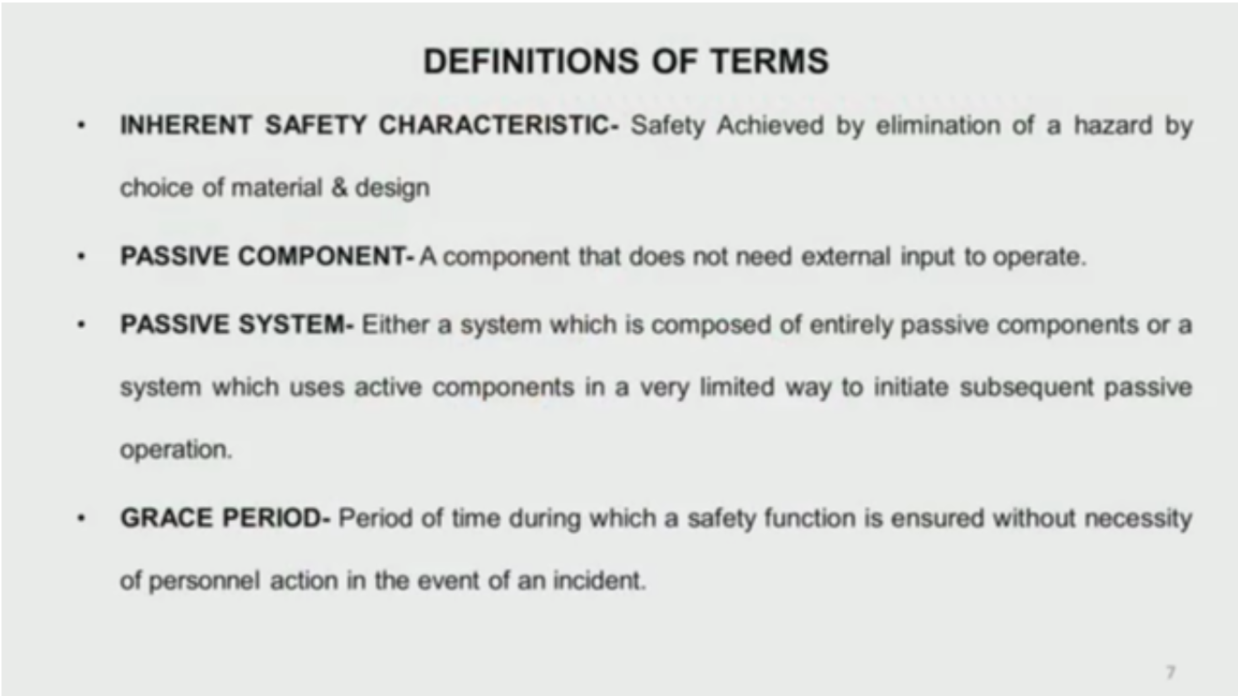

Inherent safety characteristic is the safety achieved by the elimination of a hazard by proper choice of material and design. Okay. Now your material is prone to corrosion. You have an improved material. So with reference to the corrosion, that is inherently safe, but suppose you don't provide sufficient thickness, and the pressure is more and it fails, you cannot say it is -- so the inherent safety is something like intrinsic safety feature of a particular design for a particular event. (Indiscernible 15:48) everything for a particular event.

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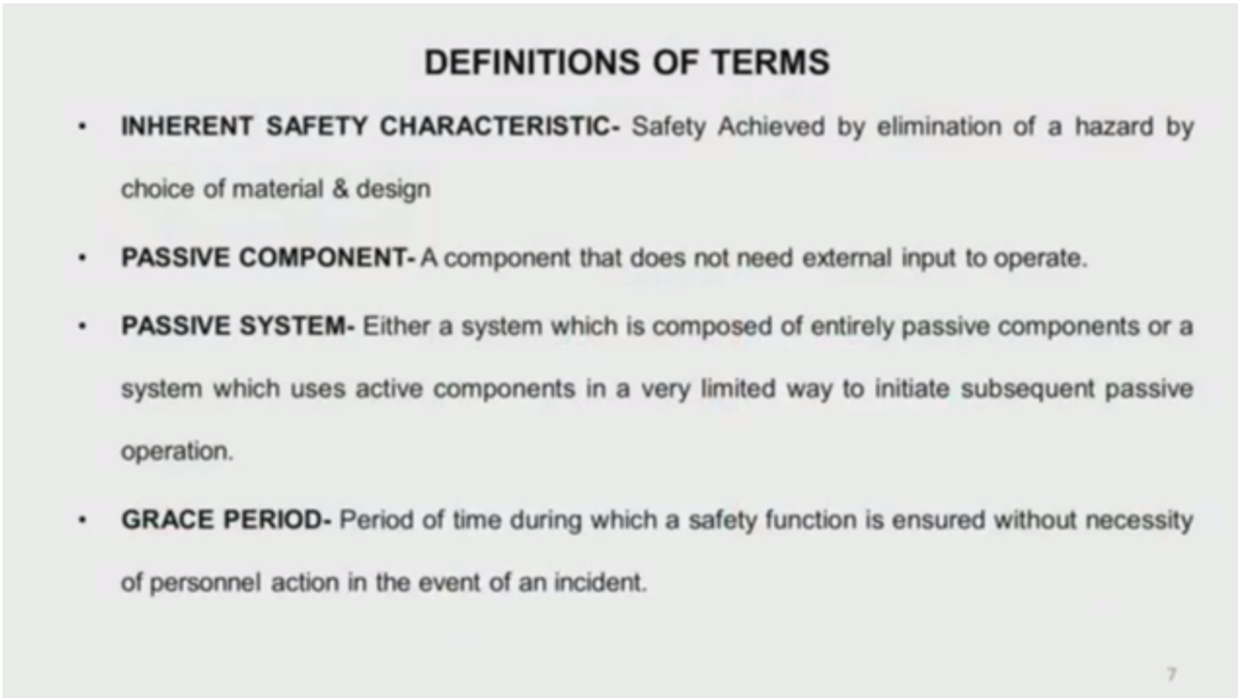

Then what is a passive component? Of course, the name passive itself you can say inactive. So passive component is a component that does not need an external input or external energy to operate. A very simple example. Now you have pumps, which are driven by motors. When the power supply is lost, the motor loses, motor starts reducing speed. The pump will reduce speed and the flow will come down.

Now but suppose I want to prolong the flow that is I want to have more -- still more flow as much time as possible I can have flow, then there is a method. You put a flywheel with a good amount of mass on the same shaft as the motor and the pump. Now when the power supply goes, you still have the stored energy of the flywheel and this can supply the energy to the pump and keep it running for quite some time. This is a sort of a passive component and a passive way we can deal with it.

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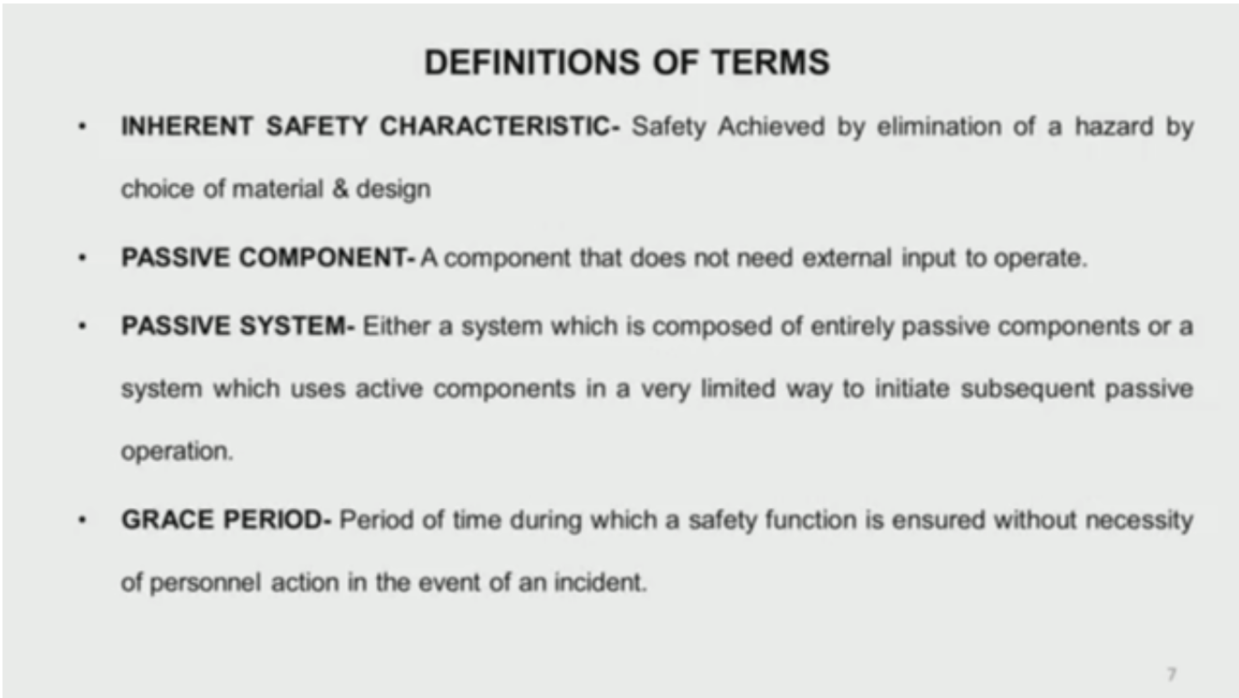

Then what is a passive system? Surely, is a system which composed entirely of passive components or it could also mean use of certain active components. You can wonder why this bit of addition of a certain active components. Now, finally, you have about 10 or 15 components. One of them may be required to start the action, very little energy, but start the action you require. So that is why this active component is there, but once that active component has triggered, that's all. Then afterwards everything is passive. Things go on smoothly by itself. That is called as a passive system.

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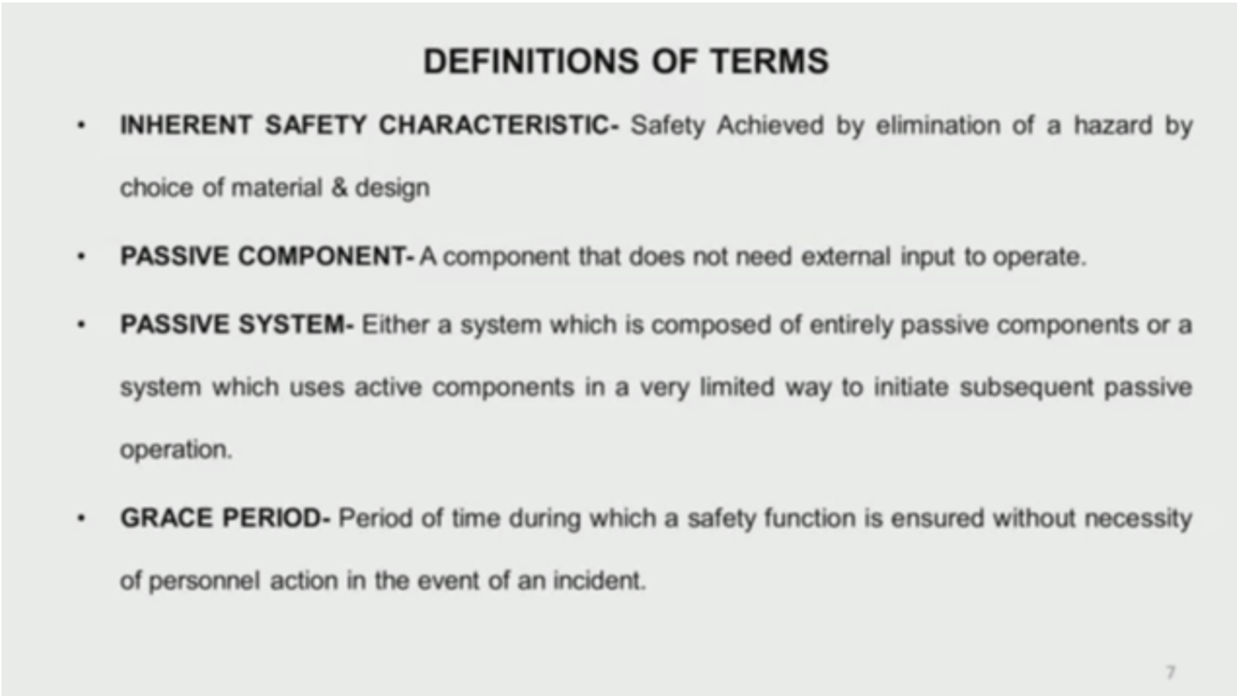

Then the other term which we call is a grace period. Now what is this grace period? Grace means you understand very well that okay, gives you some time, but what is the time you give? This is a time in which your safety function is assured without necessity of the operating personnel in the case of an event. In other words, the operator is not acted, but so it gives them time for the operator to act. This grace period is a very, very important thing which we keep in mind in the nuclear reactor designs.

Now let us say some event is happening. The operator gets lot of alarms in the control room, so many signals, and he has to operate. He has to do the next step, but as a human being he requires certain time to grasp the situation and take. Surely, there are rules available, but it does take some time.

Suppose you are able to design a reactor which gives sufficient grace time, that means the operator need not be in a hurried manner. Hurry sometimes makes -- can make a wrong decision. So how much grace time it gives is a very important factor. As I talk to you about the flywheel, the flywheel is able to give him some time because the coolant flow is reducing slowly. So the temperatures won't rise fast. So this is called as a grace period.

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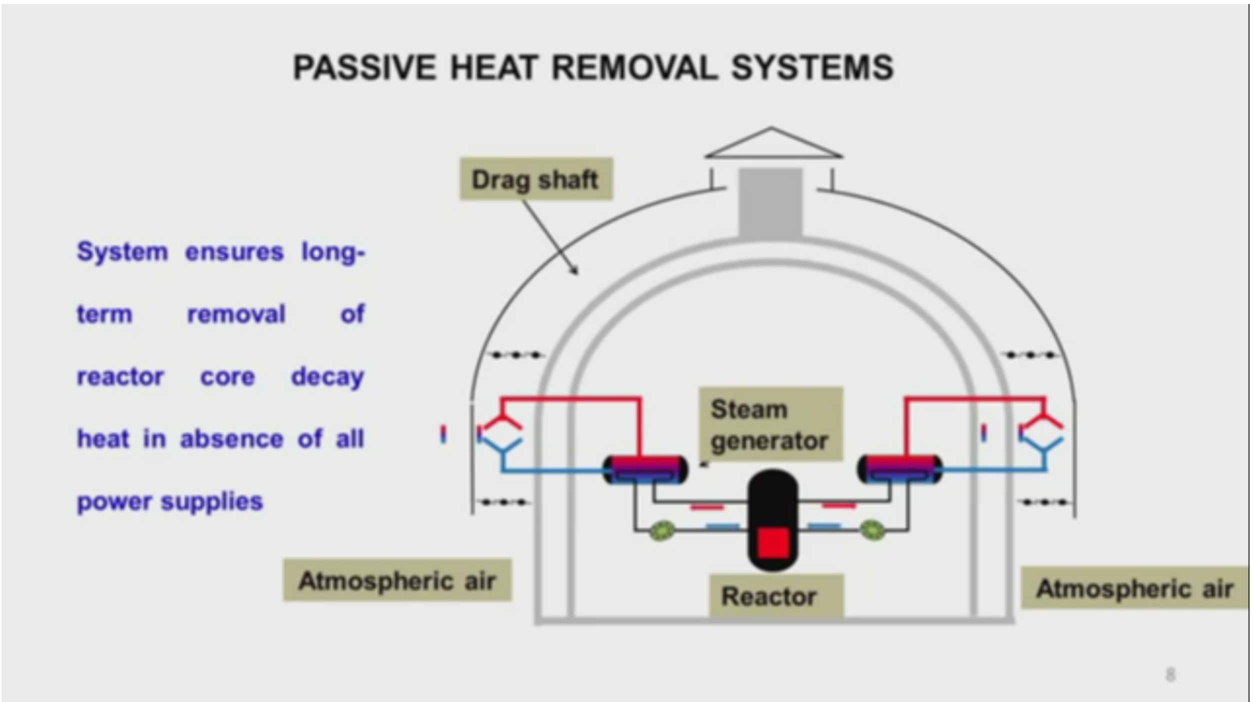

Now just to give some examples of passive heat removal systems which are there in the reactors, here this is a loss of power has happened and the core decay heat needs to be removed. So here you can see the steam generators and the heat going on to a exchanger above which atmospheric air is flowing, this is in a passive manner and that heat is going. You see the pump has stopped, but the flow is occurring because here natural air flow over these exchanger removes the heat. Once that heat is removed, the cooler Sodium comes, gets back into the core, again, gets heated and then so this is one natural circulation path created by the another natural circulation here. So this is a passive system in the absence of power supply.

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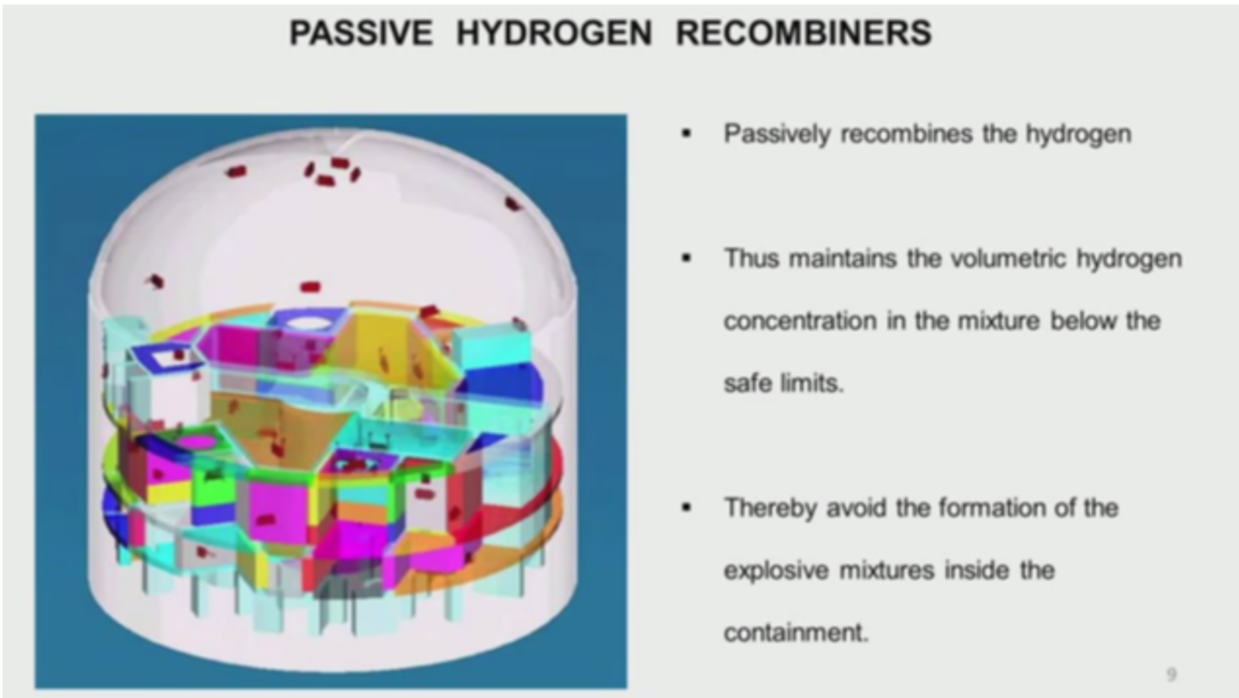

Then passive hydrogen recombiner. You might have heard that in the Fukushima accident, there are some explosions. It was not a nuclear explosion. It was a hydrogen explosion. You know that hydrogen concentration in a particular area, if it becomes more than 4%, it catches fire. So, normally, hydrogen should not be allowed to get stagnated and how this hydrogen is produced in the case of Fukushima? What happened that the coolant flow was lost. When the coolant flow was lost, whatever coolant was remaining, it started boiling and Zirconium clad, which was around the fuel element has a reaction with the clad at higher temperatures and the temperature went up. The cooling was not there. This -- whatever was the pool water, that started reacting and that started producing hydrogen, Zirconium hydroxide and hydrogen. This hydrogen came out because the primary containment itself was breached, and they got into the containment building, and the concentration was such that it became caught fire and it exploded, and that is the reason why the roof came off.

In all our reactors, we have what is called that is we design such that hydrogen in any compartment should not become and should it become also, we don't allow it to become, we have hydrogen recombiner by which hydrogen is mixed with oxygen and then it will become water.

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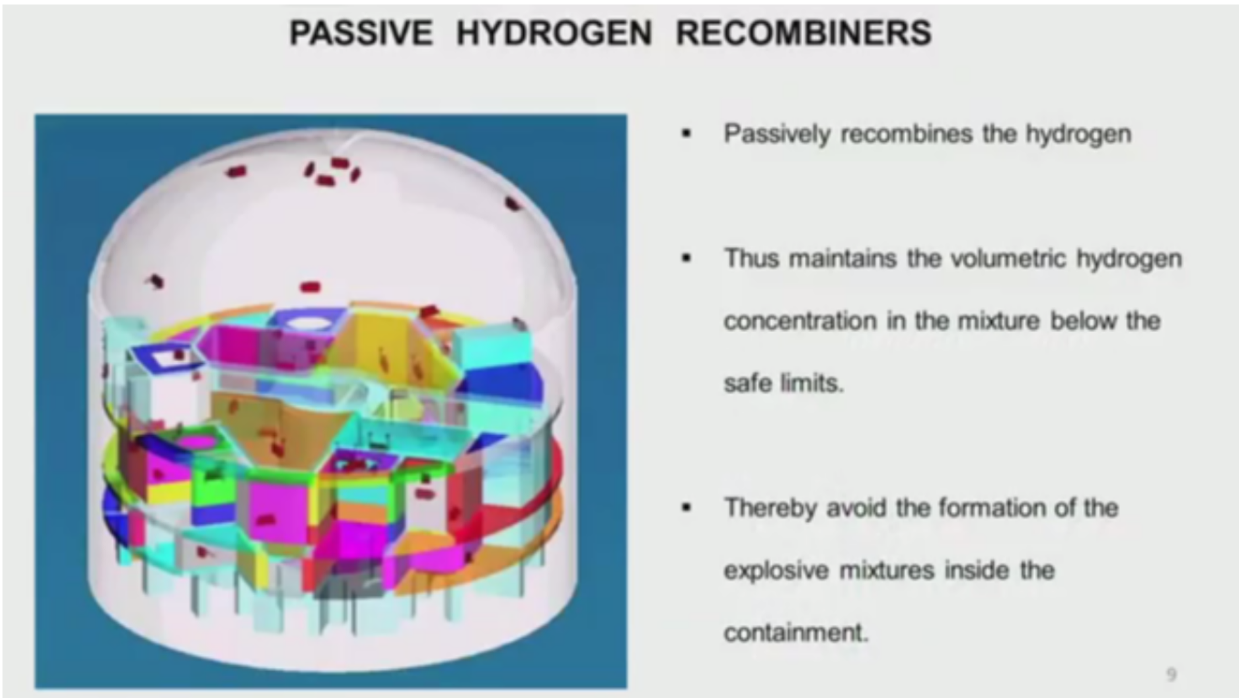

Now this should happen in a passive manner and we do have such hydrogen recombiners in the reactors. We have two boiling water reactors similar to Fukushima design in Tarapur. Units 1 and 2 are the boiling water reactors, but we have these hydrogen recombiners there. Unfortunately, in the Fukushima reactor, these recombiners were not in operation.

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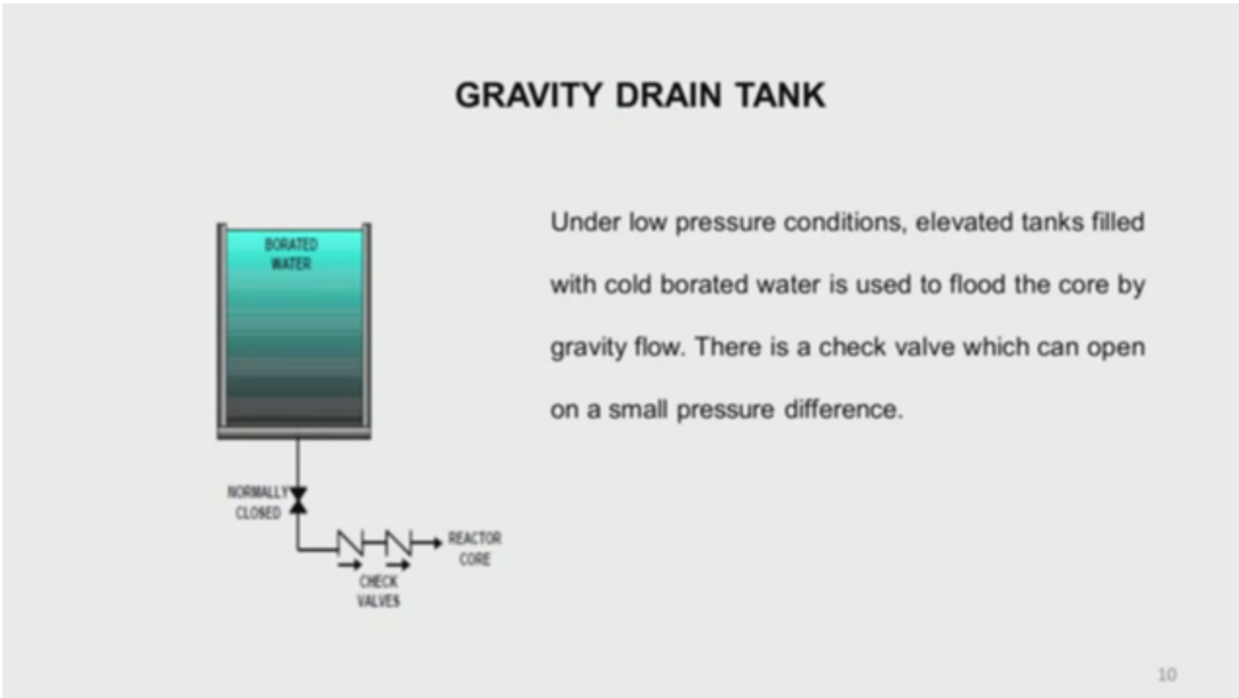

Then another passive feature which can be very easily used for decay heat removal or even shutting down the reactor, you have control rods. You -- you want to shut down the reactor, you drop the control rods inside the core. It absorbs the neutrons and doesn't allow the -- a self-sustaining chain reaction, fission reaction, so the reaction stops, but of course still the decay heat is there.

Now you have as a diverse method, you have a tank of water containing boric acid. Boron, you know, is an absorber and if I can fled the core with this flow from a tank maybe through a check valve or a non-return valve which can open on a very small pressure difference, I am assured of a shutdown. This is you can say a passive shut down.

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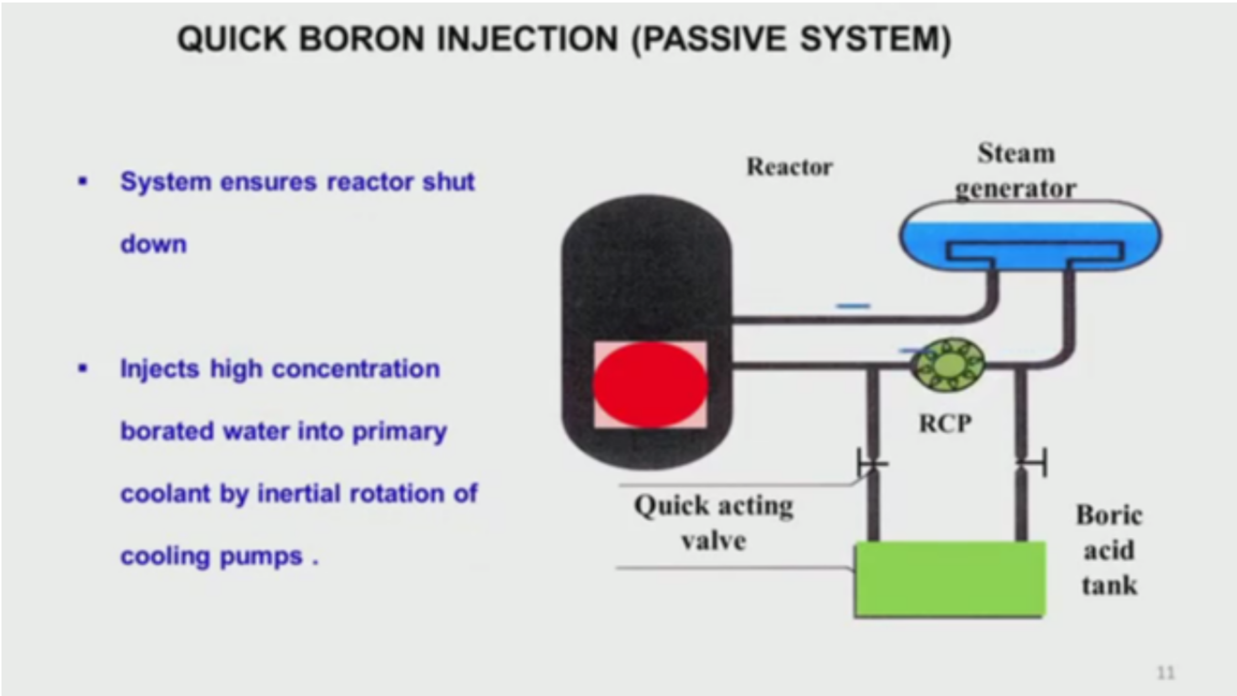

Now this figure shows you how a passive shutdown is getting achieved from the Boric acid tank, a quick-acting valve injects high concentration of borated water into the primary coolant, and here you remember this pump is driving, is getting driven because of the inertia of the flywheel. In a similar way, this, a tank, gravity tank can be used for dowsing the system with water, and seeing to it or compensating for the loss of coolant so that your temperatures don't go high and decay heat gets removed to certain extent.

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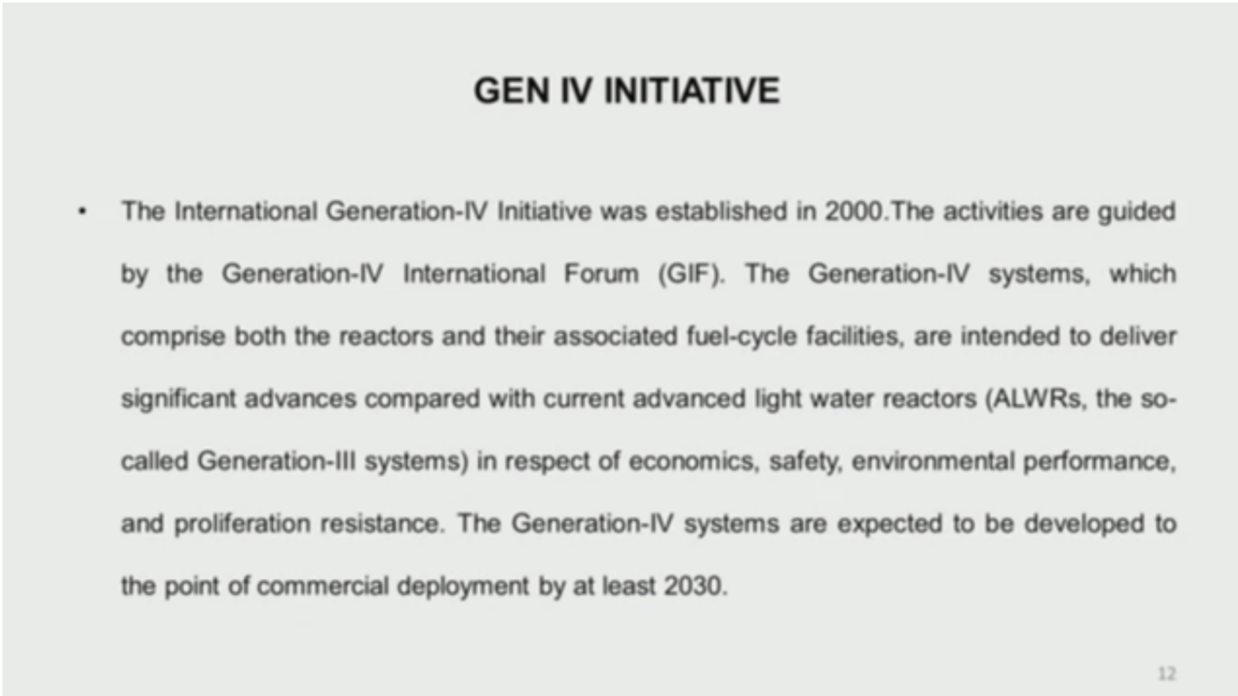

Now let us come to the Generation-IV. This initiative as I mentioned was by a group of countries. They got together and in the year 2000, they set up the Generation-IV International Forum so which would comprise not only the reactor designers, the fuel -- all the fuel-cycle facilities. As I mentioned all fuel-cycle facilities in a single location is one of the objectives of the Generation-IV and the idea was to deliver reactor or design reactors which will be safer, which will be economical, which will produce less waste and not -- not, you know, what you call able to proliferate, it should be proliferation resistant.

So as compared to the present reactors, now these reactors are still in the evolutionary stage. So you can say that till about 2030 or '40, still we have the Generation-III and Generation III-plus reactors filling this gap. So in this -- in the interim period, our current III, III plus reactors will continue.

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GEN IV CONCEPTS

Reactor	Neutron Spectrum	Coolant	Temper-ature°C	Pressure	Fuel	Fuel Cycle	Power MW
Gas Cooled Reactor	Fast	Helium	850	high	Mixed oxide	Closed	280
Lead Cooled Reactor	Fast	Pb-Bi	550-800	low	-do-	closed	50-1200
Molten Salt Reactor	Epithermal	Fluoride Salts	700-800	low	UF in Salt	Closed	1000
Sodium Cooled Reactor	Fast	Sodium	550	low	Mixed oxide	Closed	150-1500
Super Critical Water Cooled Reactor	Thermal /Fast	Water	510-550	Very High	UO2	Open/ Closed	1500
Very High Temper-ature Reactor	Thermal	Helium	1000	high	UO2-Prism/ Pebbles	Open	250

13

Now let us look at the concepts which have got evolved. One is the gas cooled reactor. The gas cooled reactors earlier have had a reasonably good experience, but they had some problems with material technology, basically, the Magnox reactor and the advanced gas core reactors built both in UK and France, and subsequently some high temperature gas cooled reactors have also been built, one or two, and then some experience has been gained, and with all around research and developments in the material technology, it is felt that gas cooled reactors could be a very good approach for nuclear power generation in the GEN IV.

Now all this time we were telling that we could think of a steam production to run a turbine, but you also could have a gas turbine. The gas cooled reactor could be used to run a turbine directly, and that way you can produce power or you could exchange heat to water in a steam generator and then produce team. So there are different ways of doing it.

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GEN IV CONCEPTS

Reactor	Neutron Spectrum	Coolant	Temper-ature°C	Pressure	Fuel	Fuel Cycle	Power MW
Gas Cooled Reactor	Fast	Helium	850	high	Mixed oxide	Closed	280
Lead Cooled Reactor	Fast	Pb-Bi	550-800	low	-do-	closed	50-1200
Molten Salt Reactor	Epithermal	Fluoride Salts	700-800	low	UF in Salt	Closed	1000
Sodium Cooled Reactor	Fast	Sodium	550	low	Mixed oxide	Closed	150-1500
Super Critical Water Cooled Reactor	Thermal /Fast	Water	510-550	Very High	UO2	Open/ Closed	1500
Very High Temper-ature Reactor	Thermal	Helium	1000	high	UO2-Prism/ Pebbles	Open	250

13

Then what are the other concepts? The Lead cooled reactor. Now the using of this Lead cooled reactor, again, the gas cooled reactor, which I mentioned is a fast reactor and not a thermal reactor. Why that point of a gas was felt needed because the sodium cooled fast reactors which are present, they have a problem of in case of a Sodium leak or a Sodium-water reaction, they can produce damage in the steam generator and in case if they leak out, Sodium leaks out, it can catch fire. So people said why not we change?

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GEN IV CONCEPTS

Reactor	Neutron Spectrum	Coolant	Temper-ature°C	Pressure	Fuel	Fuel Cycle	Power MW
Gas Cooled Reactor	Fast	Helium	850	high	Mixed oxide	Closed	280
Lead Cooled Reactor	Fast	Pb-Bi	550-800	low	-do-	closed	50-1200
Molten Salt Reactor	Epithermal	Fluoride Salts	700-800	low	UF in Salt	Closed	1000
Sodium Cooled Reactor	Fast	Sodium	550	low	Mixed oxide	Closed	150-1500
Super Critical Water Cooled Reactor	Thermal /Fast	Water	510-550	Very High	UO2	Open/ Closed	1500
Very High Temper-ature Reactor	Thermal	Helium	1000	high	UO2-Prism/ Pebbles	Open	250

13

So one was gas, other was Lead because Lead is not having that much of a reaction with water or air, so it is one of the preferred, but mind you Lead itself has got a high boiling point, high melting point and/or something like about 250 to 300 degree centigrade and then -- but a large boiling point. You can go to very high temperatures, but then these two were also as in the fast reactor spectrum, these two were the concepts which are arrived at, but the Sodium was not left off because Sodium per se the operation of the reactors has been reasonably good and they aren't -- it does not cost, you know, caused us very bad problems because of Sodium cooled fast reactors. These are surmountable.

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GEN IV CONCEPTS

Reactor	Neutron Spectrum	Coolant	Temper-ature°C	Pressure	Fuel	Fuel Cycle	Power MW
Gas Cooled Reactor	Fast	Helium	850	high	Mixed oxide	Closed	280
Lead Cooled Reactor	Fast	Pb-Bi	550-800	low	-do-	closed	50-1200
Molten Salt Reactor	Epithermal	Fluoride Salts	700-800	low	UF in Salt	Closed	1000
Sodium Cooled Reactor	Fast	Sodium	550	low	Mixed oxide	Closed	150-1500
Super Critical Water Cooled Reactor	Thermal /Fast	Water	510-550	Very High	UO2	Open/ Closed	1500
Very High Temper-ature Reactor	Thermal	Helium	1000	high	UO2-Prism/ Pebbles	Open	250

13

So you see there are three fast reactors, spectrum reactors, the gas cooled reactor, the Lead cooled reactor and the Sodium cooled reactor. One more reason why the Lead cooled fast reactor found its place, Lead cooled reactors have been used by the Russians in their submarines, and lot of knowledge base from the Russians is available today, and that also would come into the Generation-IV Forum because of which this Lead got a place.

Now if you look up the gas cooled reactors, the temperatures as much as about 850 degree centigrade we are able to reach with about Lead and Lead-Bismuth, we are able to go to about 550 to 800. Then the -- with sodium cooled fast reactors, of course, we are able to go to about 550 degree centigrade.

The other one is the molten salt reactor. This molten salt reactor, to be frank with you, lot of work was done in ORNL in USA on molten salt reactors. At the same time in the 60s, when the Sodium cooled fast reactor development was taking place, the molten salt reactors, in the molten salt reactor, the fuel is itself is a salt in a molten state. The coolant, the fuel, everything is mixed together and then getting pumped. So this concept was there and there is a molten salt reactor experimental reactor was built in the ORNL. It was functioning, but it so happened that when they had to take a decision whether to go for a Sodium cooled reactor or a molten salt reactor, the Sodium lobby had gained enough experience and was able to put up by an economic case and then the Sodium cooled fast reactors took the plunge, but it has been felt now that that from a breeding point of view as a breeder, molten salt reactors are very good. So there is an interest even in having molten salt reactors.

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GEN IV CONCEPTS

Reactor	Neutron Spectrum	Coolant	Temper-ature°C	Pressure	Fuel	Fuel Cycle	Power MW
Gas Cooled Reactor	Fast	Helium	850	high	Mixed oxide	Closed	280
Lead Cooled Reactor	Fast	Pb-Bi	550-800	low	-do-	closed	50-1200
Molten Salt Reactor	Epithermal	Fluoride Salts	700-800	low	UF in Salt	Closed	1000
Sodium Cooled Reactor	Fast	Sodium	550	low	Mixed oxide	Closed	150-1500
Super Critical Water Cooled Reactor	Thermal /Fast	Water	510-550	Very High	UO2	Open/ Closed	1500
Very High Temper-ature Reactor	Thermal	Helium	1000	high	UO2-Prism/ Pebbles	Open	250

13

As I mentioned Uranium fluoride in salt and then you have the super critical water cooled reactor. The super cooled water critical reactor interest comes basically after you have got super critical boilers, which are used in the fossil fuel plants. What do you mean by the super critical? Now as you boil water at a particular pressure, you have to give latent heat to convert it into steam. As you go up in pressure, the latent heat comes down and at a point which is called as a critical point, there is the phase changes. There is no phase change. There is no two phase. It just changes to water to steam and you are able to go to high temperatures. With high temperatures, you are able to produce steam at high temperatures and you are able to have a better efficiency of the cycle.

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GEN IV CONCEPTS

Reactor	Neutron Spectrum	Coolant	Temper-ature°C	Pressure	Fuel	Fuel Cycle	Power MW
Gas Cooled Reactor	Fast	Helium	850	high	Mixed oxide	Closed	280
Lead Cooled Reactor	Fast	Pb-Bi	550-800	low	-do-	closed	50-1200
Molten Salt Reactor	Epithermal	Fluoride Salts	700-800	low	UF in Salt	Closed	1000
Sodium Cooled Reactor	Fast	Sodium	550	low	Mixed oxide	Closed	150-1500
Super Critical Water Cooled Reactor	Thermal /Fast	Water	510-550	Very High	UO2	Open/ Closed	1500
Very High Temper-ature Reactor	Thermal	Helium	1000	high	UO2- Prism/ Pebbles	Open	250

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That is the reason which resulted in -- and very high-temperature reactors, again, based on the gas cooled reactor concepts. It has been there we can go to high temperatures, and this gives you -- and remember four of them are using closed fuel cycle or you can say five of them and the last one is an open fuel cycle. So you see that closed fuel cycle has been a preferred one in the Generation IV.

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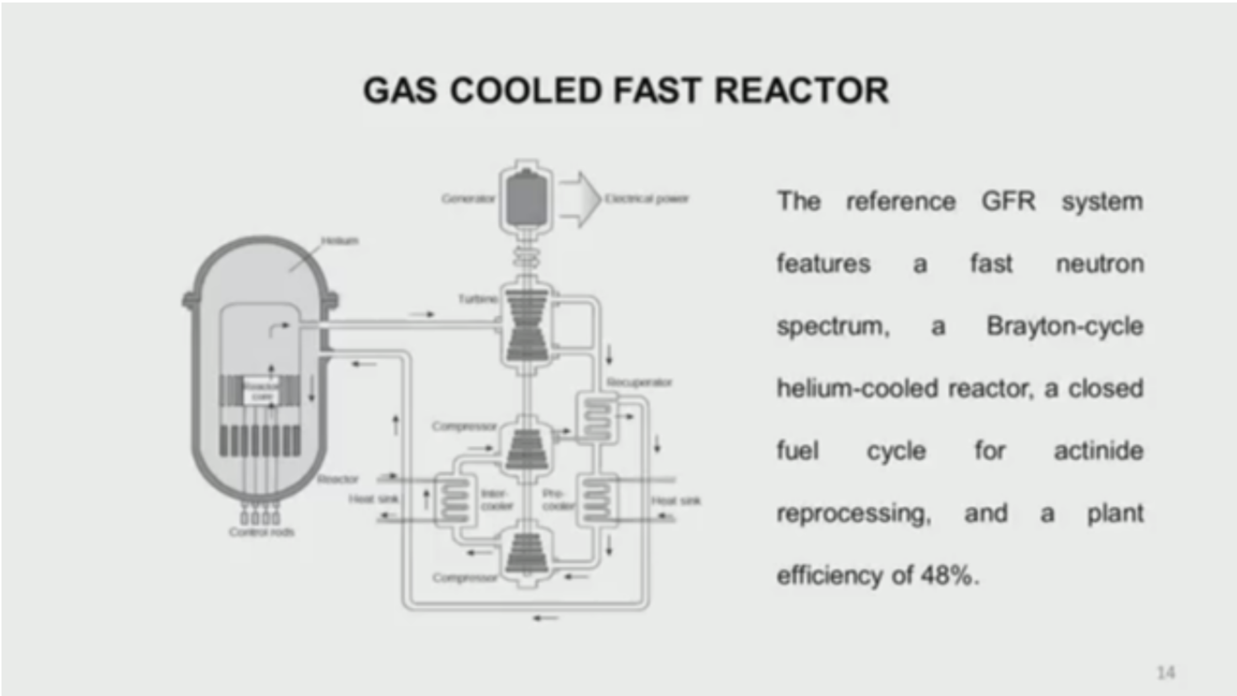

Now let us get a brief idea about, okay, what are all this. This is the reference gas cooled fast reactor system wherein you have the core here and the control rods are from down, operated from down in the bottom of the vessel. The gas picks up the heat. Gas is helium, goes to a turbine, rotates it, and this is a gas turbine and it generates power. Here you can see it is something like a boiling water reactor. Directly, the gas goes, cools and comes back. So this gas cooled fast reactor concept is one of the concepts and this Brayton-cycle, theoretically, Brayton-cycle can go to as much as 65% efficiency, but concerning losses it is felt that we could come to about 48%, and as I mentioned in my last lecture, the actinides get very well burnt in these fast reactors. So waste is getting limited.

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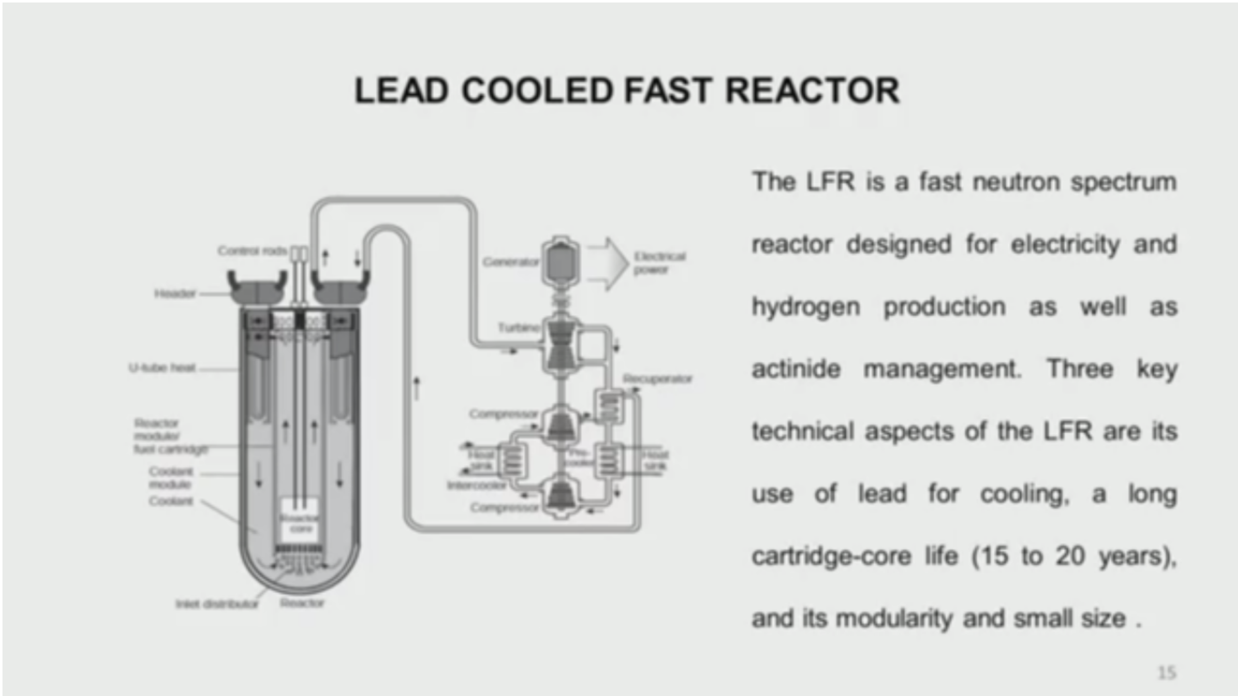

Then the Lead cooled fast reactor. Surely, being a fast reactor, this also has got a very good actinide management so that actinides produced use -- produced in the light water reactors are utilized and broken into short-lived, and so you are able to have lesser waste, lesser activity.

Now here you have the reactor core. Lead is the coolant. These are the control rods, and here you have an heat exchanger wherein there is a gas flow, and this gas again goes through a Brayton-cycle and produces electricity. So, basically, it is Lead cooled reactor, but heat is taken by the gas and then runs the turbine. So this idea of this sort of a reactor is that we are not using Sodium, but mind you Lead itself per se has some issues to resolve, basically, corrosion.

Many of the corrosion, you know, in nature happens because of oxygen. You put any iron earthing on the outside, it reacts. Iron reacts with oxygen and form rust, so iron oxide. Similarly, you have sodium with higher oxygen content will cause corrosion. Oxygen is one of the important things for corrosion. So we must minimize the amount of oxygen in a coolant, but now in the case of Lead, this has got a funny thing. Above a certain level, it has more corrosion.

Similarly, below a certain level of hydrogen also, it has got more corrosion, so very narrow band of oxygen control is necessary unlike Sodium. So here lot of research is getting on into how to do that and how to see materials which will be able to. So Lead cooled fast reactor does have some issues. One thing, Gen IV does not mean that okay, all issues are resolved. Gen IV has got, but which areas we must probe and concentrate our efforts.

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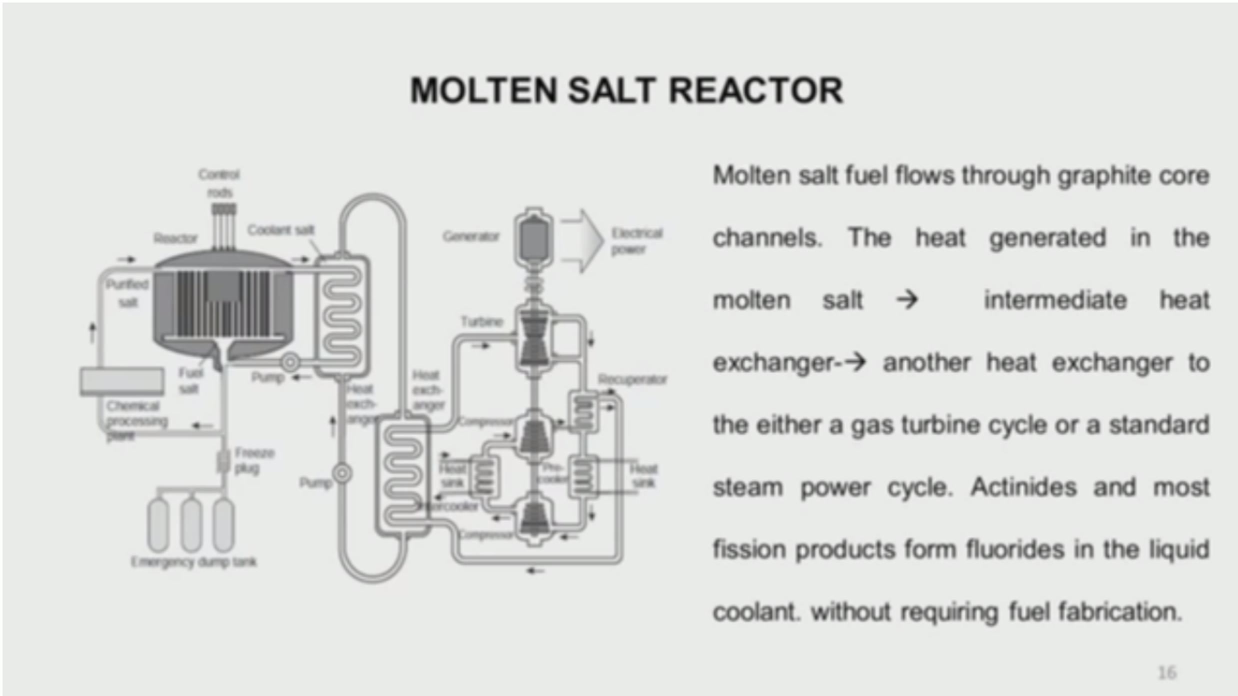

Then you have the molten salt reactor that molten salt flows through here. This is the core. These are the control rods and you have the graphite channels. So the molten salt goes through that, and then there is a intermediate heat exchanger, and here you may have, again, like another fluid like Lead, which can exchange heat with a gas which can run a gas turbine and produce electricity. Okay or you could have replace it by a steam generator. It could have a Lead secondary coolant giving heat to water, producing steam and running a steam turbine.

And here the main advantage of this molten salt is you don't need to fabricate the fuel again. You are just pushing fuel into the chamber, and then that's all. It continues. It is not a -- any special fabrication plant to be made and then put. So it just allow us a bit of flexibility in the fuel loading. That is fuel fabrication aspect is not required.

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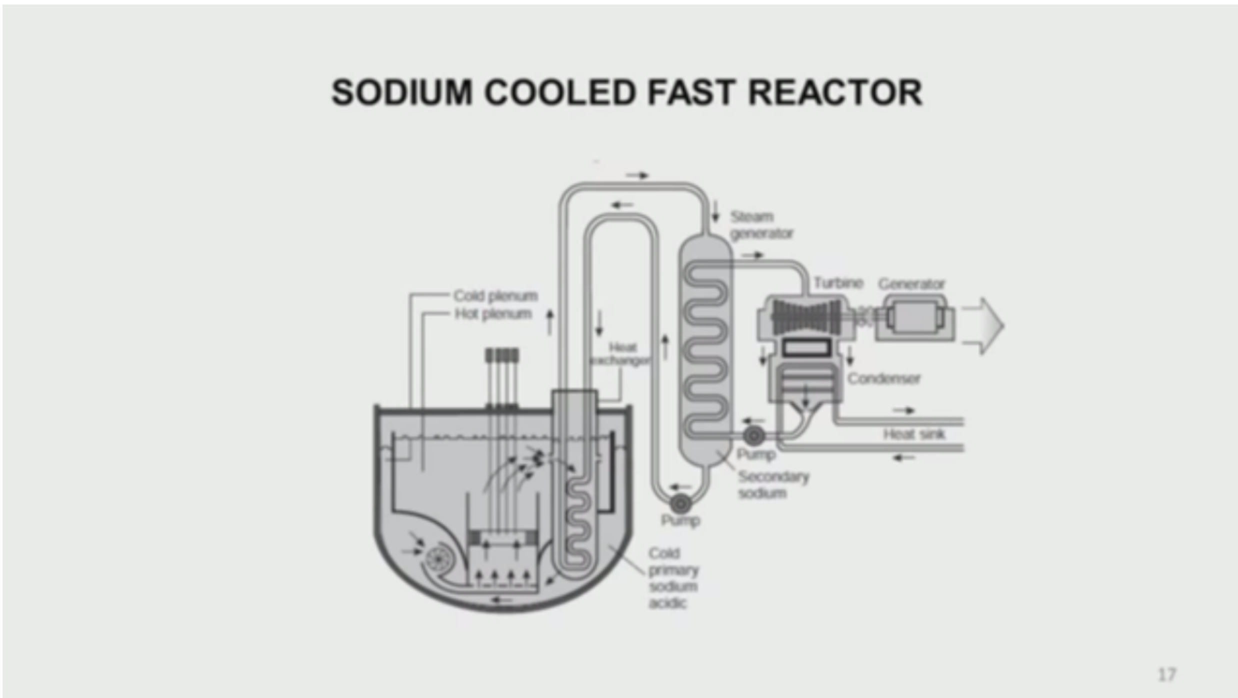

The sodium cooled fast reactor, it is just the replica of the pool type fast breeder reactors, which I have shown you. So here you have the primary sodium system, which, this is the primary sodium, which picks up the heat from the core, and gives it to IHX. This is the pump which pumps from the cold pool to the core. It goes to IHX, comes out to the pool, cold pool again, and this is the control rod. This heat exchanger contains again sodium fluid. It picks up the heat called as a secondary sodium, gives heat to water in a steam generator, then afterwards again pumped back to the IHX, and here you have the steam production and turbine running, a conventional steam cycle. So remember the old sodium cooled fast reactor is still not left out. It is a important candidate for the Generation IV.

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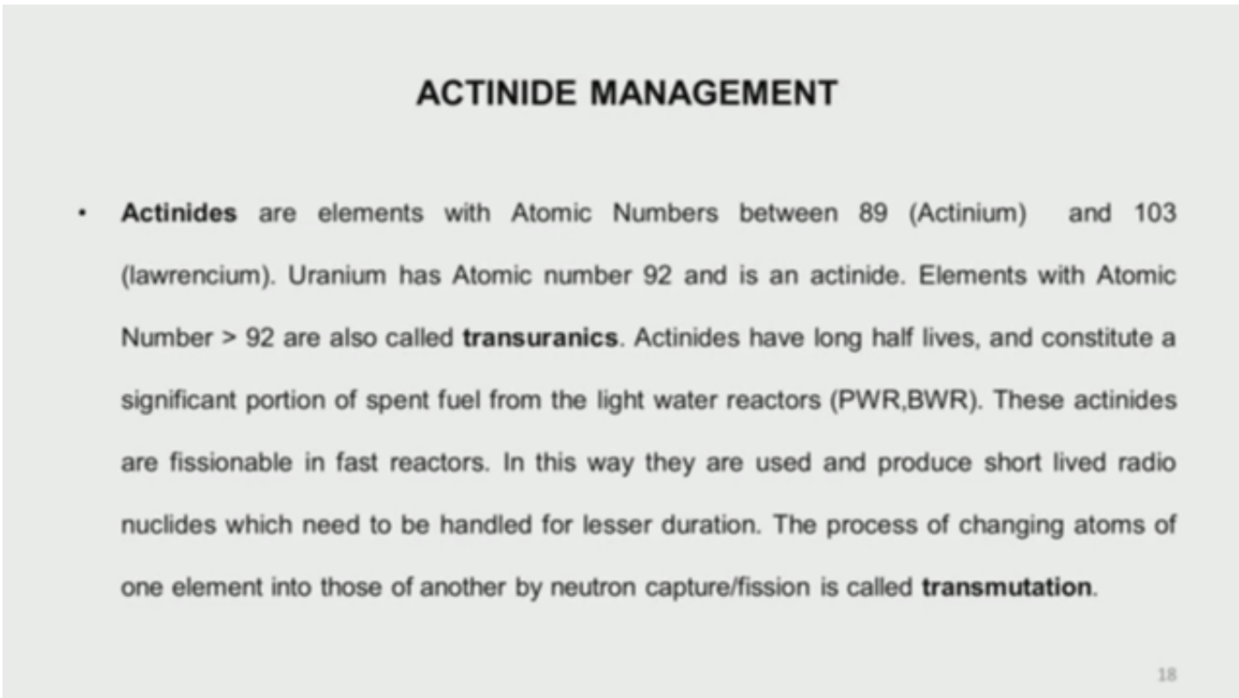

So now this Actinide management I mentioned, but let us just elaborate it a little bit. Actinides are elements with atomic numbers between 89 and 103. 89 is Actinium and 103 is Lawrencium. Uranium, you know, has an atomic number of 92. It is also an Actinide and normally, beyond 92, there is another name we give, Transuranics, beyond uranium, Transuranics.

Now these actinides have a very long half-life. That means they will decay very slowly. They have -- you saw Plutonium having Uranium, Plutonium having long half-lives. Potassium also having a long half-life. So it is the Uranium also has. So these are all very important that they have long half-lives, and when they have long half-lives, if they are in the waste, they also have to be handled with care for a longer time, and in these light water reactors, basically, the pressurized water reactor and the boiling water reactor, the actinides are produced, but not consumed, and here the way the -- in the fast reactors because of the fact that these actinides can be broken up, some of them can be fissioned, and they break up into smaller or lesser half-life elements. They can really be a very good impetus for the fuel handling because they are going to produce less waste.

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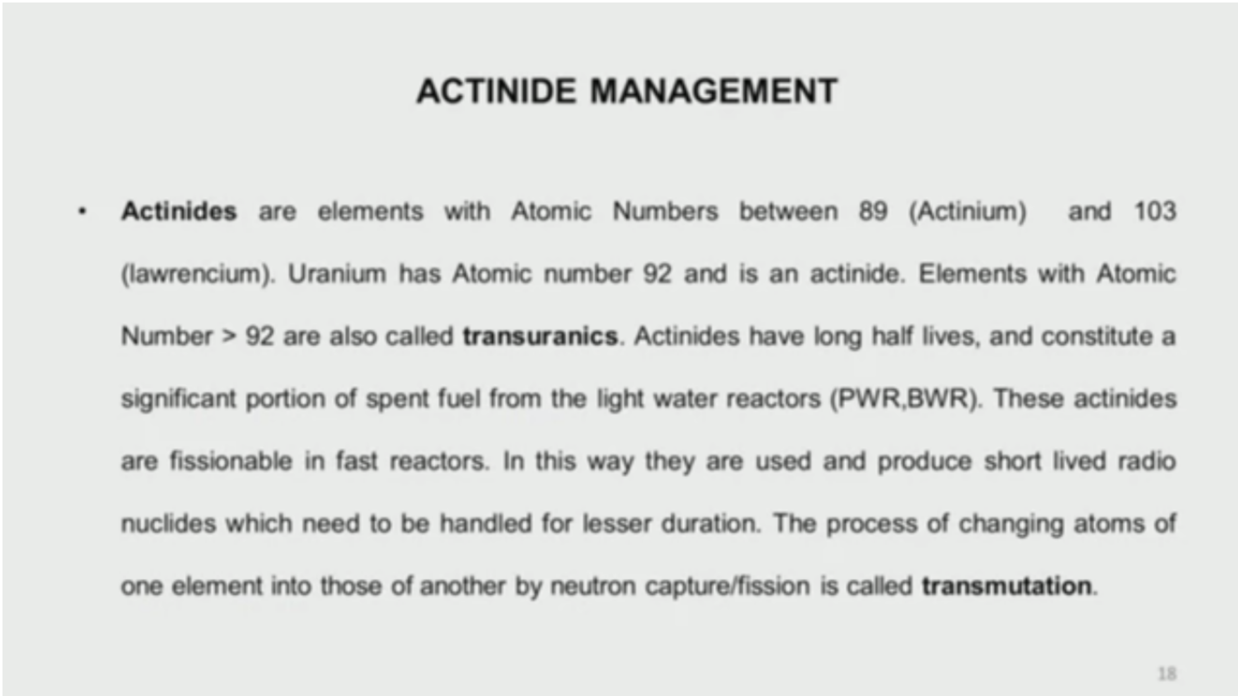

now this conversion of these high or longer half-life elements into lower thing is actually called as transmutation, and this transmutation occurs surely after it absorbs a neutron or then there is a fission.

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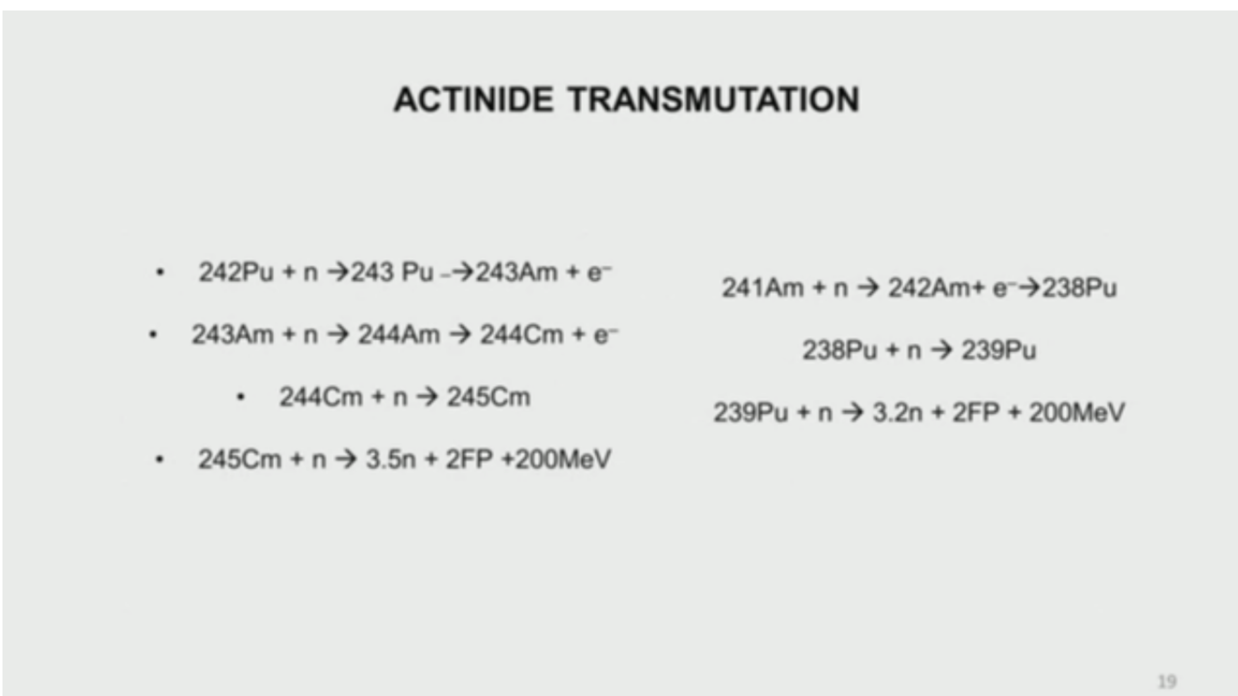

This is to give you an example. Plutonium 242, when it absorbs a neutron becomes 243, then it produces Americium. Then Americium absorbs a neutron, then gives 244, and then Curium, then like that Samarium, curium, this thing and then go on. Finally, it gives two fission products and releases energy. So release of energy is there. Similarly, for Americium how the break-up is happening. These are just to give you an idea that they can be used for a fission and also the fission products which have lower half life.

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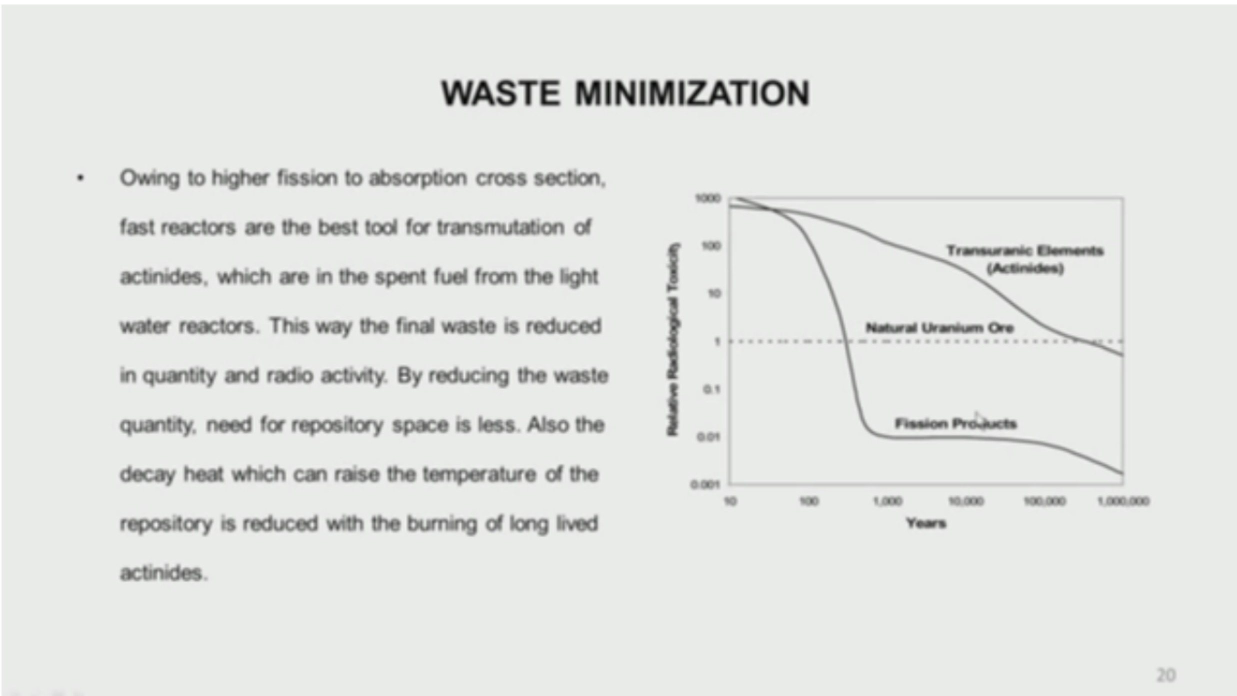

So this is to tell you about the waste minimization as I mentioned. Suppose you don't use fast reactors. You have just an open fuel cycle. See how the actinides will decay to natural Uranium ore level will take many years, over 100,000 years, but the same thing if you had used it in a fast reactor and closed, you reprocess it and use it in a fast reactor, it comes down below within about 100 to 200 years.

So there is a very great incentive to go for this sort of an approach and basically, fast reactors are better because it has got a higher fission to absorption cross section. So more chance of fission in the material compared to absorption, and the final waste is reduced, and the radioactivity, the activity which is related to that waste is also reduced. And that waste is reduced, the space is reduced. Finally, when you are going to put the waste in dispose it in some place, that is also requires less space.

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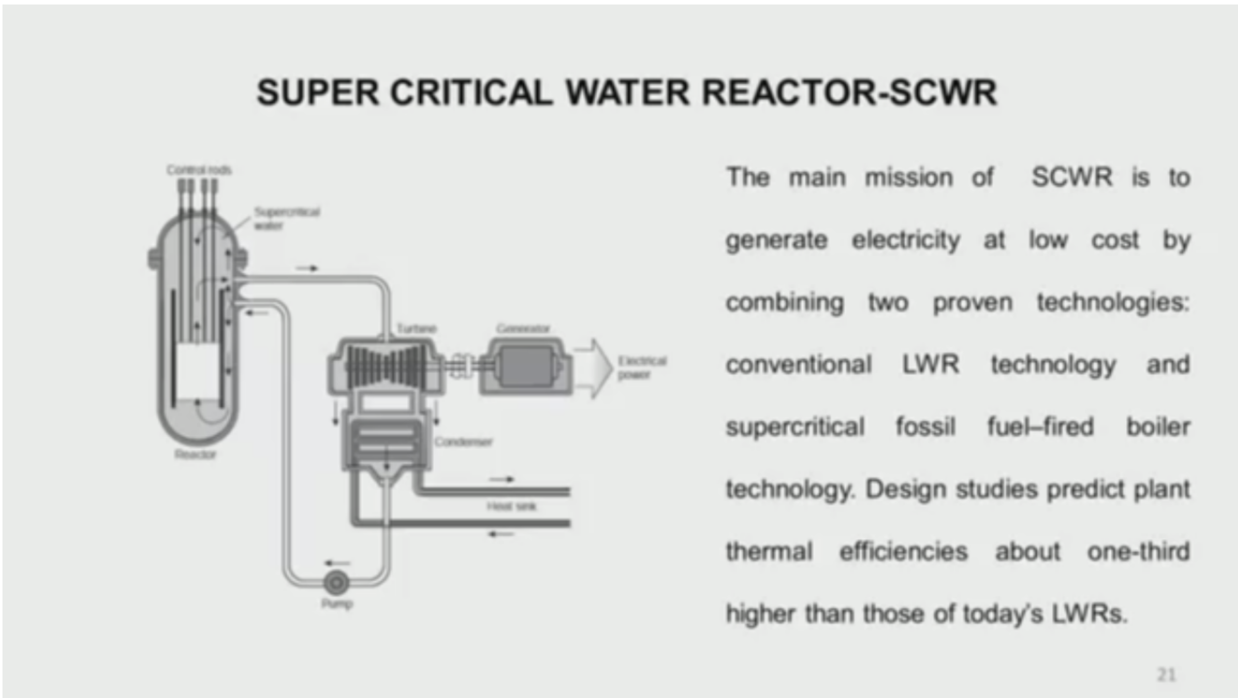

This is a super critical water reactor. As I mentioned, it generates steam at very high pressures and high temperatures, and this technology is a combination of the light water technology with super critical fossil fuel boilers, and efforts are still, of course, in India still we have to build a super critical boiler.

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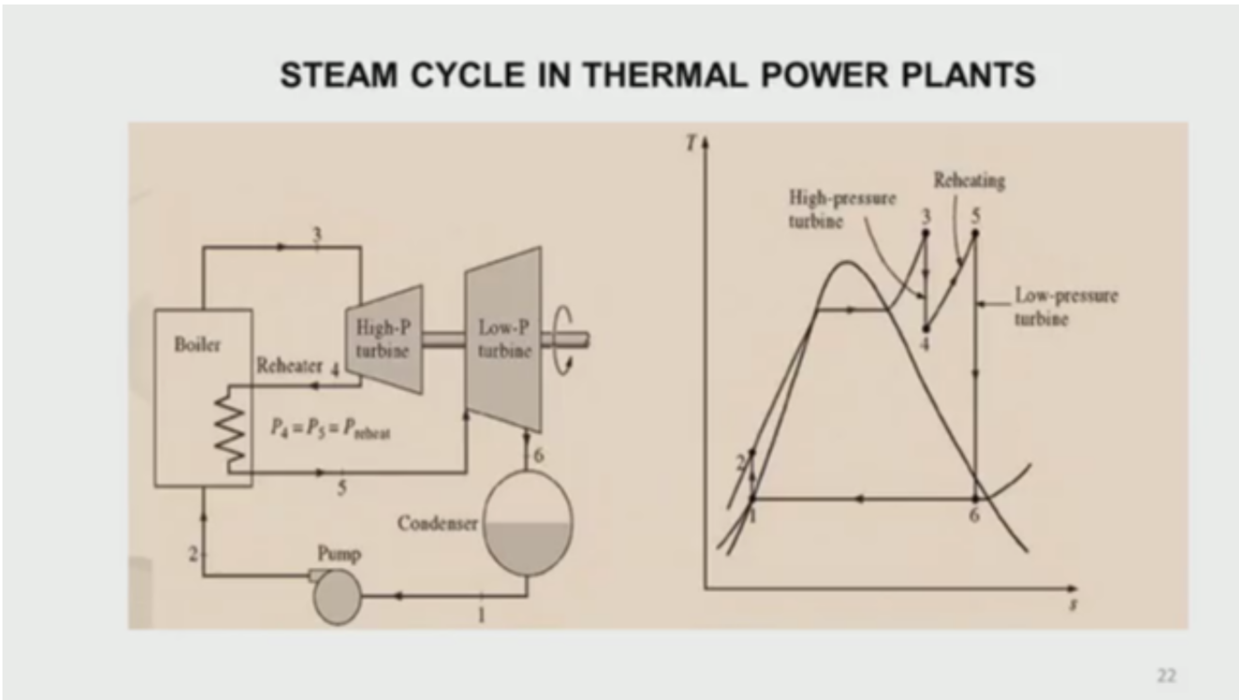

This is just to give you a quick idea about how the cycles are. This is the Rankine cycle, which is normally used in power plants. The water is pumped, sent to the boiler, picks up the heat, becomes superheated, becomes steam, works in the turbine, high-pressure turbine, then comes out, again reheated in the steam boiler, and then comes out and then goes.

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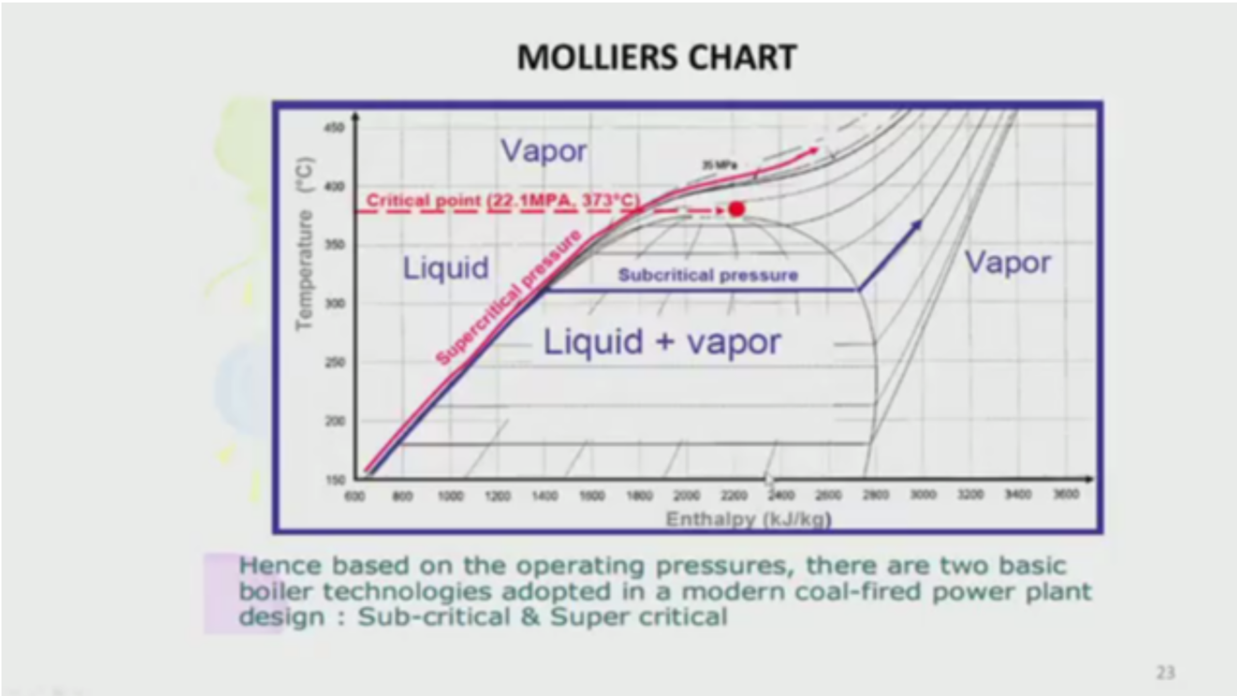

This is if -- this shows you a Molliers Chart, which is the -- shows the properties. Here this is the water going up, becoming saturation, taking the latent heat and becoming super heater. Now you see at this point, which corresponds to about 221 bars and 373 degree centigrade, there is no latent heat. It is 0. Just water. It just becomes into steam. So this is what we are talking. Above this is the super critical. Below this is the subcritical. So these are the basic differences between a normal subcritical boiler or a subcritical operation and the supercritical operation. This technology we are going to use was the supercritical water reactor.

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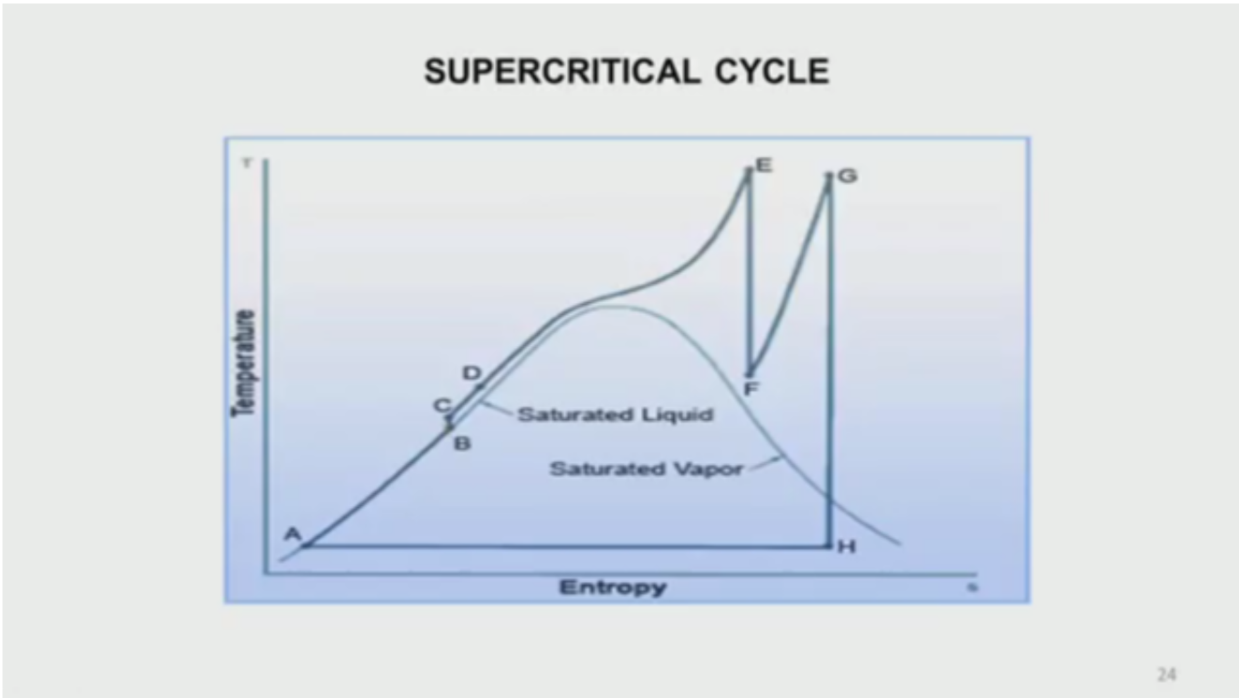

And now this is the cycle, how the supercritical cycle, water entry, pumped in, that's all, becomes -- it becomes steam, then expansion in the high-pressure turbine, coming out, expands, then again heated up to the higher temperature, again coming back and do. This reheating, of course, is there in fossil fuel boilers. Reheating in nuclear reactors is not done because the liquid has to go back into the reactor. So we may have only this portion.

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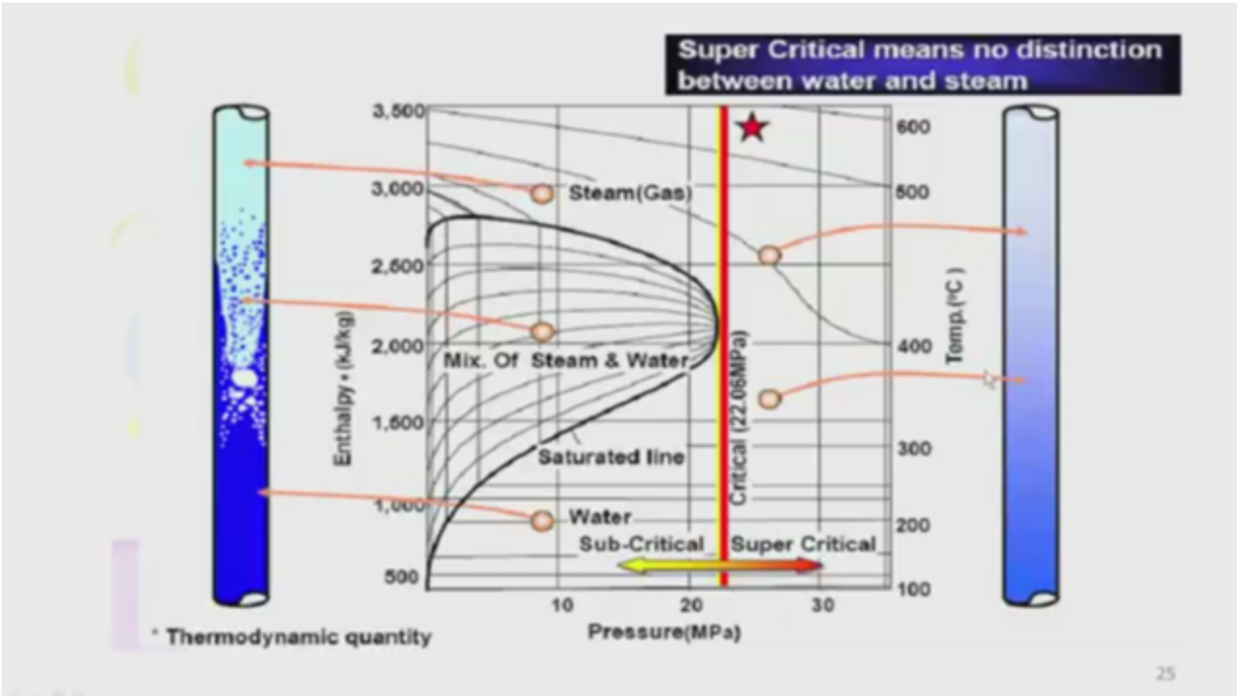

This is again another figure. Now since supercritical is there that means there is no distinction between water and steam. It is just a same.

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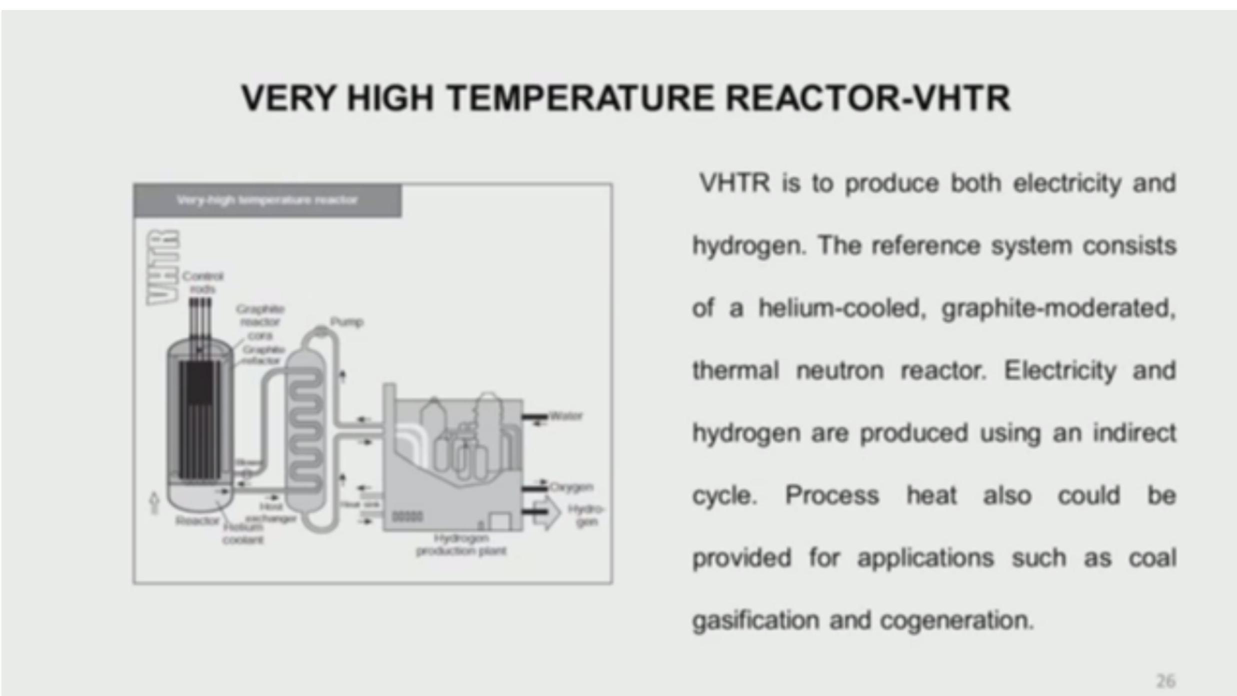

Then last is a very high temperature reactor. This temperature is aimed at producing -- this reactor is aimed at reducing both electricity and also hydrogen. As I mentioned hydrogen economy is one of the most important. Hydrogen generation, if I can store, I can use it for transportation and many other things. So this is a helium cooled, graphite moderator, thermal reactor and the process heat also could be used for other applications like coal gasification, desalination and cogeneration also.

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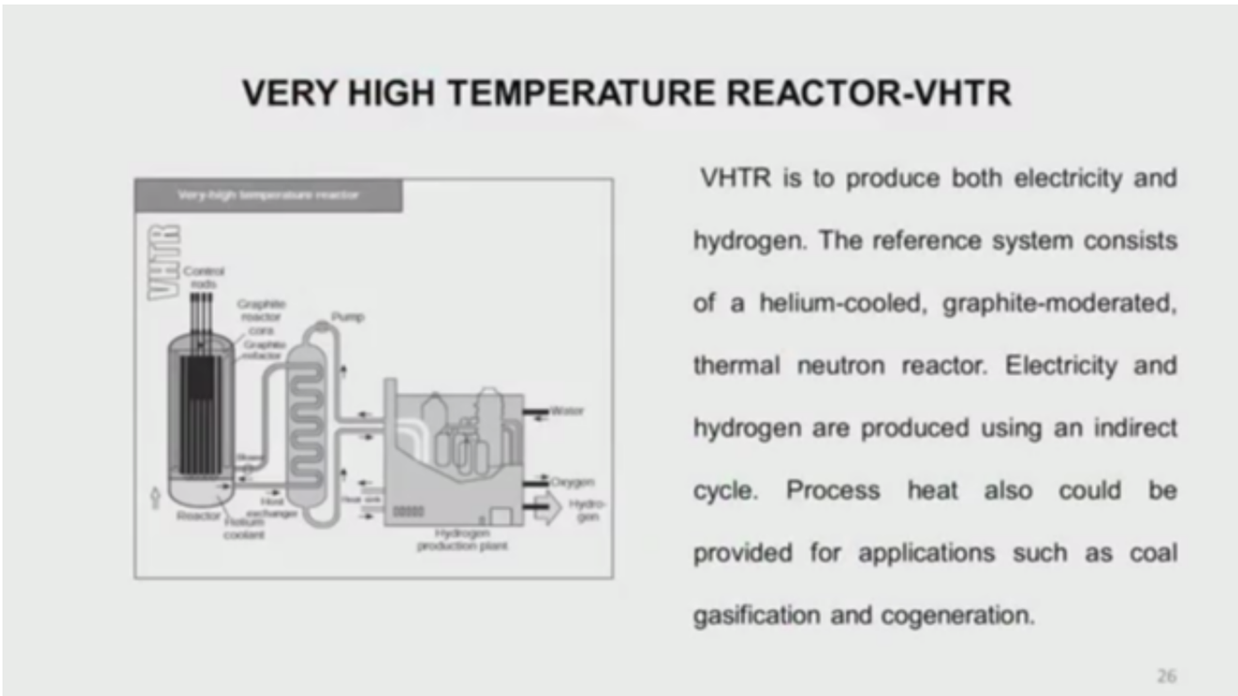

This again is in the (indiscernible 50:21) and here you see the gas cooled, helium cooled reactor. It is exchanging heat with water, producing steam at high pressures, and this is the schematic of a hydrogen plant.

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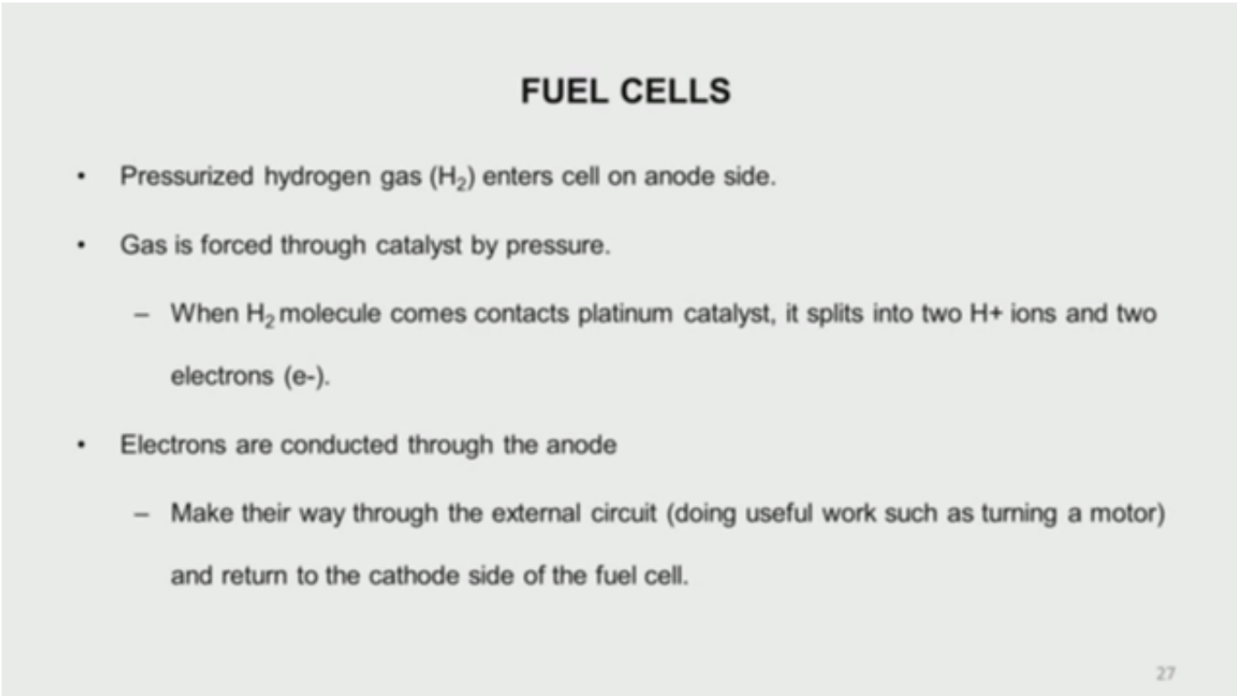

Fuel cells as the name mentioned, basically, it uses pressurized hydrogen gas where the hydrogen enters on the anode side, gas is forced through the catalyst by the pressure, and the hydrogen molecule comes in contact with the platinum catalyst. It splits up into two, hydrogen and two electrons, and the electrons are conducted to the anode, and they go to the -- complete the circuit and that way the fuel cells work.

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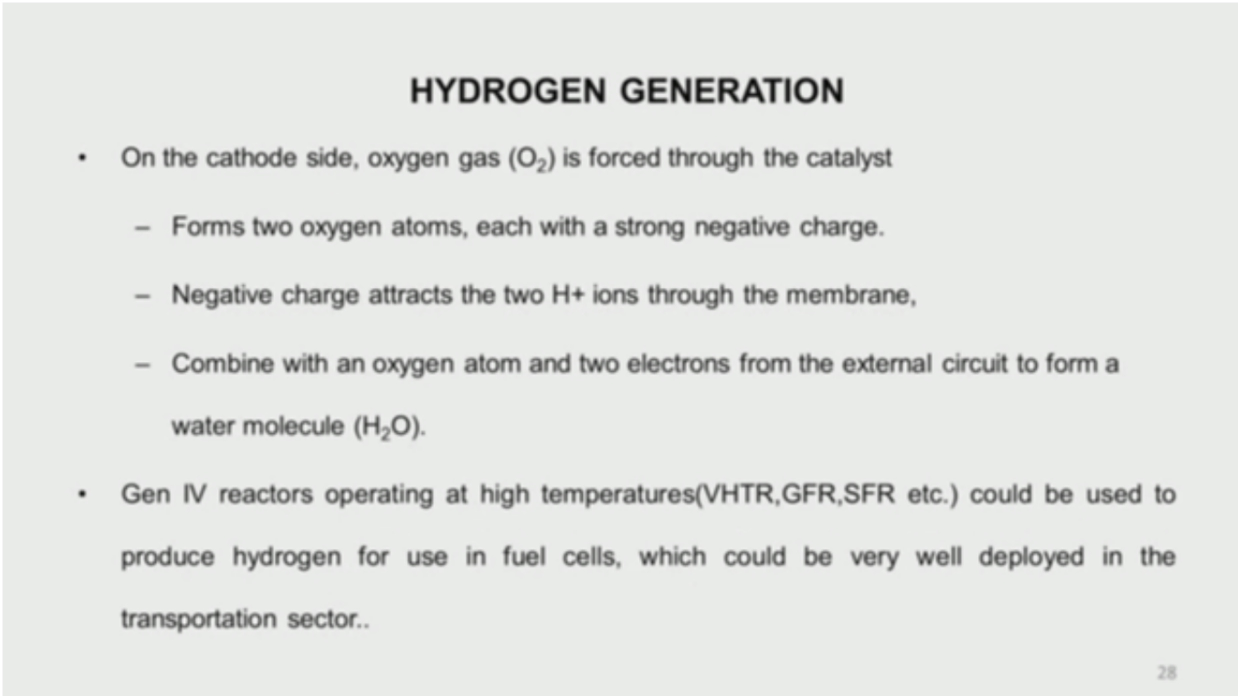

And here this hydrogen generation is where our Gen IV reactors would play a very important role, and as I mentioned in the transportation sector, hydrogen has got a very, very important role.

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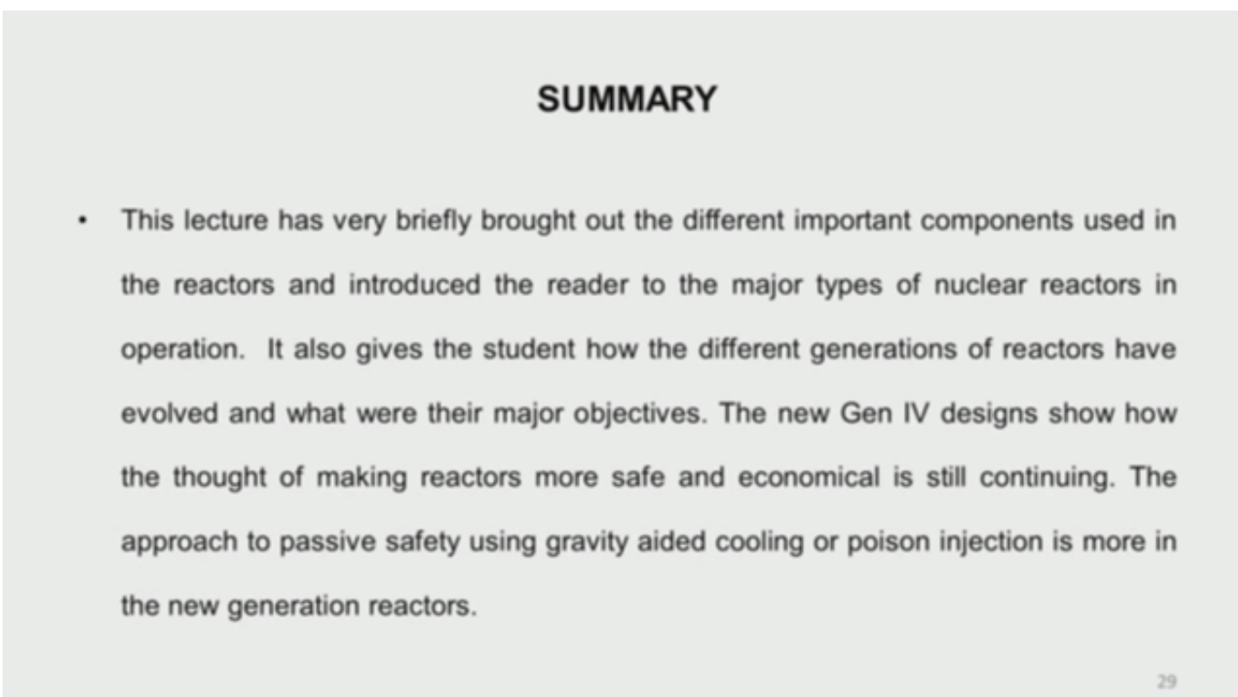

In summary, this lecture we have briefly brought out, you know, in the last lecture, we brought out the different components used in the reactors and the major types of reactors, and now we have also seen how the different generations of the reactors have got evolved, and what is our final focus now on the Generation-IV reactors to make them more safe, more economical, but these reactors will really take shape after about two decades and all our present idea is to use as many passive safety features for shutdown and decay heat removal in these new generation reactors.

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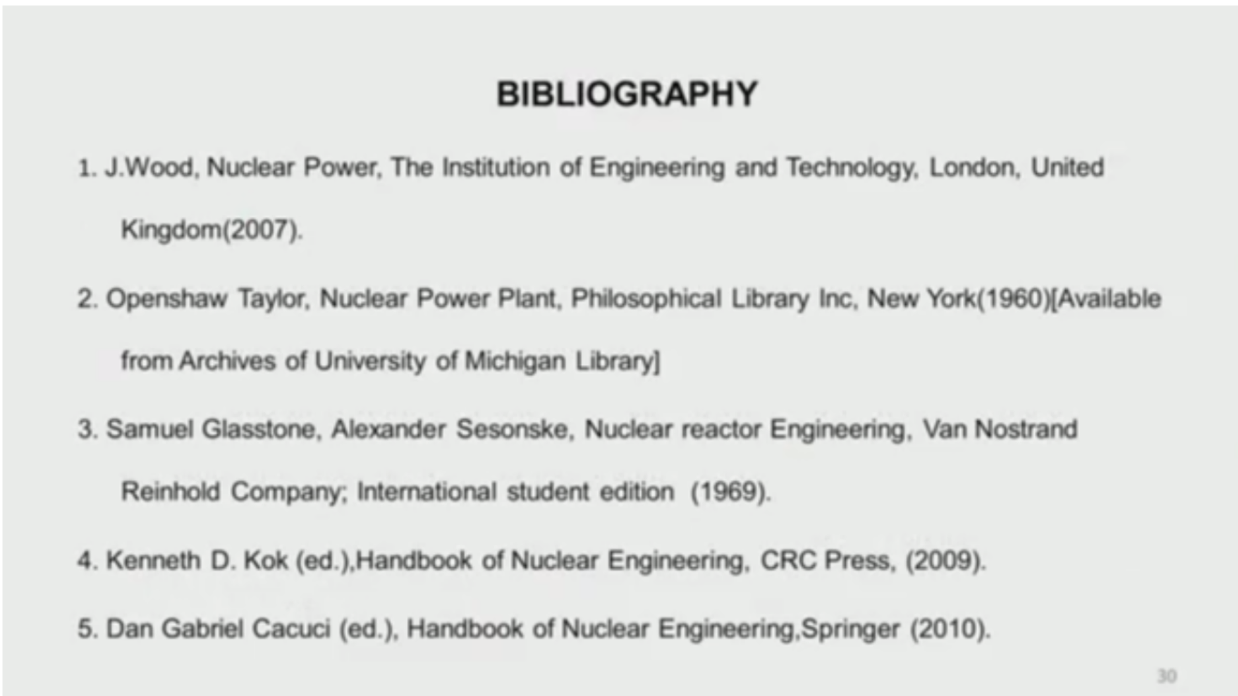

This is to give you a bibliography of the papers which you can see and.

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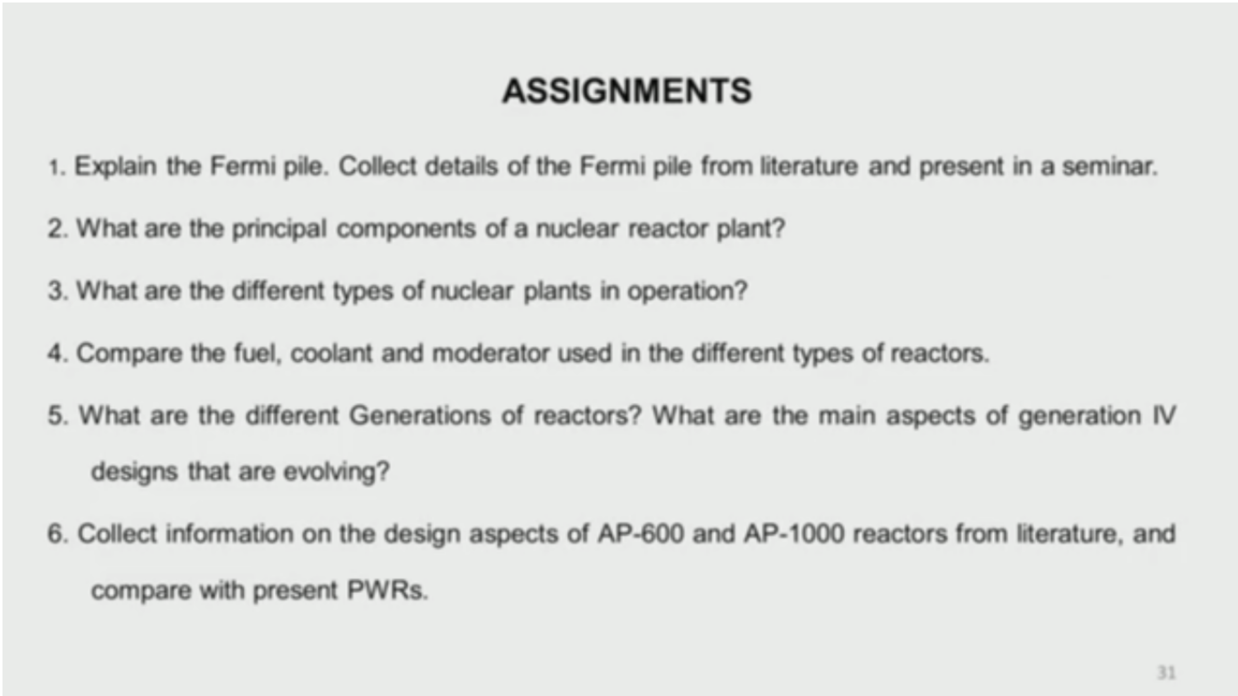

As my usual practice, I would like to give you an assignment, which you can go through and maybe submit it in the next time. Thank you.

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