Fundamentals of Nuclear Power Generation
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Module – 07
Thermal Reactors
Lecture – 02
Evolution of reactors from Gen-I to Gen-IV

Hello friends, welcome back to the second lecture of module 7 where you are discussing about thermal reactors. In the previous module, we have discussed about the classification of nuclear reactors. When you have seen that reactors can primarily be classified based upon three categories, of course, there are several kinds of classifications, but three of them are very prominent and most relevant also.

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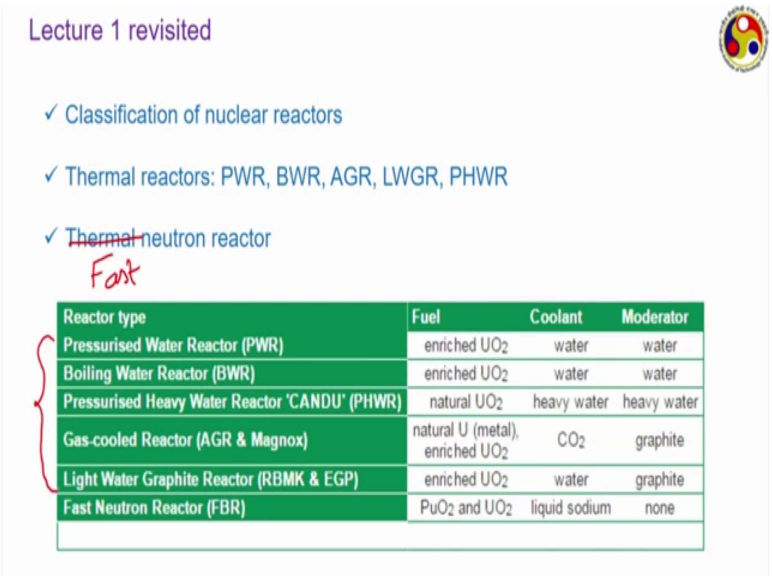

Reactor type	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	enriched UO_2	water	water
Boiling Water Reactor (BWR)	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK & EGP)	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	PuO_2 and UO_2	liquid sodium	none

The first one is based upon the neutron profile or neutron spectrum; accordingly, we can have thermal reactors; which works based upon thermal neutrons, and hence they have a moderator which slows down the neutron from the first neutron level to the thermal level of 0.25 electron, volt energy.

And other category can be fast neutrons where we do not have any moderator, and fast neutrons are used for the reaction. The second type of classification can be based upon the moderator itself, and also the third classification is based upon coolant. Generally, they are related to each other, because in several kinds of design the same fluid is used as moderator and coolant. Whereas, whenever you are using different fluids for moderator and coolant they need to be compatible with each other. Like in pressurized water reactors or I should say the so called light water reactors water is used as the moderator and coolant both.

Also, in certain designs that is also the working fluid in the secondary circuit. Whereas, there are other designs where we have graphite as the moderator and some gaseous material like carbon dioxide or helium is used as the coolant. Then we have discussed about different kinds of thermal reactors. PWR are pressurized water reactor, where I hope you remember that here we use some high-pressure liquid water as the working medium system pressure is maintained; So, as to avoid any kind of boiling of the fluid.

And the temperature is maintained such that, there is about 25 to 30-degree, gap between the maximum fluid temperature and the corresponding saturation temperature. Here some kind of secondary circuit is used, where we have it we may have a different working substance or maybe water itself context to act as the working substance there. Then the boiling water reactor, where water is allowed to boil and the corresponding steam can directly be supplied to a turbine to get the react power output; so, here water plays the triple role of moderator coolant and also the working substance.

This PWR and BWR are the two most common type of designs, then we can also have advanced gas cooled reactors where we have graphite as the moderator and generally carbon dioxide as the coolant to satisfy their compatibility. We can have variations of this AGR as high temperature gas cooled reactors or their so called RBMK designs etcetera. Actually, RBMK is not a gas cooled reactor. There but high temperature gas cooled reactor uses helium as the working substance.

Then we can have that RBMK or LWGR which is a gas cooled. But moderator is not graphite another light water or ordinary water and finally, we can have PHW or the CANDU designs; where we have pressurized who use heavy water as the moderator, as well as the coolant pressurized heavy water. And as heavy water has an extremely small neutron absorption cross section. So, natural uranium can be used in used as the working as the fuel in PHWR or CANDU reactors; however, in the others like PWR BWR AGR or in RBMK. We generally use slightly enriched uranium enrichment level may vary from one-point 5 percent to 5 percent based upon different designs.

And finally, you have discussed about the fast neutron reactors. It should be this one. So, is not thermal, rather here we discussed our fast neutron reactors. Just the working principle, where fast neutrons are used so, there is no moderator. And because of very high energy density, we knew we need some coolant with high thermal conductivity and accordingly liquid metals like commonly liquid sodium. In certain situations, liquid potassium or sodium potassium mixture is used as the working medium. Here also you need secondary sometimes even a tertiary loop to get the actual power cycle going.

This is a combined picture it is probably a correct time to look at this combined diagram. Where we have a PWR and BWR as the 2 most common designs then we have PHWR, the gas cooled reactors. Then light water graphite reactors or that RBMK and the final the fast neutron reactors; as you already know by now that these are the thermal neutrons. These use thermal neutrons assess their thermal reactor, but the first one is the last one is the fast reactor.

And out of this PHWR is the only one which uses natural uranium generally, oxide or some other compounds of uranium. Gas cooled reactors generally used enriched uranium in certain very rare cases they may use natural uranium, but that is uncommon. All others use enriched uranium. In fact, for fast neutron reactors it can use both uranium oxide and plutonium oxide, and here enrichment level can be quite high 10 percent or even higher.

So, the fuel that is used in fast neutron reactors they can be quite costly. And the coolant it is water in both PWR and BWR, and that is why they are conventionally called the light water reactors. RBMK also uses water as the working medium, but the moderator is graphite whereas, in PWR and BWR water itself act as the moderator which I have just mentioned.

In PHWR heavy water is the dual role of moderator and coolant, but whenever we are going for a gas cooled reactors apart from RBMK, it is generally preferred to have graphite as the moderator and carbon dioxide or helium as the coolant. Finally, in fast neutron reactors we do not have any moderator, but some liquid metal is used as the coolant such as liquid sodium.

So, let us now move forward, these are the classical designs of nuclear reactors, and the most common terminologies. Um actually these all these designs are quite old and the concepts of each of them PWR BWR or AGR all came long way back. Sometimes in late 1950's more in 1960's and commercial reactors which operates on PWR and BWR, they most of them started becoming functional in early 70's.

And since then the nuclear reactor technology has moved a long way, and several modifications on these designs several newer generations of these designs have been proposed, but their working principles actually start from these conventional designs only. And then further modifications or improvements were incorporated.

So, in today's lecture we shall be seeing a bit summary of the generation was development of nuclear reactors and a quick launch to some of the most advance reactor concepts at the moment.

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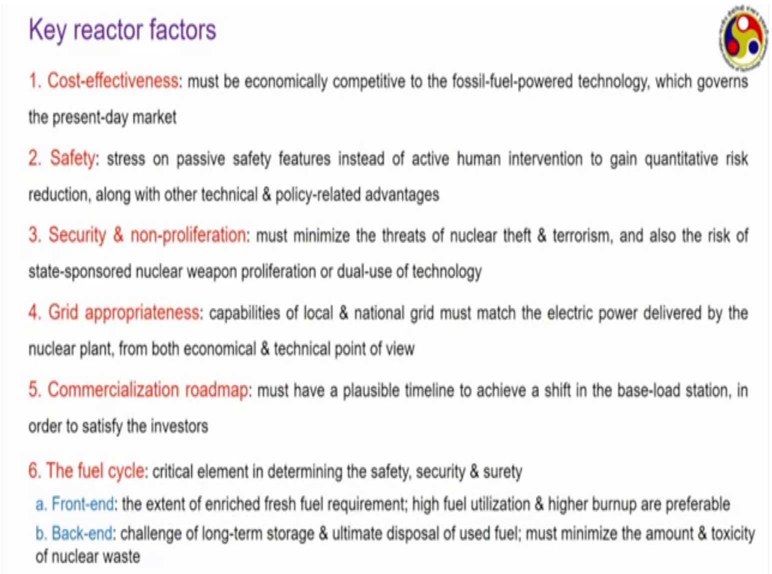

Now, in reactor designs, there are several key factors to keep an eye on. There are particularly 6 factors which must be considered along a several other auxiliary factors. As well the first one is the cost effectiveness. Of course, as huge amount of cost is involvement at the commissioning and fabrication stage of a nuclear power plant and also the running cost being reasonably high, it has to be cost effective.

And as we are looking to replace the fossil fuel base technology by some alternative methods, either renewable energy or nuclear energy, economic point of view that must be compatible with the fossil fuel technology.

Ultimately the government or the private party which is going to set up a nuclear plant that has to take the money from some kind of financers and they have to get the money back. And unless the plant is cost effective and it has a reasonable payback period that is the amount invested can be paid back in 10 15 or 20 years, which is well within the lifespan of the reactor itself, then we cannot go for the such a design. It has to be cost effective and it should have a reasonable payback period coupled with a wide span of life.

Next is the safety. The cry for nuclear safety is prevalent everywhere the stress on passive safety features which does not requires too much human intervention is the need of the or and most of the modern designs are focusing heavily on this passive safety features, where automation can take care of most of the things and not even automation they are depending more on several kinds of natural phenomena such as natural convection to operate important or to tackle day to day operation, as well as several possible kind of accidental situations. We shall be discussing a bit more on this passive safety features later on.

Then, but before I come to the third point related to the safety, another factor I should mention here that, as all of you know the term nuclear always creates a panic to the common people. And accordingly, the government has to be very, very careful about deciding where to go for a new nuclear plant or not, and whenever there is a proposal of setting up a plant and somewhere we generally always find some kind of registers from the local authorities local people and that is true for all the places of the world.

Actually, the nuclear incidents that has taken place nuclear accidents I should say that has taken place in different parts of the world, they have been analyzed by the researchers, and accordingly all the safety concepts has come into play. Like the biggest accident that has taken place in a nuclear history is chernobyl in 1986; which was there are generally different categories on which we put nuclear accidents, and that is put in like category 7 which is the topmost one of the pyramid.

And it is said that the radiation that was leaked to the neighboring areas that time, it is effect still it is effect is still active in that part of former Soviet Union or that part of present Rochelle. And following the chernobyl the development of new nuclear reactors research funding on nuclear technology virtually stopped in most part of the world; Particularly, United States and also in most of the countries in the Europe.

Only in 2000s, 2010s around again the country started to focus back one nuclear technology, and like united states I am not sure about the years, but around 19 around 2015, they set up a new nuclear power plant which was about 30 years since the last installment last installation.

And the credit of that must go to the enhancement of the safety, and now the authorities have started to get satisfied with a newer safety measure that is incorporated into the design. And only if we can convince the local authorities or the common people, that these are the newer safety features that has been incorporate in the design, then it will be much easier to go for a newer installation. So, safety is of utmost important, while the cost part is more important to the financer or to the to the policymakers, safety is something that is more important to the general public.

Third is the security again something that is related to the governmental policies. There is always threat of a nuclear theft and use of nuclear power for terrorism, and also the risk of state sponsored nuclear proliferation or dual use of technology so that must be avoided. Here the dual use I should refer that the same plant is used for both power production as well as the production of weapon grade plutonium.

Plutonium is a fuel that is commonly used in nuclear weapons. And as we have already seen in the previous module that even if we charge or load a reactor with solely uranium is a course of the reaction with course of the operation because of the breeding reaction uranium 238 can get converted to plutonium 239.

And in very trace quantity we can also get plutonium 241 as plutonium 239 may participate in 2 successive neutron capture, and lead to the formation of plutonium 241. Both of them are wind grid materials, and wind grid materials, and therefore, it is possible that a country may go for nuclear weapon proliferation or use the technology for the dual purpose of power production as well as weapon development. And also such kind of technologies is the they falls in some kind of wrong hand then there can be huge destruction.

So, that security is something the government must ensure. 4th something for the technicians grid appropriateness. Present local and national grids that are available, these are always been set up considering the fossil fuel power play stations. As that is the most common mode of electricity generation. Whenever we are going to put a new technology in place, like say wind turbines or solar plants or nuclear plants the, there may be some kind of modification in a grid, but as the grid is expected to receive energy from different kinds of sources, it is more apt for the technology itself to modify itself to suit the requirement for the grid.

Therefore, the electrical power that is going to be delivered by the nuclear plant to the grid should be compatible in the grid and both the national and the local grid should be capable enough of taking that taking that power receiving that power. It both economical and technical factors are involved into this and that is also important from engineering point of view next the commercialization roadmap; It is somewhat related to the first part only.

There must be a plausible timeline to achieve a shift in the base load station in order to satisfy the investors. That is the time from which the first stone is laid, till the moment the plant is going to become fully operational, and is able to meet the demand of it is catchment areas, and then going further till the moment when it is able to pay back every penny to the investors that complete roadmap should be ready.

If suppose the fabrication of a plant starts with a plan of a 3-year manufacture 3-year building stage, and then because of several factors the initial commissioning goes to something like 6 7 years, then of course, that will be a huge loss to the investors. But and also no one will be interested in investing a project where there is no proper guarantee that how much time it is going to take for him to get the money back.

So, this commercialization roadmap should be properly ready and that should also be quite reasonable to everyone concerned. Finally, the fuel cycle, again something for the technician something relevant to our course also. The safety security and surety purpose are the critical elements to be considered in the fuel cycle. Fuel cycle generally has two components, one is a front-end other is the back end. Front end is the initial fuel preparation part. That is associated with the entire mining process of uranium, then transportation and a refinement of that uranium. The amount of enrichment that we need to put into the fresh fuel if we at all going to use some enriched fuel there.

Then the rate of fuel utilization, and the fuel should be properly utilized or the rate should be high. So, that we can minimize the amount of waste production, and also, we can get a higher burn-up higher yield from a given quantity of fuel that comes under the front end.

So, enrichment is a costly technology, and hence how much enrichment we are going to put in that should be properly optimized. Similarly, the fuel optimization fuel utilization I should say and also the burn-up should be high. From both practical gain point of view practical energy gain and also waste management point of view. And second is the back end with deals with this storage and disposal of this used fuel, this should be minimized as I have just mentioned, and also the nuclear waste that finally, comes out of the plant is toxicity level should be low so that it can properly be managed.

So, all these are very, very important factors to be considered, while developing the concept of a new nuclear reactor. In the initial parts or in the early days of nuclear reactor development in 1940's or 1950's, hardly any of them were considered because they are the more focus on the development of the technology itself, but as we are moving forward and we have much better knowledge now about this nuclear reactor technology. So, newer factors are always getting added to this list.

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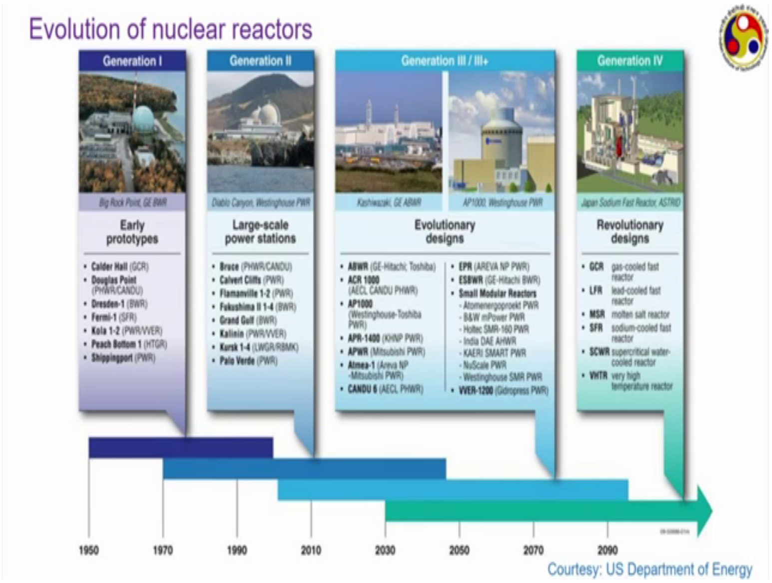

This is a generation wise development of nuclear reactor. As per the terminology proposed by us department of energy, nuclear reactors are classified or separate into 4 categories, starting from generation one to the futuristic design of generation 4.

Generation one concerns only the early prototypes, mostly research reactors are very small commercial reactors or with very low power production, general which an initiative starting something like 1950 and going up to 1970 maybe you can say, then the large-scale power stations that comes under generation 2 which starts his journey around this 1970's and is continuing up to 2010. Most of the modern-day reactors that we get for power production purpose falls under this generation 3 category generation 2 category rather.

Then we have this generation 3 and 3 plus which are modifiers modifications or improvement of the generation 2. The work something started around the 2000 or 2010, and only few commercial reactors have started to appear. But more of them will be coming in next 10 years or so. And finally, the generation 4 which is expected to become operational only beyond 20, 2030 or maybe 2040. They are much more advanced reactors, and they keep in mind all the factors that we have just discussed in the previous slide.

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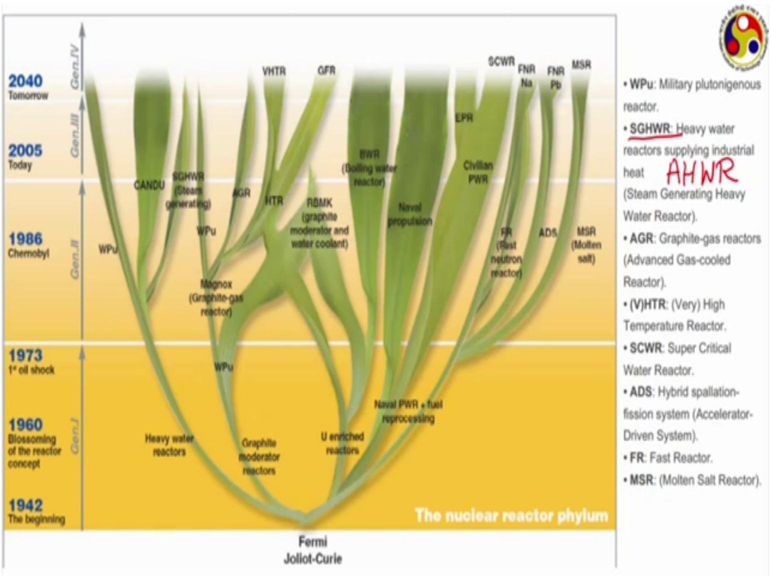

This is another way of viewing the generation wise development of nuclear reactors. Of course, the journey first started, I hope you remember this name by now Joliet curie with which phenomenon they he this particular name was assigned I hope you remember that was artificial radioactivity.

Juliet curie husband and wife together, they Irene curie basically is the daughter of Mary and Pierre curie and her husband Joliet. They together developed the phenomenon (Refer Time: 21:52) radioactivity from which Fermi was the person to set up the first nuclear reactor, under the Manhattan gold project. And from then the commercial reactor started it is journey. The fast groups of nuclear reactors generally are of 3 types or I can say 4 types. The uranium enriched reactors who is generally used water as the moderator and working medium. Then graphite moderated reactors which are related to the gas cooled reactors, and of course, the heavy water that is PHWR, CANDU reactors.

And on this side we may have the thermal reactors. So, research and all this category started as early as in 1950's. And all the classical reactors that we have discussed in the previous lecture, each one of them concerns about one of the arms of this tree. Like PHWR comes here AGR or HTGR comes under here uranium enriched reactors generally as the PWRs and BWRs are also RBMK, and here we have the fast reactors along this.

Now, as the time progressed, and we entered 1970's, then the second generation came into play. And one big factor here was a oil shock in 1973 74, where there was a huge reduction in the supply of oils, and but countries like France were who do not have too much fossil fuel reserve were heavily affected, and then they started focusing a lot on the nuclear technology.

So, there are several newer reactor designs came into picture and also there was a shoot in the number of plants availability. In the heavy water reactor technology, the CANDU came into picture around 1980's and also something comes under a very new group of reactors this SGHWR which is, in case of CANDU reactors, we have heavy water as are both working medium, that is cool rather I should say coolant, and moderator and working medium is common water which works in a secondary circuit.

But in this design, it is a steam generating heavy water reactor that is steam is generally used or ordinary water is used as the coolant, but heavy water is the moderator. One particular technology that comes under this SGHWR, that is called AHWR that is the newer generation of Indian nuclear reactors which are expected to be operational by 2000 25 or 2030, it is called advanced heavy water reactor, it is heavy water moderated, but light water or ordinary water-cooled reactor and that is something coming under this SGHWR category. As we go to these graphite moderated reactors, then we have the graphite gas reactors we have AGR here, and then high temperature reactors going to the very modern generation 4 reactors concepts of very high temperature reactor or GFR.

Then uranium enriched reactors there is a one kind of overlap between graphite moderated reactors in enriched reactor something you have already discussed the RBMK which uses graphite has the moderator, but ordinary water as the ordinary water as the coolant. And they also use enriched uranium so; this is an overlap between these 2 branches. But commonly the enriched uranium went to the boiling water reactors, in one arm and pressurized water reactor in the other arm. Pressurized water reactors have again subsequent chains in the generation 3 and generation 4 going to EPR. And SCWR supercritical water reactor, another important concept under generation 4 technology, something we shall be discussing shortly again.

And finally, in the fast neutron reactors there are several designs proposed under generation 3 or generation 4; like this, MSR FNR or these ads concepts. These are all very advanced reactors, hardly any of them exist in practice, but they are under research for 20 or more years now and is expected to be commercialized very soon.

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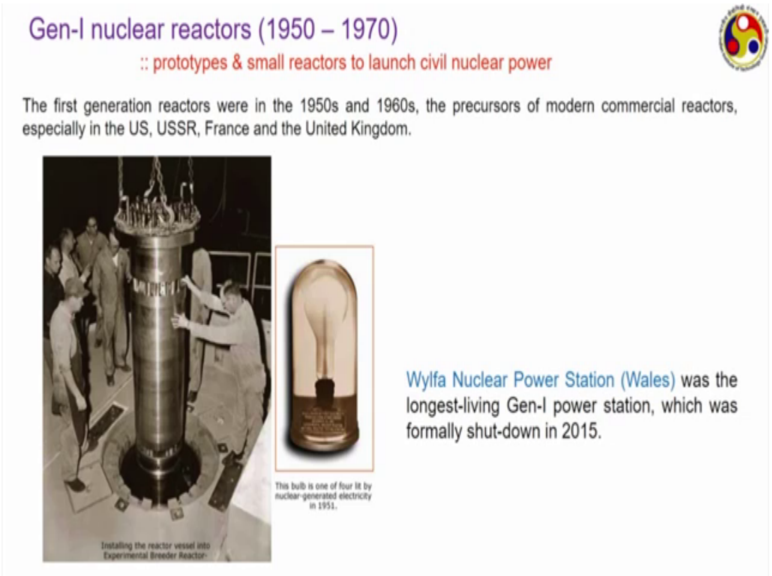

So, the first is the generation one reactors. The lifespan of that can be considered to be 1950's to 1970's. And they concerns the prototypes and small reactors to launch is a civil nuclear power objective was only to get an idea about how a nuclear plant operates hardly any power was available for commercial application.

But focuses more on research or initial development; these were the more designs that was developed in several countries including United States former Soviet Union France and also the United Kingdom. United Kingdom focused more on the gas cooled reactors and the early generation gas cooled reactors came from them whereas, the United States was former Soviet Union focused parallely on light water reactor technology as well as the fast reactors.

This was one of the probably the first breeder reactor or fast neutron reactor that was established in former Soviet Union, and the power that was developed by it in 1851 was just sufficient enough to lead 4 bulbs. You can understand the huge cost that is associated with setting up a fast neutron reactor, the outcome of that was just power enough to satisfy 4 common bulbs.

So, you can immediately get the idea that profit was never the objective rather setting up the reactor or getting aware about the technology was the major focus. Thus, quite a few commercial reactors came into play some of the names are already mentioned in the earlier slide we have shown the generation base use you can search on internet to get some more names, but all of them has what shall been shut down by now. In fact, well before, and the last of one of them, that is the longest living generation one reactor which was at Wales of United Kingdom that was also formerly shot down in 2015. It is one unit was shut down in 2012, and the last one was shut down in 2015.

So, at the moment there is no active generation one nuclear reactors; apart from this particular one. Actually, all of them are shut down well before, but this was allowed to run till the very recently.

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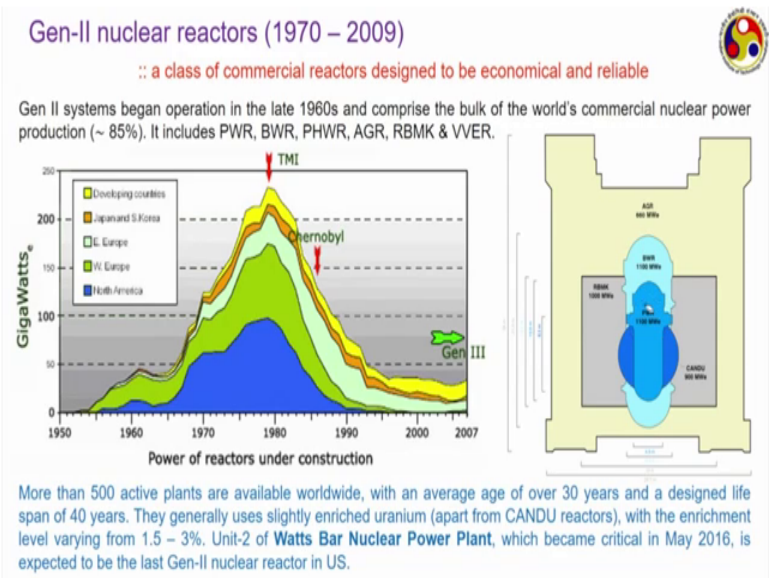

Then we move to generation 2 the research or work on that started in 1970's and went on 2009 or 2010 you can say. These are a class of commercial reactors, which designed to be economical. And also, reliable whatever research observation that we had from generation one, they are all put into place in this generation 2, improvements were suggested, and we had those commercial nuclear reactors.

You can say almost 85 to 90 percent of the commercial nuclear reactors that we have over the entire over the world at the moment, they falls under this generation 2 nuclear reactor category, most of them are about to expire, but still are expected to last for 15 10 to 15 years more.

And it is inverse all those classical designs that we have discussed in the previous lecture. PWR or BWR over the outcome of the light water technology discussed in generation one. The gas cooled reactors Magnus based gas cooled reactors which was tested by UK and certain situation France also led to the development of AGR. The RBMK concept came from USSR or former Soviet Union, Canada developed the concept of PHWR, later on India became involved and wok extensively on this PHWR and so.

But still most of the reactors over the world or of PWR and BWR category with certain countries like Canada and India focusing on PHWR and UK and France focusing on gas cooled reactors RBMK and VVER more used in the Russia. This is a time is growth chart of the power that we are able to get from the nuclear plants falling under generation 2. Category I should not say generation 2 category, it is a general timeline or, but actually the contribution that is coming to this power production are virtually all from the generation 2 category only.

It started around this 1960's where it is started to grow somewhere here, and then around this oil crisis of 1970's, you can find there is a shoot up till the TMI; which is 1979 3-mile island incident that was probably the first reported nuclear reactor accident, which is known to the world. It happens in a small plant in the 3-mile island of USA. The damage was not that much, but from physical point of view, but that was sufficient to warn the scientists that there has to be something wrong with the designs probably need to focus a bit more on safety etcetera. And you can immediately see there is a decrease on the interest in the nuclear reactor technology.

And there was a further growth following chernobyl in 1986. Chernobyl very rudely showed that the safety is something that needs to be careful of, and unlike fossil fuel plants if there is something that is going wrong, then there can be a disaster. Of course, I am not at all saying that something a wrong operation in a fossil power plant will not cause any kind of damage.

But the extent of the damage here is huge and then there is a steady decline, particularly countries like us stopped developing new nuclear reactors. And over this entire period of

1980's and 90's till about 2000, there was hardly any increase in a nuclear reactor development. Rather there is a steady decline as the older plants were shut down, they are not replenished by the newer plants, and hence there is a rapid decline in the total power production, becoming almost stabilized around here and then the generation 3 concept started to coming in. So, it has started to pick again.

And also, the Asian countries like Japan, India and china has become very active in this nuclear field. Particularly china and India are setting of several nuclear plants post 2000 period, and hence you will find I have do not have it here, but there is again a steady growth in this direction. More than 500 active plants are available worldwide at the moment, the number is above close to 600 at the moment, but some of the plants are also getting shut down in recent years and therefore, I do not have the exact numbers. But I can on officially say that the number is something around 550 at the moment with an average age of about 30 years.

And as for the generation 2 design, they are expected to have a lifespan of 40 years, but several of the reactors have already cross 40 years and have still acquired license to run up to 60 years, in that some of the older plants with some modifications in the design have allowed to run till lifespan of 80 years; which is well beyond their design capacity, and therefore, they have paid very well to the investors, and the economic factor that I was talking about earlier, they are have you showing some excellent performance.

This generation 2 reactors almost all of them apart from PHWR, or apart from the CANDU reactors, use enrich uranium enrichment level varies from one point 5 to 3 percent some cases 5 percent. The watts bar nuclear power plant of even United States which became critical in May 2006 is expected to be the last generation to nuclear reactor in United States and probably everywhere in the world.

Actually, this also has a very long history this particular plant. It is commissioning or it is setup started in 1970's, and then following the incident in TMI everything stopped there it was basically this is a second unit of this nuclear power plant then the first unit continued to operate, only very lately around 2010 it was granted to complete that operation. So, it was able to start the fabrication part again, and the in their building and other things were complete around 2014 and it attained criticality around 2016, but there are several issues because the turbines etcetera which were there in the plant, they were those of 1970's. And so, it faced issues with turbine breakdown or conventional breakdown etcetera, but at the moment it is still it is running.

This is a capacity waste view of the nuclear reactors coming under generation 2. You can see PWR is probably the smallest. If we consider reactors producing more or less similar amount of power, PWR core is the smallest as it uses a pressurized liquid water. So, the total volume requirement is quite small. BWR uses a allow uses boiling water it allows water to boil therefore, definitely it requires much volume much bigger volume I should say which is available in this diagram.

CANDU reactors use the calandria. It also uses pressurized heavy water. So, there is no gaseous medium involved, and hence it can also keep the design quite small or the core volume quite small. RBMK use also uses liquid water for it is a cooling purpose, but it has a graphite it has the moderator therefore, it is volume is much larger. It is more than double compared to a PWR core. And AGR it is gas cooled reactors. So, the coolant is gas huge amount of volume requirement.

So, while producing about half of the power compared to PWR, you can see the volume is substantially larger compared to a PWR. But of course, it has it is own advantage like gases are generally cheaper and easier to handle in certain situations. And also, there is no saturation temperature kind of restrictions with gas cooled reactors compared to PWRs or PHWRs. So, they are still used and also the gas that in high temperature gas that we are getting from this gas cooled reactors can directly be taken to a gas turbine thereby avoiding any turbine or condense any other condenser kind of equipments.

So, plant becomes a bit simplified and gas turbines generally have very high efficiency several aspects of general generation one designs were improved in the generation 2.

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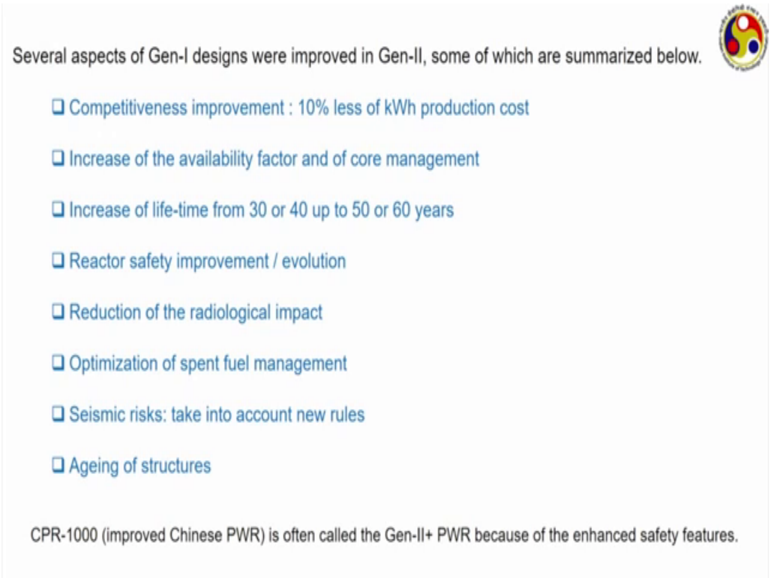

Like competitiveness improvement about 10 percent less fuel is required for per kilowatt of production, or 10 I should not say fuel the overall cost has been found to have about 10 percent reduction for every kilowatt hour. So, that is a huge reduction you can say. The availability factor definitely increased, availability factor refers to the number of days in a year over which the plant is available to give it is complete output.

So, core management was also better. The lifespan whereas, for generation one the lifespan was only about 10 to 30 years here the lifespan was more, as it was designed to go up to 40 to 50, and several plants as I have already mentioned, they are running till 60 years or even beyond.

The reactor safety improvement, it is a feature from every generation, that is more focus on reactor safety and newer designs has been incorporated, but of course, as the chernobyl disaster chernobyl was a reactor falling under generation 2 category it showed that the safety features that was there in generation 2 are not sufficient. Radiological impact that is also rated to safety itself as we move on with generations the radiological impact; that kept on reducing because we had much better containment protection systems and also better waste management systems.

The spent fuel has been managed to give some kind of auxiliary power, and also we have better ways of managing the spent fuel. Now seismic risks several of the nuclear plants are located in zones of high seismic activity, and this seismic risks were something that taken into the consideration, only in generation 2 it was never considered in generation one. Because whenever there is any kind of earthquake, corresponding oscillations may significantly affect the stability thermo hydraulic stability of a nuclear plant.

So, that something that needs to be considered and generally modern day nuclear plants considered the seismic data, for over a period of 500, 2000 years in that concerned geographical location, and considers that in their designs. So, that is a huge database that you can surely consider. And the ageing of structures was also considered with ageing what are the effects that may come in into the reactor designs, how we can modify the or what are the ways we can replenish or change the control material level chemicals shim level, other structural components etcetera, how can you replenish or how can reinforce them, at the time of running itself that are also included.

So, these are all important factors, which led to this huge success of generation 2. The CPR-1000 and improved Chinese PWR is often called generation 2 plus PWR, because it has certain enhanced safety features who I shall beyond generation 2, but probably not sufficient enough other factors rather or not sufficient enough to call it a generation 3 reactor. There so, often the it is called generation 2 plus reactors and it is a concept that came only in early 2000's.

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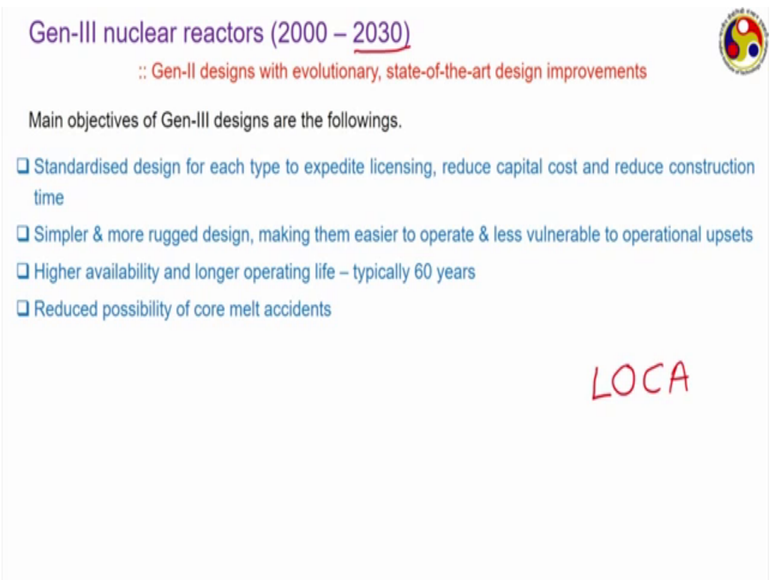

Next, we move to the generation 3 reactors. The concept of generation 3 started around 2000. And I have written 2030 here, but generation 3 nuclear reactors have just started to be commercialized in recent times, only about 5 to 10 percent of the present reactors can fall under this generation 3 categories. But in coming few years there are several more generation 3 reactors in line and hence the generation 3 reactors instead of 2030 may go up to 2050 or 2060. Here the reactors are essentially generation 2 reactors, but with evolutionary state of the art design improvements. Several objectives or several contractors are considered in generation 3 designs. Firstly, standardized designs for each type to expedite licensing reduce capital cost and reduce construction time so.

So, reduction in capital cost and reduction in construction both are most important to attract the investors. And also, the licensing of a nuclear reactor general is a complicated process if some kind of standard design is followed then licensing would be much easy. And again avoiding some unnecessary time loss, simpler and more rugged design; making them easier to operate and also less vulnerable to operational upsets.

Higher availability and longer operating life, it was a 40 years for generation 2 it is at least 60 years for generation 3 expected to be much more. Reduce possibility of coal melt accidents in certain situations, the because of some leakage of radioactive element from the core, or the something sometimes called LOCA. LOCA, Loss of Coolant Accident. Loss of coolant accident, it refers to a situation where suddenly there is no coolant available inside the reactor. It may happen because of certain kind of pumps failure, like all the reasons that we have seen their generally we have pumps to get the fluid back to the reactor and take the heat back.

Now, if certain situation happens or a situation happens or the pump fails, then the coolant will not be able to go back to the reactor, but the reactor because of the radioactive decay it will or the fission reaction rather, it will keep on producing energy, but as the coolant is not there. So, there is no one to take that energy.

That will result in an increase in the temperature level of the reactor material and if no measure is taken then that will finally, mail the reactor. That is something that happened at chernobyl, and also let us partially happened at the at Japan in 2011 the reason for the LOCA was different like in Japan the primary reason was because of the tsunami, there was no power available to run the pump, but in chernobynl it was a design failure.

So, in generation 3 designs, the focus is more on the passive safety features, like even if there is some kind of pump failure kind of situation LOCA is less likely to appear because some passive safety features will be considered.

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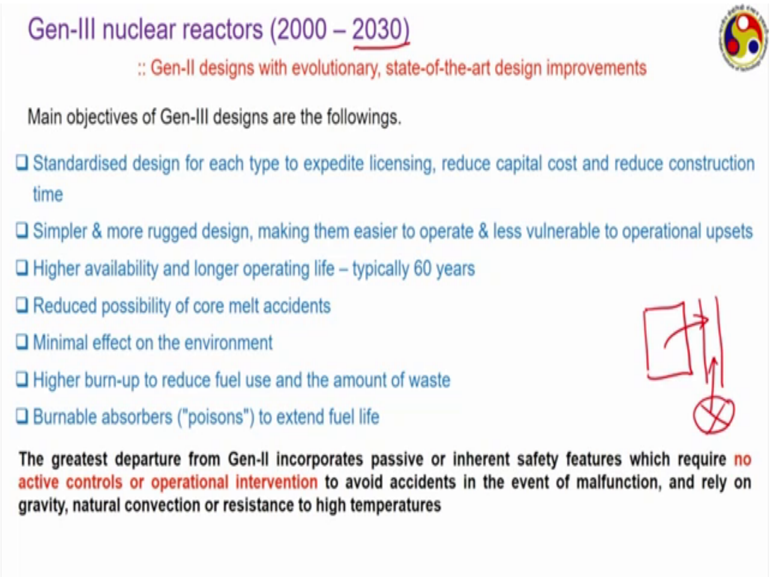

The effect on environment has to be minimum from radiation point of view, and high burn up to reduce the fuel use and also the amount of waste that can get produced. Finally, the concept of burnable absorbers, I hope you remember from our previous module, that along with control rods and chemical shames, burnable absorbers are also used to control the reactors, and or the concept of burnable control the reactivity, the concept of these burnable absorbers came on generation 3 for the first time.

The greatest departure from generation 3 or generation 2 rather is the incorporation of passive or inherent safety features; which does not require any kind of active control or operational intervention. Like you can say, if this is a nuclear reactor which is producing, let me draw it properly say, this is a the this is the reactor core which is continuously producing power. And the power that is coming out of this that needs to be taken by some coolant. This is the coolant which is flowing through a tube in the upward direction or whatever may be the direction we have a the pump here, to drive the flow of this coolant through this channel.

Now, if there is a situation where the pump fails then there will be no coolant flow and that may lead to the LOCA so, I have just mentioned. But if we design it properly then we can take the help of natural convection. Natural convection refers to you probably have started that in heat transfer, as the energy supplied to some fluid, it is temperature increases accordingly it is density decreases.

Now a lighter fluid always likes to move in the upward direction like to stay up, whereas, if a fluid which is a cooler that is also heavier and that likes to move down. And that is a phenomenon that we can always take advantage of, as the fluid is moving upward in this direction, is density is continuously reducing thereby providing it is an added potential to move in the upward direction. Such kind of natural convection is a completely natural phenomenon, it does not require any kind of pump or etcetera, and therefore, even if their kind of pump malfunction any kind of situation, natural convection you are always there to continue the circulation.

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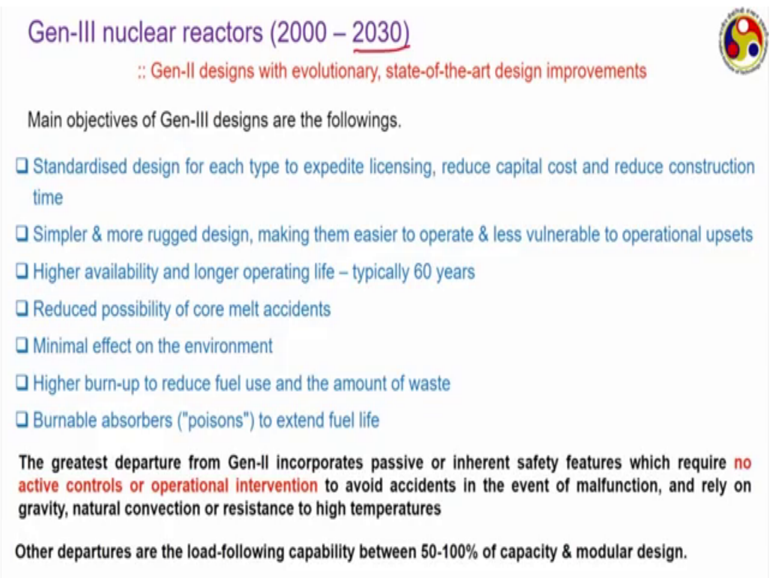

And hence there is very less chance of having a LOCA kind of situation. Another important departure from generation 2 is high load following capability. These reactors generation 2 reactors had very low less load following capability in certain designs did not had any kind of load following capability at all.

So, they can provide only the rated power. But generation 3 reactors are highly adaptable, and they can provide powers from with the 50 to 100 percent of it is capacity. In fact, some of the designs it can come as low as 25 percent of a rated capacity.

Another very important departure is the modular design. Modular design refers to different components of the reactors can be fabricated in different sites, and then they can come together and assemble together to get the final product output. Just like the modular furniture's, that we use nowadays different parts fabricated in different sides or comes in different boxes, and then they are just joined together with nuts and bolts. The same thing was tried with generation 3 reactors quite successfully. That actually led to this reduction in both capital cost and reduction in construction time.

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Gen-III reactors currently operational or under construction

Developer(s)	Reactor name(s)	Type	MW_e (net)	MW_e (gross)	MW_{th}
General Electric, Toshiba, Hitachi	ABWR; US-ABWR	BWR	1350	1420	3926
KEPCO	APR-1400	PWR	1383	1455	3983
CGNPG	ACPR-1000		1061	1119	2905
CGNPG, CNNC	Hualong One; HPR-1000		1090	1170	3050
OKBM Afrikantov	VVER-1000/428		990	1060	3000
	VVER-1000/428M		1050	1126	3000
	VVER-1000/412		917	1000	3000
	BN-800	FBR	789	885	2100

Other Gen-III designs

Developer(s)	Reactor name(s)	Type	MW_e (net)	MW_e (gross)	MW_{th}
General Electric, Hitachi	ABWR-II	BWR	1638	1717	4960
Mitsubishi	APWR; US-APWR; EU-APWR; APWR+	PWR	1600	1700	4451
Westinghouse	AP600		600	619	?
Combustion Engineering	System 80+		1350	1400	?
OKBM Afrikantov	VVER-1000/466(B)		1011	?	3000
Candu Energy Inc.	EC6	PHWR	?	750	2084
	AFCR		?	740	2084
Various (see MKER Article.)	MKER	LWR	1000	?	2085

These are the currently operational generalization 3 reactors, the advanced boiling water reactor concept of general electric Toshiba. These are boiling water reactors, but with advanced features, and they have very high electric very high-power production capacity like the thermal power that we are getting from these reactors of the level of 4 thousand megawatt.

And these are the other reactors which are available the, which all falls under the PWR category. These are improve versions of PWRs and this is a FBWR you can just you can if you are interested you can check all of them individually. But you can check this particular column. The numbers correspond to the thermal power output is huge, all of them are at least 3000 megawatt or even higher. Accordingly, they are able to provide very high electrical output, which can be well above 1000 megawatt something in this range. They are quite a few other designs also which cannot at commercial some of them were not accepted. But several of them are expected to appear soon, we have again the second stage of advanced boiling water reactor.

And PHWR can have a few newer improvements, like this the advanced heavy water reactor of India falls under this category. Actually, and also this a light water reactors which is which can be a modified forms of this RBMK version. This can also possible what some of these designs are some of these designs are not feasible and hence may not appear commercially. You can see some of them proposes extremely high power, output 5000 about 5000-megawatt thermal output that is very, very high.

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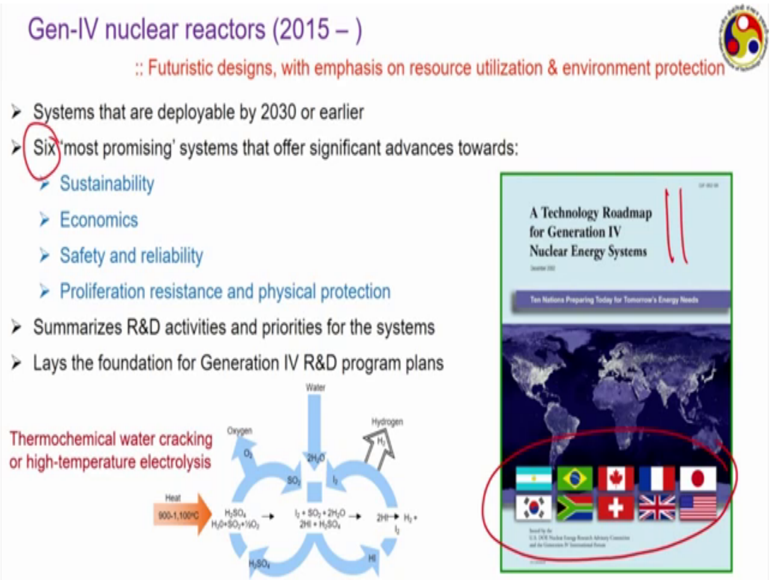

Finally go to generation 4, Generation 4 or futuristic designs with emphasis on resource utilization and environment protection. None of these reactors are commercially available at the moment, but they are expected to appear from 2030 or more.

And they are the reactors which are expected to rule the world in the years to come. There are at the moment 6 designs which I found to be most promising among several others, they offer several advantages like sustainability, economics, safety and reliability and proliferation resistance and physical protection.

Some the R and D activities in happening in generation 4 in different parts of the world have been summarized and priorities are given to the system. Actually something called the in short called GIF generation 4 forum 10 countries are part of this these are the 10 countries which are part of this generation 4 forum, they together I am not sure probably the generation 4 forum came into existence in 2000, and several countries got added to them later on, like Australia is the recent inclusion in 2016, they are discussing behind themselves and exchanging ideas about different possible generation 4 designs.

And then they have set a roadmap this technology roadmap about how generation 4 reactors can be commercialized. So, the 6 designs that I have mentioned there has come from this generation GIF, which we are going to discuss. Another important factor or features of this generation 4 designs is that along with power they are also capable of giving hydrogen as the output. And some of the generation 4 reactors are or actually have this dual objective of both power and hydrogen production.

They use either thermo-chemical water cracking or high temperature electrolysis, where sulphuric acid is broken into hydrogen and oxygen.

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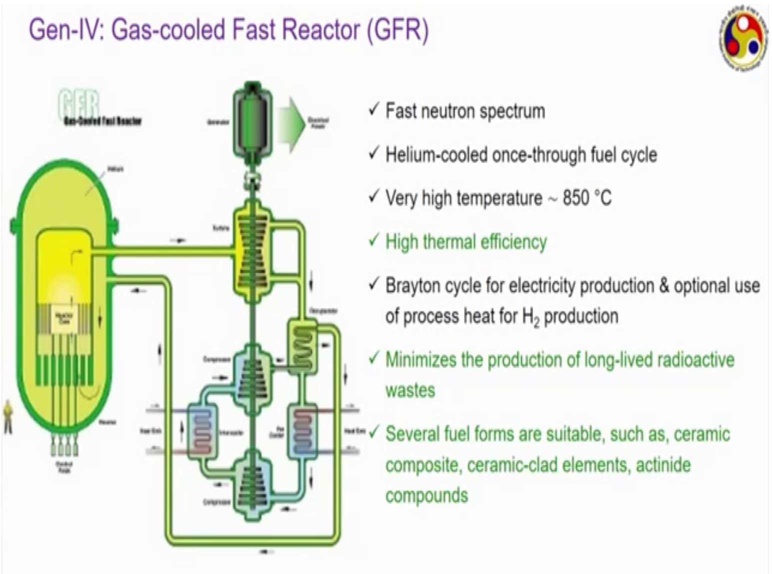

These are the first one of the 6 concepts. First one is the gas cooled fast reactor. It as the name suggests is a fast reactors to use a fast neutron spectrum helium is the working fluid that passes to this reactor, and comes to this is the turbine gas turbine through each it passes, there can be regenerator from which it can go back to the reactor, or we may have compressors to compress them to high power high pressure level, and then getting it back to the reactor again.

This generally can go to very, very high temperature level like all the gas cooled reactors 850-degree Celsius is something that is expected to be the highest gas temperature attained. Because of such high temperature they have very high thermal efficiency, you know, as per the concept of Carnot cycle higher the highest temperature of the cycle higher will be the efficiency.

These cycles like conventional gas turbines, they employ the Brayton cycle with regeneration sometimes maybe inter-cooling as well. And we can also make optional use of the process heat the exhaust heat for hydrogen production, a big advantage is the minimizes the production of long lived radioactive waste; that is, the radioactive waste that we get, it contains the isotopes which has quite short half-life.

Therefore, all those radioactive decays or radioactive emissions will be completed within a reasonable frame of reasonable period of time, and after that the waste will become dormant. It another weak advantage we can use several forms of fuels like ceramic composites or ceramic clad elements sometimes actinide compounds etcetera.

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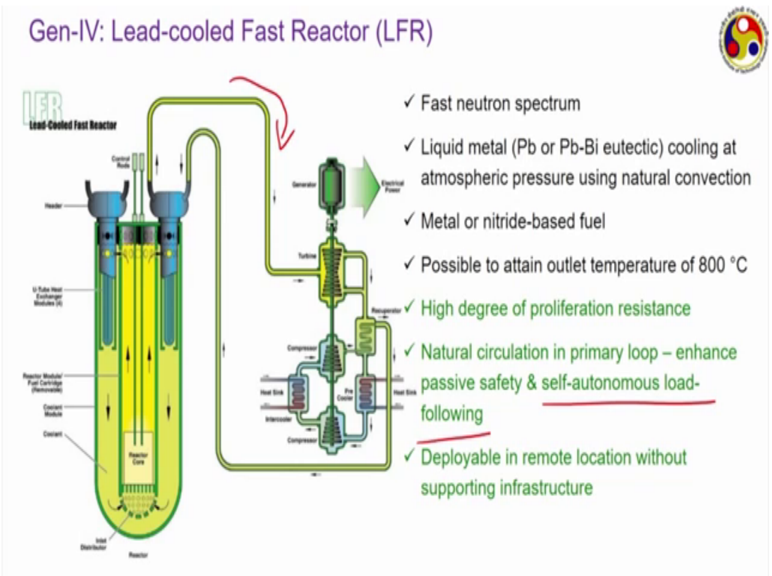

The second concept is lead cooled fast reactor. Again, it is a fast reactor, where we use some kind of liquid metal, liquid lead or lead bismuth eutectic mixture as the coolant. It works under atmospheric pressure, and makes big use of the natural convection. Then metal fuel or nitrate-based fuels are commonly used, and it can also go up to high temperature something like 800-degree Celsius.

The concept is quite similar, and here while the lead is the fluid or lead bismuth eutectic whatever may be that circulates inside the reactor core, and then the energy is supplied to a secondary fluid, which is here generally can be it can be a gaseous one as well which goes to the turbine to keep the electrical power output.

It has very high degree of proliferation resistance which is a big advantage of this one. And also, it is used natural circulation loop. So, enhance passive safety no prime over involved. So, there is no chance of failure because of electricity kind of issues. And finally, it can be deployed to very remote locations also without any kind of supporting infrastructure, because it is a self-sustained plant. And it also has self-autonomous load following capability. So, it does not require too much human intervention for his operation another reason which can put it into remote locations.

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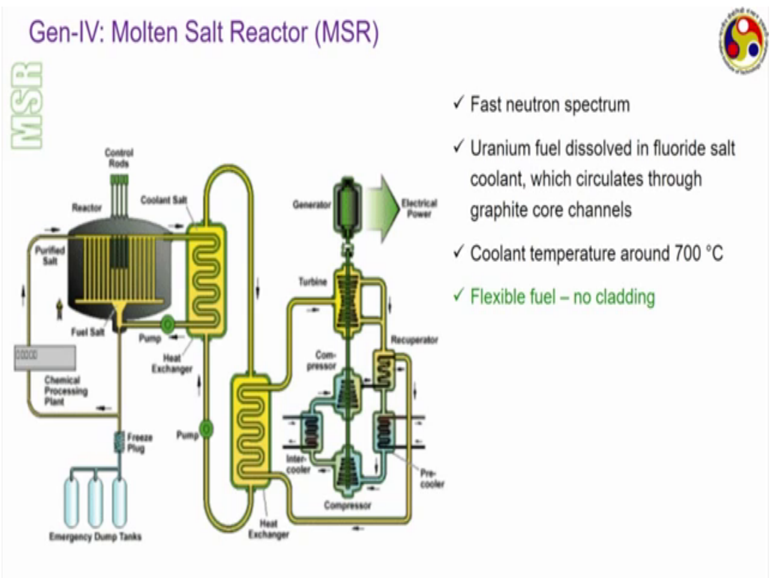

Molten salt reactors again is fast reactor, which uses uranium fuel dissolved in some kind of fluoride salt coolant which circulates through the graphite core channels. It attends slightly lower temperature compared to the previous to something in the range of 700-degree Celsius. And a big advantage is the flexibility in the form of fuel that we are using as we are a using a fuel dissolved into a coolant. So, no cladding is required, and we can use different kinds of fuels.

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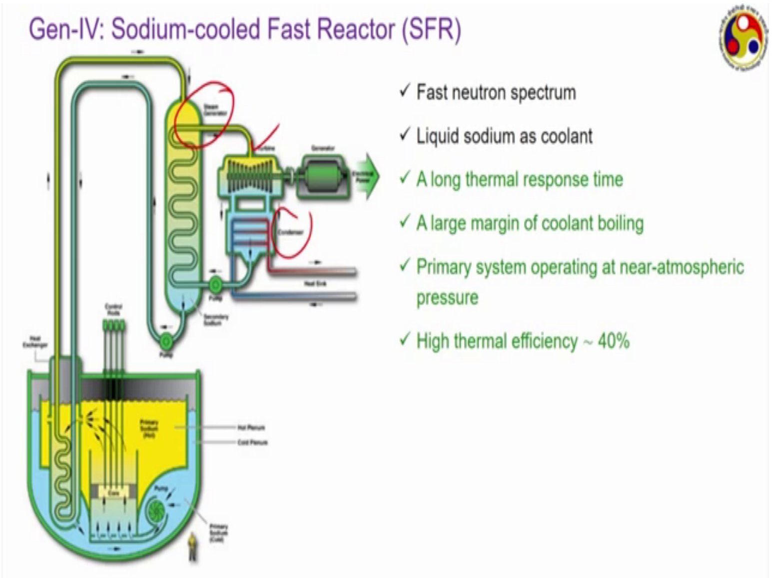

Then sodium cooled fast reactor, as a name suggests again it is a fast reactor liquid sodium is the coolant, it has very, very long thermal response time. So, controlling is very easy the range over which the coolant can be used is quite large, temperature range that is primary system operating at to the near atmospheric pressure, but we need to have a secondary circuit, which generally is a steam power plant, like here we have a steam generator where this liquid sodium transfers heat to water, there were raising steam, and their steam is taken to the turbine a condenser and then again come back just a normal rankine cycle.

Its thermal efficiency is very high of the range of 40 percent which is very high common compared to common present day generation 2 reactors, or even most of the generation 3 reactors.

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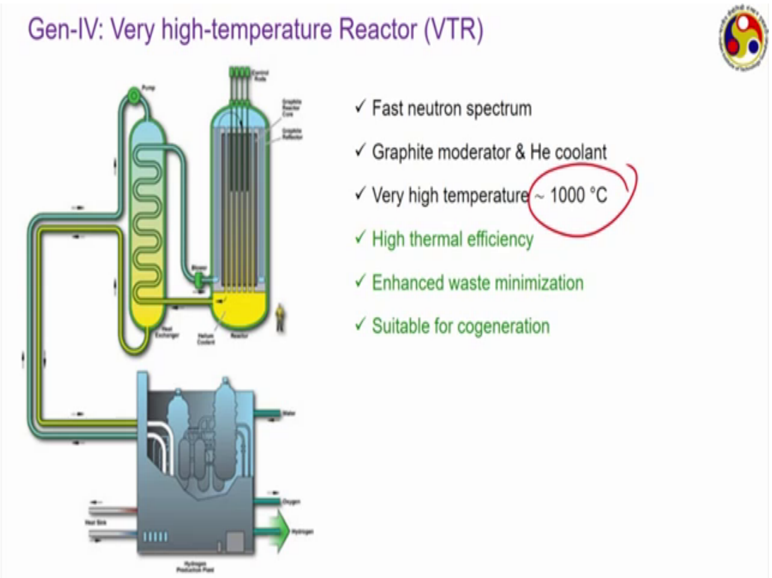

Very high temperature reactor, another concept again a fast reactor, it is an advanced version of the gas cooled reactors; It to the same graphite moderator and helium as the coolant, and can go up to extreme temperature of 1000 degree Celsius.

So, immediately you can get idea that is thermal efficiency will be very, very high. And also, it minimizes the waste production from this, and all like any kind of gas turbines they are suitable for cogeneration they are by increasing a combined cycle efficiency even further.

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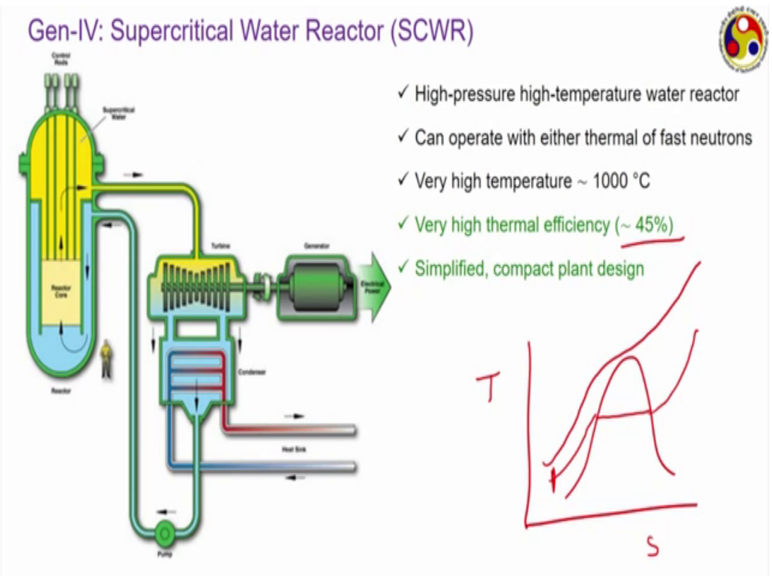

And finally, is the supercritical water reactor another novel concept. It uses high pressure high temperature water reactor. As the name suggests is supercritical that is the water that we use here as coolant that works at a condition beyond it is critical point. I hope you remember that the critical pressure for water is about 22.1 mega Pascal and a critical temperature is 374-degree Celsius.

So, the conditions at which this reactor operates is above that generally in the range of 25 mega Pascal pressure, and temperature higher than that 374-degree Celsius. The big advantage with supercritical water is that there is no exclusive phase change. And so, the water itself can directly be fed to the turbine. So, it is a once through cycle, we can use we can use achieve very high temperature of the range of 1000 degree Celsius, and can use thermal or fast neutrons. And thermal efficiency is the highest among all the 4 concepts and the range of 45 percent.

It is a simplified compact plant design, because as it is supercritical water. So, compared to other water reactors we do not need a separate stream generators or steam separating drums etcetera. Like, if we think about common T S diagram, here in a conventional boiling water reactor, this is a T S diagram that I am drawing in a conventional boiling water reactor, this how it goes it starts up liquid, and then goes through the phase change process and then finally, we get superheated steam.

But in case of is SCWR the line follows like this. There is no exclusive phase change it behaves like a single-phase medium only. And so, it suggests a once through cycle.

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	Neutron spectrum (fast/thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - **advanced high-temperature reactors**	thermal	fluoride salts	750-1000		UO_2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500-550	low	U-238 & MOX	closed	50-150 600-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2 prism or pebbles	open	250-300	hydrogen & electricity

It is a summarized view of the all the 6 concepts that we have discussed, with these two can be considered to be just same. You can see along with electricity some of them can also give cogeneration of hydrogen. Or rather most of them only this is a concept which is only for hydrogen generation and SCWR and sodium cool fast reactors are primarily designed for power production not hydrogen, others can give hydrogen as a byproduct as well.

And the temperature range always very high. Of course, our SCWR it is written much lower, but it has a capacity of going to very high temperature level.

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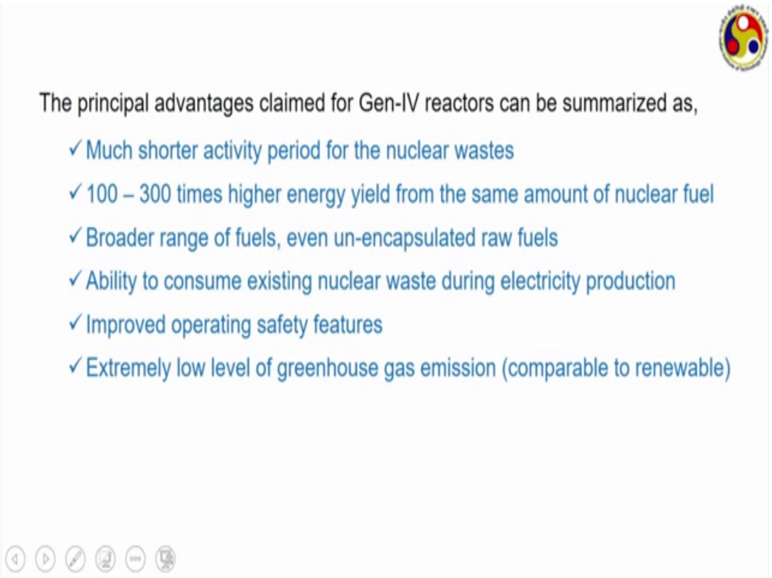

Finally, the principle advantages for generation 4 that we can summarize as which is exhibited by all generation 4 reactors more or less, much shorter activity period for nuclear wastes because the radioactive was that we are getting all those radioactive wastes contain short leave isotopes or isotopes having very small half-life. And hence they can reach a stable situation very, very shortly. 100 to 300 times higher energy will come from the same amount of nuclear fuel compared to the present-day reactors.

Broader range of fuels even raw fuels, can also be used then ability to consume existing nuclear waste during electricity production. That is the nuclear waste that you are getting from generation 2 reactors can also be used as the fuel here. That actually ok, I I am not going to deep into this term, but who probably you remember, in our very first lecture as an advantage of nuclear energy I mentioned the term renewable. This is something that I am renewable comes into picture, we are using the waste fuel for power production.

Improved operating safety features of course, this is the safest designs. These are the safest designs compared to all this proposed till date. And extremely low level of greenhouse gas emission, compared to wind or solar energies.

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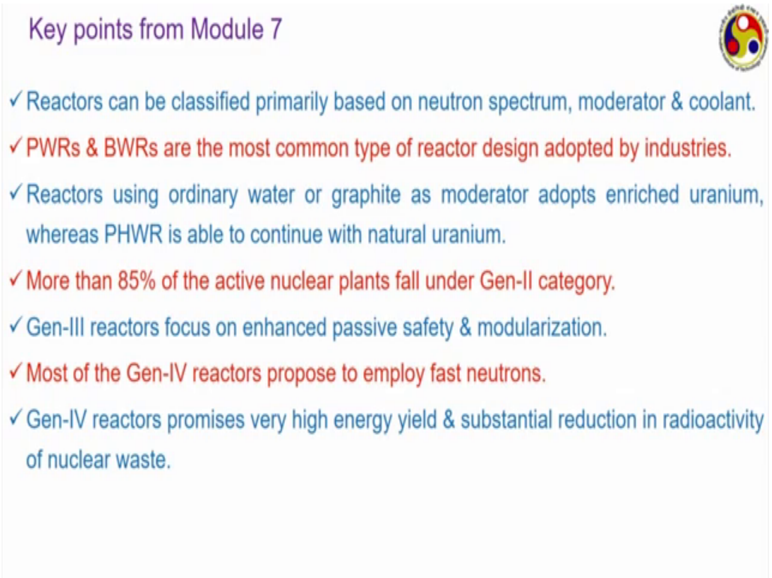

So, this takes us to the end of this module 7, where we have discussed about thermal reactors, we now know that reactors can be classified primarily based on neutron spectrum moderators. And coolants PWRs and BWRs which fall under the generation 2 category are the most common type of reactor designs adopted by industries reactor uses ordinary water or graphite as the moderator.

Like, in PWR and BWR they use enriched uranium graphite in gas cooled reactors also use enriched uranium; however, when we use heavy water we can use natural uranium. More than 85 percent of the active plants fall under the generation 2 category; but generation 3 plants have also started to come in which focus on in a passive safety and modularization.

And finally, most of the generation 4 reactors propose to employ fast reactors. And they promise very, very high energy yield and substantial reduction radioactive nuclear waste. And also, radioactivity or substantial reduction in radioactivity of nuclear waste, and also substantially higher thermal efficiency compared to the generation 2 plants.

So, I hope you have got a broad overview of the thermal plants, thermal nuclear reactors that we have at the moment and also those which are expected to come in next 30-40 years. If you are interested about any particular one of them, you can search the internet there are infinite span of material available, but from the point of view of our course I have to keep it here.

So, I am signing off here from our 7th module. In the next lecture we are going to the module number 8, where we shall be discussing about the breeder reactors.

So, thank you.