Fundamentals of Nuclear Power Generation
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Module – 07
Thermal Reactors
Lecture – 18
Classical reactor designs

Hello friends, we are back with our MOOCS course on Fundamentals of Nuclear Power Generation. And this is a, or at the present we are almost at the halfway stage of this course because we have gone through 6 weeks and 6 more to go. But the 6 modules that we have finished actually in content wise we have already covered more than half of the course.

Because the topics that we have covered in the previous 6 modules; they are more heavy involves quite a bit of mathematics and concepts etcetera. And that is why that has taken more number of lectures then what the next 6 are supposed to get. But the topics that we are going to discuss from today onwards they are probably more important from practical point of view.

Because here; you are usually talking more about the external fields or external factors which are known to any common people. And that will be starting with this particular module; in module 7 where we shall be talking about thermal reactors. In previous 6 modules if I would like to have a quick recap of that; in the first module you have learned about the very basics of nuclear energy production particularly through the concept of binding energy and mass defect.

In the second module, you are introduced to the topic of a radioactivity particularly in the topic of artificial radioactivity you have learned that by striking a nucleus with a suitably charged particle; we can induce radioactive decay even in a stable isotope also or stable nucleus. But the nature of a such a nucleus or I should say the outcome of such an interaction between a neutron and nucleus that will depend upon both the energy level of the neutron and also the nature of the nucleus.

And from there we got the concept of nuclear cross section; only if you start in nucleus can have a fission cross section of say any significance. And in the third module we have discussed about a those isotopes or those nucleus and also a more detailed about fission.

In the fourth module, we talked about the neutron flux profile because generally the energy released during fission reaction is directly proportional to the neutron flux. And therefore, we have discussed about the profile of neutron flux that we can get in different kinds of idealize reactors in order to sustain a critical reaction or I should say in a in a critical reactor what should be the neutron flux profile that we have seen there.

In the module number 5; we actually came out of the reactor a bit or I should say came out of the neutronic introduction part where we discussed about the thermal hydraulics. That is the energy which is produced during the fission reaction how that can get transferred to the coolant that we have learned in the fifth module.

In the sixth module, we again discussed about the control issues particularly on transient operation because some planned or transients or some unplanned transients; how to control that that kind of issues that we have discussed in the sixth module, where you have learned the top learned the terms like a important component of a nuclear reactors such as the control rods, chemical sheaves etcetera and also we have discussed about the role of various parameter such as the delayed neutrons, fuel burn up, temperature etcetera.

So, now we know that in any reactor generally we have four different substances number 1 is a fuel. A fuel is the one which goes through the fission reaction thereby produces the large amount of energy by virtue of its own on radioactive decay or nuclear decomposition. Commonly uranium 235 nucleus is the fuel that is used, but uranium 233 or plutonium 239 can also used as fuel. Second substances moderator; moderator is the one which allows the neutron to go through multiple scattering, thereby converting the prompt neutrons to the thermal neutron level. Or a high energy fast neutrons released from a fission reaction gets converted to the thermal neutron level by repeated scattering or repeated collision with the moderator nucleus.

And that is very important because the conventional fuels like uranium 235 or plutonium 239 as much higher neutron fission cross section, when they are subjected to thermal neutrons. That is why moderator has plays a very important role in increasing the power of two formal reactor. The third substances coolant; the energy which is released by fission that needs to be transfer to the coolant which actually will be interacting with the external world and the net output from the reactor; generally be manifested in the form of energy rise or energy gained by the coolant itself.

And number 4; just we have studied in the previous module the control rods or control electric equipments. Control rods are universally present in any kind of reactor certain other reactors can also have a chemical sheave or burnable absorbers. But they generally all use similar kind of materials like boron or cadmium or hafnium or gadolinium which has very high neutron absorbing cross sections.

So, we commonly can have four types of a elements it is fuel, moderator, coolant and also the control equipments. And we can also have certain things like the fission, products, the neutron poisons etcetera that that are generally only a byproduct of the fission reaction; so, so do not need to be considered at the moment, but the 4 that we have mentioned, depending upon their combination and also their orientation; we can have different kinds of reactors and that is precisely what we are going to discuss in this lecture.

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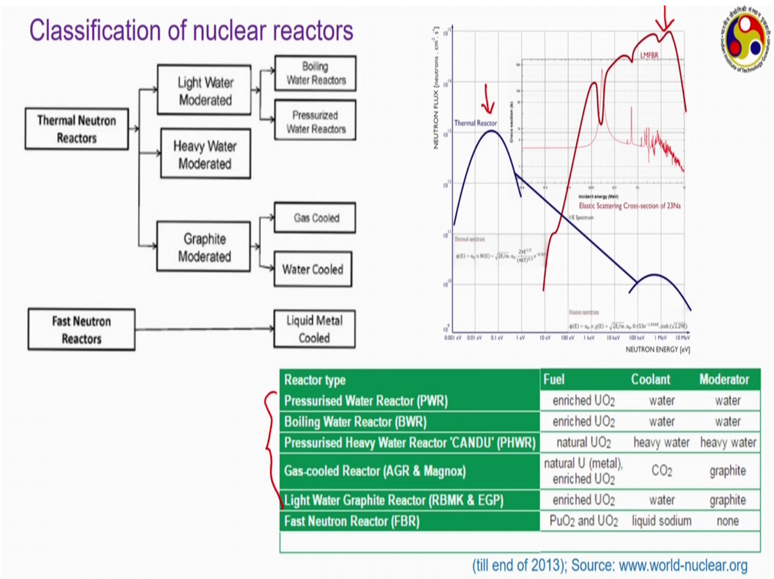

Now, nuclear reactors can be broadly be classified into two categories depending upon what kind of neutrons they use. When they use a fast neutrons, we call them fast neutron reactors; when they use thermal neutrons, you call them thermal neutron reactors. And thermal neutron reactors are the most common one more than 90 percent of the reactors maybe more than 95 percent of the reactors which are available commercially throughout the world are actually thermal neutron reactors; because of certain reasons which usually discussing later on.

Thermal neutron reactors again can be classified depending upon what kind of moderator they are using. Like three principle kind of moderators which are used in thermal neutron reactors are common water, heavy water and also graphite. Here in the slide the term light water is mentioned; I probably have mentioned earlier also that the term light water is frequently used in a nuclear or a field; however, it is not a proper term because this is just the ordinary water that you are talking about. There is of course, heavy water, but there is nothing called light water; still this being such a common terminology is the nuclear field we have to keep on using this.

So, we can have a depending upon moderator we can have three types of thermal neutron reactors; the ordinary water reactor or the light water reactor, heavy water reactor which uses D 2 O as the moderator and of course, the graphite moderator reactor. And the light water moderator reactor again can be classified into two categories; depending upon the physical state of the coolant that they use. It can be pressurized water reactor where the coolant remains under single phase because of high precise temperature or the coolant can undergo can undergo a phase change, then we call that a boiling water reactor.

The graphic moderator reactor again can be of two types; one which uses some kind of gas like carbon dioxide or helium as the coolant, other which uses water as the coolant. The fast neutron reactors by definition it needs to use the fast neutron. So, there is no moderator there and it generally uses liquid metal as the coolant. This is a typical neutron a flask profile and for the thermal neutrons reactor; the thermal neutron reactor generally operates in this zone, where the neutron energy is of the level of 0.025 electron volt. Whereas, the fast neutron reactors operate mostly in this particular zone, where the neutron energy is very high of the level of 1 MeV or can be even a higher.

These are the most common or conventional nuclear reactors that we can find throughout the world. The and as mentioned here we can have generally 5, 6 types I should say Pressurized Water Reactor or PWR, Boiling Water Reactor or a BWR, then pressurized heavy water reactor, gassed cooled reactor, light water graphite reactor and also the fast neutron reactors. Out of this all these 5; they are actually thermal neutron reactors.

Because they use thermal neutrons for to induce the fission reaction, but the last one that is a fast neutron reactor that uses fast neutrons for the to induce the reaction.

And we can also see in the first two that is PWR and BWR; water acts as both moderator and coolant whereas, in case of pressurized heavy water reactor; heavy water is used as both moderator and coolant. In case of gas cooled reactor the moderator is graphite and coolant is a gaseous material like carbon dioxide. And in the light water graphite reactor the coolant is water, but the moderator remains graphite.

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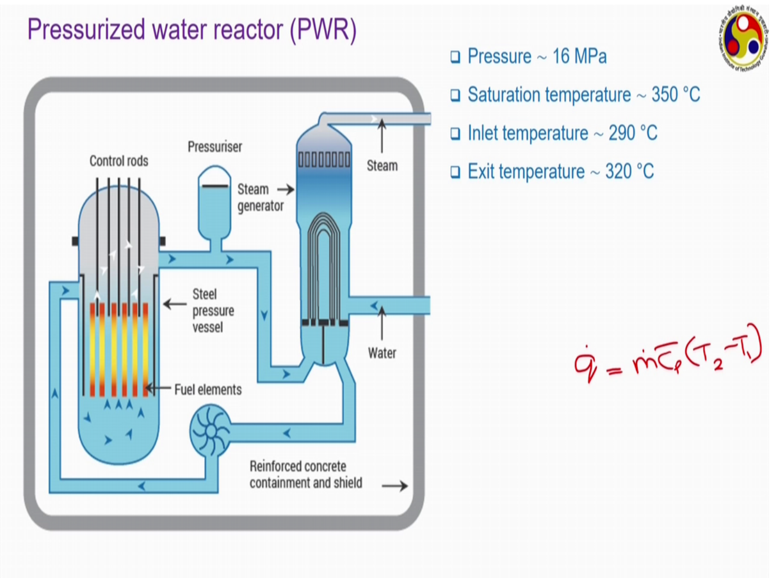

Now, the first one probably the most common one that is a pressurized water reactor or PWR; pressurized water reactor is the most common type of nuclear reactor that you can find throughout the world in different countries like in strains say United States; in several European countries like Germany or France and also in several other parts of the world.

Actually in India the first nuclear plant that was established at a Tharapur, Maharashtra that reactors are also of PWR category. In case of a pressurized water reactor; the main component is a pressure vessel. This pressure vessel generally made of steel is the one inside which all the fission reaction happens. Inside the pressure vessel we may have the fuel elements which can be of the shape of cylindrical rods or maybe a rectangular pallets.

They are placed following certain kind of a orientation and control rods graph the control rod material is generally boron or some compound of boron like boron carbide or boron oxide, which are allowed to pass through the gap between these fuel elements.

So, that they can capture some certain portion of neutrons available there; depending upon their level of insertion. It was mentioned in the previous lecture also; a previous module that in PWR the control rods are inserted from the top. And hence the control rod connecting mechanism or driving mechanism particularly the spider that is mounted at the top of this pressure vessel and this fuel elements and also the control rod they are completely immersed into the moderator. And a moderator in this case is water that is only liquid water; no phase change is allowed in pressurized water reactor and the water that is as coolant and moderator that we are using that must remain as single phase liquid in order to operate a pressurized water reactor.

So, if we follow the diagram; the liquid generally cold water that enters the reactor through a channel like this; inside the channel it passes through this line and then is allowed to move upwards through the fuel or through the spacing between two neighboring fuel rods or fuel pins. And therefore, which is able to capture the energy that is released by the fission of the neighboring fuel particles or fuel isotopes.

So, when it comes out of this fuel bundle; then this same water is at a reasonably high energy level. And if we can maintain the water and a liquid condition then definitely its temperature will be much higher than the inlet temperature. The water comes out on the reactor here and ah; so, between this point which we can mark as 1, which is the inlet for this water and this is the 2 which is the outlet of the water. Between these two points there will be significant difference in the energy level or enthalpy of this water, but physically both of them will remain as liquid.

Now the component which ensures these liquid status is this pressuriser; we shall be talking about pressuriser afterwards. But this liquid water then is allowed to come to a steam generator, inside the steam this liquid water high temperature liquid water I should say travels through a heat exchanging pins or a heat exchanging areas. Outside of that again water is flowing, but that water is not allowed to mixed with the water that is coming from the reactor itself; rather the water coming from the reactor is at a high energy level or a high temperature and therefore, it is able to transfer the energy to the water which is outside, which actually is the coolant and then this water from goes back to the reactor.

Therefore, we can clearly say that in case of pressurized water reactor we are using water as the moderator, as the coolant and also as the working fluid. The steam which is produced in this steam generator this one that is allowed to go through a turbine where it will give you the work output. So, the moderator and the coolant and also these water in the outside circuit all are water from chemical point of view. But the water which is used as the moderator inside the reactor that is that is not the working medium rather the working medium will be water for some other body of a water or a some separate quantity of water which he helpless only in the external circuit.

So, a pressurized water reactor employs water as moderator coolant and also working substance, but the working fluid remain separated from a moderator. Now in order to maintain this liquid status; we have to maintain a very high pressure and pressurized water reactor operates at a high pressure level of something like 15 or 16 mega Pascal; that time pressure also comes from there or pressurized as you have seen. Now at such high pressure level of 16 MPA, the saturation temperature water will also be very high which is somewhere around 340 to 350 degree Celsius.

Now, the water which is which is entering this reactor core; it is at this particular point this water temperature is something like 290 degree Celsius. And then the flow rate of this water is controlled such that and the exit the temperature is limited something to 323 25 degree Celsius which is well below the saturation temperature of 350 degree Celsius.

Now if we have some idea about the energy produced in the reactor that is q dot then we can always write an energy balance equation as m dot c p into T 2 minus T 1; where m dot is the mass flow rate of this water coolant, c p bar is the average specific heat and T 2 is the outlet temperature at this point whereas, T 1 is at this particular point.

So, if we have some idea about this q dot and a c p being generally a known quantity; then you can control the m dot by a pump which is mounted here to keep this temperature difference that is T 2 minus T 1 to some reasonable value of 25 to 30 degree Celsius. And accordingly the outlet temperature of the coolant which is expected to be a maximum temperature, that remains well below the corresponding saturation temperature; thereby allowing single phase evaporation throughout the loop.

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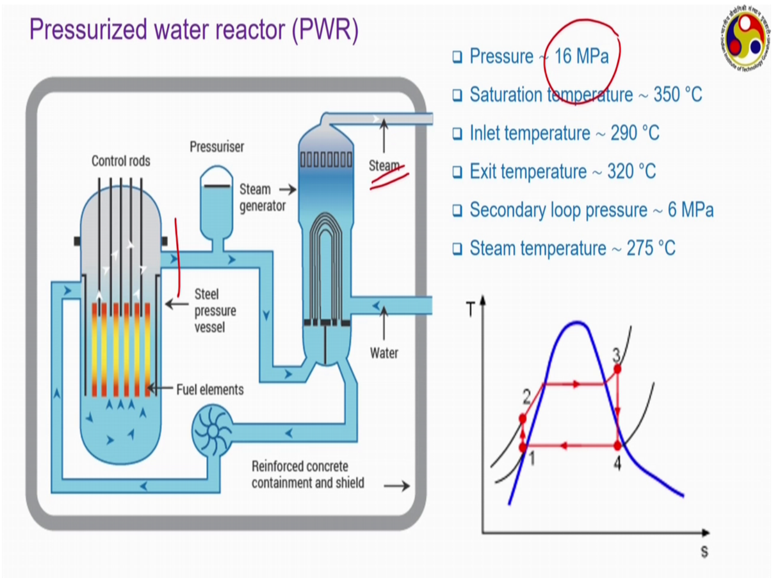

The secondary loop where this water which is coming from the reactor is transferring its heat that the pressure is something like 6 mega Pascal only and corresponding to that temperature saturation temperature is around 275 degree Celsius. So, the steam coming out through this particular point will be having a temperature around 275 degrees Celsius and a pressure of 6 mega Pascal. Because the temperature of water coming here in and entering the steam generator is of the level of 320 degree Celsius; a reasonable temperature difference can be obtained across the heat exchanging surfaces here.

The pressure that; this steam is then taken to a Rankin cycle which a conventional Rankin cycle of which may also contained a reheating or super heating and even regeneration also. But that part is external which is similar to any conventional coldest power stations um; in nuclear power plant we only get as the operation between this 0.2 to 0.3 which is in conventional cold based power station is the process that is running inside the boiler.

But one difference with the cold based power stations to the PWS is that the amount of energy released is much higher compared to the energy that is in energy released during fission is much higher compared to the energy released during cold combustion.

But the question is how can we ensure this system pressure of 16 mega Pascal? Once we can ensure this high pressure corresponding saturation temperature is already high and therefore, by limiting the exit temperature; the temperature this point this T 2, we can we can easily easily heat up the fluid or the steam here to any temperature of our choice, but the important part is we have to control the pressure that 60 MPA.

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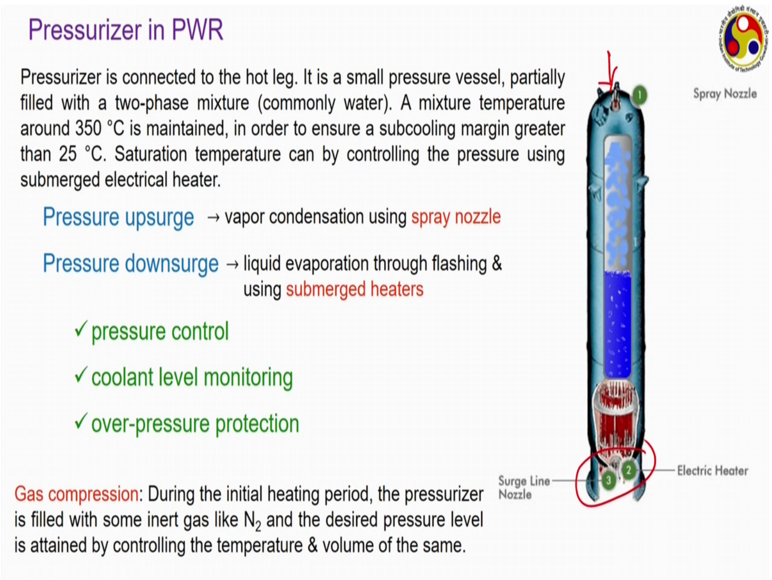

And for that purpose we have a pressurizer; this is the pressurizer that we have in a pressurized water reactor. A pressurizer is connected to the hot leg a convention in this leg is called the cold leg and this one is called the hot leg because this hot leg carries energy of much higher level.

The pressurizer is connected to the hot leg through which it is able to come in contact with the a high temperature fluid. It is actually a very very small pressure vessel its volume is very small compared to the volume of the pressure original pressure vessel, but this small pressure vessel is partially filled with a two phase mixture which commonly is water itself.

Therefore, it can be said to be partially filled up with a liquid water and water vapor mixture. We can maintain a coolant a mixture temperature of 350 degree Celsius which automatically can balance the pressure to their targeted pressure of around 16 mega Pascal. Because during a saturation state or whenever we are dealing in the saturated mixture pressure and temperature are not independent rather they are depending on each other once one of them is fixed the other has to be fixed.

And therefore, by maintaining the certain temperature in a like 350 degree Celsius; we can maintain a pressure of 16 sorry 60 we can maintain a pressure of the order of this 16 MPA inside this reactor. The saturation temperature also can be controlled by varying a pressure and therefore, we can maintain a fixed pressure and temperature inside the pressurizer. Because of this two faced nature of the fluid which is bound in this pressurizer; it is able to control the pressure inside and also it can absorb any kind of pressure up search or down search which may appear during any operation.

Now, when there is where there is a pressure up search that is there is a very small increase in the pressure inside the actual pressure vessel, then that will cause a rising the water level inside this pressurizer; water the liquid part that being incompressible in nature. So, there will not be too much change in the volume rather the water level inside this will rise a bit. And once the water level is rising that will result in a reduction in the volume available to the vapor phase which is here.

So, the vapor phase will get compressed a bit and whenever the vapor phase gets compressed; we have one spray nozzle mounted here. This spray nozzle gets activated and the spray nozzle now sprays some cold liquid water on on the vapor somewhere here; the spray nozzle will put the spray somewhere here there we condensing some amount of vapor. And once the vapor condenses; so, the pressure of these vapor part reduces accordingly it can it can able to capture or retain a new equilibrium corresponding to this new position of this free surface.

Similarly, whenever there is a pressure down search; if the pressure inside the container main reactor vessel reduces; then that will also draw a little bit of liquid out of this pressurizer and so, the pressure there is now higher volume available for the vapor which is present a higher volume of vapor available which in this portion. So, this for vapor we will try to expand, but as the pressure has fallen, but both liquid and vapor part remains at a saturation temperature corresponding to the initial higher pressure. So, some liquid from this free surface will try to evaporate and occupy that portion thereby gaining a equality; equality or equilibrium in terms of pressure, I think I told something wrong I would like to correct this once more.

Whenever there is a pressure down search there will be a reduction in the free surface level. So, the free surface say has come down here; so, now, larger volume is available for the vapor phase. And hence the pressure on the liquid surface that also reduces and because of that some liquid from this portion as both liquid and vapor part are already on the saturation temperature. So, that will evaporate or that will flash into vapor and occupy these portions, thereby contributing more molecules to the vapor part. That increases the pressure in the vapor part and hence is able to attain the liquid or the inter system can go back to its original position.

If the flashing itself is not sufficient then we may have submerged electrical heater here. This electrical heaters also can get activated and heat of the liquid thereby leading to some further evaporation of the droplets and getting the pressure level back to the original one.

So, pressurizer serves several purposes and the first one is the pressure control like I have mentioned both pressure up search and down search can we maintain. Another function done by the pressurizer is the coolant level monitoring; during the pressurizer is mounted at the top of the pressure vessel which is likely to be the highest location of the plant. And hence if the pressurizer is having sufficient amount of liquid then all components which are placed at a lower elevation has to must have the must have sufficient amount of liquid present. Therefore, that just by observing the coolant level inside the pressure vessel, we can know the pressure of or I should say we can ensure that what there is sufficient water throughout the reactor system.

And the third is over pressure protection; somewhere here on the top of the pressure vessel there will be a safety wall. If there is a certain overpressure in the system which the pressurizer is also not able to take care of it this overpressure protection all opens allowing some steam to escape. You can think this one or you can to be analogous to the safety form that we can have in a pressure cooker. Whenever the pressure inside is high then the safety valve opens allowing some steam to escape and there we gains a gains the equilibrium back.

However if the control valve is not sufficient; if the safety valve is not sufficient they will be another emergency protection valve on the lead of the pressure cooker. So, in case of emergency that opens and having some further release of a vapor phase; this over pressure protection is also somewhat similar kind whenever there is some excess pressure which the pressurizer is not able to handle. Then it this overpressure valve will open which is connected generally to a series of series of pipings finally, leading to the cold body of a certain fluid generally water and from there it can come back to the pressurized water reactor again.

Ah, But during initial phase of a PWR operation or a when we are switching on a plant; then there is no vapor present inside the pressurizer. So, to increase the pressure inside the pressurizer and also inside the entire system as a whole; the gas compression is preferred. Like the pressurizer is filled with some kind of inert gas like nitrogen and then by heating we can reach the desired pressure level because we are controlling both the pressure and the volume of the same.

So, the pressure inside the pressurizer keeps on increasing and once we reach the desired level we can stop this pressurization process. So, pressurizer is the most common type of reactor and there are next one in line is the boiling water reactor.

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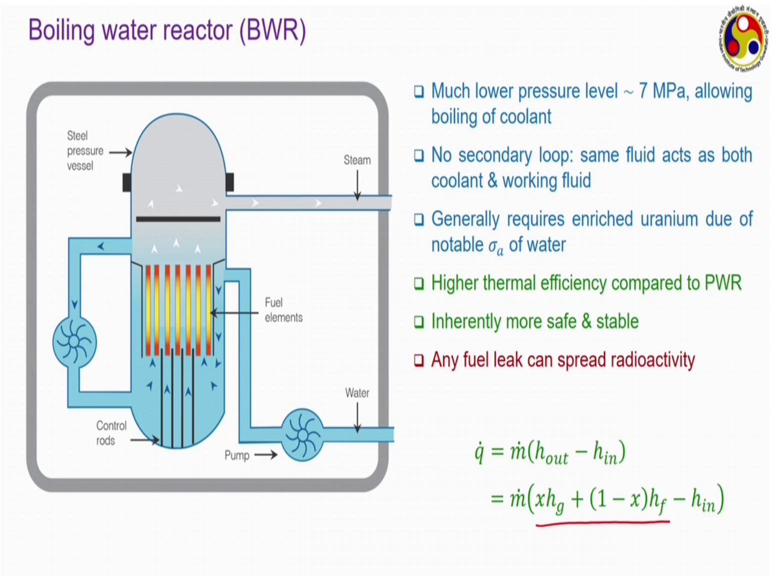

A boiling water reactor is the counterpart where again we have a big pressure vessel just like this, but inside we do not have any pressure pressurizer kind of component here which can control the pressure. And therefore, once the heat is supplied the liquid temperature can increase up to the saturation temperature level and may start boiling.

So, in case of boiling water reactor the liquid which enters the tank some a point say somewhere here; it or if I draw properly it is entering the tank from somewhere here like this. It is again passes through the it again passes through this fuel fuel elements there were getting heated up and invariably that energy received by them is sufficient to call them vaporized or partially vaporized at least.

So, they come they come out of this fuel clusters a mixture of liquid and vapor. The vapor phase is separated by some kind of separating element; we may have a separator drum also. So, it is separated from there and the vapor phase is allowed to go out where the liquid phase comes back by this circulation line. So, boiling water reactor is also very classical design and old designs used in an a several countries very very successfully and the reactor rating can also vary a lot um. As we do not need to a suppress the boiling part; so, we can operate at a lower pressure level of 7 mega Pascal which allows the boiling of the coolant inside the core.

Then no secondary fluid is required here the same fluid is acting as a moderator, coolant and also the working fluid. Because a steam which is produced here the steam inside the reactor is directly going to the turbine from the after that are going to pass to the condenser and then the result in liquid will again come back to get pumped back into the reactor which is here; which is the which can be viewed as something like the feed water or recirculation water. This boiling water reactors generally uses enriched uranium because of two reasons.

Firstly the water that we are using water has little bit of absorption cross section which may be small compared to several other isotopes, but still it cannot be, but still if we use natural uranium; then we and we shall find it very difficult with the criticality. And it generally gives higher thermal efficiency compared to PWRs also much more safe and stable from design point of view; as we are operating in a big pressure vessel um. The size of the pressure vessel being much larger; any up search or down search in the total volume flow rate can be taken care of very very easily.

But one big problem with the boiling water reactor is that; if there is in leak in the fuel side, then the radioactive elements or the fission decay products can come into the moderator stream. And when this moderator is starts boiling then the corresponding water vapor which is going to the turbine through this line that may also carry those radioactive isotopes.

Thereby they will making a big chance or a big probability of radioactive leakage to the external circuitry. That is one big drawback that boiling order reactor may have; that problem is not there in pressurized water reactor because the water that is used as moderator and coolant is remaining inside the pressure and pressure vessel only that is never going outside.

This is the corresponding energy balance equation q dot equal to m dot into delta h and delta h can be written in corresponding form corresponding mixture from where it refers to the mass fraction of the vapor phase and 1 minus x refers to a liquid fraction of the vapor phase the mass fraction of the liquid phase.

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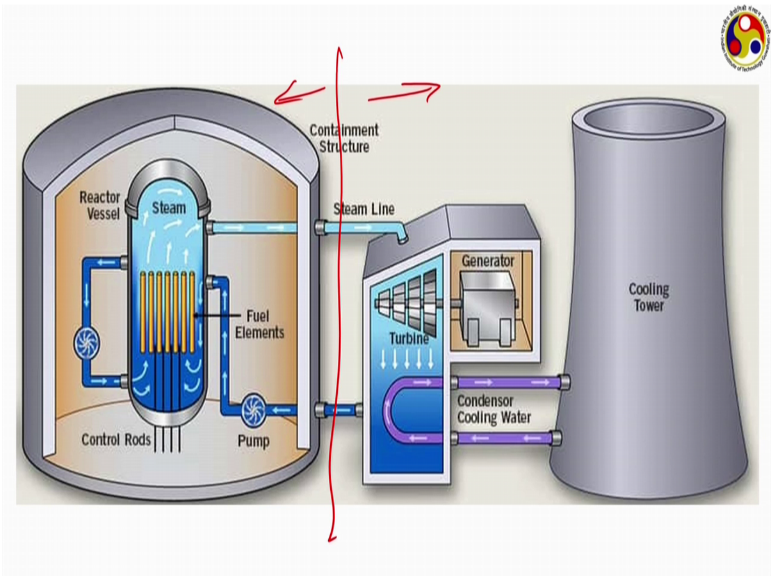

This is the complete circuitry which actually is true for both PWR and BWR; this is the reactor side, this side and this side is the external circuit which is essentially the same that we get in case of a cold based power stations. The steam originated either directly inside BWR or in the secondary loop associate PWR that is supplied to a turbine which generally the multi stage turbine; after expansion it goes to the condenser. And after condensation it can come back to the boiler through the feed water pump.

Here one another point of interest to note that the controllers in case of a boiling water is mounted below whereas, in case of a PWR they mounted from the top. As in case of a boiling water the upper part of the vessel is covered only by the vapor phase. So, there

there will be no point using a control rods there; literally much more easier to control the reaction if we are there inserted from the bottom side.

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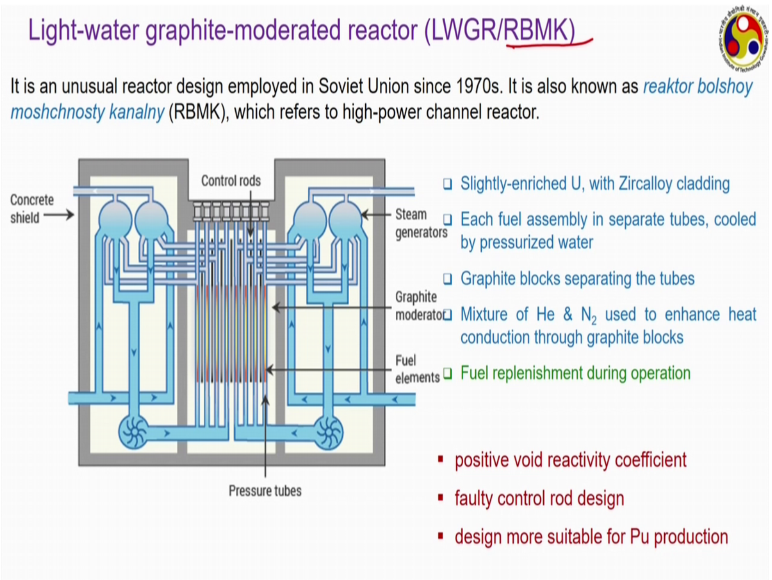

Next we come to a very interesting reactor that is called light water graphite moderated reactor LWGR, but it is an unusual design which was conceptualized in the form of soviet union in 1970s and they give a Russian name which called for as an (Refer Time: 32:54) from the generated from that is also called RBMK reactors which as per literal transmission refers to high powered channel reactor.

In case of a light water graphite moderated reactor, as the name suggests here the cooling medium is ordinary water, but the moderator is graphite like in both PWR or BWR the same material which is water was used as both moderator and coolant, but here we are having them a separate quantities. It uses slightly enriched uranium with a zircalloy cladding and each fuel assembly is put in separate pressure tubes like here; this is at each separate pressure tubes inside which we are having the fuel. And pressurized water is allowed to flow through the gaps between these fuel tubes thereby taking the energy produced during fission reaction.

The graphite blocks are used graphite is the moderator. So, graphite blocks are used to form some kind of structure within which this fuel assemblies are placed in tubes. And also conventionally a mixture of helium and nitrogen gas are used to enhance the heat transfer or heat conduction to the graphite blocks, this RBMK design is unique in several sense.

Because this is the only reactor design which uses graphite and water inside this and which itself can be a difficult combination to handle. And there are also several other issues one big advantage that they proposes is the online fuel replace replenishment as the fuels are placed in the form of separate pressure tubes. So, even during running period also we can easily remove one or two tubes and we can replenish them with phase fuels which the advantage which was not present in case of PWRs or BWRs because they are work on pressure vessel type of concept.

And everything inside the vessel needs to be stationary before doing any kind of refueling, but the these are the problems with RBMK design. One is the positive void reactivity coefficient; in the previous module we have discussed about the void reactivity coefficient and it is has to be a negative quantity, but RBMK designs gives a positive void reactivity coefficient. The control rod design was also faulty and the design that that are used in RBMK, actually are the design that is used for plutonium production, but here the objective was to produce power.

So, the same design can be used for both plutonium production power, but generally the power production is the one that is a objective of a reactor. And therefore, this design corresponding to plutonium can also be a quite difficult to one to handle. Actually there are out of all the nuclear accidents that has taken place throughout the world over a last 3, 4 decades; 3 of them are generally most well known. One is the 3 mile island at of us in 1979, other the very distant one at Japan in a Fukushima power stations in 2011; I guess.

But the one which is associated with a largest amount of a destruction is the (Refer Time: 36:21) power stations at that former soviet union. And the reactant that I had that is actually of this RBMK style and only following the disaster there people started to work on the possible drawbacks of this RBMK.

And accordingly they provided several kinds of modifications in the design; like in the future design the passive void reactivity coefficient a related issues are avoided and attempters made to induce the void reactivity um; void reactivity coefficient to a positive value, but most of the RBMK based reactors are absolute nowadays only very few of them are working that is also in highly modified stage.

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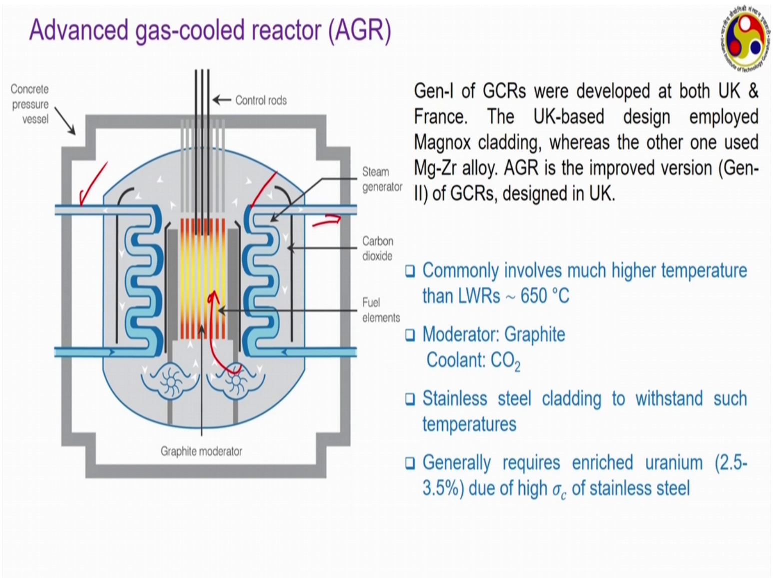

Next is the gas cooled reactors or advanced gas cooled reactors; as the name suggest here the coolant is a gas and endurably the moderator is graphite. So, the diagram is shown here the again the similar to PWR; so, PWRs we are having a pressure vessel and inside the pressure vessel the fuels are placed in the shape of our pellets. The gas which is passed into this reactor core which commonly is carbon dioxide, but can also be helium that passes through this reactor core.

And once it attains a higher relation that is once it is the gas is made to flow over this particular steam generating tubes; inside the steam generating tubes we have water which is coming from the steam generation coolant ah; which is coming from some external source. And inside the steam generation plan that water is getting converted to vapor like this is where the water is entering and here it is going out as the mixture of steam and water.

The same is true for this side as well um; the gas cooled reactor has a quite checkered history. The first generation of gas cooled reactors where develop at both United States both United Kingdom and France separately; the UK was design employed Magnox as the cladding whereas, the one in France that uses magnesium zirconium alloy for the cladding material. The advanced gas cooled reactor is only a modified version of the gas core you know gas cooled reactors conceptualized in United Kingdom. Commonly such gas cooled reactors involve much higher temperature can be as high as 650 degree Celsius. As there is they remain as a gases of gaseous state; so, there is no restriction related with the saturation temperature and hence we can go up to very high temperature level.

Then here as already mentioned a graphite is the moderator and C O 2 is the coolant. Stainless steel cladding is used to withstand such high temperature levels, but one issue in the stainless steel is that it has a relatively high capture cross section. So, stainless steel as it is absorbing a parted of the neutrons are available there; generally enriched uranium is to be used in such AGR group of reactors even I am needs to be enriched to 2.5 to 3.5 percent.

Now, the gas cooled reactors can have several kinds of modifications; there are several improved version of this gas cooled reactors have been proposed.

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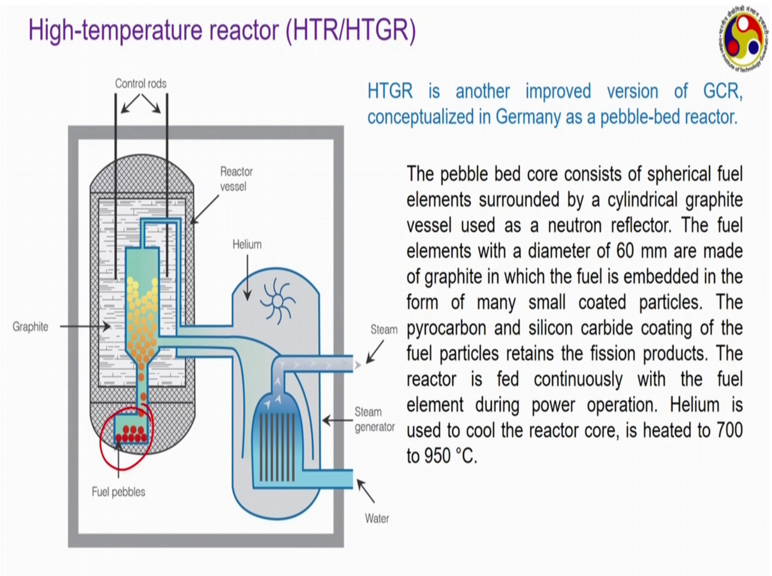

One of them is the high temperature reactor which is proposed in Germany; it is actually pebble bed reactor is very interesting one. Here as you can see from the diagrams that the fuels are shaped in the form of small pebbles; each of the diameter of about 60 millimeter actually the fuel itself is may not be present into the pebbles; rather the pebbles are made of some kind of a graphite kind made these materials. And also with poly carbon and silicon carbide coating on top and fuel is associated with or certain amount of fuel can also be present inside each of these pebbles.

The pebble bed in pebble bed reactors the fuel is supplied continuously these pebbles of fuels of fuels balls the supply continuously just similar to cold how it is supplied to a conventional coldest plant um. For cooling the reactor or as a coolant helium is used and this helium can be heated up to 700 to 950 degree Celsius. So, here the temperature level is even higher compared to the advanced gracious reactor advanced gas cooled reactors that is AGR.

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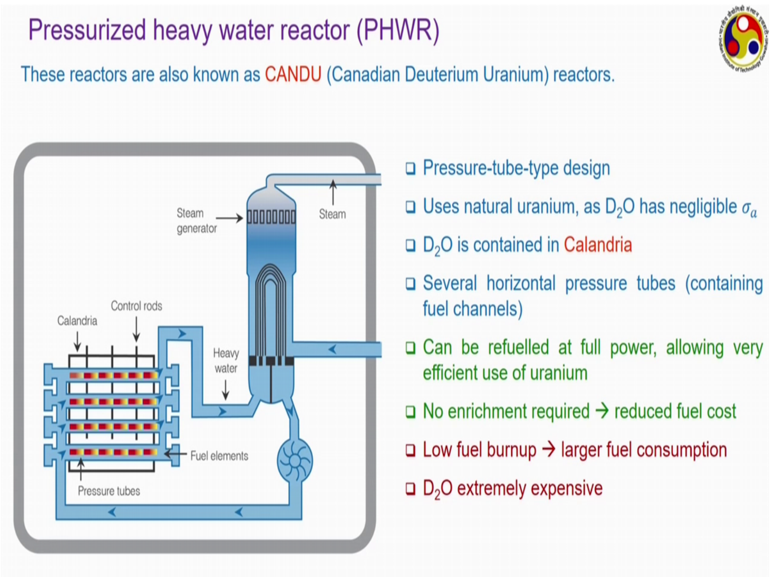

Next the pressurized heavy water reactor PHWR; this kind of reactors are also called CANDU reactors because they are originated from Canada and the term Canadian deuterium uranium combines to this pressurized heavy water reactor.

Here the most striking feature is the pressure tube type design; we have a large vessel here which is which is called calandria inside the calandria; we have heavy water stored. And then the several pressure tubes are immersed into this calandria which are the tools which are containing the fuel elements. The coolant that is allowed to pass over these pressure tubes thereby absorbing the energy.

So, the D 2 O is stored in a calandria and several horizontal pressure tubes containing a fuel channels they are also immersed into that. They also quite similar to this RBMK group of reactors, they can also be refueled at full power allowing very efficient use of uranium. And that is why the CANDU group of reactors or the PSWR has become very popular particularly in India. Apart from the initial PWRs almost all India nuclear power stations employees PSWR kind of nuclear reactor.

As we are using heavy water; it does not have any absorption cross section or this absorption cross section is negligible that is why we can use natural uranium and hence the fuel cost is significantly reduced. But one problem is that the burn-up is low and therefore, fuel consumption rate also will be much larger. And another big issue heavy water itself is very very extensive; very very expensive and so, whatever gain in terms of cost we get by using natural uranium whether that is compensated nor or whether that is compensated or not that we have to be careful.

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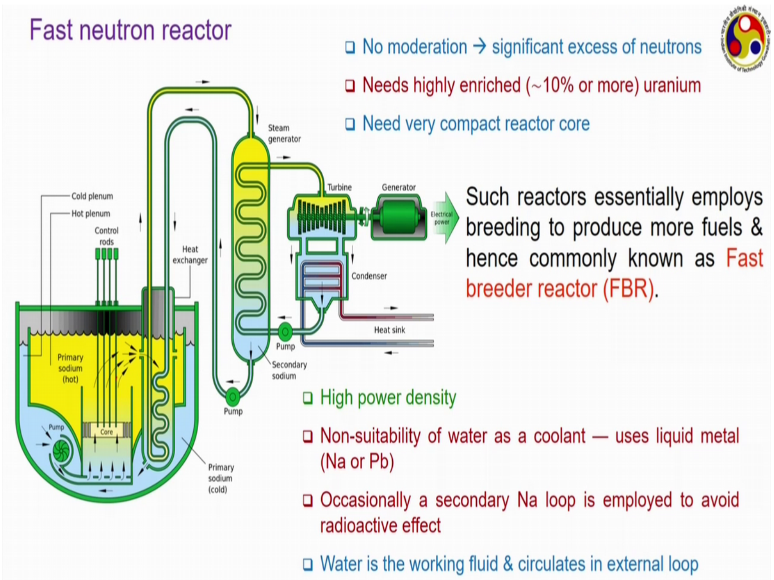

And then we come to the last one is catalysis fast neutron reactor which is truly speaking is not a thermal reactor; rather it employs fast neutron steel for the purpose of completeness I am mentioning this. Here there are no moderators because we are trying to use the fast neutrons and as there are no moderators present. So, there are significant excess of neutrons; moderators can itself also eat up some amount of a neutrons and that portion is not present. And also as the moderators are not going through sorry the neutrons are not going to any kind of scattering or slowing down process.

So, they are not likely to enter the resonance absorption zone. So, the you know resonance absorption as well that is why fast neutron reactors have significant excess in terms of neutrons. They also requires very highly enriched fuel of the range of 10 percent or even more, but they because of such high neutron excess; we general need to have a very compact reactor core and we resulting in high power density.

But one big problem for them water is not suitable as a coolant because of two reasons; common water has a little bit of capture cross sections. So, it can reduce the neutron density and also and the because of such large number of neutron presence and also the being the first neutron lifetime being quite smaller from neutral lifetimes being quite small. The rate of power production from this PSWR is very high and that is why water is not capable of carrying that amount of energy.

And we have to use some kind of highly conductive fuel that needs to be use something like liquid metal say sodium or potassium. So, if you follow the diagram; here this is a primary sodium which is flowing to the core and then that is getting pumped where this into the core. So, it passes to the fuels and comes out as high temperature sodium; that sodium is passing through or passing over a heat exchanger and a other side of it is we also have again liquid metal. And this is the secondary loop; which is taking this energy towards outside to a steam generator, where this energy from this secondary loop is being transferred to water.

So, we are using sodium in both primary as well as in the secondary reactor or secondary loop. So, the secondary sodium loop which can help us avoiding a radioactive effect also complicates the design and put some additional burden on a fabrication point of view. The in the outside loop we use water only which gives the energy from this secondary sodium loop and then in a conventional Rankin power cycle, it can produce the power.

Fast neutron reactors essentially employ a technique called breeding; by virtue of breeding it can convert fertile material to fissile materials and thereby it can produce some more fuels. That is why a fast neutron reactor are also conventionally called fast breeder reactor or FBR which is the topic of our discussion in module 8.

So, it takes me to the end of this particular lecture; here we have discussed about some of the conventional nuclear reactors like the pressurized water reactor, boiling water reactor, advanced gas, cooled reactor, pressurized heavy water reactor and also the fast neutron reactor. And as a variation of this advanced gas cooled reactor; you have also talked about the high temperature gas cooled reactor.

And in next lecture, we shall be discussing about different generation of reactor starting from the generation 1, where the concepts of PWRs and BWRs are proposed. And going through different generation to the modern day reactors which are generally belonging to the generation 4 which having several advanced categories; we will be briefly touched upon so.

Thank you for the day.