**Energy Resources and Technology**
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**Lecture - 12**
**Nuclear Power Generation**

… hydroelectric power plants and the next topic will be nuclear power plants. But, before we go, it will be good to give you a flavour of the kind of problems that one has to solve in planning a hydroelectric plant. So, take down a problem. Let me write the problem, so that you can solve it later.

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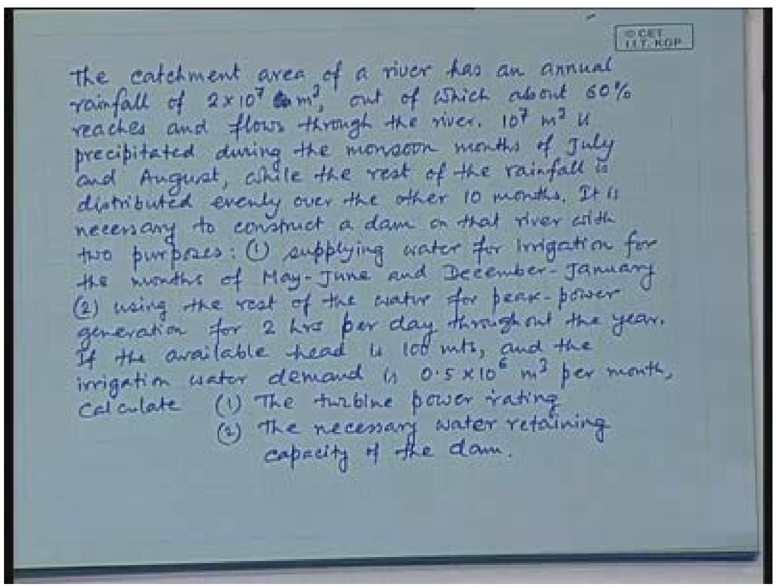


The catchment area of a river has an annual rainfall of 2 into 10 to the power 7 or m cube, out of which about 60% reaches and flows through the river. If you have any difficulty in understanding the problem just tell me. Now, 10 to the power 7 meter cube is precipitated during the monsoon months of July and August, while the rest of the rainfall is distributed evenly over ... So, the catchment area of a river has an annual rainfall of 2 into 10 to the power 7 meter cube, out of which about 60% reaches and flows through the river. Now, half of it that means 10 to the power 7 meter cube is precipitated during the 2 months and other half is evenly distributed over the other 10 months. Though that is not generally true, but it is a good approximation. It is necessary to construct a dam on that river with two purposes.

1: supplying water for irrigation for the month of May - June and December - January. Why are these two times? As you know that May - June and December - January are cropping seasons in which there are standing crops. If there is no rain you have to supply water and 2: using the rest of the water for peak power generation for 2 hours per day throughout the year.

So, there will be some amount of necessary for irrigation and the rest of it should be made available for peak power generation for 2 hours a day throughout the year. If the available head is 100 meters and the irrigation water demand is 0.5 into 10 to the power 6 meter cube per month, calculate 1: the turbine power rating and 2: the retaining capacity of the dam. Is the point clear? Is the problem clear? So, the water that is available has to be used for two purposes, irrigation and power generation and then on that basis you have to calculate what should be the reservoir capacity and what should be the turbine rating. Turbine rating should be in kilowatts or megawatts and the water retaining capacity should be in meter cube. How much has to be this, the capacity, clear. So, solve this problem. This is a typical problem. I mean, I have taken it from one of the earlier end semester examinations question papers. So, you may expect similar style of questions.

Now, let us go on to the next topic which is nuclear power. Through your education in the school, probably you have got some exposure to how nuclear power is generated. For example, there are heavy nuclei which breakup on their own, which are the heavy nuclei, fissile nuclei, radioactive nuclei. Do you, do you know which they are? Uranium yes, plutonium yes, thorium yes; so, these are the standard, there are many others. Not only the heavy ones breakdown, but also lighter ones that are unstable also can breakdown. So, they can also be sources of nuclear radiation, but in nuclear power generation, in general uranium is used. So, we will consider in the main, uranium. India has uranium mines mainly in Orissa, Jaduguda mines and there have been some other resources found in the

North East. So, India has a sufficient deposit of uranium. A larger deposit is available, of thorium mainly in Kerala beach.

So, these are two resources that India has, but all the power plants run on uranium and therefore let us concentrate our discussion on uranium only and as you know, the essential physical principle that goes behind it is that energy and mass are equivalent and when mass is converted into energy, it follows the relationship E is equal to MC square; that you all know. Now, uranium or any other such material comes in many isotopes. For uranium for example, uranium 233 is there, 235 is there, 238 is there. So, all these possible variants of the same thing are available in nature. Now uranium, when it comes, natural uranium, most of it is uranium 238. How do you write?

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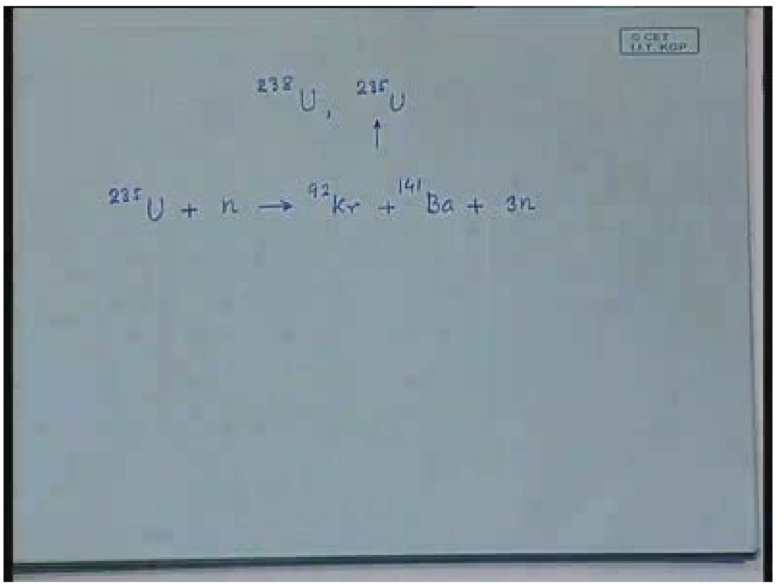


You write U here 238. So, U 238 is the abundant variety of uranium and the other variety is U 235. Now, abundant means in a naturally occurring resource, deposit of uranium, we will find uranium 238 about 99%, but uranium 238 is not naturally fissile. It does not breakup on its own; 235 is. So, the actual resource is uranium 235, but when it occurs in nature, it is mixed up with not only clay, but also a lot of uranium 238 which does not really participate in the fission process.

Now, let us first understand what happens? What is the nuclear reaction that takes place when uranium 235 breaks up? Now, when uranium 235 breaks up, it breaks up by the addition of a neutron. So, a neutron hits the uranium 235 and makes it break down. So, you will write it as U 235 plus a neutron. That will lead to krypton 92 plus barium 141 plus, these are the material products of the fission process, but it also yields three neutrons. So, one neutron is used up in the process of the fission and three neutrons are create in the, created in the process of fission. Now, if at least one of these three neutrons hit another uranium 235, it will also make it break. So, imagine it statistically that three neutrons emerging in various directions and in all probability, in a larger probability they will hit either a non-fissile nucleus or a uranium 238 nucleus, but not a uranium 235 nucleus. So, only if you can ensure that at least one, on an average, hits another uranium 235 nucleus, then only the fission process will continue. In other words, chain reaction will take place. So, in order for ensuring the chain reaction therefore, you need to ensure that if the three nuclei, three neutrons go in various directions, there will be a probability that at least one will hit 235.

What will be necessary in order ensure that? That there has to be sufficient amount of uranium 235 around; if it is insufficient, it will go out without hitting anybody. So, there has to be a sufficient quantity of uranium 235 that is called the critical mass; there has to be sufficient quantity. Not only that, it has to be in sufficient concentration, because if most of the things that the three neutrons see around it are uranium 238, obviously nothing will happen; it has be in sufficient concentration. So, these two are the major requirements and that is what actually consisted of all these years of the effort of the Manhattan project, as you know. The whole thing was started through the effort to make bombs in the Manhattan project and much of it essentially was the efforts to concentrate, enrich uranium to a process, to a state where it can be used for fission.

Now if, so you have the uranium 235 and uranium 238 in a mixture and if you can enrich it to say 5% uranium 235, then you would need one critical mass; if you can enrich it to 10% of uranium 235, it will require less critical mass; that stands to reason. But, one thing is clear that these fellows also breakdown on their own. That means here I have depicted it as, it requiring a neutron to impinge in order to breakdown and cause this fission. But, in actuality, they are naturally fissile substances which mean that some will always break down. That means always some neutrons will be created and therefore if there is a critical mass in some place it will automatically explored. So the, I mean, I should not be taken as a terrorist, but I can tell you that the making of a nuclear bomb is not a very big deal, engineering wise. Once you have a sufficient amount of critical mass of uranium, making them, just putting them together makes a bomb. But then, here our objective is to control that, so that we can get energy out of it in a controlled way for power production. So, we need to control that.

Now, how can you control that? You have understood that if you put together sufficient amount of or the critical mass of uranium 235, it is itself a bomb; obviously you cannot do that. If you then try to do that, it will explode and you will die. There is no point in it. So, what is done is that rods are made out of uranium oxide; you make rods, each rod does not contain the critical mass. When if you put a large number of rods together, then only the critical mass is reached and that will require neutrons to pass from one rod to another. So, neutrons naturally occurring or emanating from one rod must be able to pass to the other in order to have that chain reaction.

Now, you can have some material to absorb those electrons in between and a naturally occurring such substance is steel, chromium steel for example. So, if you have steel rods that go between the fuel rods and if you can have a mechanism of either pulling them up or putting them down, then obviously, by that you can control. Imagine a situation something like this.

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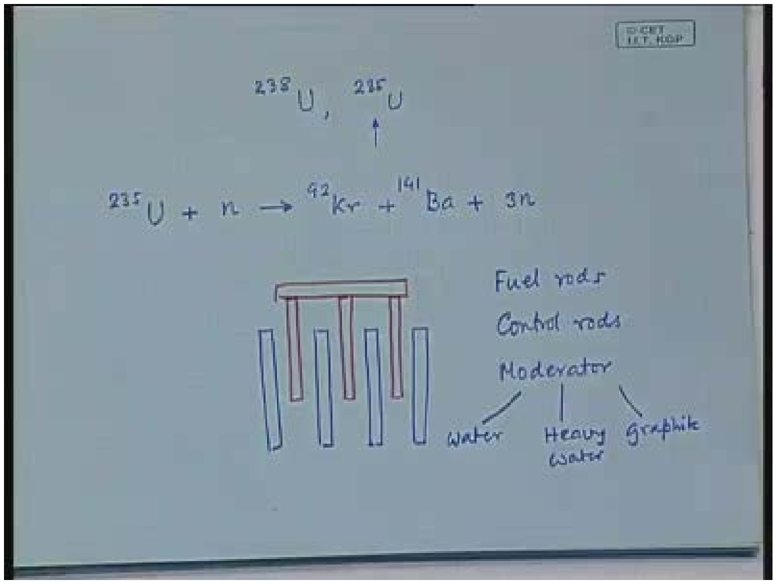


You have got the fuel rods something like this. I am drawing only a few of them, but there will be hundreds in a reactor assembly. Suppose these are the fuel rods and you can have the steel rods something like this, so that by allowing these to go up or down, if it goes up, you can see that neutrons can pass through from one rod to the other. If it goes down, it absorbs more and therefore, you can control the process of fission. This is what exactly is done in order to control, clear. But in addition to that, something more is necessary. One is that it has been found that the neutrons that naturally emanate from a reaction, these neutrons are fast neutrons. They move very fast. They have a large amount of kinetic energy and if they move very fast, they are not readily absorbed by uranium 235. So, they need to be slowed down. They need to be slowed down and the process of slowing down is to use another material called moderator.

So, there should be another material called moderator, so that while going through that moderator the neutrons slow down and therefore when it hits another uranium 235, it will have a large probability of causing fission. So, you need, we have now come to the understanding that, one you need fuel rods, two you need control rods. Fuel rods are made of rods of uranium oxide and control rods are made of steel and you need some moderator; you need some moderator. What can be the moderators? Normal water is the moderator. Heavy water is a better moderator. Graphite is another possible moderator. So, you can have various things as a moderator - water, heavy water, heavy water is D 2 O, deuterium oxide and graphite.

In addition to that as heat is generated in this assembly if you allow the heat to accumulate after sometime this will all melt. So, there has to be some way of taking the heat out; so, there has to be some coolant, something that cools down this thing, something that takes the heat out to a place where the power is generated and there are various choices of the coolant substance. So, you see, the various types of nuclear power plant that you hear about are nothing but different combinations of the possible fuel rods, control rods, moderators and coolants, nothing but, nothing but that.

So, let us now try to understand the various types of nuclear power plants that you have. India has many nuclear power plants and therefore we need to understand what exactly is inside. First let us come to, okay, let me, let me just write down what these are.

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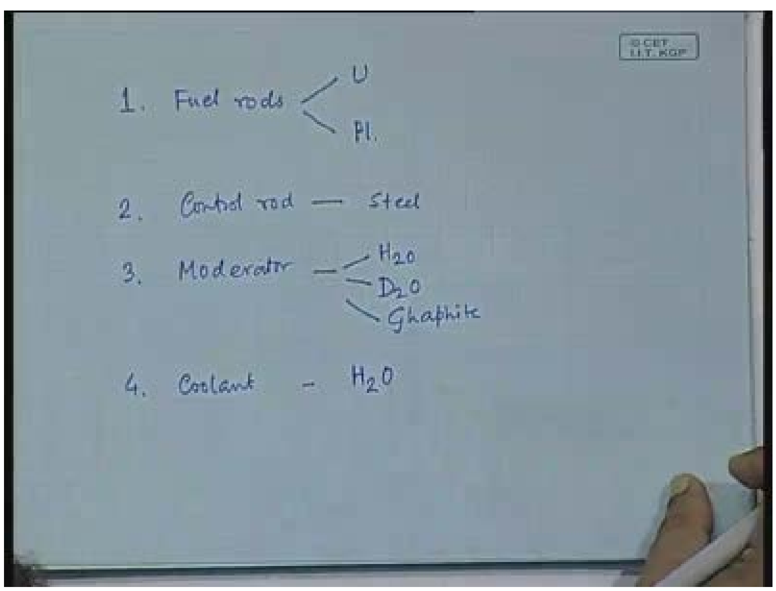


One, you need the fuel rods. This is, what are the options? Uranium 238 plus 235, of course; it can also be made of plutonium. Plutonium is also a fissile substance. Two, number 2 is control rods. Control rods is generally made of steel; various types of steel is there, but in general, the choice is nothing but steel. 3: moderator, H 2 O, D 2 O and graphite. I cannot write C; that will not be clear, what is carbon or graphite and four, coolant. Now, coolant can be various things. I will list them as we go along, but the easiest coolant obviously is water. So, the simplest possible nuclear power plant is where is used fuel rod uranium, control rod steel, moderator water, coolant is also water; that is the simplest. So, in that case what will be the structure of that plant? Let me draw with some different colours. First, as I showed you, there has to be those fuel rods.

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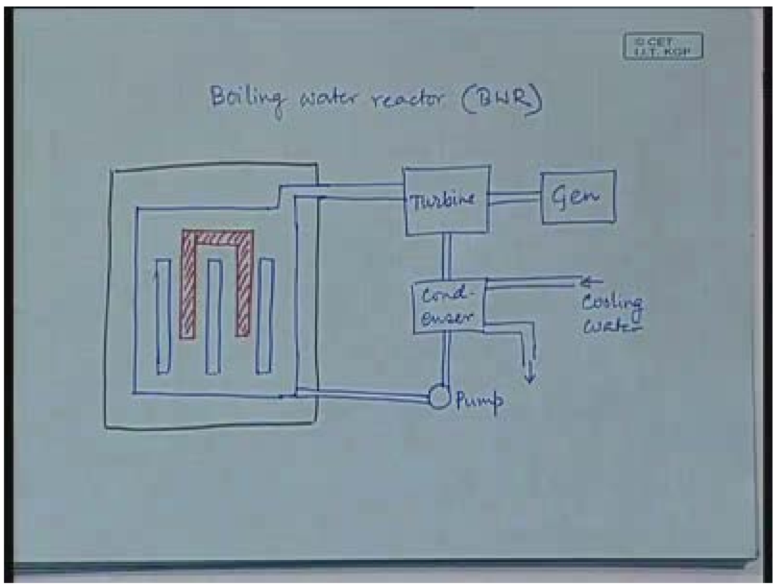


So, these are the fuel rods say and in between there have to be the control rods. This can be pulled up or down and you can see this structure that if something fails, it automatically goes down by its own weight. If it goes down it stops the reaction. So, it sort of, it is a natural safety, but it, I will show you later that it does not always offer that safety, but some safety is built into the system. Then you have the whole thing encased within a structure, in which you allow water to be there; that water acts as the moderator as well as it absorbs the heat and boils. So, what will go out of here is steam. So, you allow it to boil to steam and then that goes to the turbine. So, from here it will go to the turbine.

I will draw schematically, not showing like exactly turbines and then what will be there? Next, you have already done the thermal power plant; this is the boiler then. If this assembly is the boiler, then what will be the next? You need, after the turbine you need a condenser, right. So, here is a turbine, the condenser and you have to allow cooling water to go in and water to go out which is different from this water and here you have the electric generator. Then, after that what will you have? After turbine and condenser, what will you have? Remember, it also works on the same fuel cycle.

No, no, no; after condenser it has become water. It has to go, it has go to the pump; yes, it has go to the pump. So, it has to go to the pump and pumping, pump water must go into this. So, that is the essential structure of what is known as the boiling water reactor where you hear about the abbreviation BWR. It is nothing but boiling water reactor, because inside the chamber it actually boils. Now, this whole assembly needs to be encased in a container and that is what you see as a dome, right; that is what is seen as a dome, but I am drawing it like this, so that radiation cannot escape. Obviously there will be nuclear radiation generated inside and so, this obviously is the simplest possible thing.

But, what are the problems? Can you identify? You see, the water that is here is always coming in contact with the fissile material, the control, the fuel rods. As a result, it is radioactive and the same radioactive water is going into the turbine, same radioactive water is going to the condenser, same radioactive water is going to the pump. So, all these things will after sometime become radioactive. So, in this system, the problem is that it is not possible to contain the radiation, contain the contamination within this black coloured chamber. That is why boiling water reactors are no longer in favour, though they are the cheapest and simplest. Most of the countries are now moving away from the boiling water reactors.

What happens is that the people handling the turbine, the condenser, there has been people around; they always are exposed to radiation, because the turbine itself becomes radioactive, the condenser itself becomes radioactive. So, you understand the natural problem, clear. What is the next possible step? Next possible step is, there is another problem. Because you are allowing the water to boil here, because you are allowing the water to boil here the temperature is low. The temperature is not very high, because here it is, it is actually boiling. Depending on the pressure that you allow, it will be not 100 degrees; it will be higher, but not much higher. The water that goes out of this is allowed to expand a bit. That means the pressure is brought down. As a result, it goes from the saturated steam stage to superheated steam stage. In a boiler what happens? In a normal coal fired boiler, you had the super heater where you add more heat to it. But here, the place where heat is generated is inside here where water is coming in contact with that which at that time is boiling and therefore, you have to do something else to get into the superheated stage and what is generally done is to bring down the pressure little bit, so that it goes into superheated stage, clear.

Now, here the thing that is coming in contact with the fuel rod is water and something, water, that water that time is boiling into steam and therefore, water steam mixture and steam is not a very good absorber of the heat, right. Water can absorb the heat well, but not steam and therefore, since it is a mixture of water and steam, the overall heat transfer capability, the coolant action is not very strong. This is another problem of this design of the boiler. So, the next possible stage therefore, is to allow water to be there; water will be used in the substance, in this place as the moderator as well as coolant, but pressurize the water such that it does not boil. If it is not allowed to boil, obviously it will extract heat, act as the coolant more efficiently.

So, the next step is that within this chamber it is not allowed to boil. So, the structure would be the same chamber; water is being fed in and the water is going out, but the whole thing is water. It does not, it is not allowed to boil into steam. But later, after this there will be heat exchanger in which that pressurized water gives the heat to normal water allowing it to boil, clear. So, let use draw that schematic diagram.

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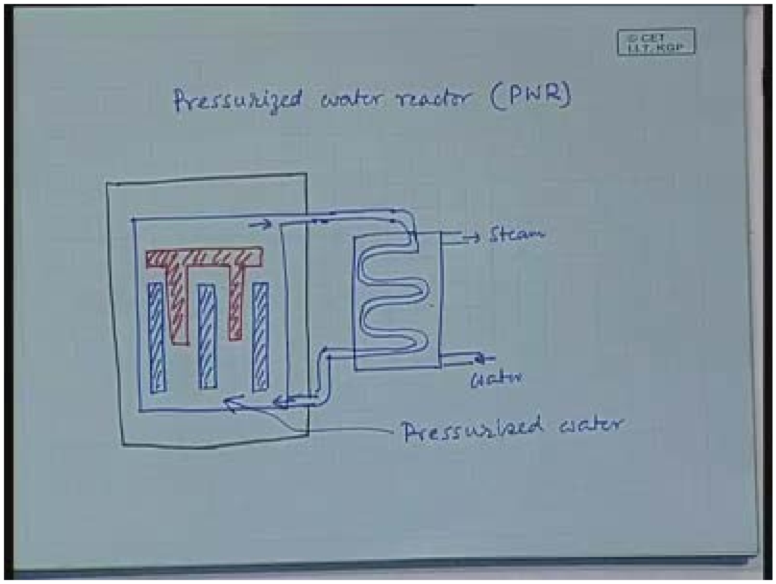


You have the control rods. So, these are the control rods, these are the fuel rods and these are the control rods and you have got a chamber. In this chamber what you have is pressurized water which is entering through this and going out through this and you have a heat exchanger in which this thing goes around like this and here you have water coming in and steam going out. The rest of it will be the same and the whole thing will be encased in a steel casing. So, here in this part you have, sorry, you have pressurized water. So, here you have pressurized water, so that it is not allowed to boil. Naturally, it acts as a very good coolant and then that passes through this. So, here is the water path, pressurized water path and here you have the normal water coming after the condenser, taking the heat from this heat exchanger and going out as steam to the turbine. Of course after that, flushing stage, flushing means where you bring down the pressure a bit, so that it becomes superheated steam, then to the turbine.

The advantage is, you can see, first that the water that is contaminated with radioactive substance is only within this zone. It does not come in direct contact with this steam, this water and therefore, this part, the turbine, the condenser, the pump, everything becomes uncontaminated with radiation, radioactive substances for a longer time; remember for a longer time, you cannot really say that it never comes, becomes radioactive because there are leakages and everything. So, this is called the pressurized water reactor or PWR. So, here also the same substance, the normal H 2 O, water is being used both as the coolant and as the moderator.

Now, in the next stage, we can think of improving the moderator to D 2 O, the heavy water, in which case it is the same cycle, but it is pressurized heavy water that circulates through, in which case the moderation will be better and since you are not needing a large amount of that substance, because it is only this, it remains encased within this zone, right, so you can use deuterium for that purpose. Many of the Indian reactors are of this type where it is pressurized heavy water that circulates through, that gives heat to the steam and of course … You may have heard the name of the CANDU type reactors Canada deuterium uranium reactors which India has installed in the first stage. These are of this type. That means these are pressurized heavy water reactor that means inside it is heavy water, clear. What other improvements can we think of?

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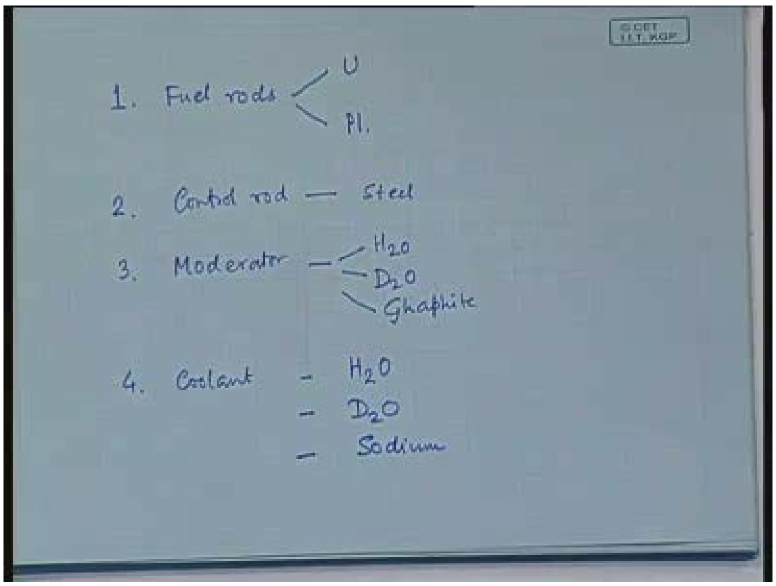


So far we have used, in the last one that I have just discussed what is the moderator? D 2 O. What is the coolant? That is also D 2 O; come on because here what is circulating is D 2 O, so coolant is also D 2 O, right. Now you have, you can see that there is also an option of using graphite as a moderator, of using graphite as a moderator. That comes as the next stage. Graphite is a solid substance, is not a liquid and therefore, you cannot use then graphite also as a coolant. So, if you use graphite as a moderator, then you will have to use something else as the coolant. Normally, some gas is used, inert gas is used as coolant. Helium for example, argon for example, this kind of gases can be used here as a coolant and here there would be graphite plates acting as the moderator.

So, I do not probably need to draw the figure again; only I will …, so that you do not get confused. In those cases here inside it will be some kind of coolant, gaseous coolant and the graphite rods used as the moderator. Gaseous coolant obviously is a bad coolant, right. In order to cool it you have to get heat out fast and heat transfer rate for a gaseous substance is obviously low. So, you cannot use that as a good coolant. So, what can be good coolant? Something that is liquid, but we have already explored the possibilities of water and heavy water. The other good coolant is sodium, liquefied sodium.

So, the other possible coolant is … So, in many of the modern reactors you have liquid sodium acting as a coolant in a similar structure, where here it will be liquid sodium that we will be circulating. Sodium is not a, not a good moderator. So, you have to have graphite as the moderator substance, get graphite plates, which is a moderator substance and sodium gives the heat to the water and sodium can be raised to a larger temperature. See, in case of pressurized water or a pressurized heavy water reactor, you cannot really bring this temperature to a very high level.

Why? Because, it starts boiling and there is a limit to the pressure that you can allow it to withstand, because these are all made of steel and there is a limit. So, the other advantage of sodium is that even though sodium is a more expensive substance and in fact, it is explosive, also you cannot really put sodium anywhere, but the advantage is that it has a larger heat transfer coefficient. It acts as a good coolant. It gives the heat fast, so that is also one advantage. The other advantage is that here you can get the temperature very high. So, that is the other type of reactor you have. Is that clear?

Now, the material that is inside the rod, as I told you, is mainly uranium 238, a bit of it say 5% uranium 235. After all that concentration enrichment it is only that. So, what happened to the rest of the uranium 238? All the neutrons that are coming out they would be hitting them and by hitting them, much of that will be transformed to something that has number 239. Because uranium 238 was there, it is hit by another neutron, something is added. What will happen? It will turn into something that has an atomic number 239. What has atomic number 239? Plutonium. So, the material that is here that was not fissile slowly turns into fissile material, plutonium 239 and that is one of the major concerns globally, because plutonium 239 is the main component of modern bombs.

So, that is why people are so very concerned, because this is the essential point that as you process the used fuel rods you get material for the bomb. I will, I will come to the these aspects a littler later, but one of the suggestion that people are now somewhat rigorously pursuing is that this wall, this wall on which much of the neutron really hits, neutrons that escape through this hits the wall and the wall if it is made of steel, simply gets brittle after sometimes, because continuously being hit by neutrons. Instead if you line them up by a lining of uranium 238 what will happen? That lining will slowly become plutonium 239, as a result it will become a fissile material.

India has a lot of thorium. That can also be used in the lining, so that that also becomes converted to some fissile material. So, what happens is that while it uses the available amount of uranium 235 and converts it into energy, it also generates more fuel and in order for that process to be fast, that process to work fast, the neutrons have to be, have to go fast and hit the thorium or uranium 238 nucleus, because here the objective is different. Here the objective is not to fission the uranium 235, rather to convert the uranium 238 into 239, so you do not use the moderator. So, there in that case, the kind of reactors would be called the fast breeder reactor; fast, because the neutrons are fast, you are not allowing them to slow down, breeder means they breed more fuel than they consume.

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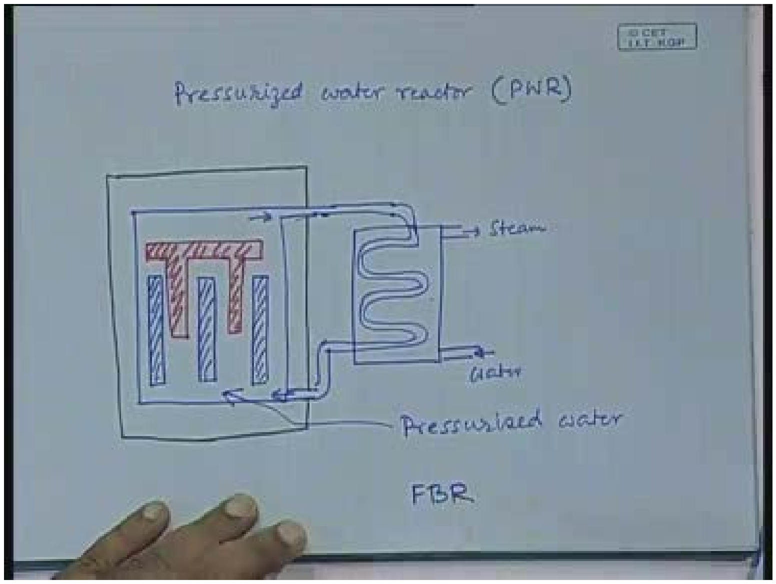


So, these are the FBR, the fast breeder reactors. In India for example, there is an experimental FBR in Kalpakkam. So, India is experimenting with this possibility of breeding more fuel while you generate energy. For today let us end here and we will continue in the next class.