Energy Resources and Technology
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Lecture - 13
Nuclear Fusion Reactors

So, in the last class we were talking about nuclear power generation.

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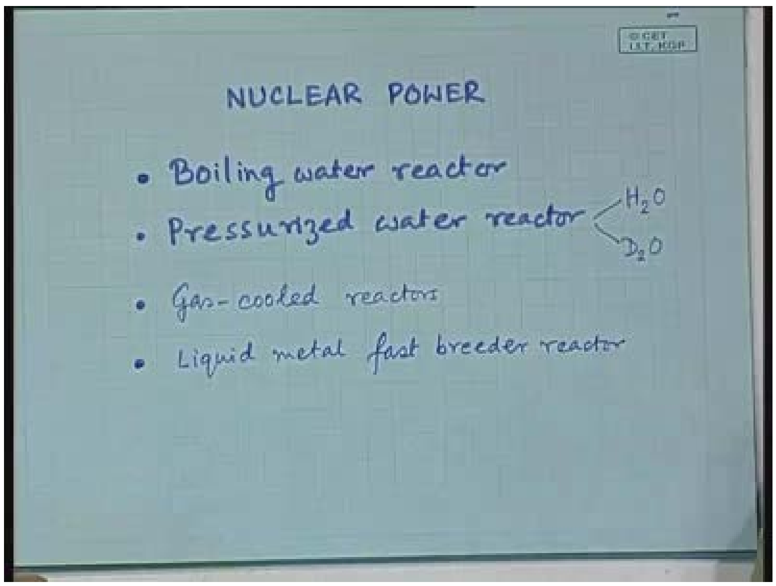

Well, if you toggle these two letters it becomes unclear power generation and so, that should not happen, right. It should be clear to you what you are talking about. Now, here we have a few types, distinct types of generators that we have heard of. We have heard of the boiling water reactor, we have heard of the pressurized water reactor, we have heard of the pressurized water reactor of two types – one, where the water is normal water, H 2 O and also the one where the pressurized water is heavy water, deuterium. So, the two types H 2 O and D 2 O; most of the Indian reactors are of this type. Then, we have the gas-cooled reactors, where the moderator is graphite. So, you have the situation where the graphite is the moderator and you have some gas, some inert gas working as the coolant and we also have the liquid metal coolant system or these are mostly used with the fast breeder reactor, liquid metal fast breeder reactor.

Why this word fast? What is the meaning of that? The neutrons are fast. They are not slowed down, so here you have the liquid metal as the coolant, no moderator and the purpose is both to generate electrical power as well as to breed more fuel for future reactors and for that you need fast neutrons. So, we have the different types of reactors and in another day, we will take up in detail the prime consideration these days the safety consideration and the environmental problems that we will take up together, in a day when we deal with the environmental problems both of the coal, nuclear, as well as hydroelectric power.

So, you have this few types of, possible types of nuclear reactors. But, all these are fission reactors, right where heavy nuclei are broken up to form smaller, lighter nuclei and you get some energy output and it is not difficult to see that the reaction products, they are all radioactive. The reaction itself is a radioactive reaction and when you are talking about the breeding of uranium 238 to plutonium 239 that is also a very, very radioactive substance. So, there are inherent dangers which have been, you know actually seen in some specific hazardous cases, like there was a Three Mile Island incident in US, there was a Chernobyl incident in Russia, Ukraine actually. So, you have these problems associated with it, but the technology is well proven, working.

One of the directions in which people are working, trying to achieve another type of reactor is the fusion reactor.

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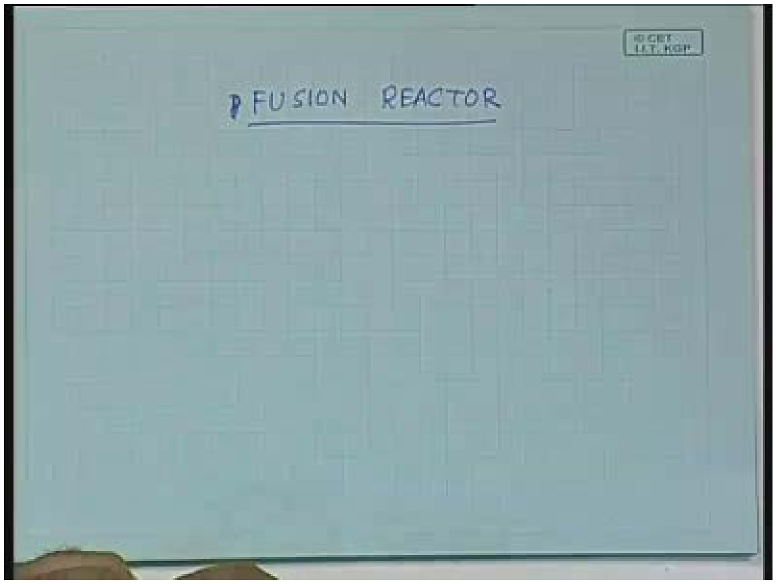

There is no fusion reactor as yet. This is a futuristic research initiative, but as energy engineers, you should be exposed to that possibility. That is why today we will take up what are the various directions in which people are trying to achieve it. Fusion is essentially the reaction that goes on inside the sun, right. What goes on inside the sun? Hydrogen fused to form helium, right. Let us consider that process. Hydrogen nucleus means what? A single proton. A helium nucleus means what?

Student: Two protons.

Two protons and two …, so four nucleons; four, four heavy things inside. So, can two hydrogen nuclei fuse to form helium? No; that is not possible. There has to be four of them and it is not difficult to see that if you put something in high pressure, then it is possible that in spite of the electrical repulsion between the nuclei, high pressure high temperature means there will be a finite possibility they will collide with each other. Two will collide with each other, but what is the probability that three collides with each other? Very low; what is the probability that four will collide with each other? Very low.

That is why four hydrogen nuclei coming together at the same time and fusing into helium is practically impossible. I should not say practically impossible, because that does take place inside some stars, some stars, not sun though.

That is not what happens inside the sun, because inside the sun there is another reaction, another process taking place whose end effect is that; that it is consuming hydrogen and producing helium, but the process is not that hydrogen nuclei are simply colliding and forming helium, no. There are other substances coming in the process, including carbon. So, had carbon not been there inside the sun, the sun would not really have fusion. That requires, simply hydrogen fusing into helium requires far larger mass and pressure. So, obviously when we try to do or enact this in Earth based reaction, obviously we cannot view fusing hydrogen into helium. Can we? We simply cannot.

We have to look at some possibility where two nuclei, two not more than that, fuse and produce something. Is that clear? So, it is a common misconception that we are looking at a fusion reaction in which hydrogen will be fused into helium, no. Nobody is looking into that; nobody is trying to fuse hydrogen into the helium, because that is practically impossible to enact on the surface of the earth. So, what are we really looking at? What we are really looking at is a reaction where two isotopes of hydrogen, deuterium and what is the third one?

Students; Tritium.

Tritium, so that they merge together, they fuse to produce helium.

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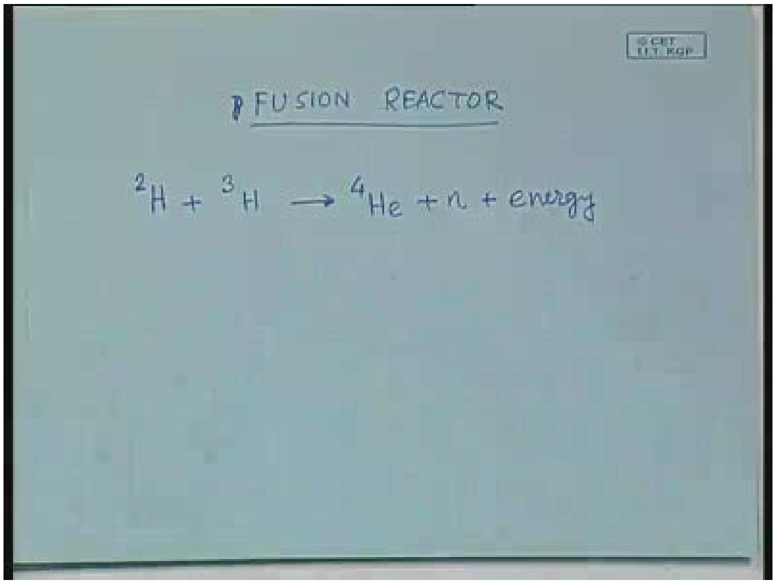

So, what is the symbol of deuterium, is this, to produce what? It will produce … Then, you have one extra plus energy. So, it is this reaction people look at, because that can happen at a relatively lower temperature, which that relatively lower temperature is also very close to the temperature inside the sun, but nevertheless it is not an impossibly high temperature. So, it is this reaction that people are looking at and obviously in order for hydrogen and helium to fuse together, they should be at very high temperature. Temperature means nothing but the inherent speed of motion of the molecules.

In that temperature, obviously they will not be molecules they will be individual atoms, but nevertheless not only individual atoms, but also at that temperature the electrons will be stripped off from them. So, electrons and the nuclei will freely move together, a state that is called plasma. So, we are looking at a situation where these two things are heated up to a temperature where it becomes plasma. The temperature is so high that of their own effort the deuterium and tritium nuclei they can overcome their electrical repulsion, because both are positively charged, they can overcome the electrical repulsion and they can fuse. The temperature is of the order of a lakh of lakh of degrees, 10 to the power of 6 degrees or so.

How can we produce that? Most importantly if you really produce that temperature, obviously you cannot really burn coal and they produce that temperature; you cannot. So, there has to be some way of generating that temperature and then a greater problem is how to contain it? Anything that will come in contact with that will melt. So, these are the two major problems that have to be overcome in order to produce a fusion reactor. First, how to produce that temperature and second, how to contain that? Now, how to produce that temperature is not all that big a problem; how to produce that temperature is not all that big a problem.

For example if say, you generate high speed neutrons which is possible now, nowadays and put into the plasma. The energy that is there in the neutrons will be, by means of their internal collisions will be transferred into the other substances inside and obviously then that will increase their average speed of motion which is nothing but temperature. So, that is one way. You produce high speed neutrons and bombard them; you put them into that ….. . Suppose you have got a chamber in which you have put deuterium and tritium together and you will simply put in lot of energy by that means. If you keep on putting it and if you do not allow this energy to escape by means of proper shielding, obviously the temperature will go on increasing and it is possible to reach that kind of a temperature.

There is also the possibility that you inject radio waves which will ……, which frequency will be tuned to the natural frequency of oscillation of these things, so that they will sort of oscillate in resonance and that imparts the kind of the energy in the radio waves into those nuclei. So, it is possible to impart energy into that and if you keep on doing that, it is possible to raise the temperature to very high level. So, raising the temperature to that high level is not the big problem, but the big problem is really the confinement. So, there are two issues.

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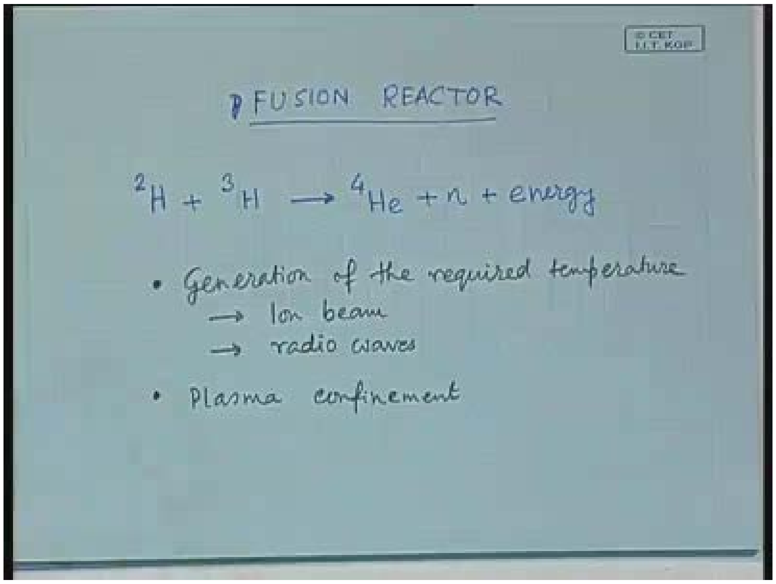

One … and two, this is actually overcome by injecting either an ion beam or a neutron beam or whatever and the other is through radio waves. The next problem is the bigger problem that is plasma confinement. So, plasma, do you understand what plasma is? It is where the gas is raised to such a temperature that the electrons are stripped off and you have the electrons separate and the nucleus separate moving inside the gas. That is, that state is called plasma state. So, what we are talking about is plasma confinement. How to confine the plasma?

Now, there are essentially two methods of plasma confinement that people are trying off. To understand the first one, try to picture, visualize this. It is magnetic confinement, magnetic confinement; try to picture like this.

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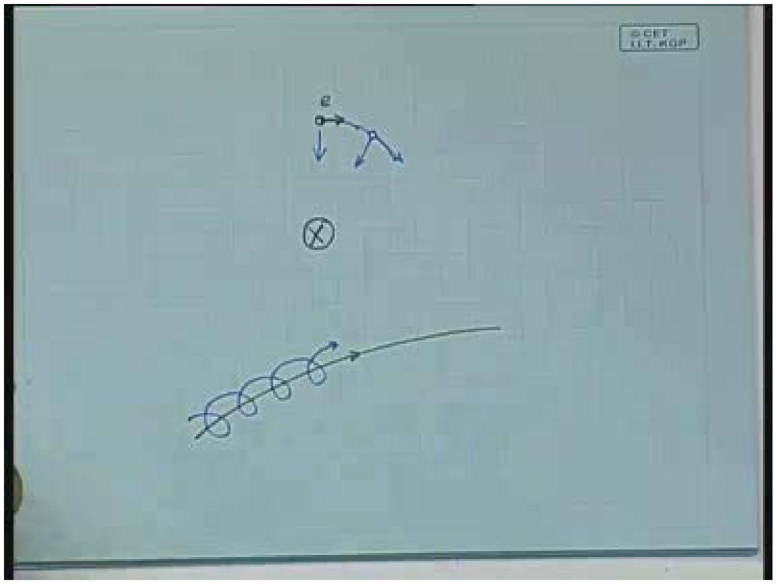

Suppose you have a magnetic field going into the sheet of paper which means I will draw it like this. Do you understand this notation? This is going into the board and if I draw it with a dot it comes out of board and suppose here, there is one charged particle say an electron say and say that this fellow has a motion this way, so here is a I have, I have drawn it here, but actually the magnetic field is going everywhere and here is the electron that is moving in the magnetic field that direction. What will be the force felt by the electron?

Yes, ….. in which direction?

Which law? Which law?

Yes, so do that and tell me which will be direction of the force?

Downward, so because of that downward motion what will be the resultant motion of the electron? It will move; it will deviate from the straight path, it will move towards this say it has come here. When it has come here this is the direction of the force, this is direction of the velocity. What will be the direction of the force? Again towards the center; so, it will again be deflected, so it will be moving in a circle, right. So what has happened in effect is that the magnetic field is in that direction and the electron is forced to move around the magnetic field. Now, the electron, there is no reason to believe that the electron has only one direction of velocity. Suppose it has also some component of velocity along the magnetic field, what will happen? That means it is moving in some arbitrary direction which has a component this way, another component along the magnetic field. Will the component along that magnetic field be affected?

Students: No.

No, it will produce no force. So, if you have a magnetic line of force going like this and if you have an electron here, how will it move? It will have two directions. As I told you, one along the magnetic field another perpendicular to the magnetic field and the direction perpendicular to the magnetic field will cause this rotational motion. As a result what will happen? So, the electron in effect has got locked into the magnetic field. It cannot escape. That is exactly why in fact you have the charged particles falling into the Earth's atmosphere through the north pole where you see the Aurora Borealis, because of this, because you have the magnetic field going and the charged particles get locked to that and go into the Earth's atmosphere through that point.

Similarly, if you have the proton with a different charge, you will still have the locking effect; only it will move in the opposite direction. So, you have, if you have a magnetic field produced, the charged particles get locked to the magnetic field; charged particles get locked to the magnetic field and they cannot escape, right. Can we use that for producing a confinement of the plasma?

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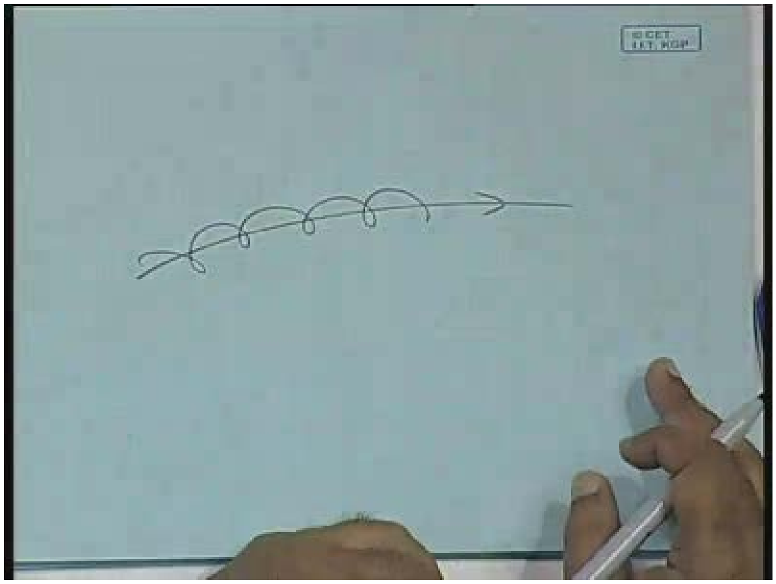

Suppose you have got a magnetic field that goes like this and these poor fellows will get locked to that and will move like this, fine; but, after that it will hit the wall, after sometime. So, that wall will melt. So, how can we, yes you are moving the hand like this; yes, you are right, it has to then go around which means the magnetic field has to be circular. So, the magnetic field being circular, how can you produce that magnetic field? By winding a toroidal coil, right. So, you will wind a toroidal coil that will produce a magnetic field that goes in a circular direction and the charged particles will be locked to it, clear and since if you wind a toroidal coil, the magnetic fields concentration will move toward the center, less toward the edge, so most of the material will be concentrated at the center. It will move as concentrated at the center and there will be very little towards the edge. So, actually the plasma will not touch the wall. Is that concept clear?

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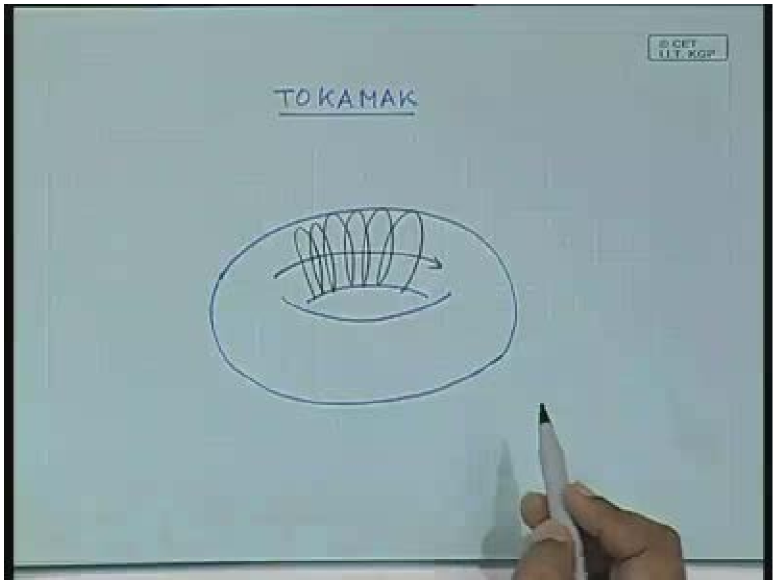

That concept was proposed quite long back by Russian scientist. He is called Tokamak and since then various groups around the world including in our country our Saha Institute of Nuclear Physics has a Tokamak reactor. So, we have the Tokamak concept tried out in various places, but the main problem as yet is that the confinement that people have been able to achieve is rather transient, it does not last long. After that it tends to escape, because the magnetic field and plasma interact and there are instabilities. The magnetic field does not really stay like this; that sort of oscillates. So, the plasma touches the wall.

One way people have tried to bring in some stability is to have not only a toroidal coil; a toroidal coil means something that goes like this and comes back something like this and you would wind like this, so that the magnetic field is produced like, so that is a toroidal coil. So, in effect, all these windings are essentially around a circumference of the torus. Some stability can be a brought in if in addition to that you also have a poloidal magnetic field, a poloidal winding which goes more or less along that. So, as a result, the magnetic field will be, you know winding around; it should not be exactly around the circle, but that produces some amount of stability. So, in general the way people try to overcome this problem is to add, is to have a combination of both the toroidal coil as well as the poloidal coil.

Now, the way the actual reactors are, I mean people have tried and confinement have been achieved for a period of a second or so, that is considered to be a big break through, right. When we are able to confine plasma and generate energy out of such a thing for a second that is also a big break through, because that is how people proceed. Now, let me give you a schematic diagram of the way people are trying to do it.

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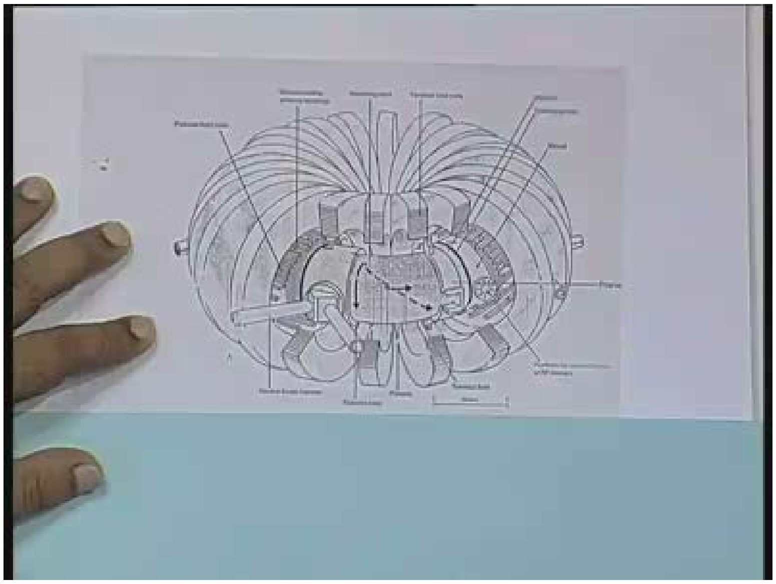

You can see, so here in this case you see these are the toroidal winding that goes around; so, these are the toroidal windings that go around. Here are the poloidal coils. Can you see? Here are the poloidal coils that go like so; not exactly like so, it also have a certain amount of winding something like this.

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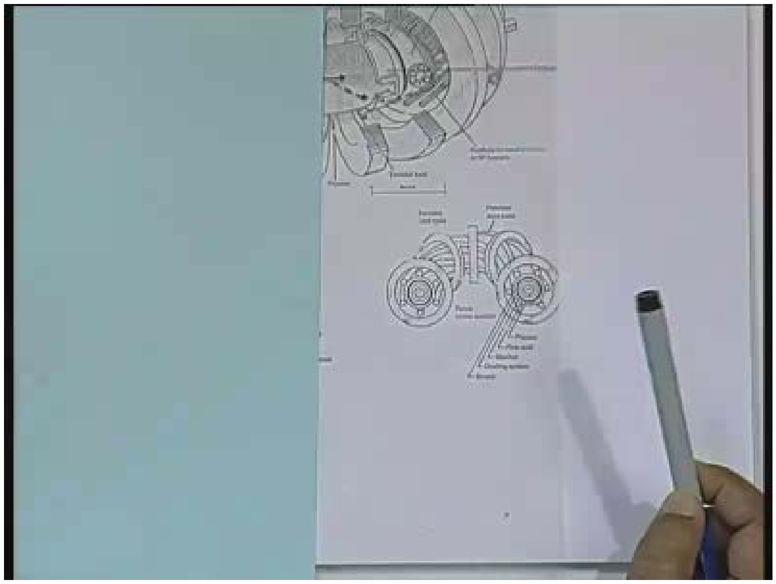

If you, if you look at this picture here, if you look at this picture here it will be clearer, where these windings are the toroidal windings and poloidal winding go like this. These are the poloidal windings. Yes, it is a bit twisted, right. Why do we need to have them twisted? Because, if you have a high amount of current flowing through, they will try to fly off; so, unless you twist it there is no structural stability. So, you have to have a bit of twisting around it. So, there are two windings really - the toroidal windings, the poloidal windings. Inside you look at the core. This is the section of the core. At the center there would be the plasma that is confined. Beyond that there would be a first wall and then there would be some kind of a blanket. Then, there will be cooling system. So, there will be all sorts of, you know, layers in that. You have to take the heat out; there has to be a cooling system.

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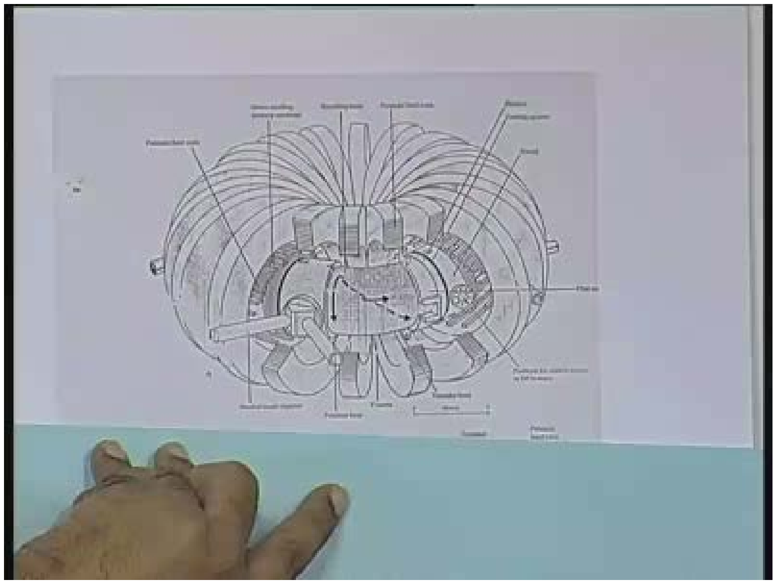

So, let us go back to this, this diagram and let us see what it is. So, you have the internal structure that you can see here. This is the toroidal field produced and this is the poloidal field produced. As a result, this will be the direction, resultant direction of the magnetic field. So, that will again wind around. Teek hai? Now, there has to be some ports through which you first inject the fuel, right; so, there has to be similar ports for that. There has to be also ports for the neutral beam injection. As I told you, one way to produce the heat is to accelerate something. It is easier to accelerate by, easier to accelerate, you know, charged particles, but ultimately when you put it in, it has to be neutral. So, you first accelerate and then neutralize it and then put that in, so something goes in with a high kinetic energy. These are done through these neutral beam injector points, right. So, if you put that in, can you see that clearly? So, these are the neutral beam injection points.

Here is another port that is for RF heater, radio frequency heater. So, there are two possible types of heating system, I told you. Both are generally employed. So, this is the RF heating, this is the neutral beam injection. So these are the two ways of heating it up.
Now, after it is heated up, it is assumed that that will circulate around, more or less be concentrated towards the center, a line and it will generate, what? Helium as well as neutrons. Now, neutron, what do you do with that neutron? What do you do with that

neutron? You cannot really collect the neutrons, put in a bucket and keep it for your future use; obviously you cannot do that and also tritium is very expensive. So, one way people try to overcome that problem is to make a blanket, a blanket made of lithium. When that is bombarded with neutrons that breeds tritium; so, you need to produce tritium in that process. That is the lithium is bombarded with neutrons and that breeds tritium. So, you have the tritium produced in the system and as the product of the system is taken out, you get helium inside the plasma and you get tritium in the blanket. So, that can be used. So, that is why there is a blanket.

Outside the blanket there is a cooling system. Here you can see a cooling system through which you can have the same way of water walls that means water pipes go in to cool the system. Then, there is a, just before the cooling system there is a fast wall made of steel. That means that really takes the heat and stands there. So, there is a fast wall here and inside you will have the plasma. You understand the toroidal field, you understand the poloidal field and these are the toroidal field coils, there are the poloidal field coils. Initially you can also have some ohmic heating. That means you allow high current to flow through wires that can also initially produce the heat, but not much. Beyond that it has to be either through ion beam injection or neutral beam injection and the RF heating. So, is that concept clear? Yes? So, this is the concept of the Tokamak.

So, a Tokamak is nothing but a very large system of producing magnetic field and this magnetic field, in order to produce very high magnetic field you have to have superconducting magnets. So, all these things are generally superconducting. Most of the Tokamaks which we use are, use superconducting magnets. I hope you are exposed to the idea of superconductivity. At very low temperature certain materials become superconducting, so that unless you do that, at that high current it will also produce a lot of heat. So, you cannot really pass high current. The current will be limited. As a result, the magnetic field will also be limited. So, in order to produce a high magnetic field you need superconducting magnet and the superconducting magnetic technology is more or less developed these days, you can have.

Student: Sir, …

With the cooling system, behind the first wall you have the cooling system where there are tubes, copper tubes. It is behind the first wall, so it is not exposed to the neutron beam. So, you have copper tubes through which water passes. That water heats up and that is carried to another channel. That coolant could be anything really, that coolant could even be liquid sodium, as you have seen earlier. So, you can have water, you can have any substance, but here the water should not boil. So, it should be pressurized water, so that it effectively takes out the heat, clear. Now, this is the concept of magnetic confinement which people are trying in various places to do it by the Tokamak reactor.

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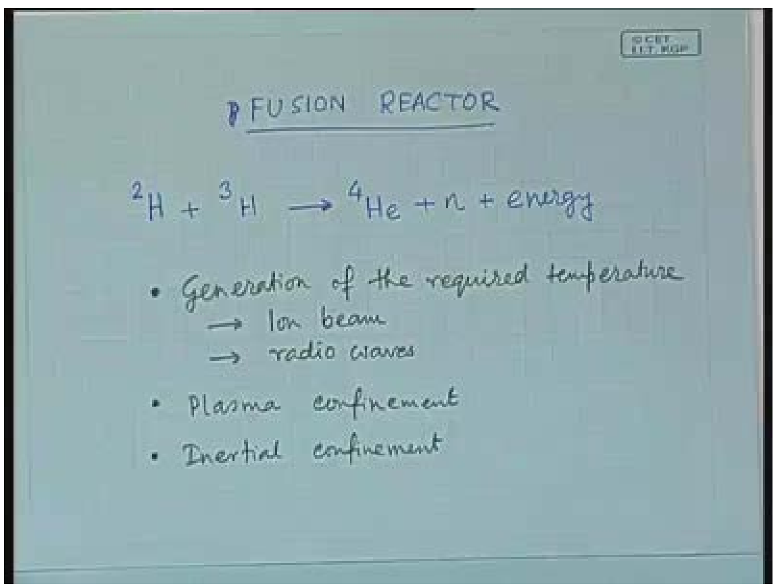

The other concept is, the other concept is called inertial confinement. In the inertial confinement concept, we do not produce plasma at all. Instead, we cool down the deuterium and tritium to make them solids, so that you can throw and solid means it is already confined. So, that is how people try to do it. That means the fuel is made into solid pellets, but then they have to be heated to that temperature in order to cause fusion. As you heat it to that temperature, it will after all become gaseous. So, how to, how to overcome this problem? This is done by doing it in a fraction of second. Very fast you fuse it, so that it immediately produces the heat and that's it. So, the concept is something like this.

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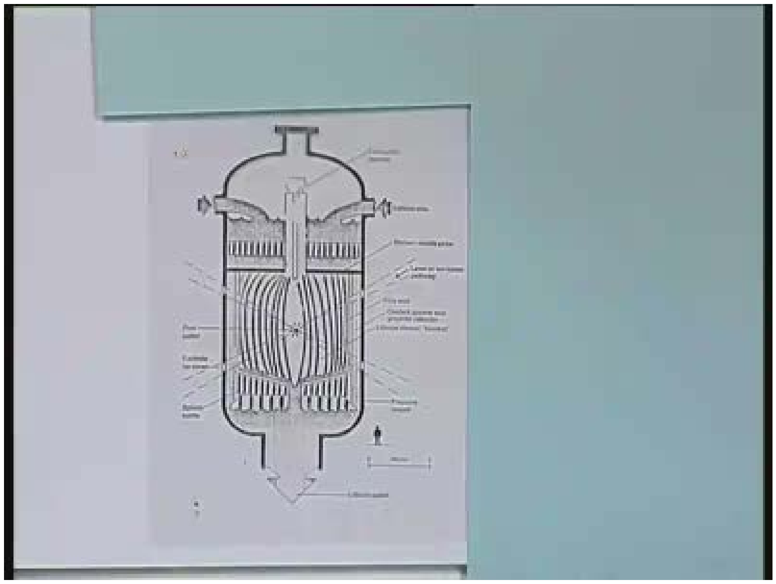

Can you see? So, imagine that this is the reactor in which you have made those fuel pellets. These are brought in here and injected or sort of there is a gun here that you know fires the bullets downwards. As it goes down it is contained by means of its own inertia. That means it is solid; solid thing is fired which means that it moves with a certain velocity and things does not escape and as it reaches a certain point, very pointedly there are port holes through which laser beams are injected aimed at that moving pellet, so that the laser beams from various directions converge onto that pellet at a single moment and then, it imparts a great amount of heat so that it explodes and since you are heating it from all the sides, it will implode really. There will be heating from all the sides and they will try to expand and the inner, inside part will implode. That means inside part will compress producing very high compression, very high heat and as a result of that it will fuse, clear.

So, that is the concept, where at this point when it comes, it is bombarded from all directions by laser beams and that is what makes it fuse. Now, here also you will need to breed tritium and for that the lithium is fed in as liquid which sort of rains through absorbing the emerging neutrons. As it falls here, it is collected and it is taken out which has, which contains the tritium, so that is the blanket. It is a lithium shower that falls and breeds a tritium. The whole thing is a pressure vessel of very high, very thick steel construction. So, what else is there? Is the concept understood then? More or less I have said, so just, just to repeat, you have a casing. You have got a container, a thick steel container in which there is a partition. Above the partition you have the lithium, liquid lithium being collected and through small holes here the lithium rains through. There is a shower and here you have the fuel pellet injection system which is fired from the top. It goes down and as it comes to this point, it is bombarded from all the sides.

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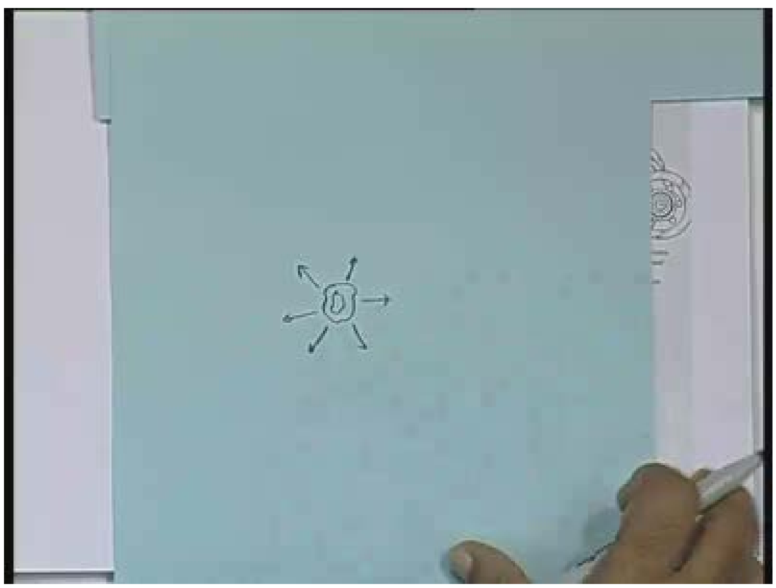

So, what happens is, essentially you have the pellet which is bombarded from all the sides, so it tries to explode. As a result, the inside part is compressed and to such an extent that in the inside part it produces tritium.

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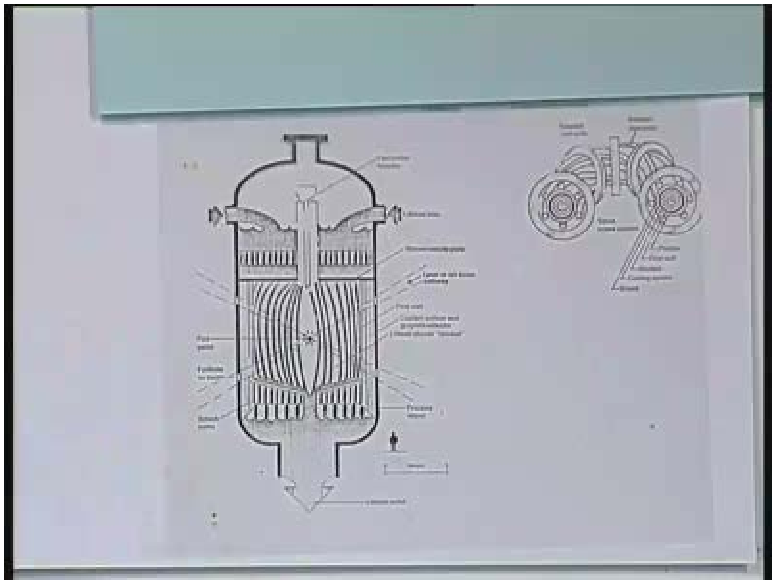

So, you see, again after this is done, in another second another will be injected, again another will be injected, again there will be explosion. Do you see what type is it? It is like an internal combustion engine where there are discrete NO x, discrete explosions. Any internal combustion engine in a car, what happens? You inject fuel, put a spark, it explodes and then the rest of the cycle you take the heat out. Again you put in fuel, spark it, so the energy is not constantly generated. It is generated in discrete times. Here also it will be generated in discrete times, as a matter similar to an internal combustion engine. So, this is another direction in which people are trying.

As yet it has not become clear which concept will be a clear winner. Both concepts are being tried out and by the time you become engineers possibly you will see one concept out of these two or a third concept, nobody knows, emerging a clear winner. There have been some reports, in the meantime, that there has been cold fusion. That means there were reports at some point of time that people have been able to achieve fusion at room temperature, but that has later been proved to be wrong. So, if you hear of those things that it is possible to have fusion at room temperature, do not be carried. This is, this has been proved to be a wrong report, so that is not possible. You have to have that temperature in order to produce fusion.

Notice the result of the fusion process, this is nothing but helium. Helium is abundantly available on this planet as well as in all the other planets, as well as in the sun. It is nonpolluting, it is inert, it is a nice substance and so, fusion process if you really are able to do it, will produce a nonpolluting energy source, you know that.

So, that is exactly why not only the availability, huge amount of availability, the fuel is also abundantly available as we see. Deuterium is abundantly available in the sea water, tritium can be bred, lithium is available. So, you have all the fuels quite abundantly available on this planet and the product of the fusion is also environmentally benign. So, this is a very desirable process, but we are yet quite a few miles for achieving it. But, in India also there are attempts to do this, so it is not, we are not trailing behind the advanced countries in that, we are in the game. So, you have the fusion reactor concept more or less clear to you now.

There are other concepts also, but these are somewhat off beat and these two are most vigorously being pursued and that is why I talked about that. You may hear about other concepts, but you know there can be, people should always try various concepts, but at some point of time at the undergraduate level you should know the ones that are hotly pursued. These two are most hotly pursued. So, let us now try to understand today rest of the class and tomorrow's class will be mainly considered on the issue of environmental impacts of power generation, environmental impacts.

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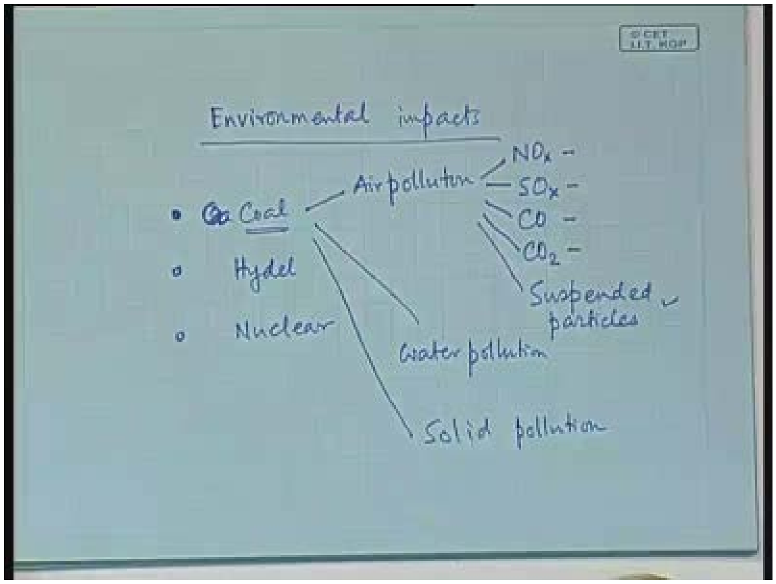

We will have to, both, we have to consider coal power generation, we have to consider hydel and we have to consider nuclear. You have understood all of them; I have talked about all of them. So, you should now be able tell what would be the possible impacts, environmental impacts of coal power generation.

Student: Air pollution.

Air pollution in form of what? So, air pollution that to NO x, SO x, CO, CO 2, yes, suspended particles and anymore?

Student: S

S goes here. After the, after it burns, it does not really go into the ash. Ash contains a lot of things but that is a separate issue, not air pollution. What else do you see? Water pollution, solid pollution; I had given you a brief idea about how to overcome this, but let us just recapitulate that. Is suspended particles a real problem in the modern power plant? No, because you can have very good electrostatic precipitators. You see black soot coming out of the stacks only when the electrostatic precipitator is not working properly.

So, this problem is more or less known how to solve it. NO x, how to solve it and what? No, no, that is for automobiles. How to, how to bring down NO x? By bringing down the temperature and you cannot bring out the temperature in the pulverized coal boilers.

So, you have to have the fluidized bed boilers and bring the temperature down below the level of NO x production. So, that is the way to avoid NO x. SO x, one advantage Indian coal does not have much of sulphur. It has, but not as high a quantity as the European coal. That is why acid rain is a bigger problem is Europe than in India, but nevertheless since it has sulphur, you should understand how to overcome that. How can you overcome that? Very difficult to do in pulverized coal boilers, relatively easier in the fluidized bed boilers, because with the fluidized coal pellets, you know in fluidized bed you have small chunks of coal that is fluidized. Along with that if you mix a bit of lime, then that absorbs the SO 2. So, that can be used as a process.

CO, it is just a matter of proper stoichiometric ratio. So, CO, CO production can be minimized. Unless there is a, there is a bad mixing of air, CO is not really produced. CO 2 is big problem. CO 2 is not a big problem, could not have been a big problem unless the amount of coal power generation were so high. So, now the total quantity of carbon dioxide in the air is going on increasing as a result of what? What happens? We have the global warming problem. The global warming problem is produced by certain gases, out of which methane and carbon dioxide are considered to be prime culprits and there is no way to avoid production of carbon dioxide if you use coal for power generation. So, that is one of the major problems. That is why there is an international treaty nowadays that if you produce electricity by some other means, then you gain, because you gain internationally; also that has monitory benefits internationally. So, those who produce electricity by producing CO 2 have to pay those who do not. So, there is a, there is a treaty regarding that and as you can see, the more advanced countries are producing huge amount of CO 2, because they have to have a larger electricity production.

So, CO 2 is a problem, remember that and nevertheless these ducts that carry the gas, that flue gas does contain pollutants and where it touches the ground there it directly affects the inhabitants of the place, right. So, even though you install a good amount of, a very good electrostatic precipitator, there will be some particles which on a long run, large space may not be all that matter, but the fellow who is sitting just there, who has a house there, for whom it does matter a lot and you can see that in the regions surrounding the Kolaghat thermal power plant, there is a region where the plume touches the ground and that is where there is a huge amount of pollution and we will, we will deal with this issue in the next class.

What is the water pollution source? No; there are two things. One, the water is heated up. The cooling water that is used from the river or lake or whatever that is heated up and released into the river, as a result of which the flora and fauna that were adopted to that particular temperature will now have to adopt to a different temperature, which does not happen. So, that is that is one source of pollution. Again, you cannot do anything about it. Remember, since the whole cycle works on the basis of the Rankine cycle principle, any cycle will have a source, a sink and the limit is, there is a limit. Normally, you have the thermal power plants efficiency less than 40%, which means 60% of the heat must be released into the atmosphere and most of it is released into the atmosphere that is 40% in the water, 20% percent through the chimney. Other than that, the solid material that goes as the ash waste, that contains various substances that mixes with the water that seeps into the ground water. So, that is another source of the water pollution problem.

So, you can see the coal as a source, is a very polluting source. Remember that it is not all that benign source; it is not all that benign, clear. Today time is almost up, nevertheless I will, do you have class after this?

Student: Yes, sir.

So, in that case, I cannot really continue, I will then carry up in the next class. We will consider the environmental effects of hydel and nuclear and then we will make a rational comparison between the three. So, that is all for today.