Fundamentals of Nuclear Power Generation
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Module – 08
Breeder Reactors
Lecture – 20
Evolution of reactors from Gen-I to Gen-IV

Hello everyone, today we are going to start the module number 8 of our course on fundamentals of nuclear power generation. And here our topic of discussion are the breeder reactors. in the previous module, that is in module number 7 we talked about thermal reactors mostly. Of course, the topic of or the under different classification of nuclear reactors, we have seen that it is also possible to run a nuclear reactor with fast neutrons, and correspondingly the liquid metal cooled fast reactors are also mentioned above.

But still we mostly talked about thermal neutrons like the PWR BWRS PSWRS etcetera, all of which works based upon the thermal neutrons. Now in case of thermal reactors moderator plays a big role, because it is the moderator which close down the fast neutrons to the thermal neutron level. And as we already know that, the common fissionable the isotopes like uranium 235 uranium 233 or plutonium 239 has significantly higher fission absorption fission cross section or absorption cross section, at thermal neutron level corresponding to the fast neutron level.

So, the probability of happening having a fission reaction is much higher at for at thermal neutron level, and that is the main reason that most of the global nuclear power plants. So, that we have at the moment are of thermal reactor type; however, there are a few fast reactors that are also available, some of them are already commercially produced power or some more are expected to be operational in next few years, where the main operating principle is based upon fast neutrons only. So, there is no moderator like we have already discussed as a part of the previous module there is no moderator it is the fast neutron which is allowed to strike the fissionable nucleus or the fissile nucleus, and accordingly we get whatever fission reaction that is possible.

But another big difference between fast and thermal reactors is this particular term the breeder or I should say breeding. And in this particular module we are going to discuss about this breeder reactors only. The importance of this one probably you can understand if you carefully think about all those generation 4 reactors. That we have discussed about a among several possible concepts under generation 4 category, 6 concepts we have mentioned which are expected to be the most powerful ones, and hence they are expected to be operational in next one or 2 decades. But out of those 6, at least 4 of them are actually fast reactor types, like you can think about the sodium cooled reactor or a molten salt reactors etcetera, all are fast reactors, or I should say not fast reactors rather fast breeder reactors in short FBR.

Now, there are 2 terms, one is this F, that is fast, which you already know fast refers that the working principle of this reactor is based upon the fast neutrons. So, there will be no moderator, and it is only the fast neutrons that we are going to utilize. But what about this second term is B, the breeder? That is something that we have to discuss now.

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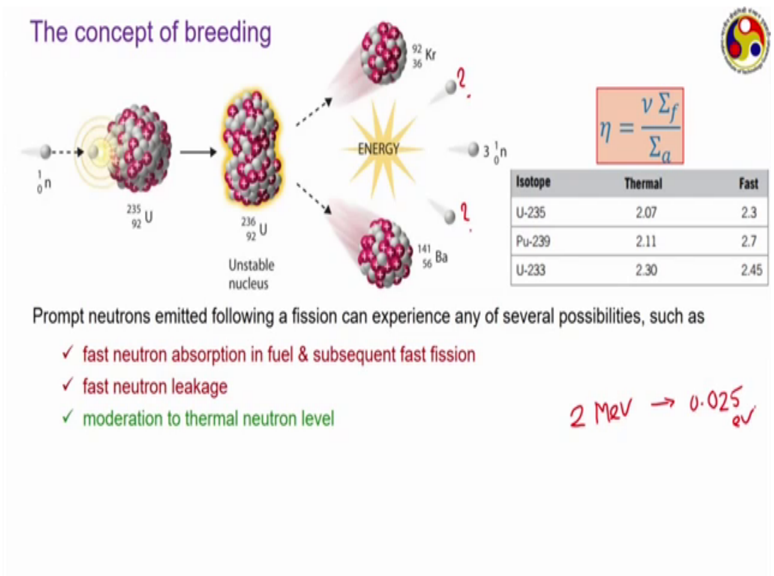

This diagram you have seen several times throughout this course now. Whenever we are striking on uranium 235 with a neutron, preferably a thermal neutron it initially captures that neutron to form an form an unstable isotope uranium 235 or uranium 236 I should say which immediately breaks into two different components, two fission fragments, like in this diagram it is krypton 92 and barium 141.

And also, it release quite a few neutron. The number of neutrons that are released during a single fission reaction can vary from 1 to 7, but most common numbers are 2 or 3, like

3 are shown in this particular diagram. Now the next question is exactly how what will happen with these neutrons, but before that the number of neutrons that are released following a fission reaction that definitely depends upon this eta. Do you remember what is eta? Eta is the thermal fission factor which we have already defined earlier. And it is defined as the ratio of number of neutrons produced during a fission reaction divided by number of neutrons which was absorbed in the fuel, solely in the fuel.

So, the mathematically it can be written as nu which is the number of neutrons produced per fission into the, a fission cross section divided by absorption cross section common of fission materials. Or common fission fuels can have significantly higher fission cross section particularly for thermal neutrons. particularly in a reactive thermal neutrons, and they are non-fission capture cross sections in earlier quite low. And therefore, and also this nu generally is quite high it is significant it is greater than 2 as shown in this diagram. For most of the common isotopes like for uranium 235 or 233 or Pu 239 , they are in that this range of 2.07 to 2.3 on an average whereas, when the same one is subjected to fast neutron.

These numbers are much higher. These are the values of this nu the number of neutrons produced during a single fast fission can vary from 2.3 to 2.7 which for any one of them this is significantly higher like if you compare plutonium 239, it is just 2 point one one for thermal fission rest it is 2.7 for first fission. So, it is definitely significant increase in a number of neutrons availability.

And when we multiply this particular number with the corresponding fission cross section and then divided by the absorption cross section, we get the value of this thermal fission factor. Now the total number of neutrons which are produced like 2.7 on an average in this particular case, what will happen to these neutrons? Instead of focusing on such a fractional number 2.7 let us just stick with these 3. Here in this particular reaction you can see there are 3 neutrons which are which have got produced.

Now, what will happen to these 3 neutrons? We know that in order to have a sustained chain reaction, we need only one out of these 3 neutrons to induce in a subsequent fission, if all of these 3 neutrons or even if 2 out of these 3 neutrons are allowed to cause subsequent fission, then in a next generation which are going to have instead of one in here. We are going to have 2 or 3 fusion reactions, and each fission reactions are expected to produce 2 or 3 further neutrons. So, the number of neutrons will keep on increasing and accordingly number of fission reactions also will keep on increasing or the reaction rate. Which is an unwanted situation such a diverging nuclear reaction is un can be uncontrollable. And so, generally not prefer to in a in order to have a sustained chain reaction a critical reactor, once out of these 3 only one of the neutrons to get engaged in a subsequent fission. Then what will happen to the remaining 2? Out of this if we consider that out of this 3 neutron, this one participates in a subsequent fission reaction in order to continue the chain, then what will happen to this one and this one?

Then let us see what are the possibilities that this neutrons can have; this neutron initially of course, these are there are the prompt neutrons you already know the neutrons emitted really from the fission reactions are called prompt neutrons, and they carry a significant amount of energy and they all are essentially fast neutrons. So, these fast neutrons themselves can get absorbed in the fuel and participate in subsequent fast fission. but the probability general is quite low for such fast fission because of fast fission cross section for these isotopes are generally quite low. Then we can have fast neutron leaking out of the core as well.

Leakage or diffusion of neutrons is a very natural process. Of course, you can control that by controlling the diffusion lengths etcetera, something we have analyzed a earlier, but still we cannot make leakage 100 percent of 2 absolute 0, some leakage will always be there. These are the 2 possibilities that a fast neutrons can have, then we can have the moderation also means this prompt neutrons can go through the moderation that is success in subsequent elastic collision with the moderating nucleus, due by virtue of which it loses it is kinetic energy and come to the thermal neutron level.

Typically the prompt neutrons can have energy in the range of 2 mev, and during a moderation process that can come to the thermal neutron level of 0.025 electron volt. So, that is a huge change in their energy, and we know by knowing the atomic weight or I should say the mass number of the isotope of the moderator nucleus, we can calculate the number of collisions required average number of collisions required to get this conversion done to the thermal neutron level. And also, when this moderation is going on the neutrons has to pass to the resonance absorption zone.

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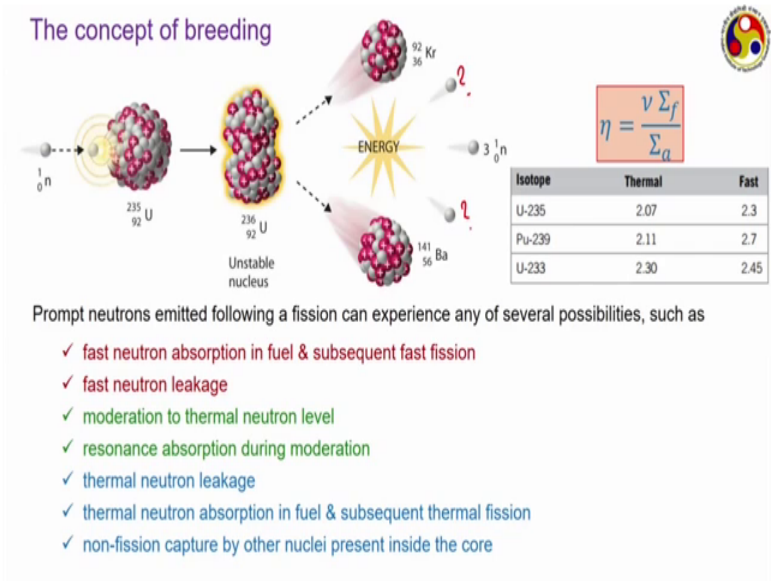

And accordingly, they can also suffer the resonance absorption. Like if it is an uranium based reactor, then uranium 238 is also that we generally has very high absorption cross section, there are several very peaks of the cross section at certain energy levels.

So, the significant amount of neutrons can get absorbed. Then it comes to the thermal neutron level, the neutrons which escape this resonance absorption and becomes thermalized, some of those can again leak out of the core, and the thermal neutrons can get absorbed in the fuel and subsequently an induced thermal fission which is the most desirable one and that is characterized by this terminal fission cross section. I should not say this is the thermal fission factor.

And finally, we can also have non-fission capture by some other materials that are present inside, the core like the coolant like the moderator itself, the poisons which are created by virtue of the reactions the structural elements. All of them can capture some neutrons and thereby take it completely out of the equation such kind of capture or non-fission absorptions are generally termed as parasitic capture.

So, these are some of the most prominent possibilities the neutron can have. The fast neutrons which are produced during the fission reaction, only very few of them will further participate in further reaction. possibility of fast neutron is there, but it is generally a very small, but the thermal fission it is very likely. So, thermal fission can always be there, and it is always desirable that like here a single neutron has induced on fission reaction from where we are getting 3 neutrons. We want only one out of these 3 neutrons to get participation to participate further in a subsequent fission reaction which is most likely to be a thermal fission one.

But can also be fast fission, but then the question is what will happen to the remaining 2? As you can see, they can leak out of the core either in the form of fast neutrons or thermal neutrons. Moderation is actually an intermediate step. So, during the moderation process, they can also get absorbed by because of resonance absorption, and they can also get captured by the other nuclei present inside the core. But out of this the other nuclei that we are talking about actually all of them are not called parasitic capture, rather some of these non-fission captures also can lead to the formation of something unimportant or something which can be used for the downstream.

So, parasitic captured refers to those kind of non-fission capture reactors where we do not get any fission of course, and you also do not get any kind of useful product like which may happen in certain nuclei is.

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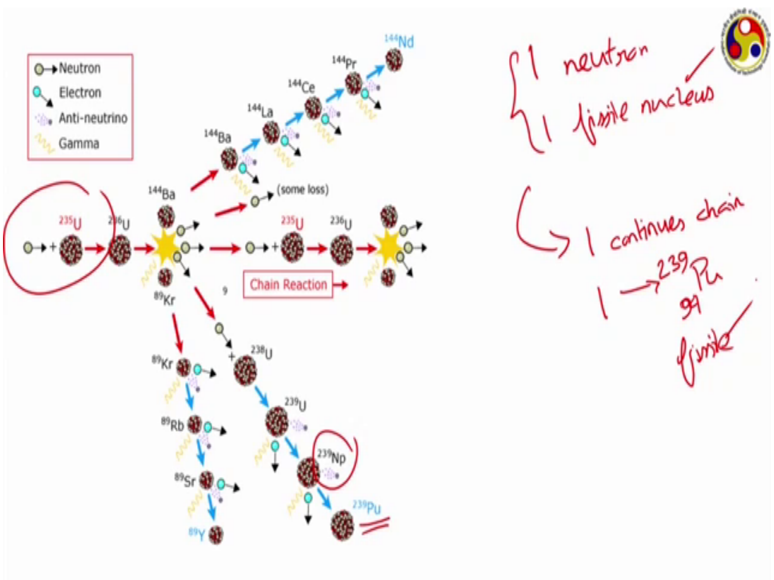

Now, take a look at a more elaborate diagram. Again, one uranium 235 has been stuck by one neutron here that. So, to cause a uranium 236, and then we have this fission reaction happening. During this fission reaction we now have 3 neutrons. And also, you have that products Ba 144 and Kr 89 or the products that are shown in this diagram.

So, out of this Ba 144 which is highly radioactive goes to this radioactive chain, final to settle down as a Nd 144. And all these steps in generally involve electron emission or beta emission beta minus emission. Thereby, their mass number remains the same, but atomic number continually keeps increasing by one. So, that it finally, gets from barium it finally, gets converted to Ned. Similarly, krypton also goes through 3 steps of a beta decays, and finally, this Kr 89 gets converted to k a k it is Y 89, I should say Y 80 finally, just converted to Y 89 yttrium.

So, all this beta decay processes are all these radioactive decay process processes involves beta decay. So, they do not contribute any further neutron with the system then the 3 neutrons which are originally produced. Let us just number these neutrons, let us say this is number 1, this is number 2 and this is number 3. Now number one strikes another uranium 235 that may pass through the moderation. So, get it gets thermalized, and then strikes another uranium 235 to form uranium 236, and we have another fission reaction.

So, the chain is sustained and out of corresponding to one neutron here we have one fission, and then the neutrons which are produced from this fission leads to again a single fission reaction. But still we have neutron number 2 and 3 left neutron. Number 2 may go for some kind of loss. Loss may referred to leakage, leaking out of the core either in the form of fast neutrons or thermal neutrons, loss may also referred to the resonance absorption, even loss may also refer to the absorption after be becoming thermalized by the by other materials present in the core like the coolant the moderator the structural elements control rods etcetera.

So, neutron number 2 is also gone out of the system, but still we have neutron number 3. This neutron number 3 that may get absorbed by uranium 238. You remember in natural uranium is primarily uranium 238 and only 0.7 percent is uranium 235 uranium 235 is a fissile isotope. So, that is participating in the fission reaction, but uranium 238 is not fissile. So, it cannot participate in fission reaction. Therefore, only kind of absorption in reaction it can have with neutrons is a non-fission capture.

But as soon as it captures one neutron it becomes uranium 239, and uranium 239 is highly unstable it has extremely small new half-life. Therefore, it immediately decades following a beta emission to get converted to neptunium 239, again neptunium 239 is also a highly unstable isotope. It also goes through a beta decay thereby finally, producing plutonium 239. Now what is the nature of plutonium 239, plutonium 239 is a fissile material. And therefore, one of the neutrons which are produced because of the initial fission reaction leads to the formation of another nuclear fuel which is plutonium 239.

Just see here, we started with one neutron, we have just started this with one neutron, one fissile nucleus, and from there these are the 2 things we had initial to start with, from where the neutrons was whichever are produced one continues the chain reaction others may leak out, but one leads to the formation of Pu 239. Which itself is another fissile material or fissile nucleus. Therefore, we have started with a one fissile nucleus, and we have also ended up with maybe different, but still a fissile nucleus. And this is what we refer to as the breeding. the fissile nucleus which was initially present in the system, that has completely disappeared by virtue of the fission reaction.

But the corresponding fission products or a our fission the corresponding fission products are the neutrons emitted during the fission reaction leads to the formation of another fissile isotope. That is the whole concept of breeding, that is the and that is also we you call something like uranium 238 a fertile isotope. Fertile means it can participate in a breeding reaction to lead to the formation of a fissile nucleus, in this case uranium 239.

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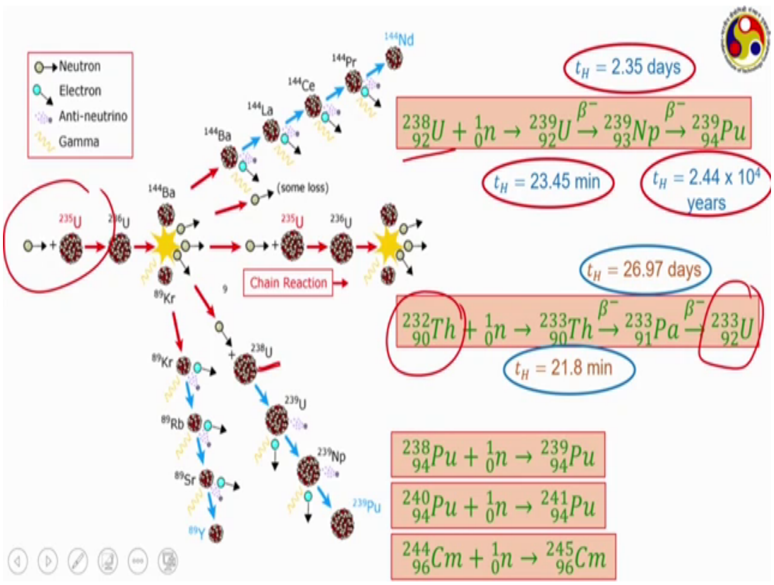

This is the corresponding reaction uranium 238 captures the neutron to fermium 239, which goes to 2 steps of beta decay to really get reduced to plutonium 239.

Uranium 239 has extremely small half-life just about 23 minutes, and even neptunium 239 also slightly longer, but still it is just 2.35 days. And therefore, within 2.35 days, the uranium 238 since the point of capturing the neutron will give to the formation of plutonium 239. This one is a fertile isotope, this one is a fissile isotope, and one fertile isotope gets converted to a fissile isotope. Thereby lead thereby somewhat conserving the total number of fissile isotopes that may be present in the system or.

I should not make that kind of statement, rather further moment you just keep it here that uranium 238 is a fertile isotope which is converted to a fissile isotope of plutonium 239. And this is not the only breeder reaction depending upon the content of the reactor we may have several kinds of breeder reaction. plutonium 239 is a long leaving isotope, it is half-life is 2 0.4 into 10 to the power 4 years. So, it can participate in fission reaction, and it can be stored or it can also be used for some other subsequent purposes. This is another breeder reaction , thorium 232, which is the fertile isotope, absorbs a neutron to get converted to thorium 233, which is a highly unstable one having half-life of just 21 minutes.

Then thereby via beta decay that is just converted to protactinium, which is having about 27 days of half-life, which goes to another level of beta decay to produce uranium 233. Again, here we are starting with a fertile isotope and getting con that converted to a fissile isotope. So, the total number of fissile isotopes present in the system, that keeps on increasing or at least is are maintained. Protactinium has a slightly longer half-life of the order of 27 days.

So, whenever you are working with thorium 232 and want to produce uranium 233 need to be very careful about not allowing this protactinium 2 participate in some other neutron absorption. If it absorbs neutron, it will become protactinium 234 which is actually a stable isotope. So, some of you have to keep this protactinium, just in this particular form. So, that it can go to a beta decay and not the neutron absorption. We can have quite a few other kinds of breeding reaction also. Which are just single step breeding like plutonium 238 is a fertile isotope which can absorbs a neutron to get relative produced relative produced plutonium 239.

Plutonium 240 another one which can get converted to plutonium 241 a highly fissile isotope a very interesting one it is a curium which has an atomic number of 96 where definitely in artificially produced isotope, a curium 244 can lead to the formation of curium 245 which is actually an well material and generally used in nuclear weapons only.

There can be few other examples also, I am not listing it, but the objective of all this discussion is that where the process of breeding we can convert a fertile isotopic fissile one, and out of all the neutrons which are emitted following a fission reaction, it is these neutrons they can lead to the while they can participate in subsequent chain reaction, they can also lead to the formation of new fissile isotopes. Like, if we just stick to the diagram that is shown here, here initially you have started with one fissile isotope uranium 235, and once the first stage of reaction is done, means just to consider the first stage of reaction let us separate out this dq of and these fission fragments. And also separate out the second stage of fission.

Then what we are left with, and the fission fragments some neutron were getting lost. And also, this particular chain reaction, this particular reaction line which finally, ends up with another fissile isotope. So, we have started with one fissile isotope here, and we have ended up with another fissile isotope somewhere here. Therefore, the total number of fissile isotopes inside the reactor is somewhat conserved, or the total number of a or the fission reaction can keep on happening yeah or rather the fission contribution is coming not solely from uranium 235, but from plutonium 239 also once it is concentration becomes sufficient.

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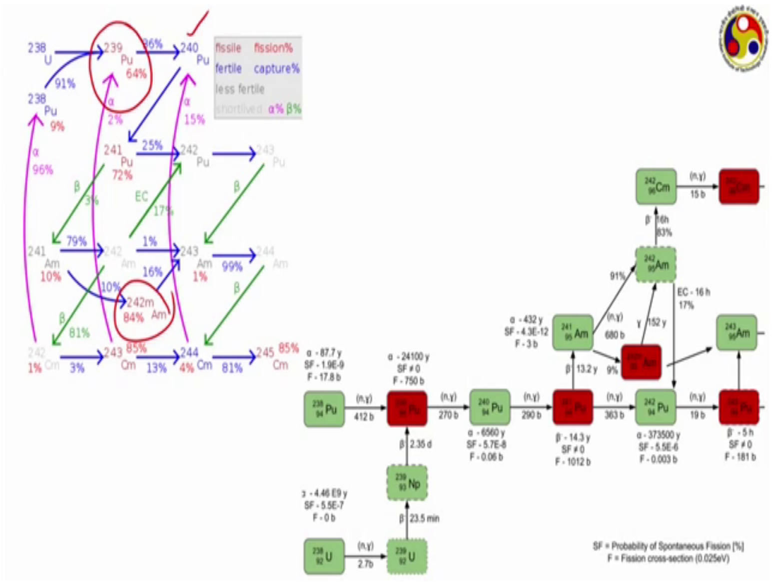

This is a more elaborate view of the same, we are starting with uranium 238 which goes to an N gamma reaction to participate a in a neutron capture to form plutonium uranium 239, which is has a small half-life of 23.5 minutes. So, that forms neptunium 239, which is a half-life of 2.35 days which leads to the formation of plutonium 239. Plutonium 238 can also participate in a N gamma reaction produce plutonium 239.

. So, plutonium 239 can get produced in 2 ways. One is just by a neutron capture cross section just by a direct neutron capture of plutonium 238. Or because of 2 successive levels of beta decay of plutonium 238 it sorry, 2 successive stages of beta decay of uranium 238. This plutonium itself can also capture some further neutrons. So, if you goes to 2 steps of a further neutron decay step number one here, and step number 2 here, then it leads to the formation of plutonium 241 which is a highly unstable isotope.

And now this plutonium 241, that can also go through 2 possibilities and kinds of reaction. It can go through a beta decay to perform am 241. It can also go through an N gamma N gamma (Refer Time: 25:09) reaction to form plutonium 242, and then this plutonium 242 can participate in another step of a neutron absorption that is 2 steps 1 and 2, 2 steps of neutron absorption by plutonium 241 leads to a function of plutonium 243, which is again fissile.

So, plutonium 231, plutonium 241, plutonium 239, plutonium 241 and plutonium 243 all are fissile, and there are several ways they can get produced. Plutonium 241 can also go through a beta decay process to produce am 241 and there is a less possibility that Am 241 can plutonium sorry, Am 241 can find it going through 2 different kinds of a reaction. 91 percent chances it will go to an N gamma to reaction to produce am 242. But there is also a very small probability of Am 242 Am appearing and finally, the Am 242 that are getting produced that can participate through a beta first a beta and then an N gamma reaction to again form corium 243.

So, there are several ways a particular several ways breeding can happen and a fission reaction can get produced. Um either following a route like this, a fissile isotope can be produced either following a root like this, or following a route somewhat like this. This is another view of the same thing. Here we are starting with uranium 238 as we have already seen the half-lives are extremely small. So, it can be viewed that uranium 238 is almost instantaneously getting converted to plutonium 242 39, which is a fissile one and it is fission absorption cross section is something on the range of 64 percent of the total absorption cross section. There is a 36 percent probability for this one to go through a capture reaction to get form to the plutonium 240.

If we follow that plutonium 240, this one that I am talking about, it can go through 2 levels of reaction or I should say 3 levels to end up somewhere here. 242 Am, and we can also get this cm 245 from some other means. So, the breeding can happen because by different routes or through different routes and then depending upon whatever is the final outcome we may get some higher amount of energy than expected like. If you are talking about just an uranium fuel reactor, then initially when the reactor is loaded with fuel it contains only uranium 235 and 238, other isotopes of the uranium can be neglected.

Now, as the reactor continues to operate, while the uranium 239 concentration keeps on going down because of this radioactive decay, uranium 238 concentration also keeps on going down. Because uranium 238 captures neutron and there is a high probability that uranium 238 after uranium 238 after capturing that neutron becomes uranium 239, and then can lead to the subsequent appearance of a fissile isotope of plutonium 239.

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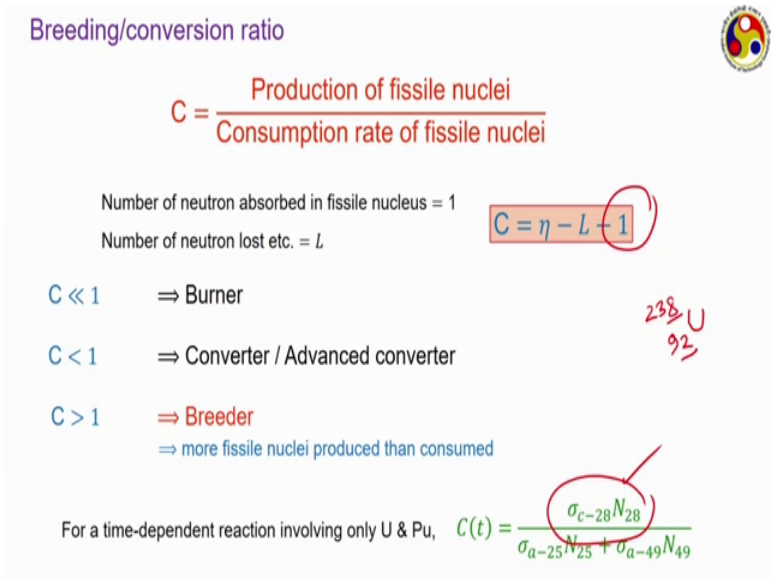

You have to quantify this process of breeding. We define something called a breeding ratio or conversion ratio.

Conversion ratio is defined as is written on the screen production of fissile nuclei divided by one consumption rate of fissile nuclei. But you can say production rate of fissile nuclei by conversion rate of fissile nuclei. Let us consider a situation where a single neutron has been absorbed in the fissile nucleus. So, total number of neutrons which are produced, because of this fission will be equal will correspond if this one will be equal to eta because eta represent the total number of a fission divided by total number of neutrons absorbed.

Then if we assume that one number of neutrons are getting lost or by getting absorbed into some other parasitic elements, then C should be equal to eta minus l minus 1. Here you have this one comes because 2 in order to sustain the chain reaction, one neutron should one neutron should be eliminated from this. So, even if eta C equal to eta minus l. When C is extremely small; that is, a neutrons are fissile nuclei are getting consumed, but hardly anything is getting produced. That kind of reactors are called solely burners, these are old reactors, which generally are in the first or a early second generation on nuclear reactors. Then when C is C is having certain value, but it is still less than 1, those kind of reactors are called converters or advanced converters.

The term converter is generally used when the C is in the range of a 0.3 0.4 whereas, the advanced converter is something which takes you to advance converter is something where the value of C is still less than 1, but maybe in the range of 0.8 0.9. When C becomes equal to 1, the number of fissile nuclei produced during a reaction which is equal to the number of fissile nuclei absorbed. Therefore, total number of fissile nuclei inside the reactor will be conserved in that limiting case of C equal to 1, but the interesting session is when C it becomes greater than 1 .

C greater than one refers to whatever may be the number of nuclei of nuclei that is getting consumed because of fission more number of nuclei are getting produced, thereby increasing the total fuel concentration inside the reactor. So, such kind of reactors are called breeder reactors which produce more fissile nuclei produced then con that con then consumption rate. So, our topic of discussion here are breeder reactors and therefore, we would always like to talk about C greater than 1. There are other ways of or calculating this C also if you are talking about if you are talking about a time dependent reactor which involves only uranium and plutonium that is initially loaded only with uranium and plutonium appears with time.

Now, it can also be written as this particular formula here the numerator refers to sigma into N of 28, which is the total macroscopic capture cross section of uranium 238, there if we are talking about time dependent reactor of course, there are others are calculating this breeding ratio also like if we are talking about a reactor which involves only uranium and plutonium, then in the numerator we are having this quantity sigma C into N 28, here this 2 8 I hope you remember at the convention that we used while dealing while discussing about the criticality of reactors, or I should say the time dependent reactor analysis that we have done a still just as a recap 92 u 238 can often be written as 2 from there here and 8 from here so, that is 28.

That means, in this particular numerator refers to the total capture cross section of uranium 238. And each uranium 238 capture will lead to the each you such a capture reaction will lead to the formation or appearance of one new fissile plutonium 239 acetone. And in the denominator is the consumption rate of fissile nuclei. So, consumption can be of 2 types one is the consumption of this 25, 25 means uranium 235 and consumption rate of N 49, 49 is plutonium 249.

So, for a time dependent reactor as the concentration of this 3 isotopes; that is, the uranium 235 238 and plutonium 239 keeps on changing the value of this conversion factor ratio can also change and in this counts account text.

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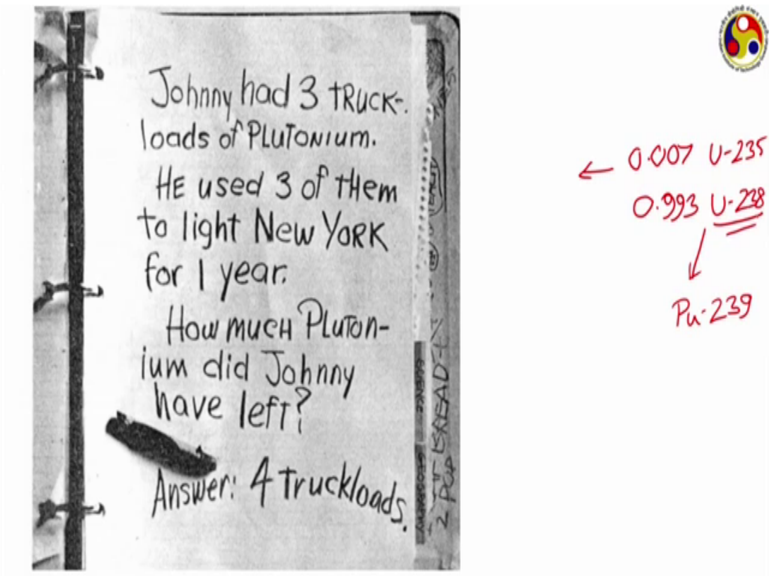

This is a picture that I found on internet and I found this probably is the most apt representation that we can have for this concept of breeding. it is just like it seems quite funny that like in this example. Some 3 trucks of plutonium has been consumed to produce electricity, and at the end of the year the total number of trucks left are actually 4; that means, whatever fluid we have started with, at the end of one year we have ended up with more amount of fuel.

It seems quite puzzling, because you may think out from where this additional mass is coming. But you have to remember that like in a reactor fueled with natural uranium, we have 0.007 fraction of uranium 235, and 0.993 fraction of uranium 238. While this one parties in fission reaction, a good fraction of this one participates in the non-fission capture reaction to form this plutonium 239. Therefore, the new plutonium 239 which are appearing this, there actually at the express of this uranium 238 with time as the concentration uranium 238 decreases, plutonium concentration will. So, will start to decrease I should say as the concentration of uranium 238 starts to increase plutonium concentration also will start to increase, or in a reactor where we are using enriched fuel the fraction of uranium 238 will be lower accordingly the plutonium production also will be lower.

But whenever the plutonium is getting produced that will immediately part as in the fission reaction because of it is extremely high fission cross section, leading to a emission of reaction of some further neutrons um.

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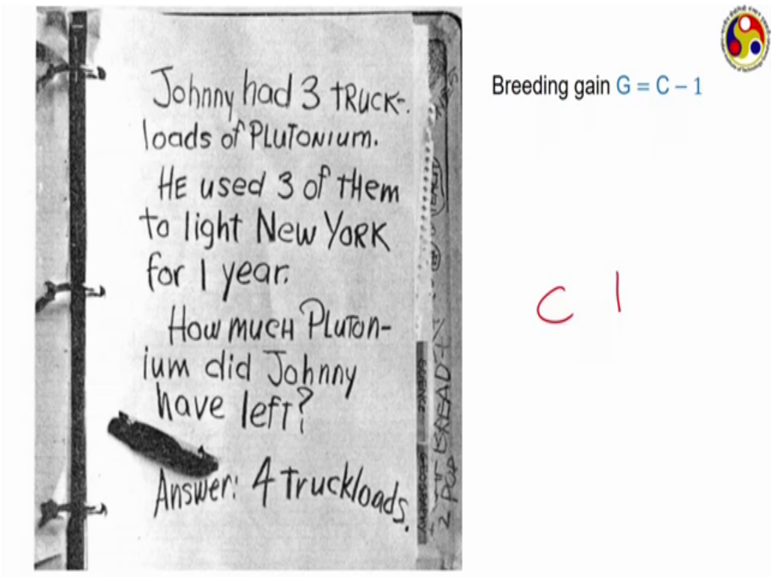

So, as an answer to this particular thing, we define something known as the breeding gain, G is equal to C minus 1 where C of course, is the conversion factor or breeding breeding ratio. And so, if we are talking about just a single neutron that is getting absorbed in the fuel, then that will lead to the formation of C number of neutrons, and then out of this C one neutrons will consumed or I should say not neutrons C number of nuclei.

And out of this one nuclei nucleus will participate further fission reaction. So, whatever left with this C minus 1 which is this breeding gain. For a non-breeder reaction G of course, is less than 1, but for a breeder reaction value of G is greater than 1.

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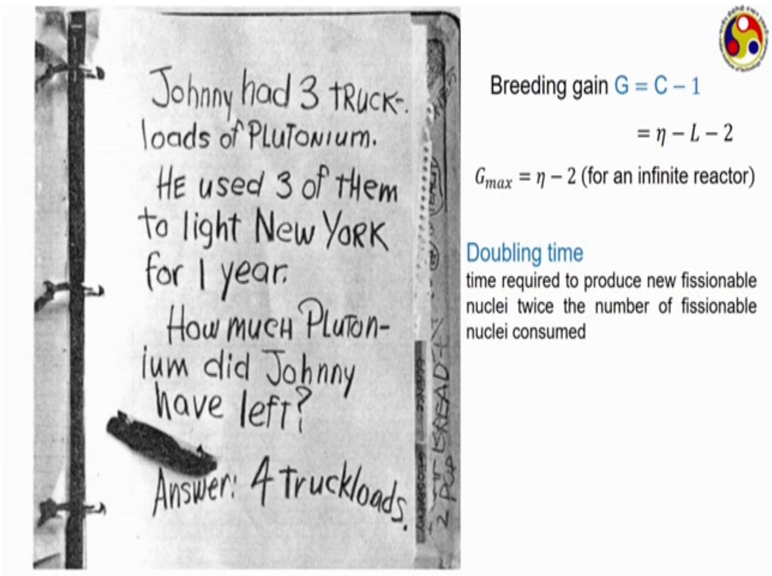

Now, it has to be greater than 1. We can also put the expression for C here and get eta minus l minus 2. And if you are talking about an infinite reactor, the maximum breeding gain can be eta minus 2 because l is 0 for an infinite reactor.

Sometimes another terminology is define which is called the doubling time, doubling time refers to the time required to double the total number of fissionable nuclei with compared to the number of nucleus that we had to where initially to start with. Like again going back to the example of union fuel reactor, initially suppose we are having 100 numbers of uranium 238, and one thousand number of sorry 100 numbers of uranium 235 and one thousand numbers of uranium 238.

So, number of fissionable nuclei to start with is actually 100, but there are thousand numbers of uranium 238 also the neutrons which are getting emitted from the fission of this uranium 235 some of them can participate in further fission, and thereby converting the uranium 238 to uranium 230, uranium 238 to uranium 239 plutonium 239 I should say similarly if a thorium is present there thorium 232 will get converted uranium 233. Therefore, those 10 thousand number of uranium 230, there will be reduction in the total number of such isotope, but there will be a continuous increase in the number of plutonium 239 that are available.

And doubling time requires is that. So, doubling time refers to the time, by which the total such fissionable isotope or fissile isotopes the number of that will become double of whatever we had double compared to whatever we had initially.

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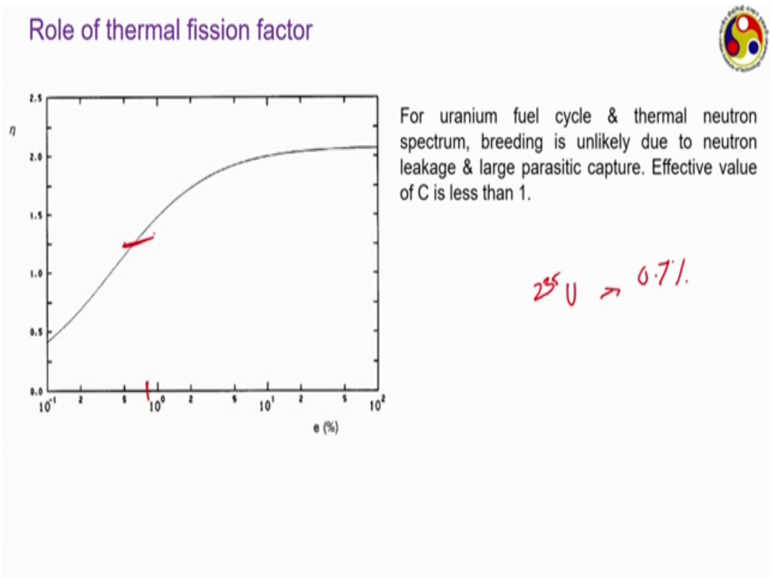

The thermal fission factor plays a very important role here, thermal fission factor we know how to calculate, and we also know that for thermalized neutrons that is sorry means for natural uranium, I should say for natural uranium the uranium 239 fraction is 0.025 something I am saying wrong ok. In natural uranium uranium 235 is present in 0.7 percent.

So, if you search on this diagram, it is somewhere here corresponding value of uranium 235 is somewhere here, which is around 1.3. For uranium fuel cycle, which are operating based on thermal neutron spectrum, such building is very unlikely. As the neutron leakage can be quite high, there can be significant amount of resonance absorption, and parasitic capture can also be high.

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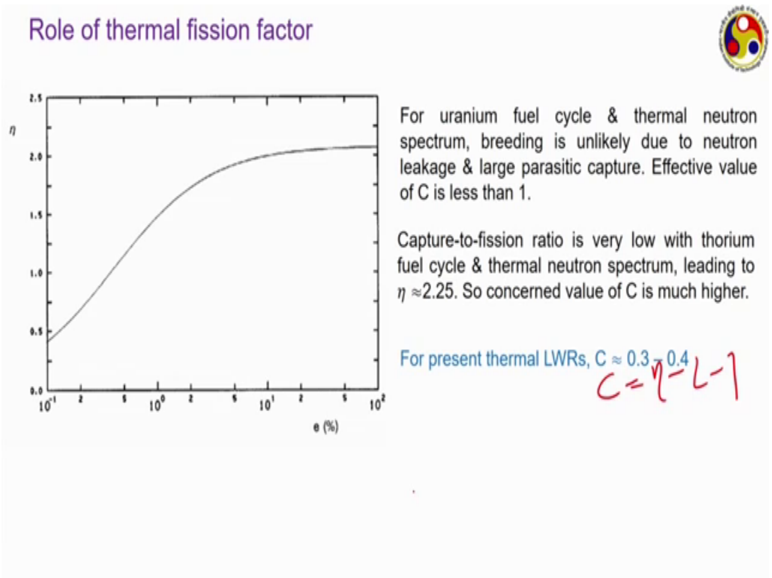

So, effective value of C in thermal fission reactors generally less than 1 for thorium based thermal reactors, capture to fission reaction ratio is very small, because thorium itself is a fertile isotope, but the uranium 233 which can be a produced from fission of which can which can be produced from non-fission capture in this thorium can lead to the value of eta equal to 2.25.

And hence the constant value of C also is expected to be much larger. Because we have just seen the value of C is equal to eta minus l, minus 1 or I should say not 1 eta minus l minus l minus 1 earlier we have seen. For a present day thermal LWRS that is PWRS or BWRS value of C is quite low in the range of 0.3 to 0.4

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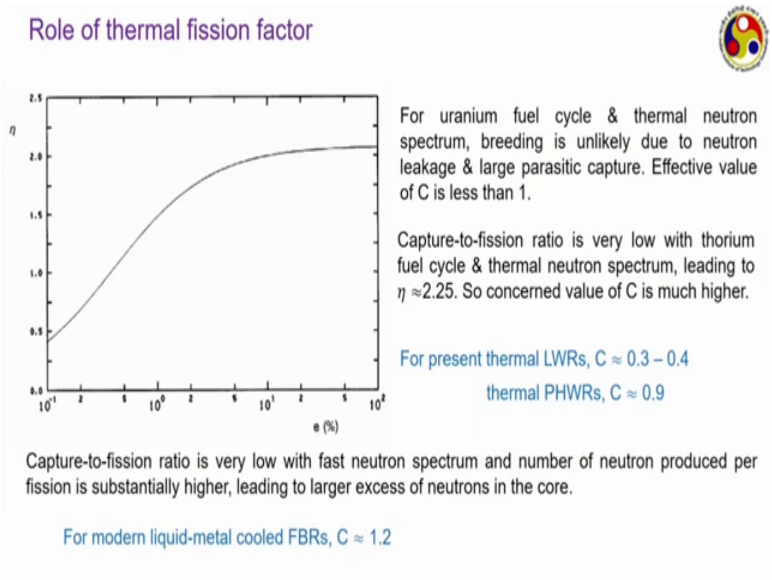

However, in PHWR we use deuterium as or heavy water as the moderator, which has extremely low absorption cross section therefore, parasitic capture itself is quite low.

In case of LWRS the water an ordinary water which is used as the moderator and also is coolant that has a quite noticeable absorption cross section. So, that can definitely parties in the parasitic capture; which is not true for PHWRs their absorption cross section is extremely low and therefore, we have very high value of this conversion factor. Finally, the fast neutrons the capture to fission cross section is very low with fast neutron spectrum, and number of neutrons produced per fission is also quite number of neutrons produced for fission is also quite high compared to thermal reactors, leading to quite a high it is a large number of neutrons present in the core excess neutrons; which can have a C value of 1.2 or in that range.

So, thermal reactors are very unlikely to act as proper breeder because their value of C is less than 1. So, the total number of neutrons or fissile isotopes produced because of non-fission capture is less than the number of isotopes that are consumed. But only for the fast breeder reactors, because of the fast neutron spectrum and the large number of neutrons which are emitted, and because of fission they can conveniently act as breeder reactor.

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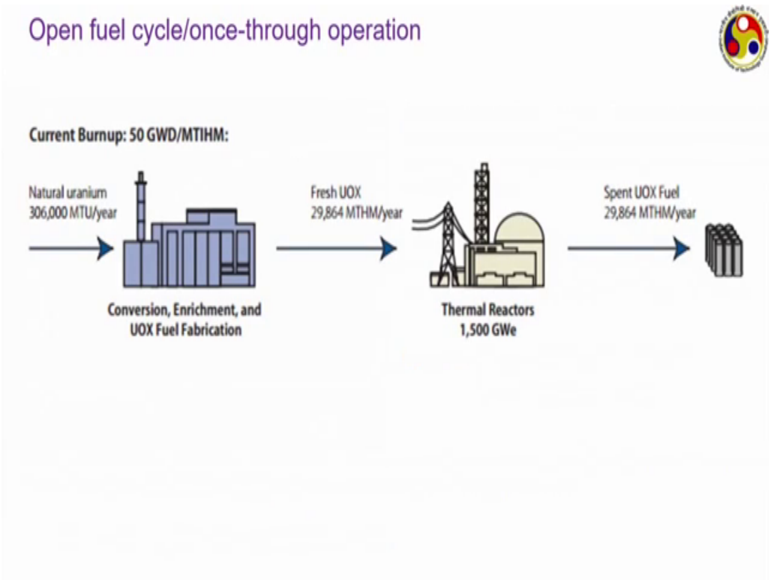

At this particular point before I close to this lecture I would like to quickly discuss about 3 different fuel cycles which are followed in industries.

Um just here we have seen that a different kinds of reactors can give different kinds of kept the breeding or conversion ratio and that conversion ratio is a function of thermal fission factor. Now thermal fission factor continuously increases, with enrichment and settles around a enrichment level of 5 it more or less settles into this value, which is something like 2.06 for uranium to ah, but uranium 235 it is. But the natural uranium ore that is available that has if a fraction of only 0.3 percent a 0.7 percent rather.

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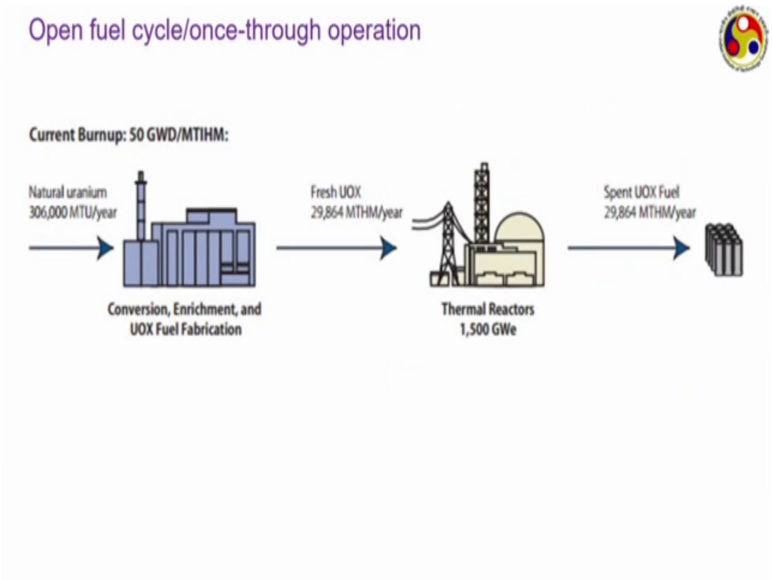

So, we somehow have to enrich that fuel to in increase the percentage of uranium 235 in the final mixture that is going to the reactor. And also, we expect the burnup of the fuel to a very high so that the amount of waste available is smaller. And accordingly, we can have different cycles of fuel. The first one is the open cycle fuel or open fuel cycle, in case of open fuel cycle the fuel which is taken from the raw uranium ore taken from the mines are converted if required enriched, and then it is converted to a some kind of oxides. And then that oxide is and which everything is done here. This is the natural uranium coming from the ore, and this conversion enrichment and oxide formation are done in this converter.

Here the other numbers that are shown corresponds to this amount of energy released that is 50-megawatt day of energy release per metric ton of per metric ton of the metal that is coming from the ore coming from the mines. So, which is 306000 metric ton unit per year and then this uranium oxide that is getting this uranium oxide is taken to the thermal reactor of 1500 gigawatt capacity. And corresponding this number such as this 1500 gigawatt, we get spent UOX fuel of this much.

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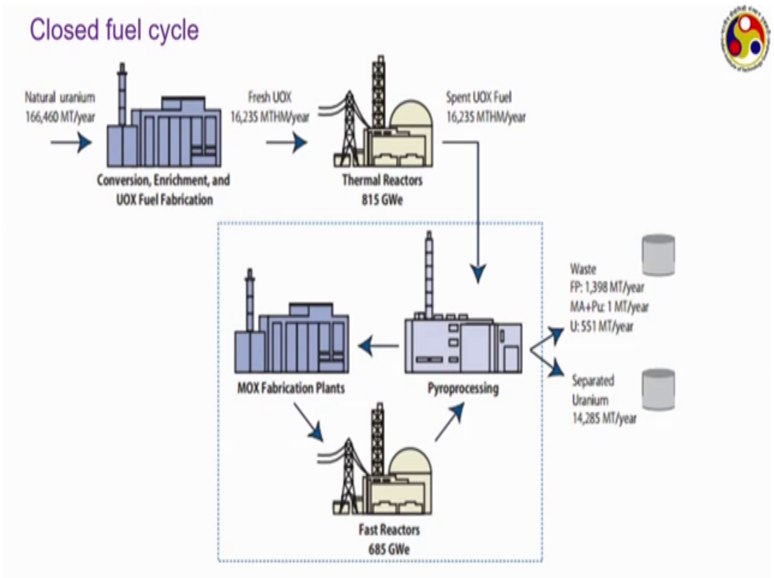

But more popular one is a close fuel cycle here; initial part is the same natural uranium coming to the coming to the processing industries or processing industries, where they are converted and needs to form uranium oxide. And that is taken to the thermal reactor here the capacity of the thermal reactor is considered to be slower or I should say smaller.

But the spent uranium oxide fuel that is coming out of this thermal reactor, that are not just thrown to a atmosphere rather that is supplied to a fast reactor which is also coupled with a pyroprocessor and a MOX fabrication plant MOX. Or MOX refers to mixed oxide which are actually combines uranium oxide plutonium oxide together and this mixed fuel is commonly supply this fast reactor. Which is giving 685 gigawatt of energy and the 685 plus 815 together is equal to that 1500 gigawatt.

And the because of the breeding that may happen is at the fast reactor, while it of reactor itself is consuming fissile material or fissile nucleus, it is also producing fissile nucleus which are the by this process of pyroprocessing and MOX fabrication can again come back to the reactor, thereby minimizing the total emission from this, here the waste amount of waste that are produced because of this is also very small.

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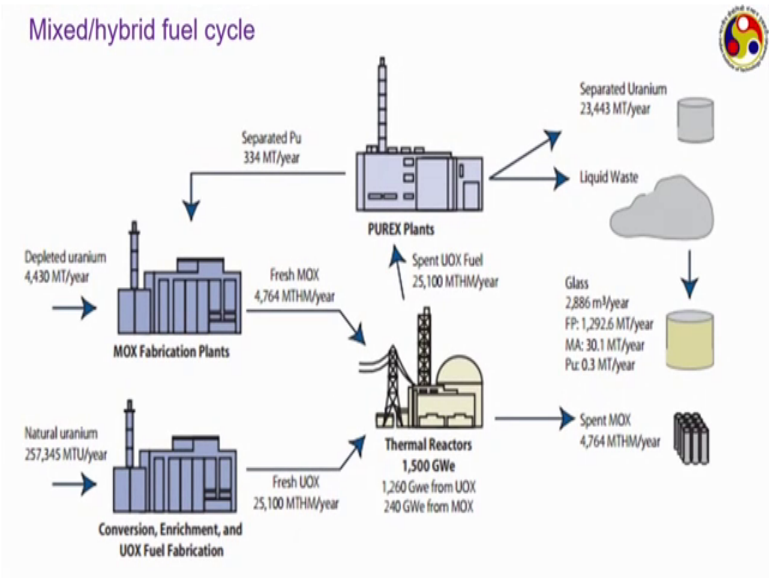

And finally, the mixture hybrid fuel cycle, where it is using both natural uranium or uranium oxide and also MOX. So, the natural uranium after being converted and oxide formation is subject to the thermal reactor, and also depleted uranium coming from some other source, that is supplied to a MOX fabrication plant and the MOX is also supplied to the thermal reactor. What I was painting in oxide fuel is supplied to purex plants, from where basically plutonium is separated. And uranium is also separated this purex plant separates both plutonium and uranium. And it can also leads to the formation of liquid wastes.

. So, it we can have 3 different kinds of fuel cycle one is a open or closed to open or once to cycle where the raw fuel or raw uranium taken from a mine is converted to uranium oxide, and that is used and once the reaction once the energy has been harness from that it is directly disposed as a waste. In case of the second one which is closed cycle or the cycle which is based upon the MOX; it can have both thermal and fast heater components.

The thermal reactor component uses uranium oxide, and the spent or the waste from that uranium the thermal reactor is supplied to the first reactor through the reprocessing unit which produces MOX and harnesses further power from the thermal reactor. Further power from the first reactor and finally you have this mixed fuel cycle where the same thermal reactor is utilizing both fresh uranium oxide and a fresh MOX to give similar level of power output.

We shall be discussing further about this fuel cycles and also fuel processing, that we have and also fast breeder reactors generally require quite high level of enrichment like we have seen for thermal reactors enrichment they will be quite low, restricted to something like 1.5 to 4 percent or 5 percent, but breeder reactors very high level of enrichment something in the range of 10 to 15 percent. And therefore, in the next class we shall be discussing about the process of enrichment as well before we can come back to the topic of breeding again. So, that is it for the day, I would like to close it here itself, and we shall be continue our discussion in our next lecture.

Thank you very much.