Indian Institute of Technology Madras
Present

NPTEL
NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

NUCLEAR REACTOR AND SAFETY
AN INTRODUCTORY COURSE
Module 02 Lecture 02
Basic Physics of Nuclear Fission Con...

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Good morning everybody. Hope you had a nice weekend. We will now continue with our lecture on some more basic physics related to the nuclear reactors.

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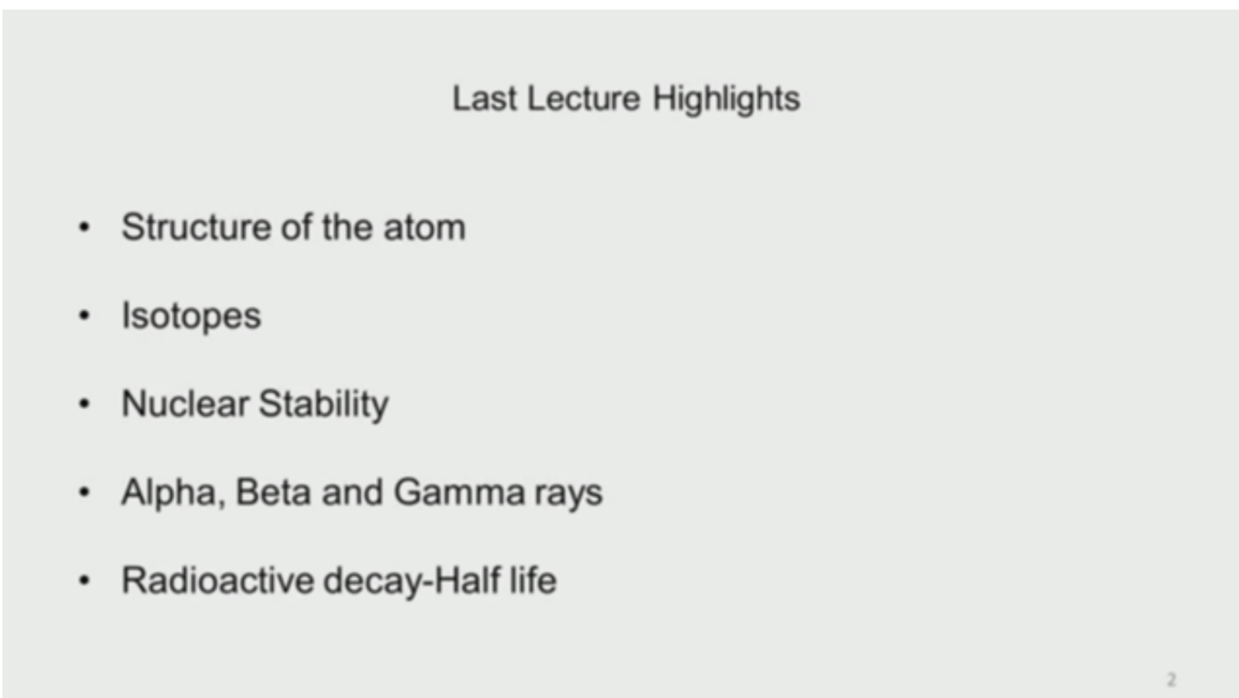

In the last lecture, we had a look how the structure of the atom was. Then we referred to isotopes, basically, an element having similar atomic number, but different mass numbers, essentially, because of more neutrons in their nucleus, but since the atomic number decides property of the things, they are all called having the same they are called isotopes. Then we talked about nuclear stability, what is required to be stable? How the -- what are the conditions under for which the --

we have most of the nuclear stability and beyond a certain mass number, we don't have stable nuclides? Then we talked about how these unstable nuclides radiate radioactivity in the form of Alpha, Beta and Gamma rays and we also talked of something like a concept of Half-life and how the -- what is the Half-life of the different elements?

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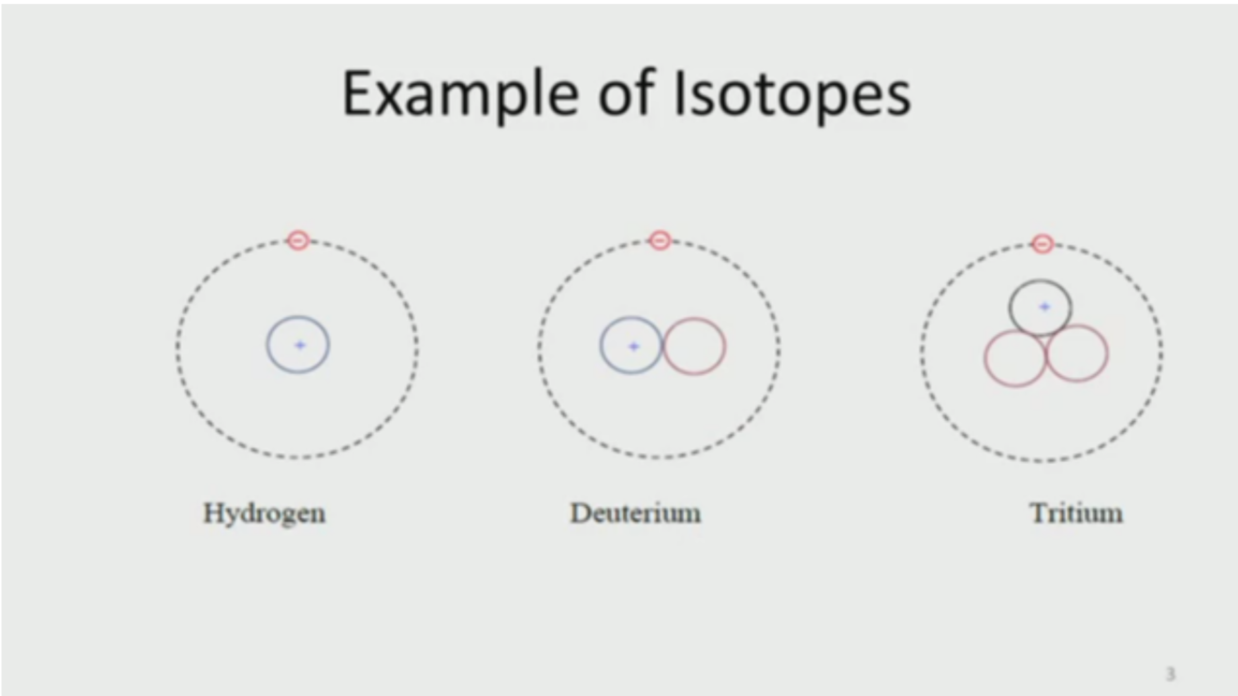

Now just to reinforce the fact about isotopes, I thought I would just present you the isotopes of hydrogen. Hydrogen, we know what we know is one, which has one proton and one electron. So this is called as a normal hydrogen and Deuterium or the heavy hydrogen as it called, it has one neutron, sorry, it has one Neutron added in the nucleus. When you go to Tritium, we have two neutrons added, but the number of electrons and number of protons remain the same, which decides the chemical property. Here we'll be surprised, Deuterium is not a radioactive one, but Tritium is a beta emitter. So it's not necessary that all the isotopes are radioactive. Some isotopes may be radioactive. Some may be not.

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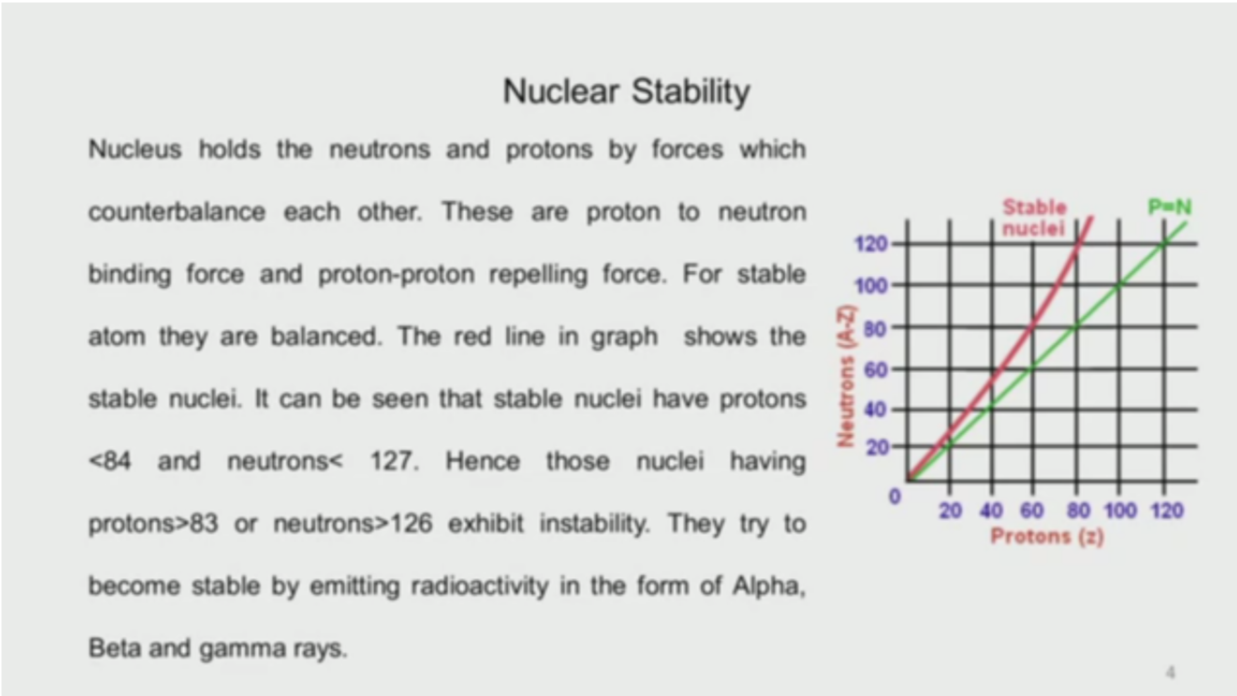

Now just to one question was the nuclear stability we made clear. There was one of the clarification sought by a student. I thought I'd put it in this way. See nucleus holds the neutrons and protons by what? Some forces, the attractive forces and the repulsive forces, when they balance each other, then the nucleus is stable. So, basically, what are the forces? The proton to neutron binding force and proton to proton, which is a positive to positive repelling force. So they are balanced for a stable atom.

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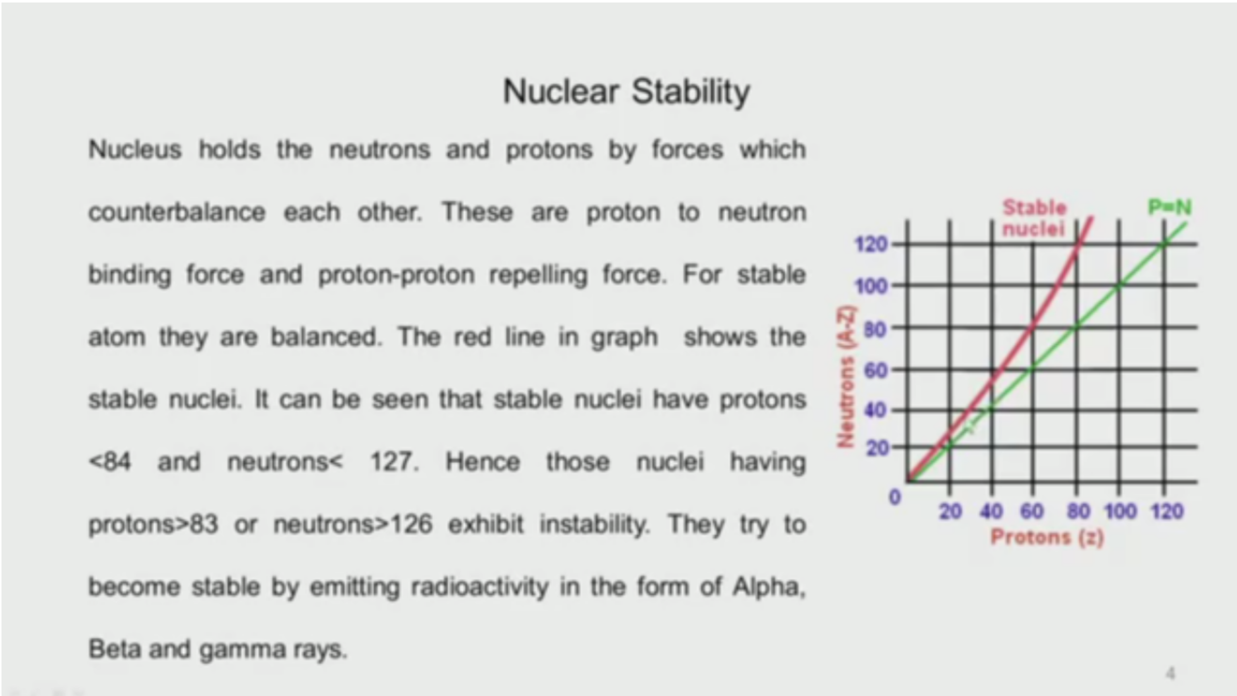

Now here the red line shows where all the stable nuclei in nature have and you see it stops with the number of about 84 protons and neutrons beyond 120. Basically, beyond this, there are no stable atoms at all, no stable nuclei available. So what happens? Those stable, unstable nuclei to be -- they would like to become stable. So they emit radioactivity in the form of Alpha, Beta and then they become stable. So this is what and the green line is just to show if N is equal to P, the number of protons is equal to protons, what it is. So you can see more or less everything lies very close to that.

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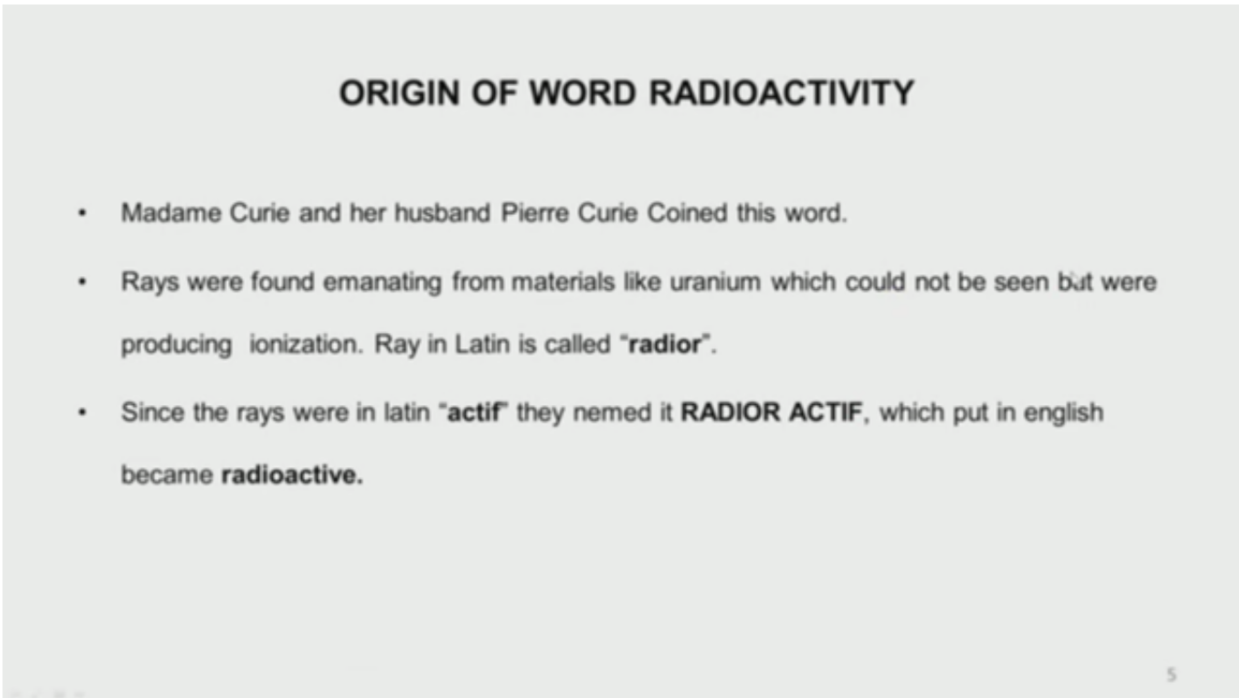

Now one word was a very interesting question. What is the origin of the word radioactivity? In fact, this word radioactivity came after Madame Curie and Pierre Curie, they actually coined this word. When they were working with Pitchblende, actually, Madame Curie was trying to have an ionizing -- ionization chamber nearby and when she was working with this Uranium, of course, she was working with the pitchblende which is ore of Uranium and then it started showing some signals, some current. So she says, "Oh, some rays are there which are ionizing." So the name Ray in Latin is called Radior and then it is active because some current is generated. So she called it as RADIOR ACTIF, which put in English became radioactive. Remember it has got nothing to do with radio. So this is from the Latin word. So this is the background of the word radioactivity.

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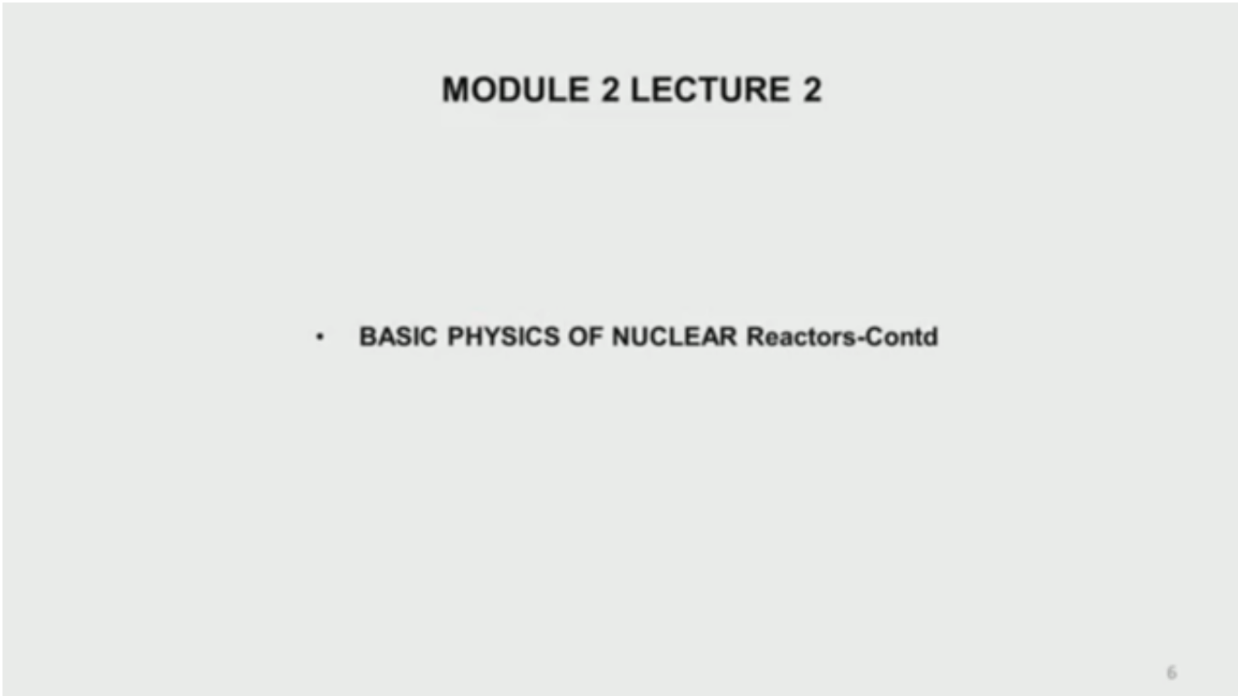

Now we'll go to the further to the -- this lecture.

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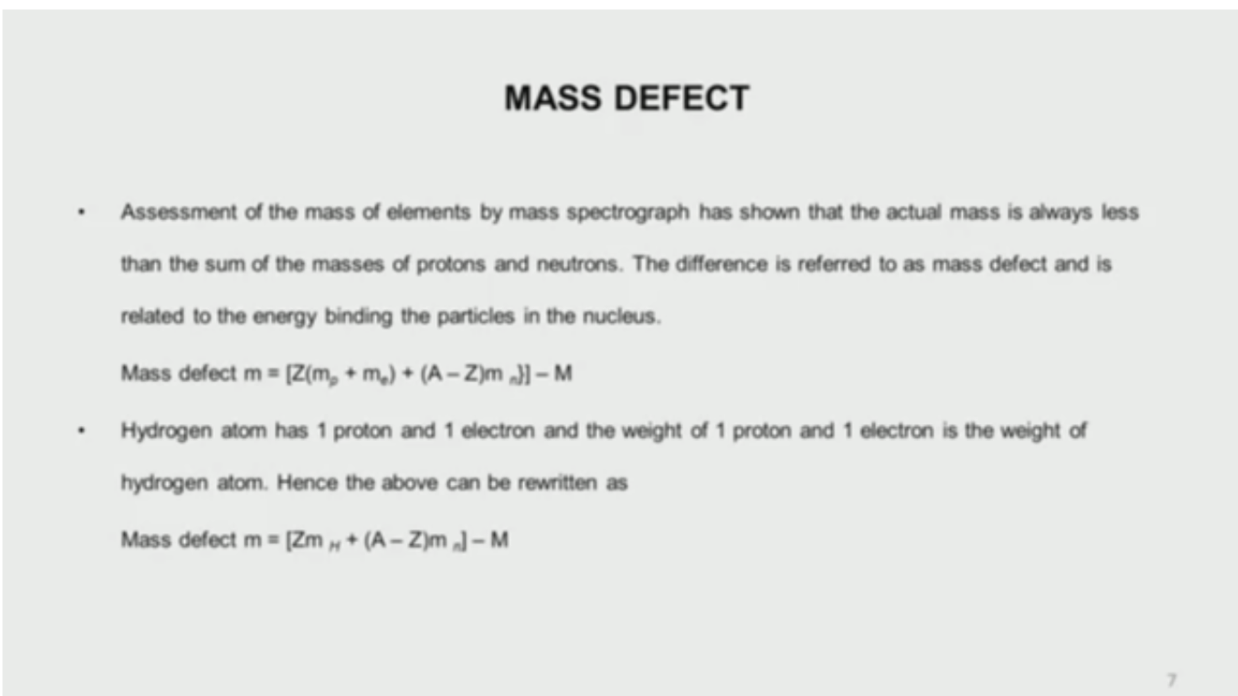

We will first talk about mass defect. What is this mass defect? Now when we assess the masses of the elements, we find normally what is the mass of an atom? It should be the mass of protons and neutrons, but the total mass and the mass of the neutrons plus protons, there is a difference.

That difference is called mass defect. If let us say we have Z is the atomic number, then we have the mass of the protons plus neutrons into the number of atomic number plus A minus Z will be tell us the number of neutrons into mass of neutron minus the total mass of the atom. So if this difference is what we call as mass defect. The difference exists.

For example, you take Hydrogen has got one proton and one electron. So we can say m_p plus m_e I can replace by mass of a hydrogen atom. Then this is what will be the mass defect.

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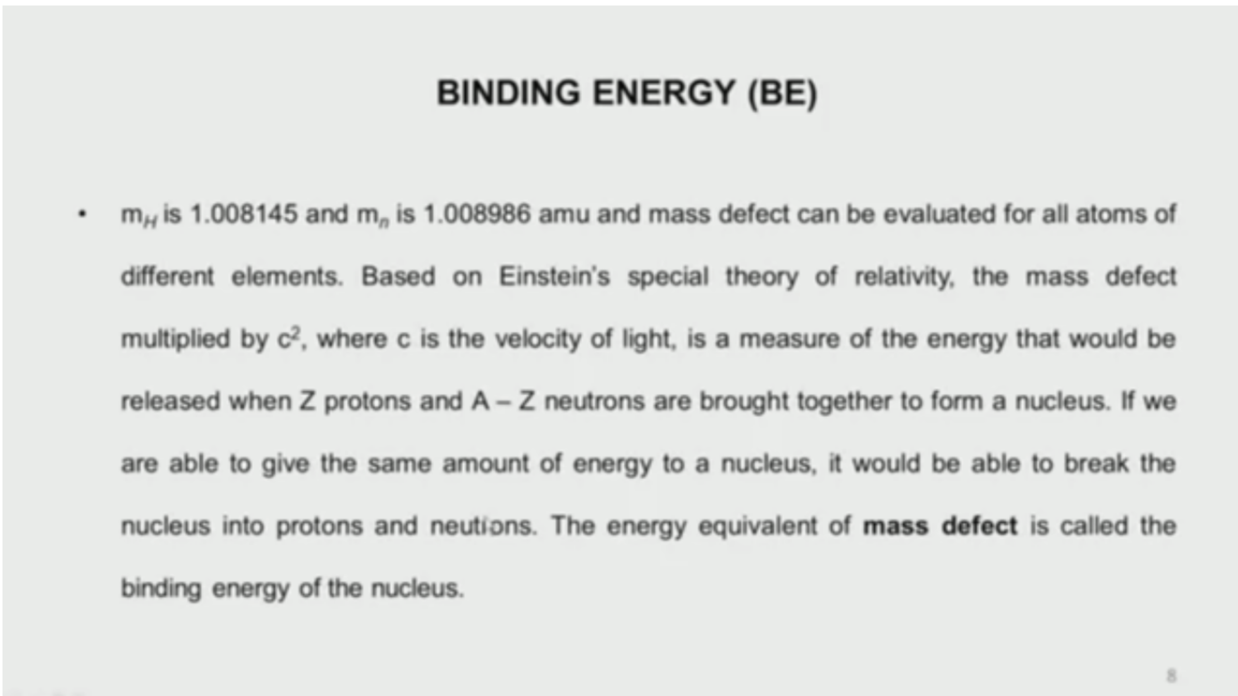

Now let us see how much this comes out to. Now m_H is about 1.008145 amu, atomic mass units, and your neutron mass is about 1.008986, and this mass defect whichever is there, you know by the Einstein's theory of relativity, any mass can be converted energy and the energy will be MC squared.

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BINDING ENERGY (BE)

- m_H is 1.008145 and m_n is 1.008986 amu and mass defect can be evaluated for all atoms of different elements. Based on Einstein's special theory of relativity, the mass defect multiplied by c^2, where c is the velocity of light, is a measure of the energy that would be released when Z protons and A – Z neutrons are brought together to form a nucleus. If we are able to give the same amount of energy to a nucleus, it would be able to break the nucleus into protons and neutrons. The energy equivalent of **mass defect** is called the binding energy of the nucleus.

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So here this mass defect converted to energy form is that energy that would be released when Z protons and A minus Z neutrons are brought together to form your nucleus. Now if we are able to give the same energy to the nucleus, that energy will be able to break the nucleus. That is basically the neutrons and protons, and this is what is -- what we are doing in the fission reaction and this energy equivalent of mass defect is what is termed as the binding energy of the nucleus. That is this is the energy which binds the neutrons and protons together.

Just to repeat, when Z protons and A minus Z neutrons are brought together, there is an amount of energy needed to bring them together and now if we are able to give the same energy and able to break it, then that is what we call as the fission. It can -- it leads to the breaking of the atom.

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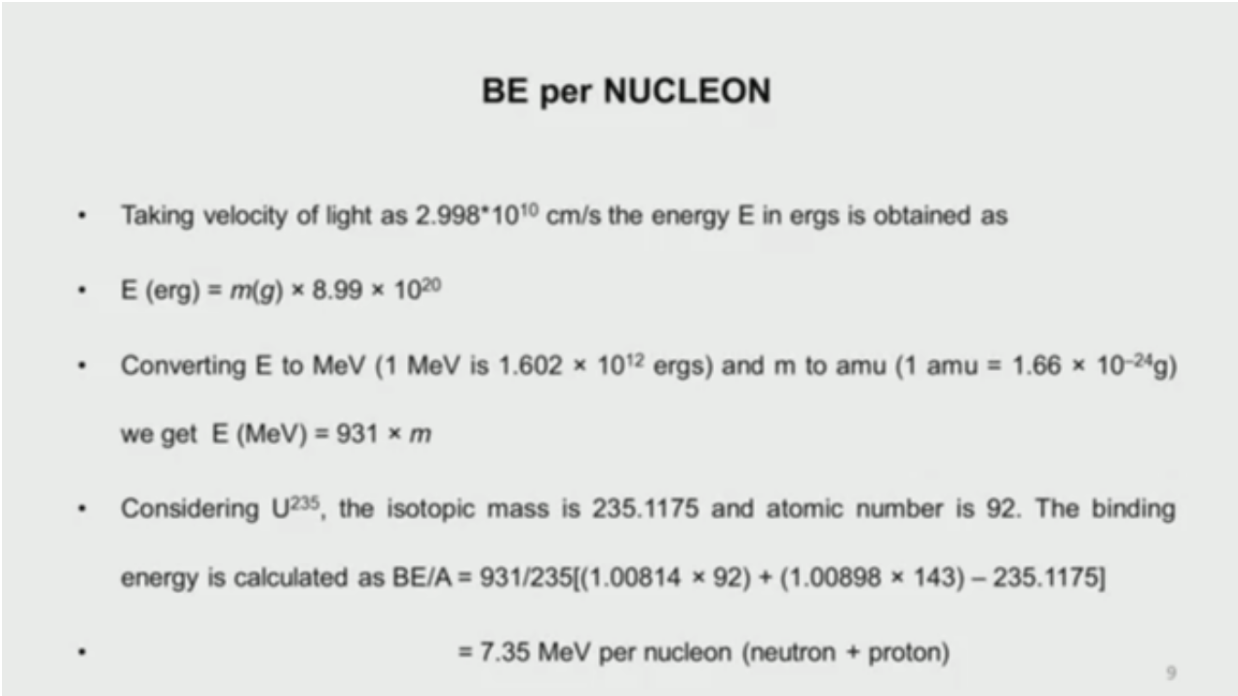

Now if you look at the velocity of light, we know it is about 2.998 x 10^{10} centimeters per second, and if you calculate the energy in erg, mass into this squared, this should be C squared, not -- so this is a square term only, 8.99 x 10^{20}. Now if we convert from erg to MeV, this is what we get. We got E energy in MeV binding energy is equal to 931 into the mass defect.

Now let us consider U^{235}, which is a very common fissile atom. The mass is 235.1175 and the atomic number as you know is 92. So if we calculate the binding energy as per the formula which we saw, it comes out to something like 7.35 MeV per nucleon. So nucleon means the neutron plus proton. So the binding energy for an atom of -- or binding energy of per nucleus of $Uranium^{235}$ is 7.35 MeV.

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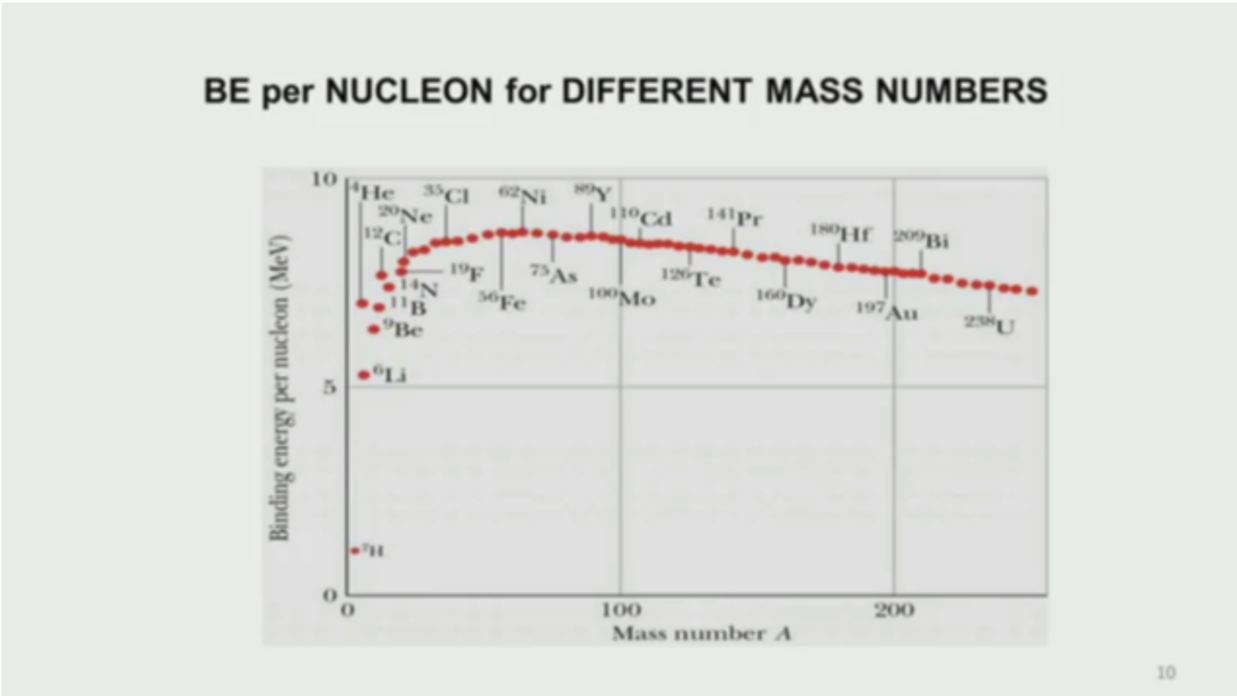

Now let us have a look at the binding energy for different elements of different mass numbers. You see the curve starts somewhere around 5 MeV per nucleon. It goes up and then -- then more or less steady, but it slides [indiscernible 00:11:00]. Here you have find something like a peak. Peak is somewhere and this is for iron and in reality iron is the most stable element. To the left and the right are not that stable. In other words, you require a very high binding energy, energy you have to give to break an iron.

Now these higher mass number elements, what happens? Their binding energy is less whereas this side the binding area is very much less. So here everything would like to go to your stable state. So elements on this side, atoms on this side would break mostly by fission, and try to come this way and become stable whereas the lighter elements like helium, or hydrogen or lithium, they will get fused together to come to a higher level of binding energy, and become more stable and so these elements can contribute to fusion. These elements can contribute to fission. So this is where the binding energy concept is useful to explain fission or a fusion.

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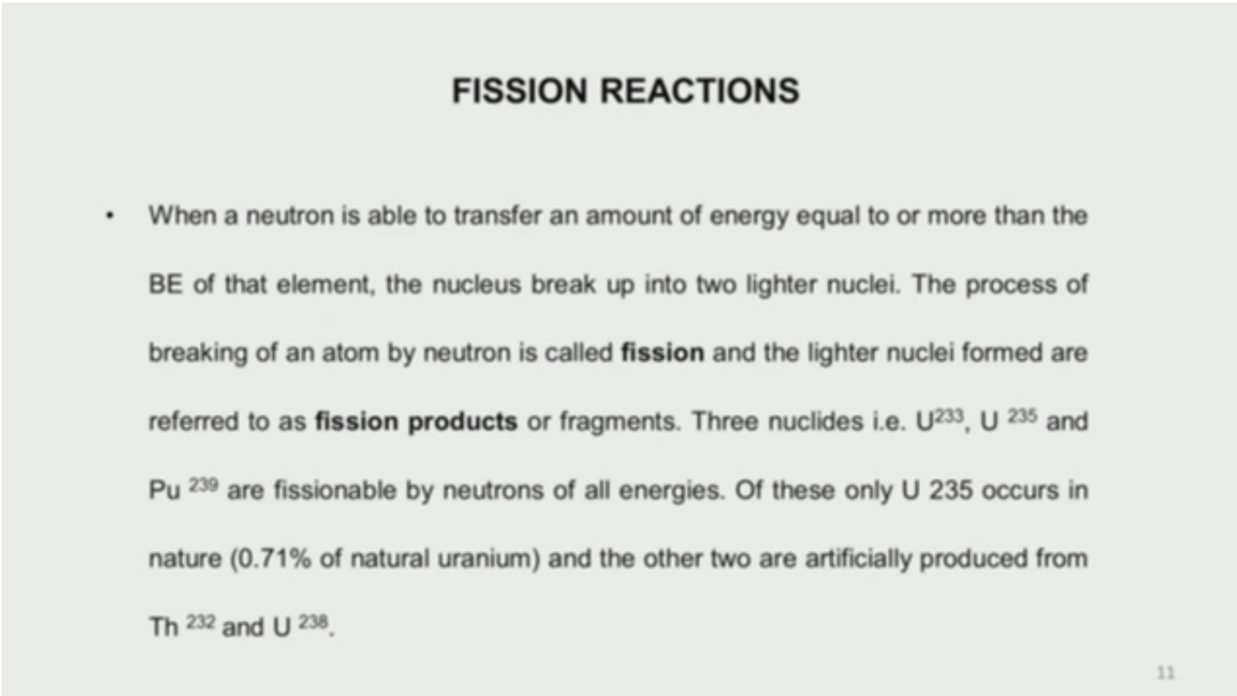

Now what is a fission reaction? When a neutron is able to transfer an amount of energy, which is more than the binding energy of that element or atom, then the nucleus breaks because something more than the binding energy, so it breaks and it breaks up into two nuclear, lighter nuclei because it's heavy one. It has become into two lighter nuclei and this process of breaking of an atom by a neutron is called as fission. It is fissioning, breaking. So that is what it is and this lighter nuclei which are formed, they are called as either fission products or they are also called as fission fragments.

So if you take the -- which are the elements which are fissionable, they are Uranium^{233}, Uranium^{235} and Plutonium^{239}. These are fissile -- fissionable by neutrons of all energies. Now one must note here out of these three Uranium 235 alone is found in nature. Uranium 233 is not found in nature, but is obtained by converting Thorium^{232} in a nuclear reactor. Similarly, Plutonium^{239} again is not a -- is a man-made one wherein Uranium^{238} absorbs a neutron and gets converted to Plutonium^{239} after certain radioactive elements decay. So now these two are artificially produced fissile isotopes.

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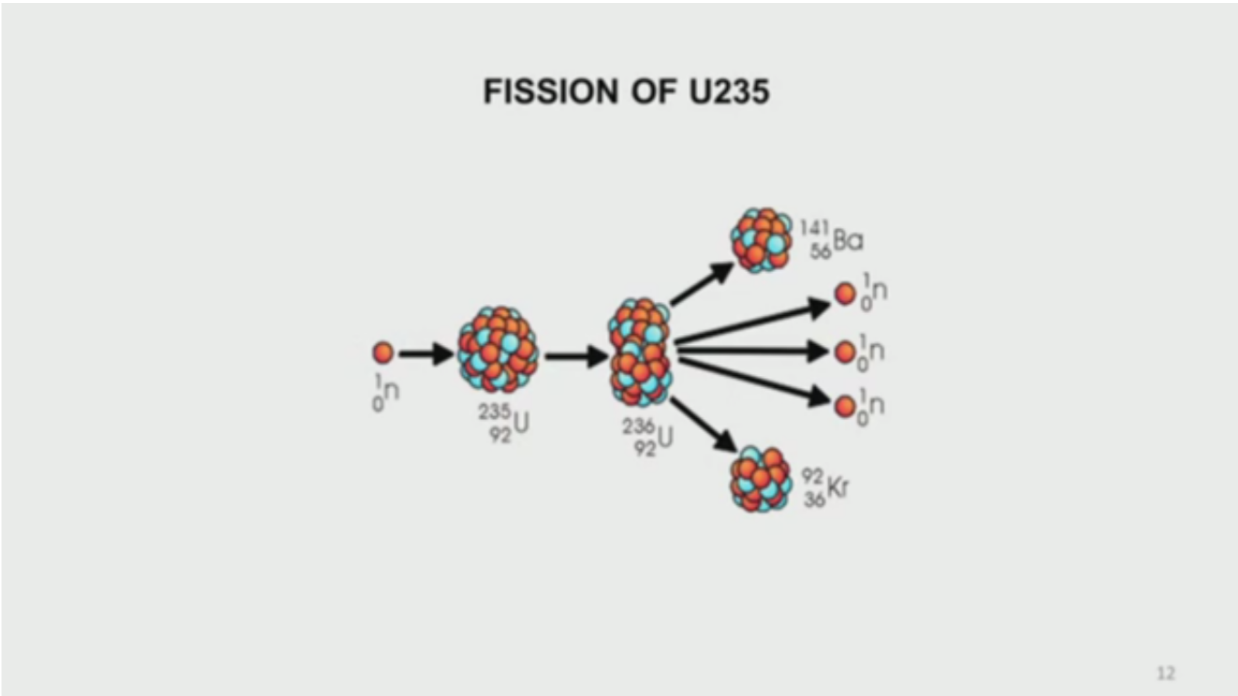

This is to give a picturesque idea of what happens. You see your neutron is hitting Uranium-235 atom. Then it becomes Uranium 236 atom and then this is unstable. It results into Barium and Krypton and also it gives on an average about 2 to 3 neutrons, 2 to 3 neutrons besides the fission products it releases, 2 to 3 neutrons.

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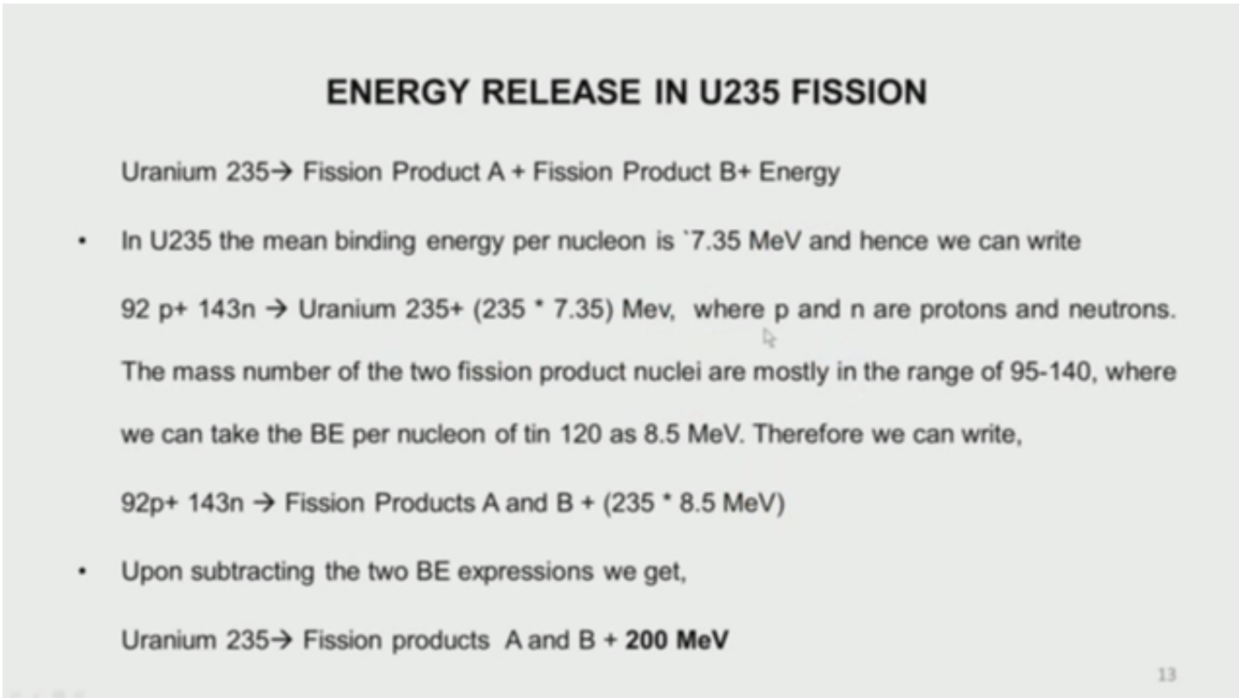

Now how much energy is getting released in fission if you look up, we said Uranium 235 splits up into two fission products, Fission Product A and Fission Product B plus some energy. Now we saw that the mean binding energy of Uranium 235 is about 7.35 MeV. So we can say that 92 protons plus 130 -- 143 neutrons is Uranium 235 plus 235 into 7.35 MeV. Now the mass number of the fission products are in the normally in the range of 95 to 140. You can say half the -- that range 240 means around 120. So if we take a binding energy of a nucleon, which is having a mass number of 120, it's about 8.5 MeV. So I can say this 92 protons plus 143 neutrons are giving Fission Products A and B plus 235 into 8.5 MeV.

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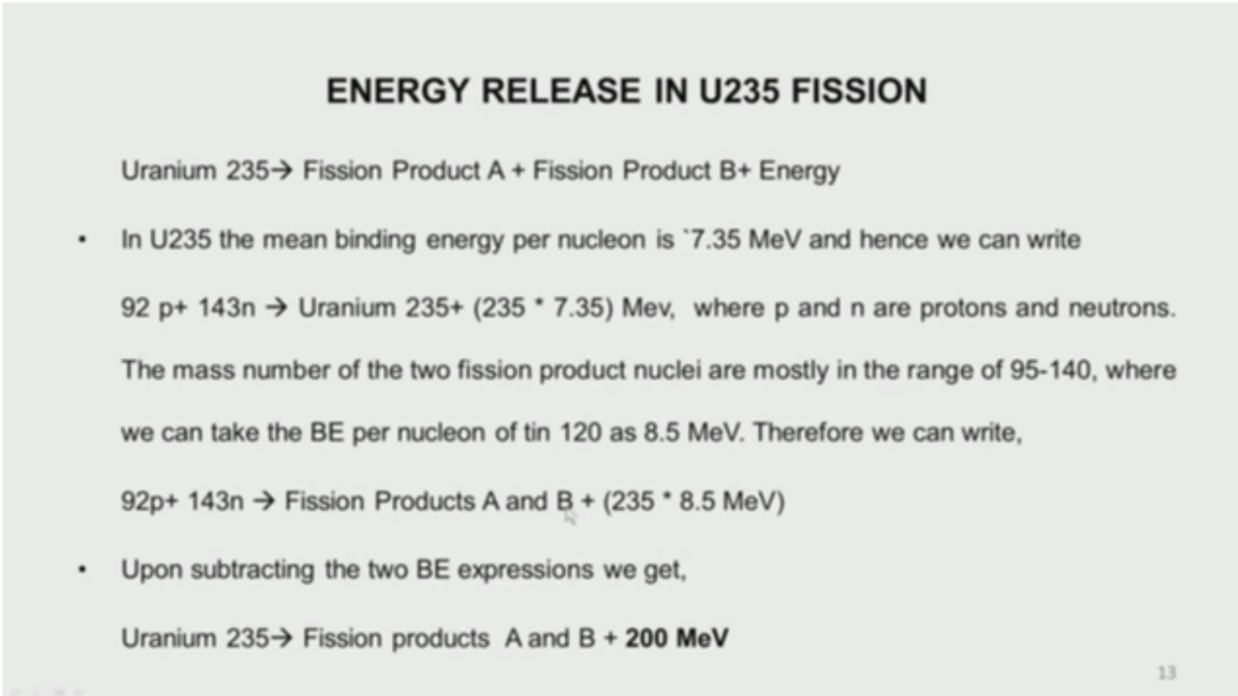

If you just take the expressions and subtract, you get Uranium 235 will give fission products A and B plus 200 MeV. In other words, in one fission of Uranium 235 atom, you get 200 million electron volts of energy. This is a quite good amount of energy.

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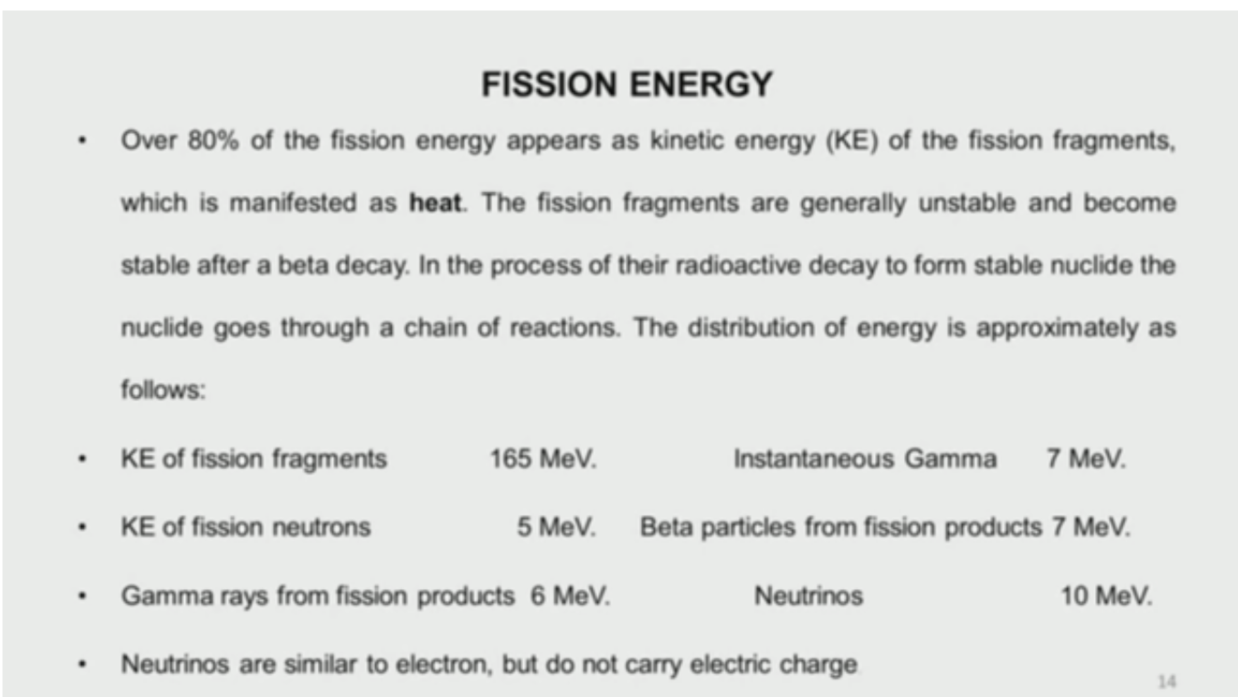

Now how this energy in what form it is? 80% of this fission energy appears as the kinetic energy of the fission fragments and this get manifested as the heat. We say heat produced in a fission reaction is this. So 80% of that is getting converted to heat. Now the fission fragments if you take, they, you know, that they are unstable. They are not completely stable. They take some more steps. So they have stable after some beta decay and it goes through a chain of reactions.

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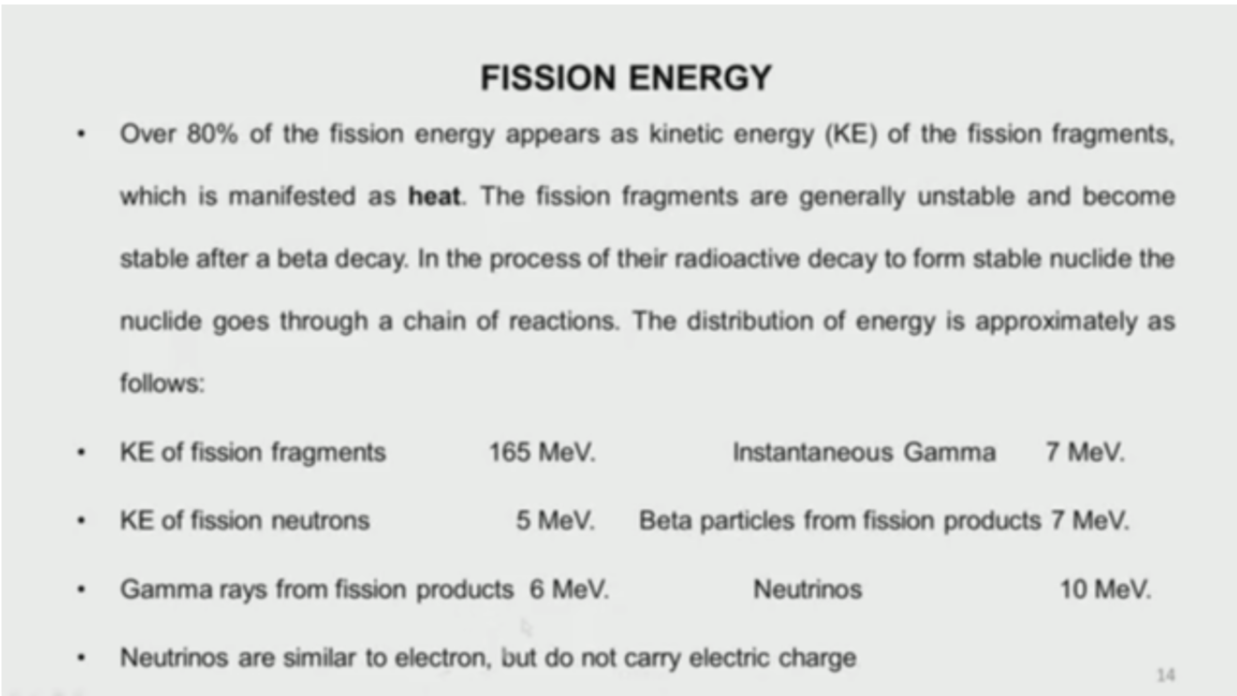

What is the distribution of this total energy of 200 MeV if you look up, the fission fragments as I said is about 80% about 165 MeV. Then these fission neutrons, we saw 3 neutrons, 2 to 3 neutrons being generated, they carry some energy with them. Then there are some instantaneous Gammas, which about 7 MeV. These beta particles which are emitted, they carry about 7 MeV. Gamma is about 6 MeV and we have neutrinos about 10 MeV. These neutrinos are similar to electrons. They have the same mass as electrons, but they don't have any charge. So this is a another part of an atom.

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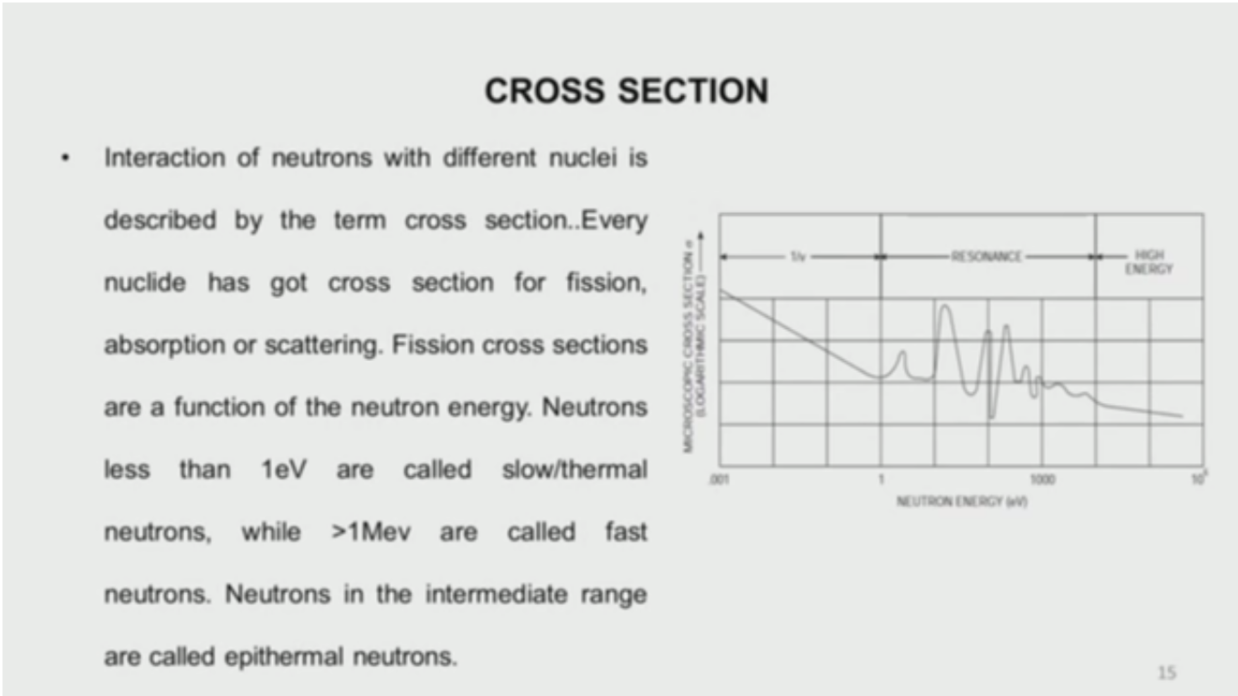

Okay. Now we saw that neutron has interactions with nucleus of different atoms and in some cases, it produces fission. In some other case -- in all cases it doesn't produce fission. Then what must be happening? Maybe in some cases, it may be getting just absorbed. It may not really produce a breaking up or it may absorb or it may just hit. It may scatter. So the processes are something like absorption and having fission or just absorption or it could be scattering. Now we must have a measure of how much ability to fission, how much ability to absorb, how much ability to scatter? So we use a terminology called as cross section.

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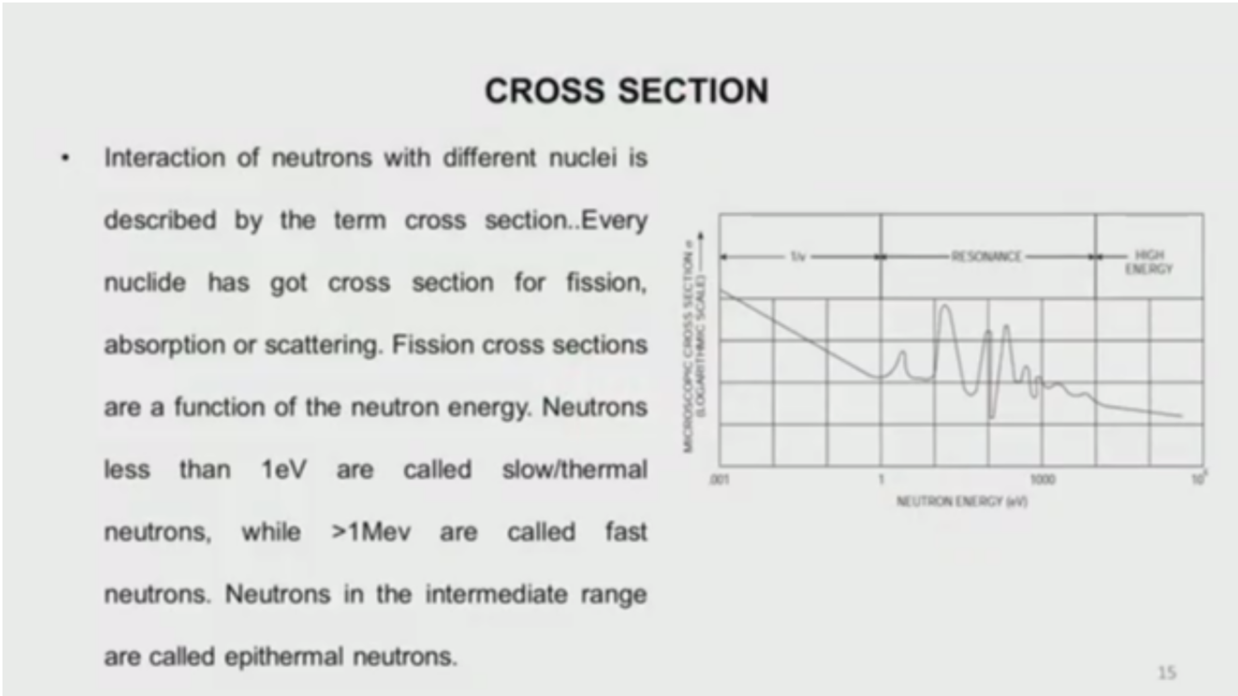

So interaction of these neutrons with different nuclei is denoted by the term cross section. So as I said we have got cross section for fission, cross section for absorption and scattering. Now the fission cross sections are again a function of the neutron energy.

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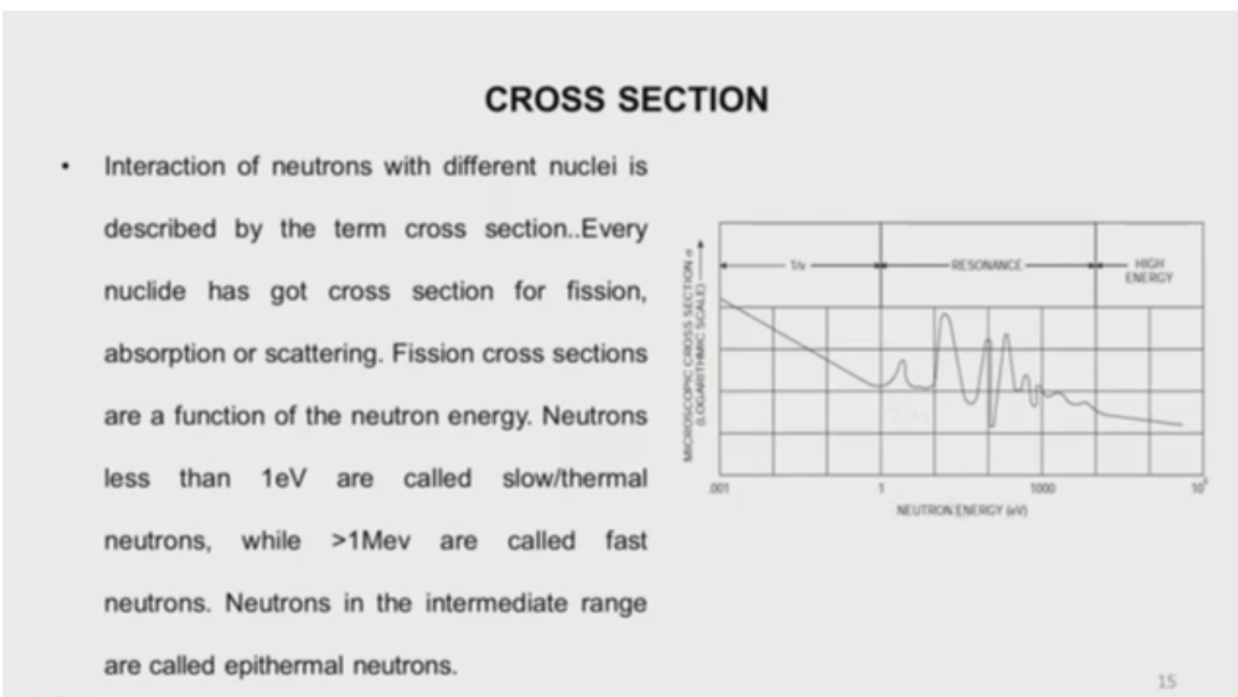

Here you can see Neutron energy is put here in a logarithmic scale, 0.001, 1, 1,000 and 10^6. You see the cross-section is high here and it comes down. What does this explain? When the energy of the neutron is low, there is sufficient time for it to interact and you know transfer the energy. So the possibility of a fission reaction is more when the neutron is slow or having a low energy level.

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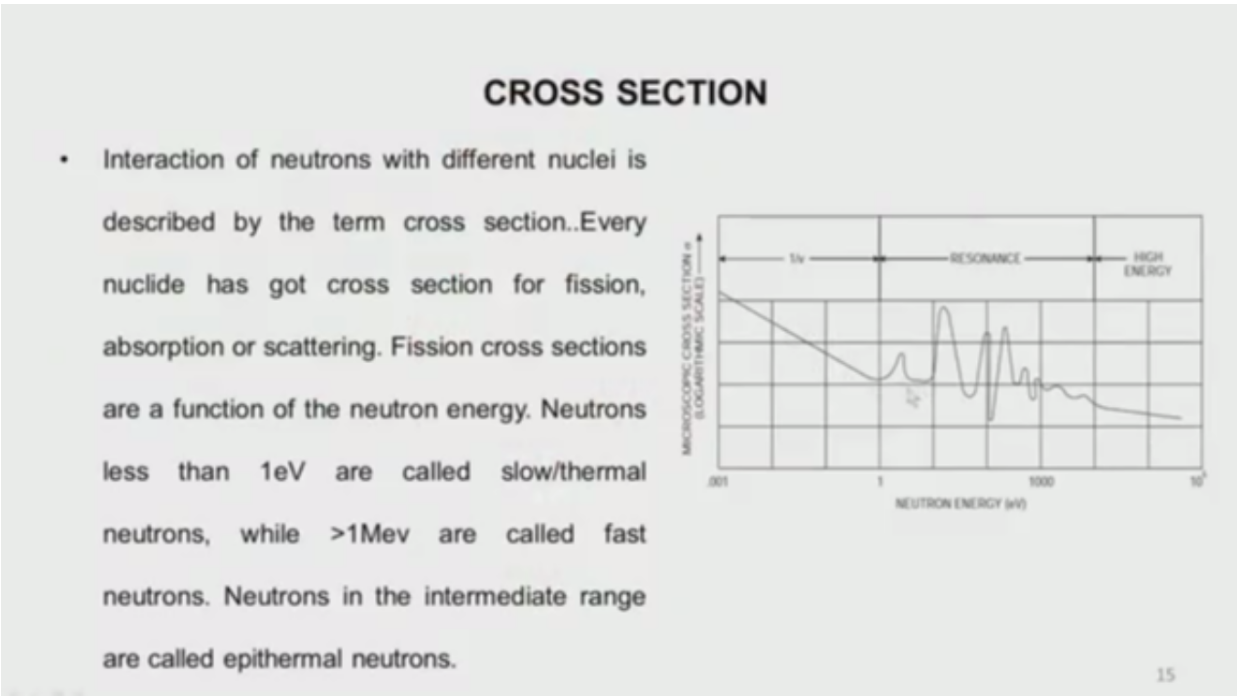

As it comes down -- increases the neutron energy, you see the cross-section comes down. Then here there are some variations, but if you come to the other side, here this region beyond about 1 MeV is called as the fast neutron region. Here the cross sections are very low. This area is what is known as a intermediate region or the epithermal region. There are certain energy levels where there is a resonance between the hitting neutron and the atoms or the nucleus which are getting hit and under certain conditions, they reinforce each other and the cross-sections increase. So that is only a small region.

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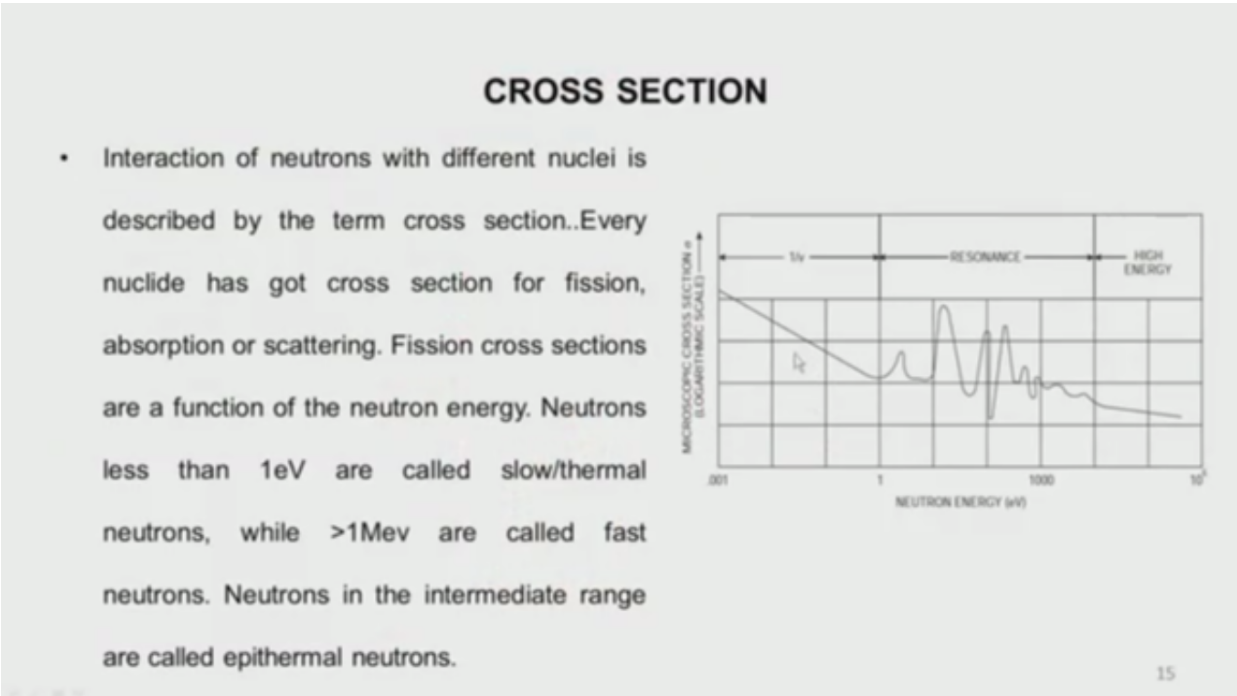

But major interest for us would be this and this. Not that fission is not possible. Fission is possible here, possible here, possible here, but the probability of fission is more here in the lower energy range and probability of fission here is less, but fission is possible at all energies. Now reactors which operate with slow energy neutrons are called thermal neutrons, which operate in the fast neutron region are called fast neutrons.

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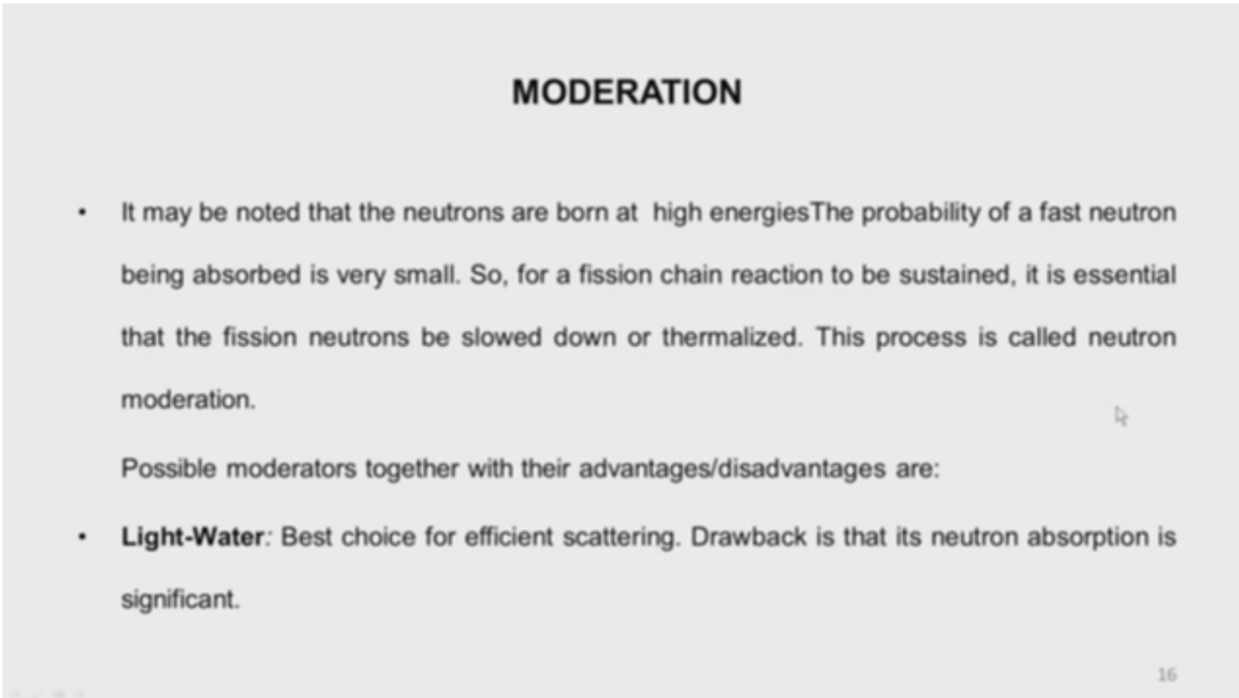

Now let us look you have the fission. Surely, when neutrons are produced, they have a very high energy. They get slowed down because of many other reactions. Now if I take a fission to happen in any material for that matter, whether it is Plutonium 239 or Uranium 235 with a high probability, I require a slow neutron. So what I do? I have some material, which can absorb the energy of the neutron, and then slow it down. So this process is called as neutron moderation. We moderate the neutron.

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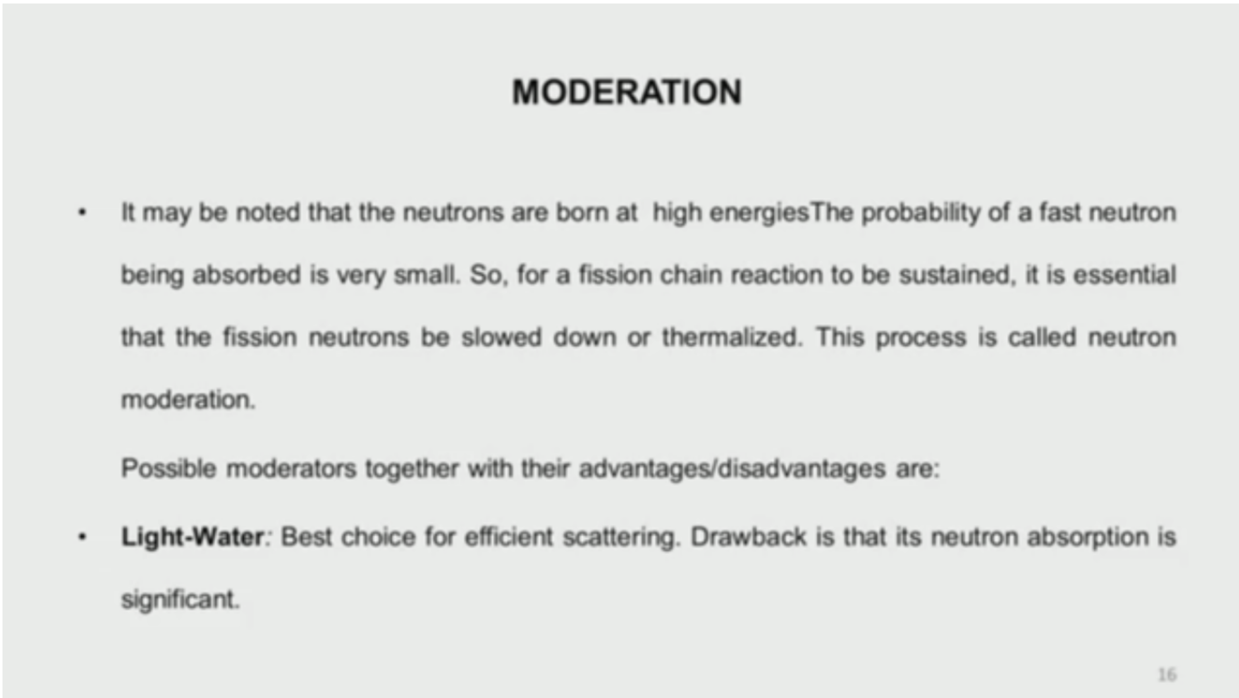

If we look at which are the possible moderators, Light-Water itself, all hydrogen materials are very good moderators. Light-water is a very good choice. It scatters the neutrons. The light-water absorbs some energy. Of course, it doesn't cause fission there and then the neutron is sent back with lesser energy, but as I said there are three types. It could be fission. It could be absorption, scattering. Absorption is more than the scattering. Even though it does scatter, absorption is significant.

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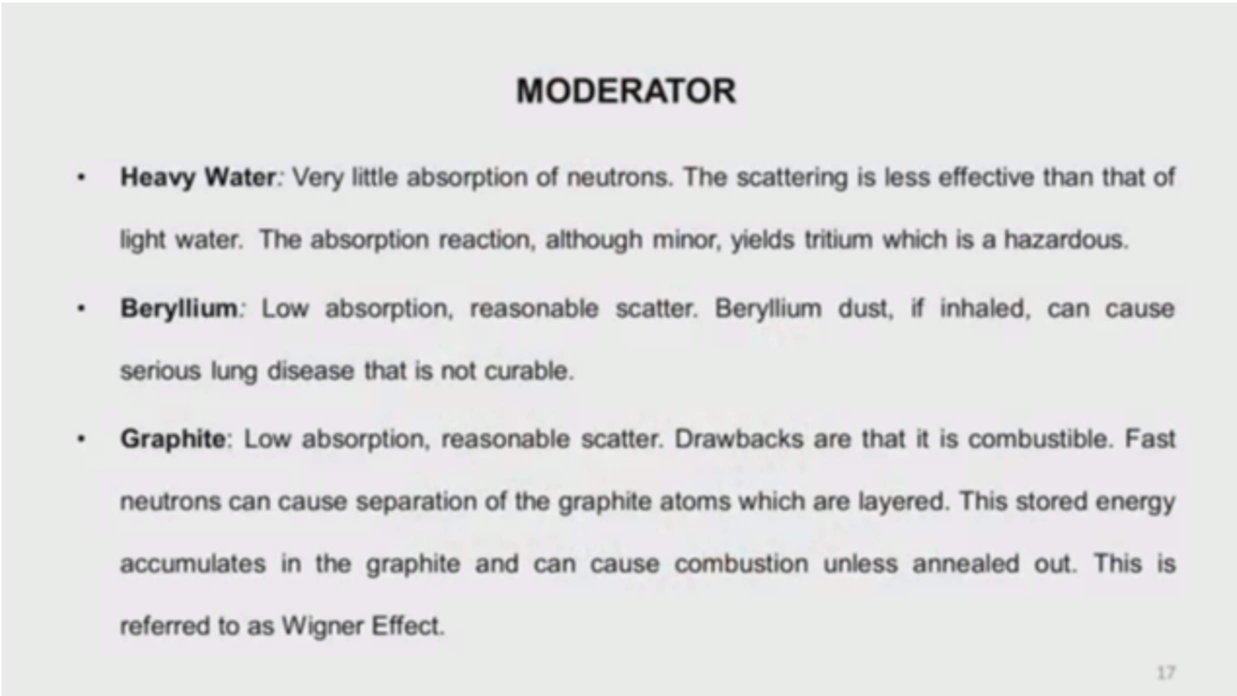

The other one is the Heavy Water, which is D_2O. Advantage of this over light water is it is having little absorption, but you have good scattering. So really speaking, when you want to compare the moderating material, you try to compare which has got a better scattering by absorption. D2O because absorption is going to be less, your ratio will be high. That is also sometimes referred to as a moderating ratio, but the absorption of Deuterium of a neutron by Deuterium, it does produce Tritium and you know Tritium is a beta emitter. So it's a bit hazardous.

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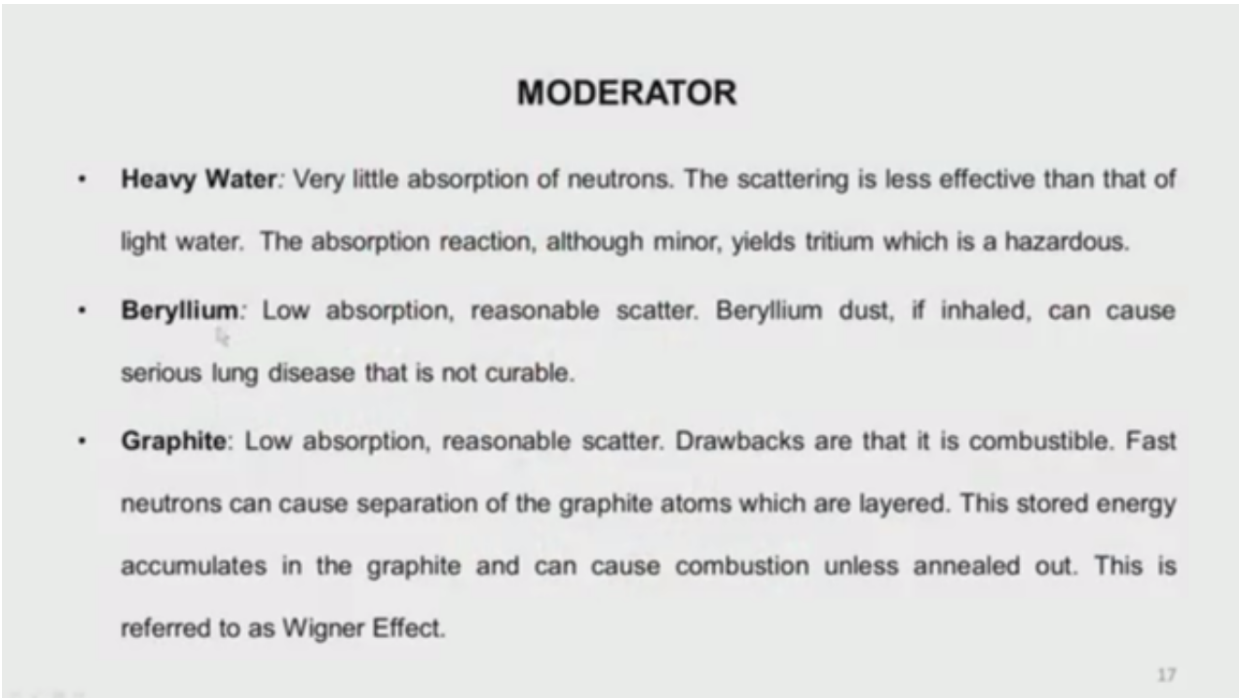

Then the other one is Beryllium. Beryllium has got a low absorption and reasonably good scattering cross-section. Again, Beryllium dust, if it is inhaled, it can cause lung problems, but of course we are not going to get in the reactor and inhale the Beryllium. Last, but not the least, graphite. Again, it is similar to Beryllium, but one problem with graphite is it can catch fire. You know, graphite is after all carbon -- allotropic form of carbon so it can catch fire.

Now another problem is all neutrons may not get slowed down. Some fast neutrons may still get escaped, and they can cause the segregation of the graphite items, and in some cases this fast neutron energy which gets into the graphite, it can accumulate and this accumulation at a certain temperature or energy level, it is possible that it can come out as a spurt, and if the value of the energy is high, it can really catch -- caught, you know, catch fire in the graphite. This is actually called as Wigner effect -- on -- based on the scientist who found out this effect. So we generally see to it that annealing of the graphite is done so that there is no stored energy possible.

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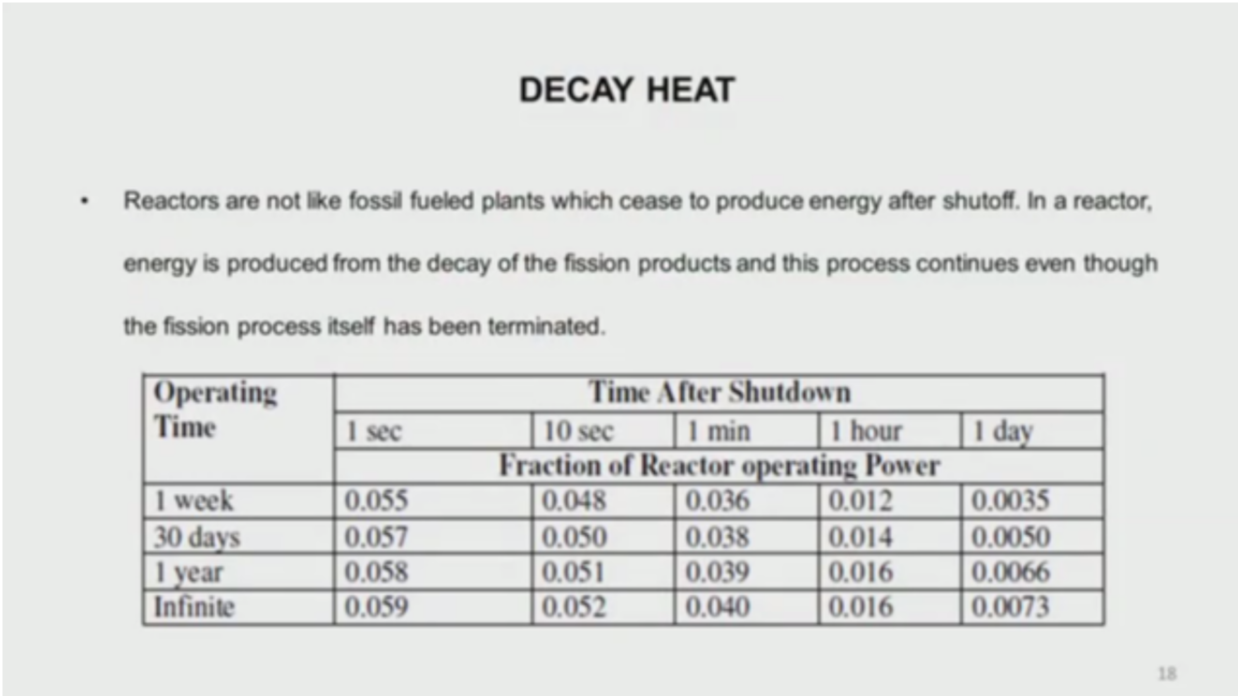

Operating Time	Time After Shutdown				
	1 sec	10 sec	1 min	1 hour	1 day
	Fraction of Reactor operating Power				
1 week	0.055	0.048	0.036	0.012	0.0035
30 days	0.057	0.050	0.038	0.014	0.0050
1 year	0.058	0.051	0.039	0.016	0.0066
Infinite	0.059	0.052	0.040	0.016	0.0073

Now one more characteristic of this fission process is what we call as decay heat. It is also called as residual heat. That means we have -- we are operating the reactor with the fission reaction. Fission reactions are producing heat. Now we stop the fission reaction. How do you stop the fission reaction? We put a absorbing material, neutron-absorbing material so the fission reaction stops. No neutrons are coming out. Then, but still these fission products which have been produced in the fission, they continue to decay and in the decay process, they produce heat, and this heat is not small. It is quite considerable.

Give you an idea, it is depends on how much the reactor is operated because the amount of time the reactor is operated shows how much of fission products accumulation is there and how much time after the shutdown, both these factors.

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DECAY HEAT

- Reactors are not like fossil fueled plants which cease to produce energy after shutoff. In a reactor, energy is produced from the decay of the fission products and this process continues even though the fission process itself has been terminated.

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So here if you look, let us say a reactor is operated for one week and after shutdown it will produce about 0.055 or about 5.5%. Slowly, in one day it will come down to 3.5%. Suppose it is operated for a year, it will be about 5.8%, then about 0.66% here. So, slowly, it will come down. Now this means heat is continuing to be produced even after shutdown. So this aspect is very important to be recognized. You take a coal-fired plant. The moment you stop coal firing, there is no heat produced. The whole thing starts cooling whereas here this heat is very important, so we need to keep, have a coolant to remove heat even after the reactor is shut off.

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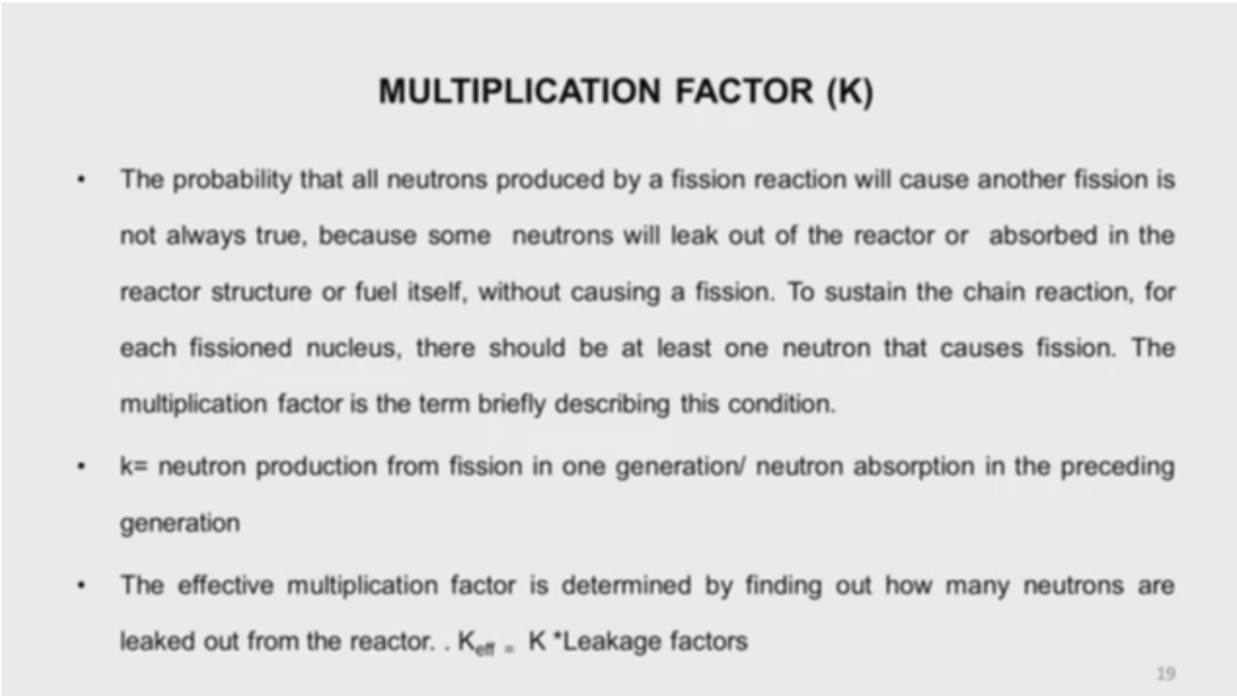

There is we saw that in one fission reaction, one atom goes and hits the nuclei of a Uranium-235 and on average it produces about two to three neutrons. Now out of these two to three neutrons, some may get absorbed, some may get, you know, some may cause fission and the absorption could be either in the fuel itself or it may get any structures, you know, you have got lot of material. The materials may just absorb. So, finally, if one more fission reaction is to occur, one neutron must be less out of the -- out of the three. So if in out of every chain reaction -- every fission reaction, one more neutron is able to be available for fission, like that, so it is like a chain, chain of fission reaction. This is called as a chain reaction.

So the -- and in every one, one fission, next fission, suppose you had 10 neutrons, 10 fissions, continues. If you have 100 neutrons, 100 fissions continue. So this way the chain reaction continues, sustained chain reaction as we say. This sort of a situation that means in each generation the same number of neutrons are causing fission. So this is called as the ratio is called as a multiplying factor and here it is one. For a sustained reaction, K is equal to 1.

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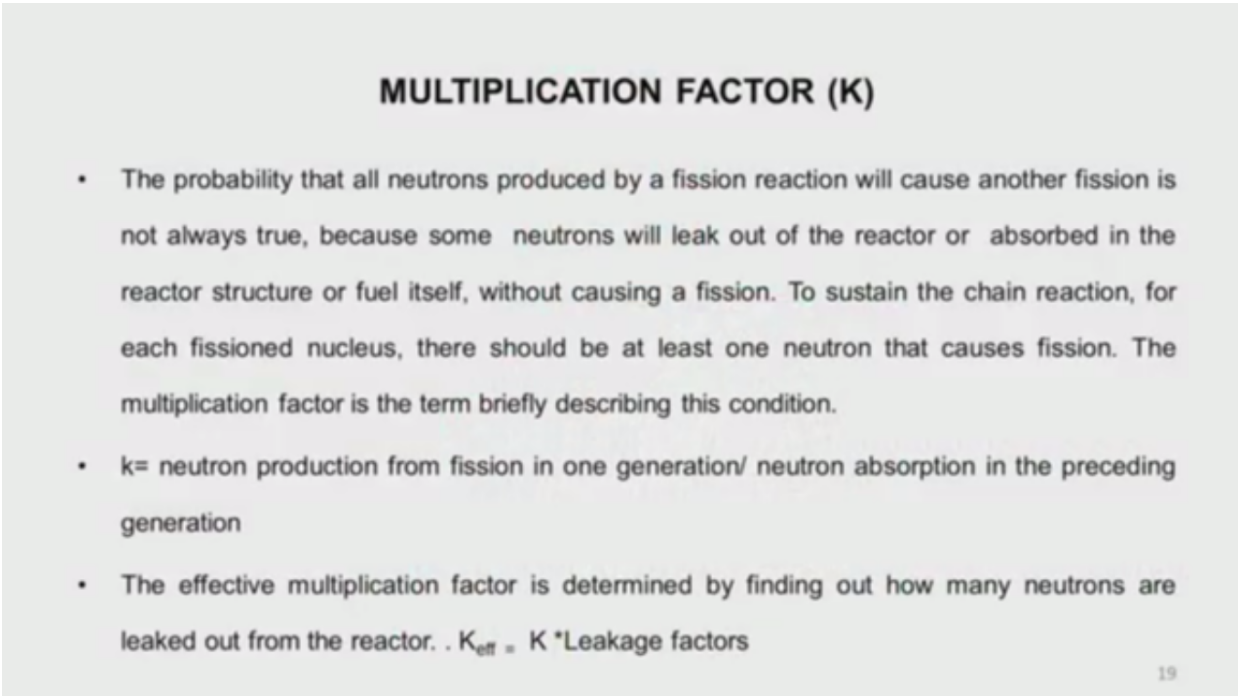

And K, this multiplication factor is defined as the neutron production from fission in one generation to the neutron absorption in the preceding generation. Now this is okay as a definition, but in a real reactor, leakages will be happening. So the effective multiplication factor needs to take the leakage into account. So when it multiplied to the leakage factors, that is what we called as a $K_{effective}$, that is effective multiplication factor.

Now I mentioned to you about a self-sustained reaction, chain reaction causing fission. We when this reactor has got a self-sustained fission reaction, we call it as critical. Reactor is critical.

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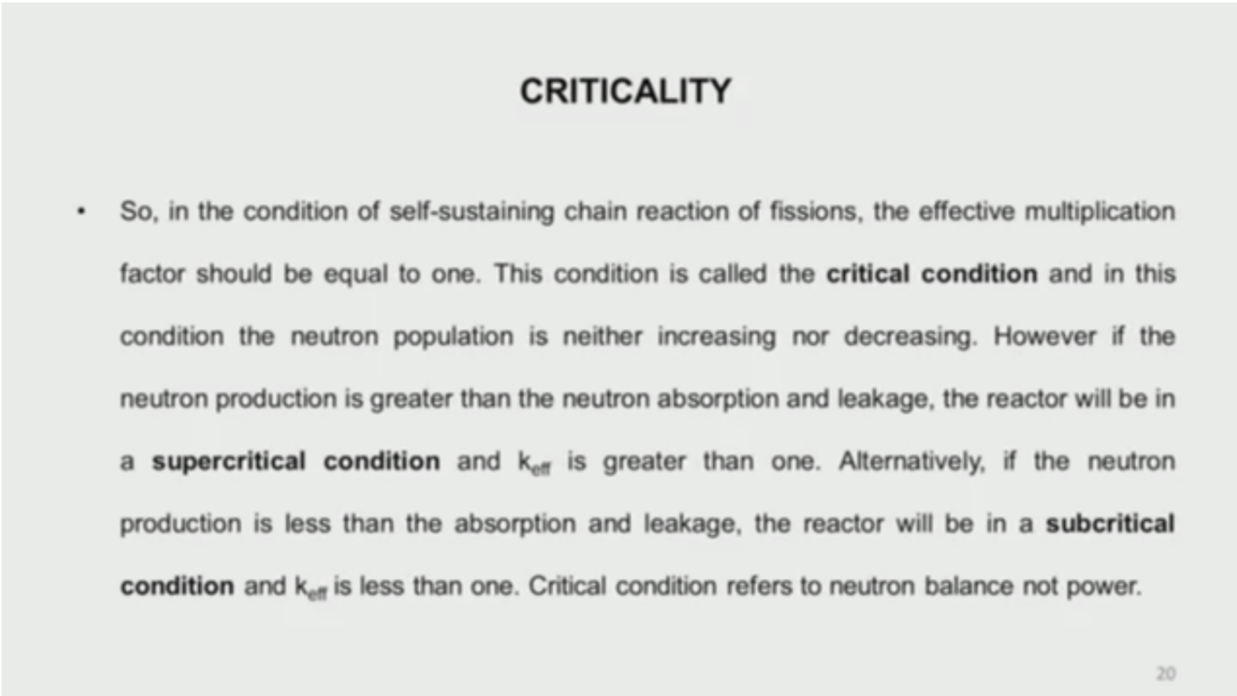

Unfortunately, this name, the term or terminology as critical does create a sense of fear in the minds of the people, but I always used to say, when the reactor become critical we as nuclear scientists are very happy, but any person who reads the newspaper and say oh, reactor is critical, he get disturbed, but anyway this is just a terminology. So if you say nuclear reactor is critical, don't get afraid. Be happy. So in this condition, the overall neutron population in each generation remains same. It is neither increasing, neither decreasing.

But suppose let us say the neutron production is high means absorption and leakage was less, so it was high, then your neutron population will increase in one from one generation to other. That we call it as a supercritical condition. That means the multiplying factor $K_{effective}$ is greater than one. So it is called as supercritical and it is not correct to allow the reactor to become supercritical. We should control. So that's why the control element is required.

Again, alternatively, the other, if suppose let us say, the neutron absorption and leakage are high, neutron production is not that much, then there will be a decrease of the neutron population and in that case, we refer to it as a subcritical condition. That means $K_{effective}$ is less than 1. So we saw three things. $K_{effective}$ is equal to 1 means it is a self-sustained chain reaction continuing. If $K_{effective}$ is greater than 1, that means the reactor power is going to increase because more neutrons are available now, and if $K_{effective}$ is less, okay, the fission reaction is coming down. That's what it means.

But now one thing which normally people tend to confuse, criticality is referring only to your neutron balance. Everything is fine. Your reactor will be critical when it is producing say 5 megawatts, when it's producing 10 megawatts. Maybe when it is producing 10 megawatts, your neutron production, number of neutrons interacting would be more. Let us say 5 neutrons are interacting it 5 megawatts about to be 10 neutrons, so 10 neutrons giving rise to another 10 neutrons, 30 neutrons, but then again 10 are available for the next fission. It continues. So here also K is 1. There also K was 1. So criticality should not be confused with power. It is referring to the neutron balanced condition.

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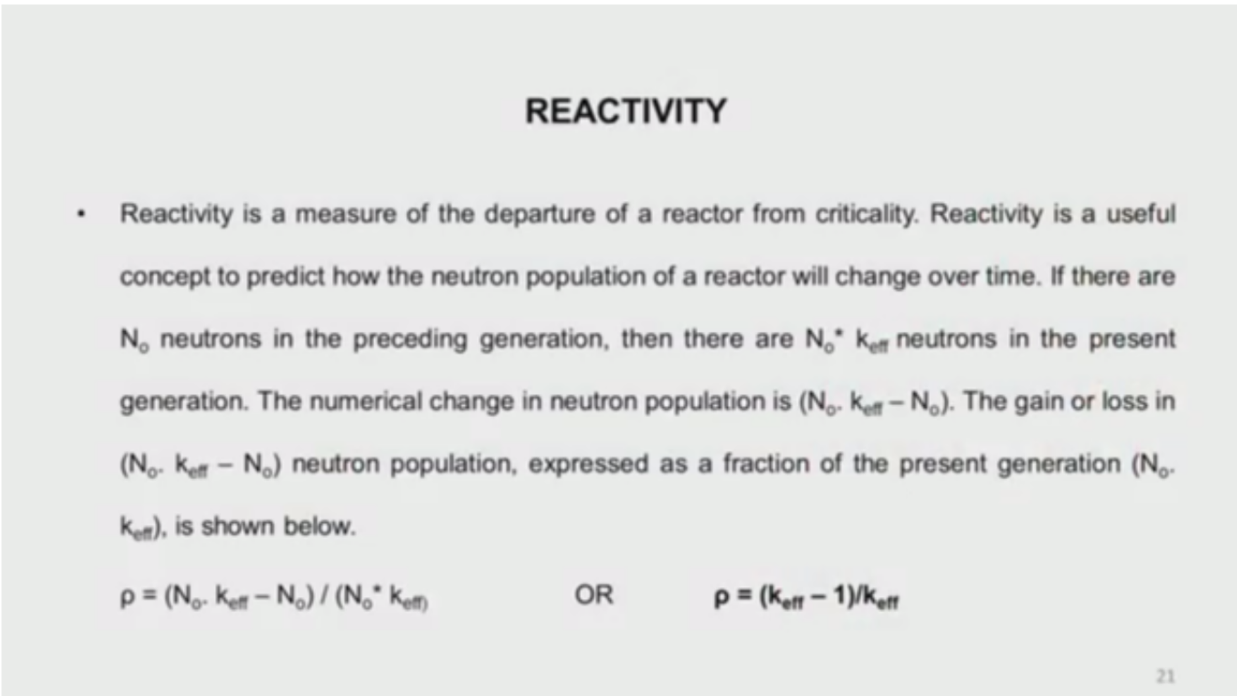

Now there is one term called as reactivity, which nuclear scientists and physicists use very frequently. So hence it is essential for us if you have to appreciate. Now reactivity is a measure of how much your reactor is away from the criticality condition. So, in other words, whether it is becoming super critical or whether it is becoming subcritical. So what is the measure of this? How do we do -- how do we get this reactivity?

Let us look at let us say there are N_0 neutrons in the first generation, then there will be N_0 into $K_{effective}$ neutrons in the next generation. So what is the change? N_0 into $K_{effective}$ minus N_0. Now this if I express it as a function of N_0 into $K_{effective}$, what I get? A quantity called as $K_{effective}$ minus 1 by $K_{effective}$. This is called as reactivity and believe it, it has no units. $K_{effective}$ has no units. It is just a factor. So this reactivity is a measure to tell whether the reactor is getting into supercritical or getting into subcritical.

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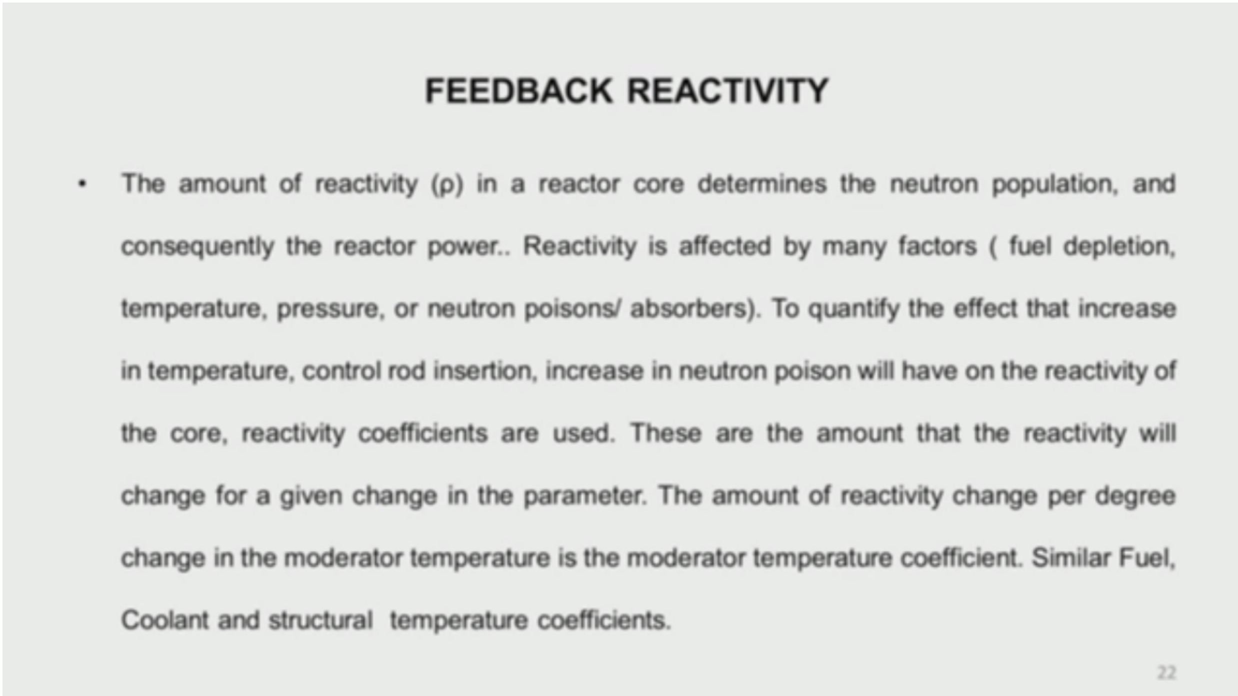

Okay. Now how does the reactivity change in a reactor? Is it always constant? What are the things which go and changes reactivity? Now, essentially, let us take the fuel. Fuel is the one which is getting fission and releasing neutrons. Let us say the -- you have a certain amount of fissile element concentration in the beginning and the reactor is operating for some time. As it operates for some time, your fissile neutron availability is becoming less. So even if you have neutrons for fission, number of fissile atoms available are less. So there is no fission. So fission will not happen. That means this effectivity will not produce neutrons. So that means there will be a fall in the reactivity.

Similarly, let us take temperature. Now, initially, when you are starting the reactor, things are cool condition. As the reactor power goes up, your fuel temperature goes up. Now any material, when the temperature goes up, it expands, but the mass of the fissile atoms remain same, but what is happening? The amount of fissile atoms per unit volume has come down because it is now occupying more space. So in one unit volume, the number of fissile atoms available are less now. So this gives a negative reactivity effect.

Similarly, let us say, if some neutron absorbing material falls into the core like Boron, it will absorb the neutron then also or any other material, which has got a neutron absorption, this can cause a negative reactivity. Similarly, let us take control rod. When I said Boron, you have the control rods made of Boron or Cadmium. When you insert the control rod into the core, it is going to absorb more and more neutrons. This is a negative effect. So to quantify all these each effect, we try to define reactivity coefficients.

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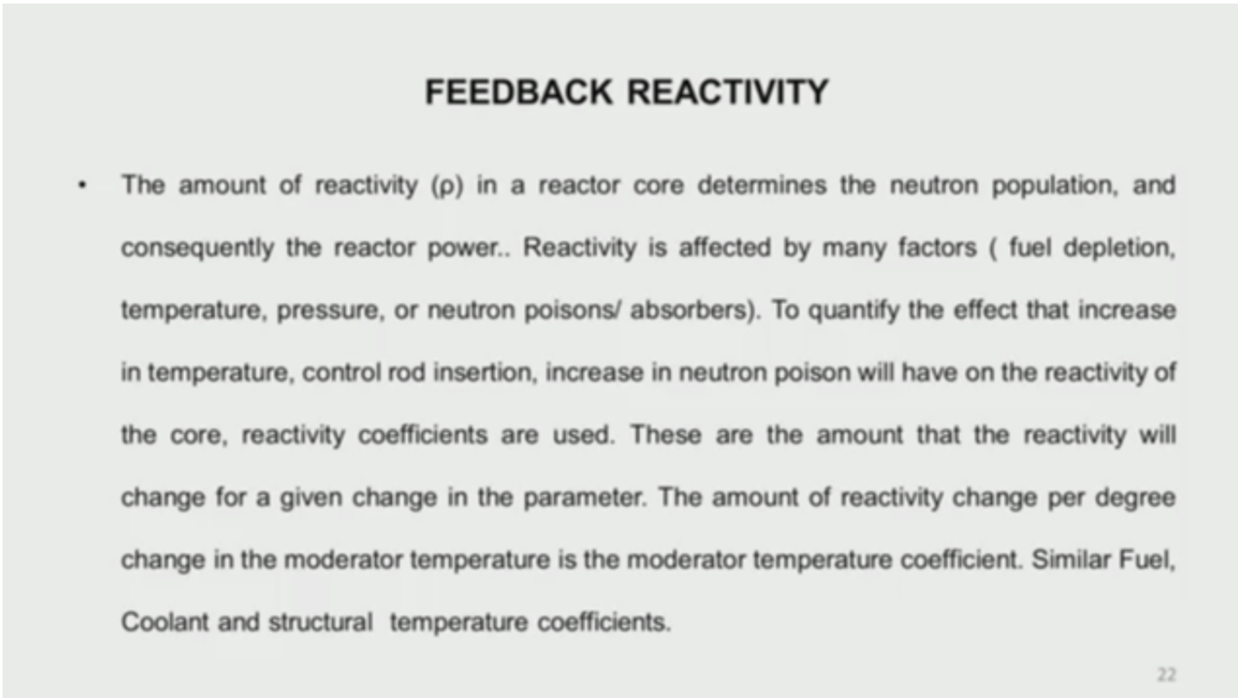

For example, if moderator temperature changes and there is a reactivity change, we call this -- that as moderator temperature reactivity coefficient. Then fuel temperature increase, so fuel temperature reactivity coefficient. If it is a coolant, if the structure like that, so the net effect on the reactivity is taken by considering all these constituents.

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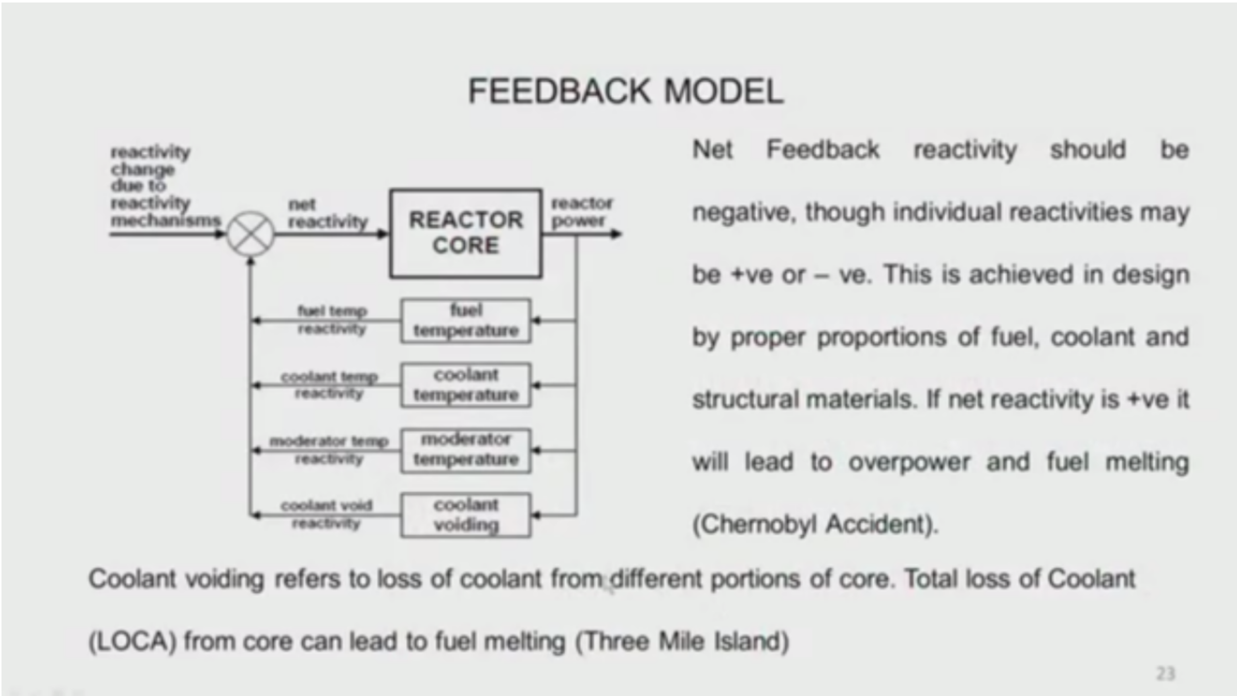

Let us look at it in a more systematic way. Now this is the reactor core and as I mentioned, any reactivity change, if there is a net reactivity, as long as it is critical reactor, the reactivity is zero, but if there is a change, it goes to the positive or negative, then this reactor power will change. If the reactor power changes, the fuel temperature will change, the coolant temperature will change, the moderator temperature will change and let us say the coolant leaks out, loss of coolant, then coolant voiding takes place. Again, that is another type of effect. So the net total of all these feedback reactivities with combined with your control rod decides what is the net reactivity to the reactor core.

Now just to give you an idea, this coolant voiding was one effect which caused a net positive reactivity in the case of the Chernobyl accident and the power really rose to very high levels. So one of the important things is to keep this void coefficient as low as possible and preferably negative. The total under any circumstances should not form -- become positive. So this has to be maintained.

Now in the case of Three Mile Island accident in USA also, there is a loss of coolant. Again, there is a fuel melting. So in both these cases, the effects were not very similar -- in one case it was over power whereas in this case it was shutdown. It was only having the decay heat, which could not be removed whereas here it was over power.

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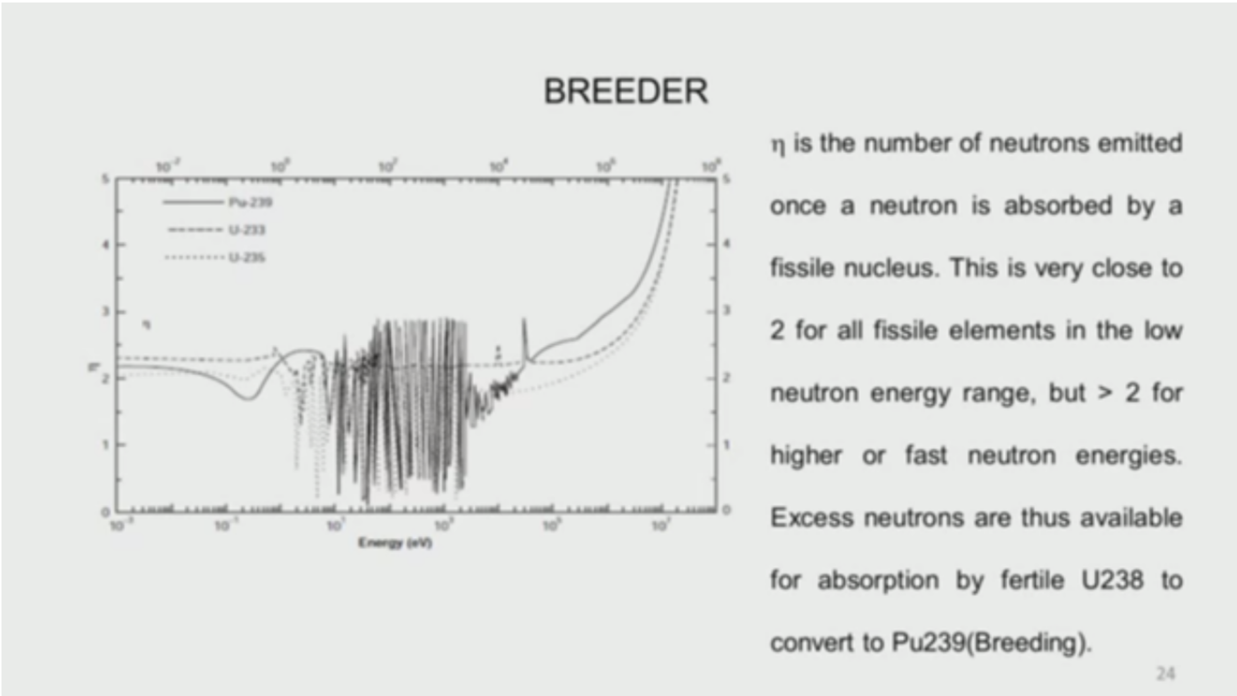

We saw about the how many neutrons are emitted once your neutron is absorbed by a fissile nucleus. This number is a function of the energy of the neutrons and let us look at this number for the three fissile elements: Uranium-235, Uranium-233 and Plutonium 239. If you look here, Uranium 233 appears to be the highest and Uranium-235 low. Plutonium and Uranium 235 are nearly having the same ratio. This ratio is actually called as Eta. That is the number of neutrons emitted once your neutron is absorbed by a fissile nucleus.

Now here this is the resonance region, but in the fast region if you see, Plutonium 239 has the highest Eta, again, followed by Uranium 233 and Uranium 235 is -- but now you look at here. Eta is very close to 2. Now what does this Eta really tell us? Now we saw that more than two to -- around two to three neutrons per fission are released in a fission normally. Now out of this, some may get absorbed in non-fissile -- non fission reactions and at least one must be available for fission.

So suppose let us say Eta was 2. If Eta was 2, okay, one will be available for absorption, one for fission. But if suppose you have more than 2, this excess neutron, if we can get into a element like Uranium 238 or Thorium 232, then we can get Plutonium 239 or Uranium 233. This conversion of a fertile element into a fissile element is what is called as breeding. We breed. So that means we must choose a fuel, which has got more and more Eta. That means it has got lot of spare neutrons after fission for breeding.

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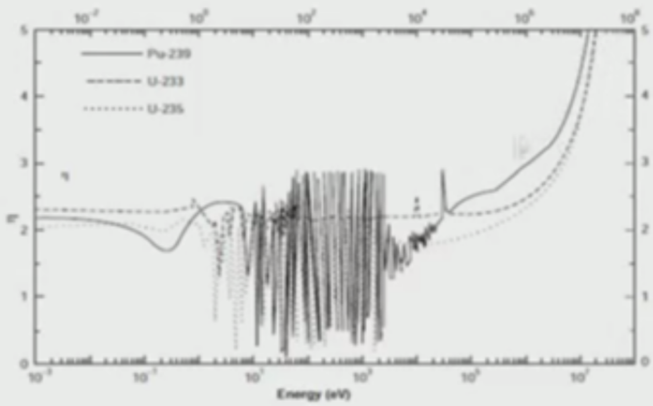
BREEDER



η is the number of neutrons emitted once a neutron is absorbed by a fissile nucleus. This is very close to 2 for all fissile elements in the low neutron energy range, but > 2 for higher or fast neutron energies. Excess neutrons are thus available for absorption by fertile U238 to convert to Pu239(Breeding).

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So if you look, very obvious, Plutonium and that too in the fast neutron spectrum, that is the reason why fast reactors most of them use Plutonium 239 and are convert Uranium 238 to Plutonium 239. So this is a very important concept of breeding.

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FAST REACTORS

Neutron Energy	U_{233}	U_{235}	Pu_{239}
< 0.025 eV	2.29	2.07	2.14
> 100 KeV	2.31	2.10	2.45

η Must be >1 for chain reaction as some neutrons get absorbed in non fission reactions in fuel, coolant, moderator and structures. For Breeding we therefore require η>>2. In the low and fast neutron energy range with U233 as fuel we have η>2.29 and we can have the breeding of Th232 . With U235 as fuel and low η (2.1) no breeding is possible. With Pu239 as fuel breeding is possible only in fast neutron range where η is 2.45. Reactors having fission through fast neutrons are called fast reactors.

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Now we saw in a graph, you just look at numbers. I have given two classifications. One is neutron energy less than 0.025 electron volts that we call as the slow neutrons or the thermal neutrons. In this Uranium 233, the Eta value is 2.29. Uranium 235 is 2.07 and Plutonium 239 is 2.14. So really speaking, if you see breeding is if at all possible with Uranium 233 only. Uranium-235 practically nil. There is very little left. But with fast neutrons, say more than 100 KeV, you have a figure of Eta of 2.31 for Uranium 233, 2.1 for Uranium 235 and 2.45 for Uranium -- Plutonium 239. So here you can see that breeding with Plutonium 239 is a very good thing and if I want to convert Thorium 232 and use it Uranium 233, then I can either work in the thermal reactor or a fast reactor. They are quite close. I could have Thorium breeders and whereas Uranium 238 breeders will be surely better possible only with the fast reactors. So in what is the fast reactors? In the fast reactors, the fission is by fast neutrons.

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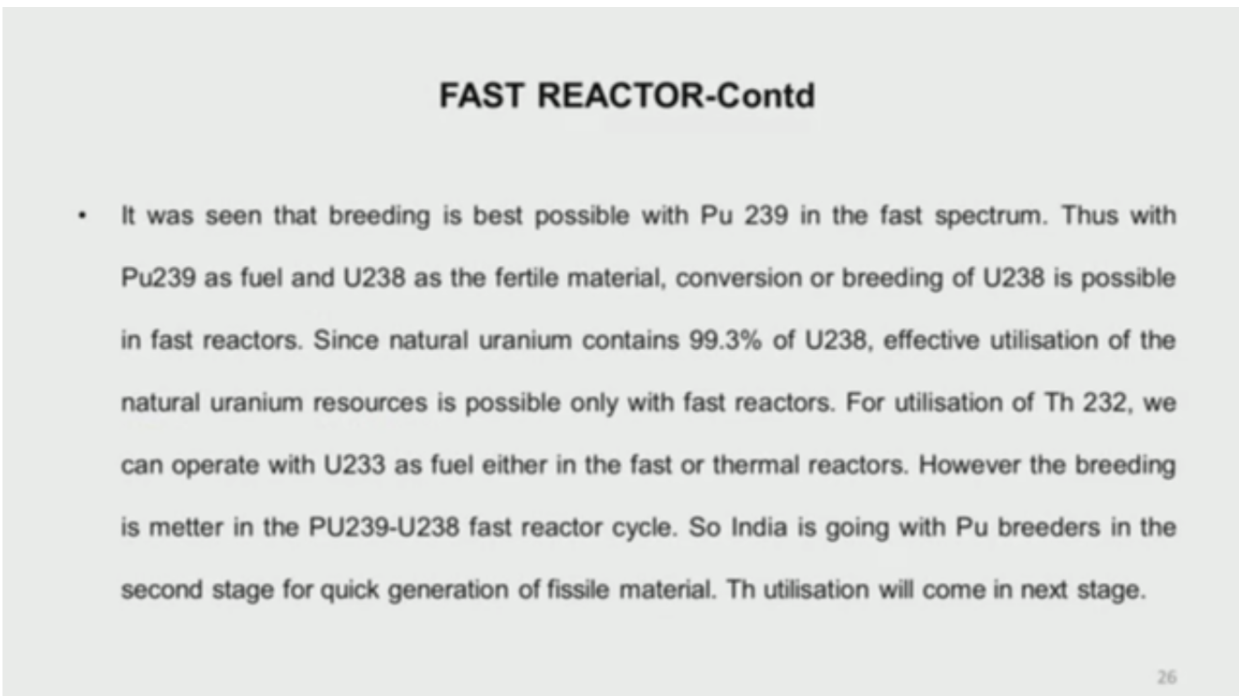

So let us see, fast neutrons, fission is only by fast neutrons are going to cause fission in the fast reactors, but their probability of fission is low compared to your thermal reactor. So you have to have an increased amount of fissile elements beginning itself. What is after all the total reaction? The probability of a fission into the number of fissile elements. Probability of fission is less. You increase the number of fissile elements. Then you have the same amount of reaction. So that is why fast reactors use enriched fuel or they use enriched Uranium. The 35 or enriched or -- or more of fissile elements like Plutonium.

Now natural Uranium if you look up contains only 99. -- 0.7% of Uranium 235 and 99.3% is Uranium 238. If you suppose don't have fast reactors, what are we going to do with the -- that

Uranium 238? We are just going to call it as a waste and not use it, but if I use it in a fast reactor, I can convert it Uranium 238 effectively into the Plutonium 239, and that is why effective utilization of the Uranium, natural Uranium resources is possible only with fast reactors and in India we have limited natural Uranium resources and is very imperative on us that we should go for fast reactors.

Regarding Thorium the -- we saw that the Eta value was less. When the ETA value was less, the breeding potential is also less. So we in India are using at the first level Plutonium 239, Uranium 238 breeders so that we will produce more amount of fuel, which can be used in a large number of reactors. So our nuclear base of the nuclear program will be able to increase faster. We will just take up Thorium in the next stage.

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Now in this lecture we have tried to cover the basics of the fission reaction. We also mentioned that the chance of fission is more with neutrons of lower energy or slow called as thermal neutrons. So you need to reduce the energy of the neutrons from its production at that time the neutron energy is high. So you have to moderate. Of course, in a fast reactor moderators will not be there. The fission is only by the fast neutrons.

Then we looked at the concept of criticality where the multiplication factor is 1. We also saw criticality refers only to the neutron balance, doesn't have anything to do with the power. Your reactor at any power is -- is the critical state. Then we looked at the concept of decay heat production. Why this concept of decay heat production is very important? Even after the reactor is shutdown, heat continues to be produced and if this heat is not removed, the fuel can melt and fuel can fail and come out. That's what happened in the Three Mile Island and Fukushima. So that's why even when we are handling fuel after being utilized in the reactor, we need to really have cooling. Then we saw the concept of reactivity and how this reactivity changes based on the fuel, the coolant, the coolant void etc.

Finally, last but not the least, we looked at breeding, how breeding happens in a nuclear reactor and why breeders are necessary for effective utilization of the resources of natural Uranium.

Thank you.

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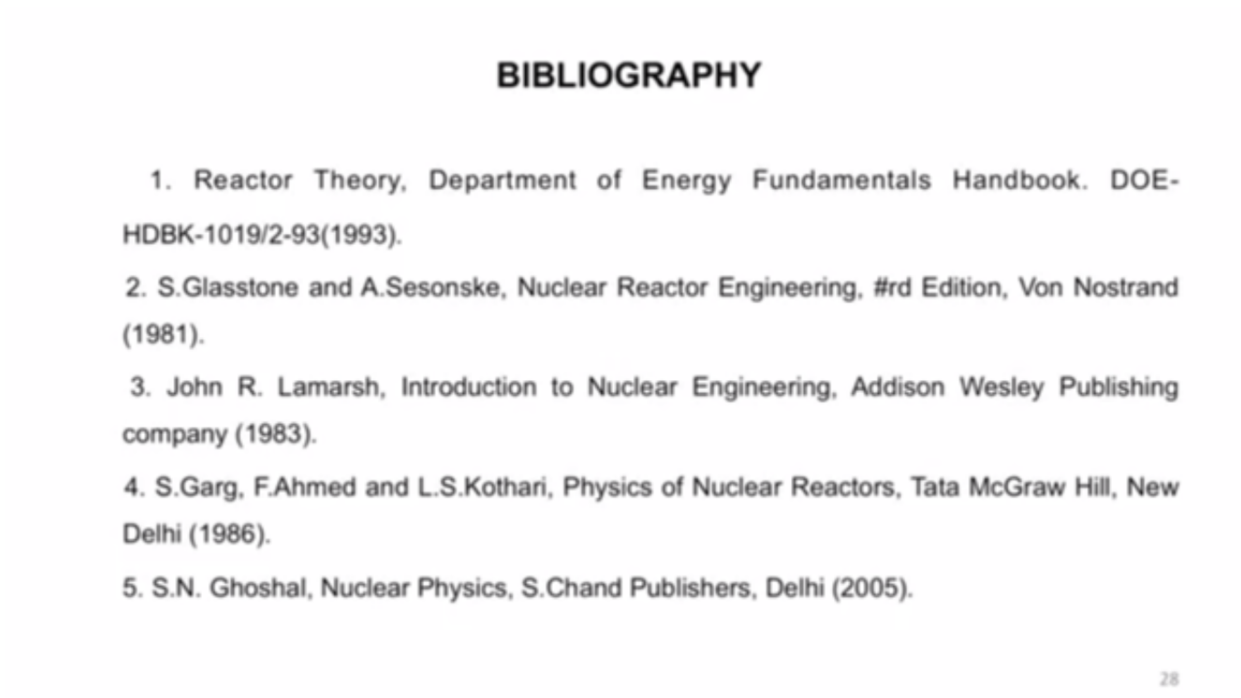

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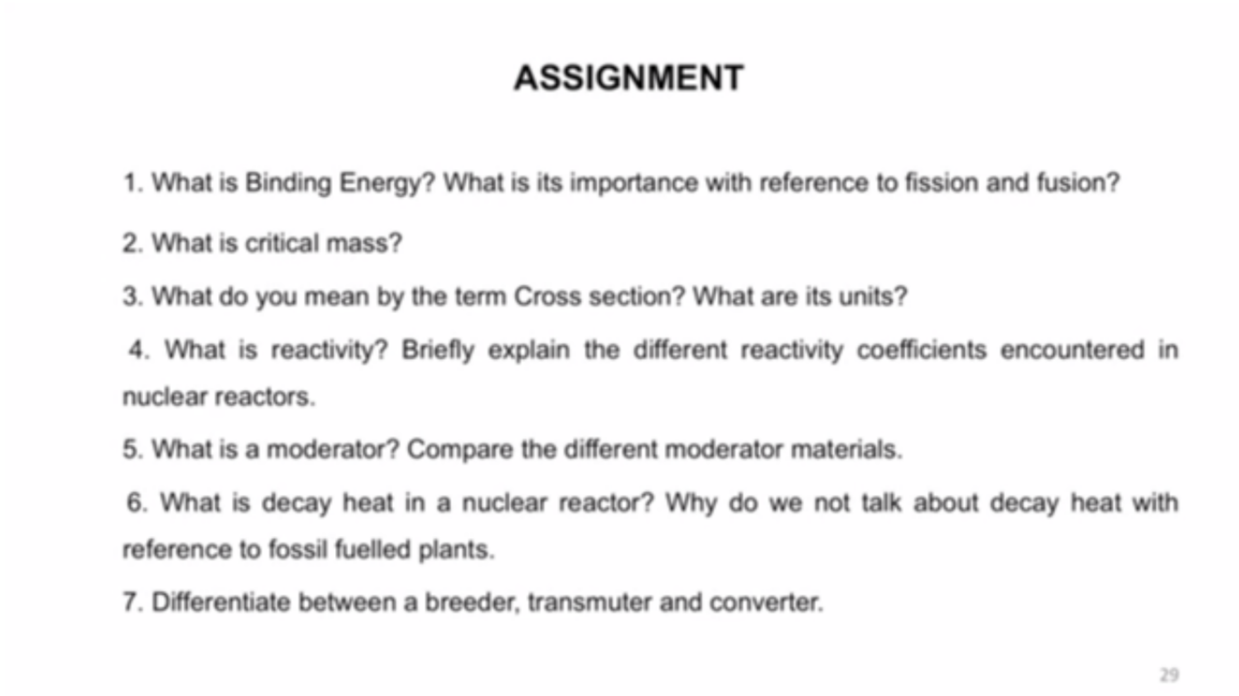

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