Fundamentals of Nuclear Power Generation
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Module – 08
Breeder Reactors
Lecture – 03
Fuel cycles & FBR

Hello everyone. So, today we are into the third lecture of our module number 8 or the week number 8, where we are talking about the breeder reactors. We already had 2 lectures so, I am surely your by now know the concept of breeding and also have started to understand the difference between of a breeder reactor with a conventional thermal reactor. Just to have a quick recap, in the previous two lectures we have discussed about the concept of breeding and also the breeding ratio, now we know that the term breeding basically refers to a reaction like this.

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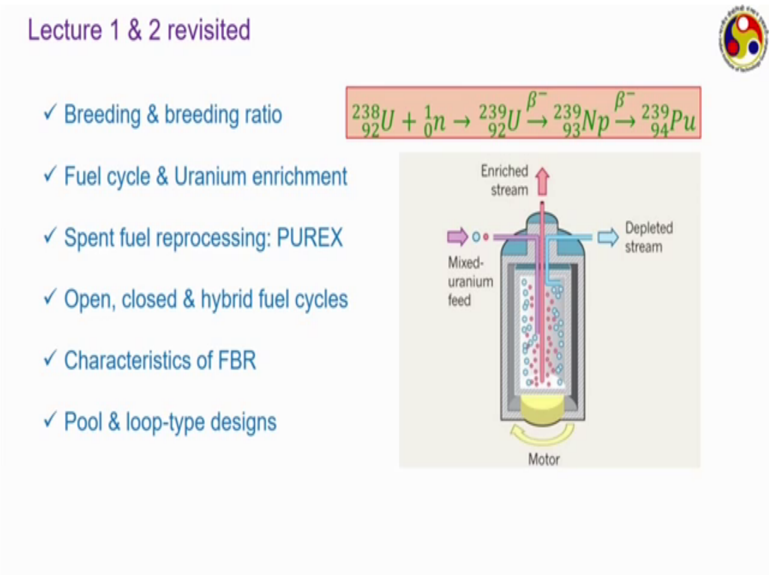

Where a fertile nucleus absorbs a neutron and that goes through successive decay processes.

In fact, I should not say all the breeding reaction involves such kind of decay, but the common reactions like involve those involving uranium 238 or thorium 232 is always in these cases, you will find such kind of decay that is one neutron absorption step followed by 2 successive steps of beta decay, leading to the final product of plutonium 239 in this case. And when it starts with uranium thorium 232, then after absorption of the neutron we get thorium 233, which goes through 2 successive states of beta decay to produce uranium 233.

But there can be other kinds of beta de sorry, other kinds of breeding reactions as well which are direct like plutonium 238 and absorb a neutron to prodius plutonium 239 or more commonly plutonium 240 can absorbs a neutron to produce plutonium 241. Which such kind of direct single step breeding reaction is also possible, but generally the 2 most common kind of breeding reaction that you will find in industries one refer to the one that is shown here, uranium 238 absorbing a neutron to produce plutonium 239 and the other one which is of which is of increasing popularity, where thorium 232 absorbs a neutron to produce uranium 233.

As I have already discussed that thorium reserve in the world is at least 3 times more compared to uranium, and therefore, and it is primary isotope is also thorium 232 just like uranium 238 in case of uranium. And therefore, several countries are looking to build their future plan of action, in case of nuclear power generation based upon thorium. Which involves India as well; like Indian nuclear power program has a big dependence on thorium India has a quite small stock of uranium, but very large stock of thorium. And therefore, we shall be a talking about later on in the next module where you will find that the thorium 232 plays a big role in India nuclear power program, where we use this particular breeding reaction to produce uranium 233 and subsequently that uranium 233 is used as the primary fuel isotope.

And breeding is also plays a very important role in showing the prospect of nuclear energy for future. While the stock of uranium is quite limited, only through the breeding we can still continue to use nuclear power for something in the range of 25 to 30,000 years which is near infinite considering a present scale. And also as one particular isotope which is uranium 238 which before up to this module was thought about of no use at all, it can be found to be of great significance through this breeding reaction.

Like earlier whenever we have discussed about factors like resonance absorption, you must have always failed that is a loss. Because uranium 238 has a very high resonance absorption cross section at certain energy levels. Therefore, when a neutron of that energy level comes in contact with an uranium 238, nucleus that immediately gets a absorbed, which we have called resonance absorption and immediately that neutron goes out of the system, because that is no longer available to become thermalized and cause any kind of thermal fission.

But that neutron which has been absorbed by thorium 2 uranium 238 that actually can lead to this breeding reaction thereby adding some more fuel into the system. And hence that is also of great importance. And as a result, a reactor a thermal reactor which is fueled, only by uranium can still have 30 to 40 percent contribution in the total power production coming from the plutonium. And plutonium is entirely generate inside the reactor alone.

Breeding ratio we have defined as the ratio of the number of fissile nucleus present, after a reaction divided by number of fissile number of fissile nucleus consumed during a particular reaction, and when a reactor is having a bleeding ratio greater than 1, then only you called a breeder. we have discussed about fuel cycle and the neutron a or uranium enrichment process in the previous lecture, of while we get only raw uranium ore from the mines, that needs to go through the milling and conversion processes.

Out at the end of the conversion processes we get uranium hexafluoride gas, which success goes through this enrichment process there are several ways we can achieve enrichment, basically enrichment refers to a process which increases the fraction of uranium 235 in the total mixture. And out of all the possible methods, this particular one which is the gas centrifuge is the most popular one at the present, but the laser one also the laser-based method also has a grid feature ead probably.

So, once we get a stream of uranium, which is enriched that is which has higher fraction of uranium 235, that is subsequently taken into the nuclear plants or nuclear reactors for utilization. And also, once the entire process is done, the spin fuel that we get out of the reactor that can also contain significant amount of fuels itself. Like say if we are starting one reactor with in natural uranium N, then after going through the process for a prologue duration something like one year or 3 years, whatever we get back at the end, that still contains about 97 percent of uranium 238, about one percent or so.

It will less than one percent of uranium 235, about one percent of plutonium 239, and rest or I am actually withdrawn means initially about 95 percent of uranium 238. Nearly one percent of plutonium 239 and uranium 235, and rest 3 percent generally corresponds to the fission fragments those fission poisons etcetera.

So, still there are about 2 percent of that mixture, which can further be utilized as fuel like that one percent of uranium 235 and one percent of plutonium 239. And thus, painful reprocessing generally focuses on separating out those fissionable nucleus from that mixture and also removing that 3 percent of fission fragments from this. Because that is generally of no use that fission fragments goes for some further very disposal which is a topic of our last module, but the useful components that is that uranium 235 and plutonium 239, that are reprocessed purex is one proce particular procedure, which is quite which has been standardized through the years, and at the end of such a process like purex we generally have 2 kinds of products one is pure uranium oxide, and other is mocks or mixed oxide which contains both uranium oxide and plutonium oxide. And that can go for further utilization.

We have also discussed about open close and hybrid fuel cycles in open cycle there is no reprocessing. So, it is a once it is just a once to process in case of closed cycle ; however, we generally have both thermal and fast reactors involved, the waste coming out of the thermal reactor is said at through the pyro processors and recycling plant. And corresponding output is fed to the first reactant thereby produces some more fuel for future use. And a hybrid plant though it is only a thermal plant, but it generally utilizes both, uranium oxide and mocks for it is power production.

Then we have discussed about the characteristics of a FBR, and also compared this performance with a classical pressurized water reactor. And finally, we have discussed about the pool and loop type designs of the FBR. Both have it is own advantages in case of pool type we have everything like the new sorry the reactor core, the primary pump and also the heat exchanger or intermediate heat exchanger. All immersed into a pool of liquid fuelers generally liquid sodium. Whereas, in case of loop type design the palm it is only the reactor which is immersed into the liquid sodium, both the pump and the intermediate fixed heat exchangers are kept outside both designs have it is own advantages. And therefore, are being used in different designs

So, today we are going to finish our discussion on the breeder reactors and then to facilitate that we shall mostly be discussing about the coolants that we normally using breeder reactors. But one question I should answer at this point, that why we are talking about breeder reactors in such depth. Like in the previous module we talked about thermal reactors and there are several types of thermal reactors available. Like, the pressurized water reactor boiling water reactor, pressurized heavy water reactor, gas cooled reactor or the RBMK group which is graphite moderated light water reactors. So, there are so many variations, but still we went through them quite quictly quite quickly and finish that module in just 2 lectures.

But in this FBR group, we are discussing in more detail and taking our time to discuss. That is because of this generation 4 initiative. Under generation 4 initiative, which basically proposes the future nuclear reactor designs, which are going to rule the power production industry in the years to come, if you remember from our previous module, there are generally 6 reactor designs which are found to be very prospective under this generation 4 initiative.

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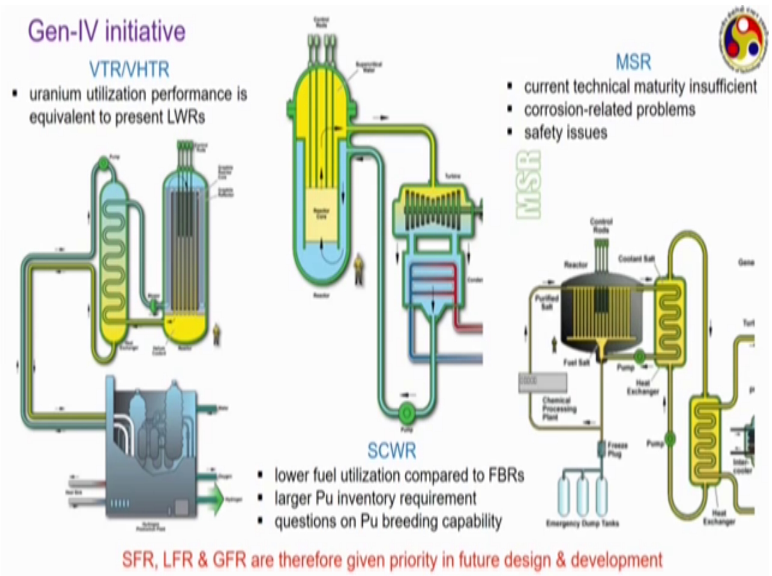

The one of them is this VTR of VHTR very high temperature reactor. we have discussed these characteristics earlier, but of course, none of the generation 4 reactors are active at the moment, some while some of them are restricted to the research laboratories, some of them are only concept and has gone through theoretical analysis or very small scaled test runs.

Now, from the knowledge that we have gained from there, the vh VTR shows that, it has a very poor fuel inflation performance. In fact, it is utilization performance is quite similar to the present light water reactors or thermal reactors. And it does not offer any extra advantage all for like we get in case of FBRs. In fact, a VTR general is a thermal reactor only and therefore, it is only expected that is utilization performance will be similar to the mode and the thermal reactors like PWRs.

So, the other one is SCWR of course, it is very promising because it works at the supercritical pressure and temperature level. And so, promises very high thermal efficiency something in the range of 40 4 to 45 percent, but it has own issues like very high pressure and temperature, and also from fuel utilization performance point of view, it is utilization is lower compared to the present FBR’s. The present design fast reactor shows a much better utilization of the fuel. And better fuel inflation means, much less amount of waste product. So, laser report is required for the waste disposal, SCWR are fails in that category.

And as the fuel inflation is poor so, it requires much larger fuel inventory particularly a plutonium inventory requirement. And also, it has some questions raised about the plutonium breeding capability, which still needs still needs to or it is a still not in a position to demonstrate a very high breeding ratio. And therefore, doubt remains whether we at all can go for this SCWR in future. Because whatever future reactors we are going to have under this generation 4 or maybe even future generations, we must ensure that breeding a proper breeding ratio, or high breeding ratio is a must. So, that we can get a good fuel economy a very high utilization of the fuel. But both VHTR and SCWR fails in that category.

And the other one is a molten salt reactor; here the knowledge base is quite small. In fact, that technology itself is not very matured and still lots and lots of rnd is required on MSR before it can at all be realized it is still a concept which has hardly got tested at the laboratories. And as the molten salts are used here so, there will be a big amount of corrosion problems, and safety issues or maintenance issues are also very much prevalent for MSRs.

Therefore, out of the 6 designs selected in generation 4, at least or these 3 have their own issues; which leaves us with the remaining 3 that is a SFR LFR and GFR or namely the sodium cooled fast breeder reactor, lead cooled, fast breeder reactors and gas cooled fast breeder reactors, which have given priority in future design and development. And incidentally all of them are fast reactors. And that is the reason we are discussing so much in fast reactors or a fast breeder reactor, because fast breeder reactors are the future. In the present day that is under generation to all those PWRs and BWRs or all those thermal reactors that we are using at the moment in next 3 or 4 decades to come, they all may get extinct and slowly, but surely, they will all get replaced by the breeder reactors. And that is why it is very important to get some more idea about the breeder reactors.

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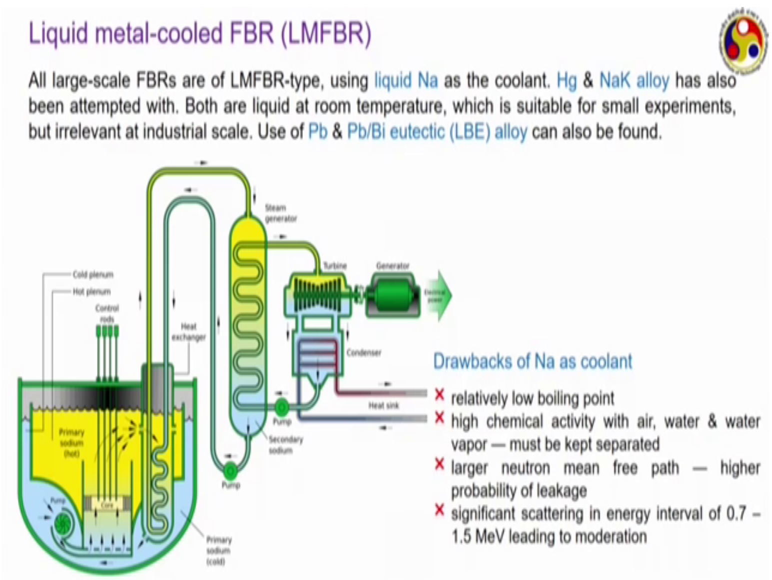

Now, most common design of breeder reactor is this LMFBR or liquid metal cooled FBR. And this particular picture we are seeing from the beginning only, where we are using a liquid metal generally liquid sodium has the coolant, this design can you guess it is a pool type or loop type, sure it is a pool type design. Because here you can clearly see the reactor core, the primary pump and also this intermediate heat exchanger. All of them are immersed into this big pool of sodium, big pool of liquid sodium.

So, as there all immersed in to this big pool of liquid sodium, we call it a pool type design. The cold sodium or cold liquid sodium is allowed to be pumped through this line into the core where they gets the energy. So, becomes high temperature sodium which is termed as the primary sodium here , and this high temperature liquid sodium passes to this intermediate heat exchanger through this line, and there it passes it is energy to a secondary heat exchanger where the working medium is also liquid sodium. So, the liquid and then this primary sodium comes out from here and then again gets pumped through back to the core.

But the liquid sodium which is flowing through the secondary circuit, that comes over a this line, and then gets the energy and then goes back side. And then it goes to the other heat exchanger which is basically a steam generator here on the high temperature side we have this secondary sodium, which has just come out of the intermediate heat exchanger with large amount of energy and on the primary side we have a liquid water, which comes through this pump and then as it passes through this heat exchanger, as it passes through the heat exchanger it gets the energy thereby gets converted to steam. And finally, the steam comes out of from here to go to the turbine and gives the electrical output through the alternator or generator.

So, this kind of liquid metal cooled fast breeder reactor is the most common design. and whatever FBRs that you can finds out the world now there are only very few countries which are working on FBRs, which includes Japan China India and Canada. And of course, Russia, the where the, whatever FBRs they are having they are all of this liquid metal cool type. And liquid sodium is the coolant that is universally being used. It is not that other fuels have not been tried rather some (Refer Time: 17:52) reactors employed mercury as the fluid, and also some research reactors are using this sodium potassium alloy as the fluid. One big advantage of both of them or both mercury and the sodium potassium alloy their liquid at the room temperature. Which sod where sodium is not liquid at room temperature it has a melting point of around 90 degree Celsius.

So, once we can use a material like mercury which is a liquid at room temperature directly we can apply this to the reactor, and that is very suitable for small experimental districts or research laboratories. But when you are talking about the industrial scale, there basically that is irrelevant, because anyhow we are working at the high temperature, and there is not very many and there is a very less probability that the temperature will fall below that 90 degree Celsius. So, sodium will always remain under liquid condition.

But a more prospective fuel can be lead or lead bismuth eutectic alloy which is also called LBE alloy. Sodium of course, is universally used in FBRs, but it has it is own issues. Like, it has a relatively low boiling point compared to lead or other materials usually seeing the number shortly, but this is boiling point temperature is quite low. Then the biggest issue, sodium is highly chemically active. Whenever it comes in contact with either air or water or water vapor it immediately starts to react and a highly exothermic chemical reaction and that is always a component by a fire.

And therefore, sodium must be kept separated from the steam which we are using here as the working medium of in the final turbine generator circuit. That is the reason of having this intermediate heat exchanger. The sodium that we are heating up in the primary vessel, and that we or in the pool that sodium cannot directly come out and supply or exchange energy with a steam in the steam generator. Rather we are using the secondary sodium glue which is operating at a lower temperature level. And also that provides some kind of safeguard so, that the sodium is never coming in contact sodium in the primary side side at least, that is never coming in contact with the water or water vapor.

The mean free path of neutrons inside sodium is much larger which increases the possibility of leakage as well. And finally, another problem which happens generally in the energy travel of 0.7 to 1.5 MeV, the scattering cross section of sodium with within this particular energy level is quite high. Both elastic scattering and inelastic scattering, and therefore, there is possibility of some kind of moderation effect, that may come in when the neutron falls in this particular energy band.

So, these are quite a few drawbacks that we should be careful of while using sodium as a coolant.

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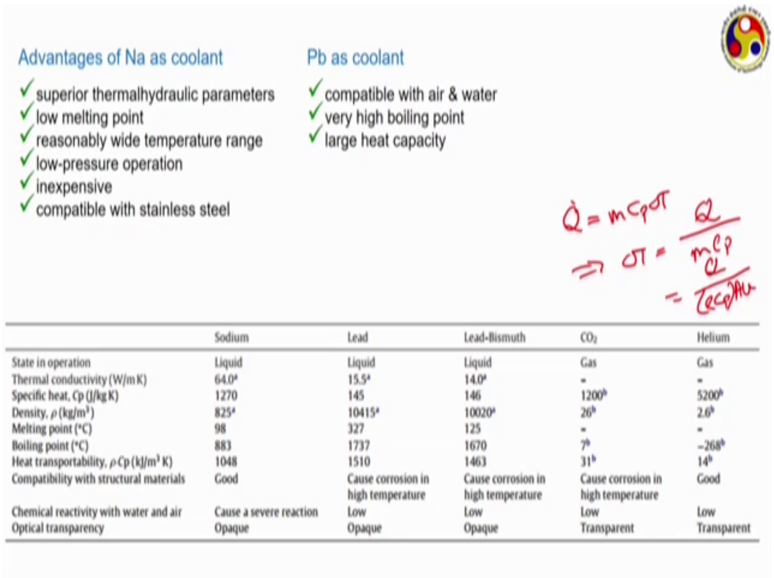

	Sodium	Lead	Lead-Bismuth	CO_2	Helium
State in operation	Liquid	Liquid	Liquid	Gas	Gas
Thermal conductivity (W/m K)	64.0[a]	15.5[a]	14.0[a]	-	-
Specific heat, Cp (J/kg K)	1270	145	146	1200[b]	5200[b]
Density, ρ (kg/m^3)	825[a]	10415[a]	10020[a]	26[b]	2.6[b]
Melting point (°C)	98	327	125	-	-
Boiling point (°C)	883	1737	1670	7[b]	−268[b]
Heat transportability, ρCp (kJ/m^3 K)	1048	1510	1463	31[b]	14[b]
Compatibility with structural materials	Good	Cause corrosion in high temperature	Cause corrosion in high temperature	Cause corrosion in high temperature	Good
Chemical reactivity with water and air	Cause a severe reaction	Low	Low	Low	Low
Optical transparency	Opaque	Opaque	Opaque	Transparent	Transparent

But sodium has it is own advantage also for that just take a look at this table. Here we are comparing the coolants which are commonly used in generation for fast breeder reactors. Sodium is the coolant for SFR lead or leas, lead bismuth eutectic are generally thought about for the LFR, and in gas cooled reactors we may use carbon dioxide or more preferably helium. Look at their properties, both sodium cooled reactor that is SFR, and LFR comes under the a liquid metal cooled FBR category whereas, CO 2 and helium are used in gas cooled reactors.

Now, first let us take a look at the melting and boiling point. Data sodium has a melting point of 98 degree Celsius, and a that will low boiling point of just around 83 degree Celsius. Compared to that lead has a boiling point of 1737 and lead bismuth eutectic is also quite similar. So, they have extreme very, very high boiling point, and thereby allowing the coolant to reach much higher temperature. Whereas, when you are operating with sodium the final coolant temperature may has to be lower than this value. In fact, it should be reasonably lower than this value. May be hardly allowing something like 800 or 820 degree Celsius. Whereas, with lead or lead bismuth eutectic we can go easily up to 1500 degree Celsius, without ever bothering about the cooling or rather the phase change of this coolant.

The another point that we should consider which actually is favorable to. Sodium sodium has it is own advantages, because it has superior thermal hydraulic parameters. It is melting point is not of any consideration, but boiling point is, but apart from that all other thermo physical properties of sodium are excellent. Like, look at the thermal conductivity. It is thermal conductivity is 64 watt per meter Kelvin, which is just in order of 15 for lead.

Similarly, if you take a look at the say rho CPU product, which is also called the heat transport ability or heat capacity. It is also quite good for sodium. Of course, lead is even better both lead bismuth eutectic and pure lead they are, even better specific it for sodium is much larger to 1270 which is significantly higher than lead.

Another big issue that we may have using liquid lead as the as the working medium, sodium is a very, very light metal. So, look at the density of sodium it is around 825 kg per meter cube and this is 10000. So, is this one? So, it is about 12 to 14 times more dense compared to sodium. And as it is as the density is much larger. So, sigma that in that proportion the pumping point needs to be introduce in needs to be enhanced much larger power will be required to drive this liquid lead or liquid lead bismuth eutectic mixture to flow through this coolant channel or maybe through the around through the circuits through the zones around the core. And there will also be chance of pipe clogging because of it is high density.

So, from all this cons point considering, sodium has superior thermal hydraulic parameters, and apart from the boiling point once you can restrict the highest temperature it is definitely more suitable fluid compared to lead. melting point is very, very low lead has a melting point of 372 27 degree Celsius 327 degree Celsius compared to just 100 degree Celsius. Therefore, while the upward working temperature or allowable temp working temperature, and on the higher side is very high for lead, but the lower side temperature is also quite high the operating temperature should be something like 350 degree Celsius or higher the lowest operating temperature.

And. So, we have be generally handle much higher temperature level in LFR and the coolant temperature in no case should fall bellow that 350 degree Celsius. The temperature range applicable for sodium is reasonably avoid like, if we compare this range, still we are getting a range of about 7 100 degree Celsius. But the range definitely is much larger in case of lead, where I can find it is around 1400 degree Celsius. So, if such kind of high temperature change is desirable, then we cannot go for sodium we have to go for something like lead or LBE. LBE refers to lead bismuth eutectic.

But another advantages for sodium is as the melting point as long as the boiling point can we manage around that 8 83 degree Celsius, or I should say as long as the maximum coolant temperature requirement is while below that 83 degree Celsius, we do not need to go for any kind of pressurization. The system can operate under atmospheric pressure only, and still allow a descent temperature range of for operation.

Sodium is definitely inexpensive, and also it is compatible with stainless steel. Therefore, there are several points we generally make sodium the most suitable coolant. But lead is also not far behind. Lead is the biggest advantages compatibility with air and water. The biggest problem for sodium as I have mentioned earlier, it is highly reactive particularly in contact with air and water it reacts immediately and starts to burn on it is own born on it is own. But lead and does not have such level of chemical activity, or it is very compatible with both air and water, and therefore, we can use the lead cooled reactor or LFRs with even open to atmosphere also. Or I should not say open to atmosphere; I should say in case of LFRs, we do not need to have that secondary loop or intermediate heat exchanger loop.

In case of SFR, we need that intermediate heat exchanger because the primary coolant which is liquid sodium, that should not come in contact with the water which is flowing in the external circuit. That is why you use that intermediate circuit, where the working medium is again sodium, but working at a much lower temperature level and that can supply a energy the coolant.

Another advantage for lead is very high boiling point which I have just mentioned we can easily go up to 1600 7000 degree Celsius. Heat capacity for lead is larger like if we compared the heat capacity it is 15, 10 it is 1463 for LBE [vocalized-noise. So, about 50 percent larger than what we get with sodium and what can be the advantage of having a high heat capacity? I hope you can guess, because we know that for any incompressible you could we can always write Q equal to m CPU delta t or delta t is equal to Q by m sorry, into Cp. And if we break the CPU then becomes cross section area, rho CPU into cross section area into the velocity of the liquid coolant. And therefore, higher the a rho CPU value a smaller will be the temperature difference of the coolant.

But a lead or LBE both have quite high heat capacity compared to sodium, and therefore, they can be more preferable from temperature rise point of view. Sodium lead like similar to sodium can also allow low pressure operation it is also inexpensive and quite easily available, but lead has it is own issues it is chemically toxic, which sodium was not it is chemically toxic, and it is melting point is very high like 327 degrees Celsius here.

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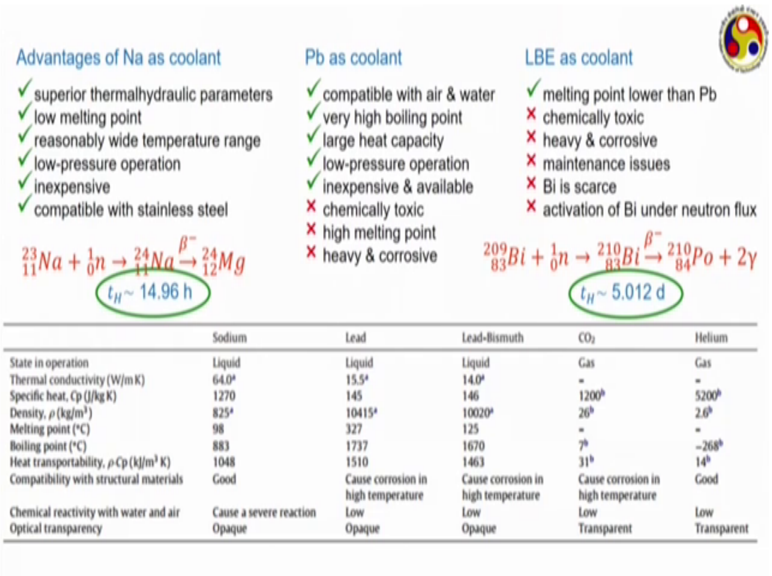

So, in no case the coolant temperature in the core should fall close to through 377 it should always remain something like 350.

Another problem is heavy and corrosive it is extremely corrosive and. So, can damage the metals of the worlds and if we talk about LBE LBE shears most of the issues of lead, means from advantage point of view again it is melting point is low it is melting point is lower than lead, but not by a huge degree. And so, that is quite decent. Or I should say the melting point of LBE while it was 327 for lead it is just one 25 for LBE which is quite close to the value for sodium, and therefore, it is much easier to use LBE and we can allow is the temperature to drop to something very close to the ambient temperature or ok, let me correct. Melting point being so low for LBE we can easily operate it much lower temperature level compared to lead.

But it has other advantages like similar to lead is chemical toxic it is heavy and corrosive. Then there has been maintenance issues. LBE has not found used in power reactors so far, but there are a couple of a couple of examples, where LBE has been used as a fuel in nuclear powered submarines in Russian submarines. And both cases maintenance issues are found. There may be some other reasons also, but on both 2 or those 2 Russian submarines both reported several maintenance issues, and that was related to the flow of this LBE itself.

And bismuth is not that easily available lead. Of course, is easily available, but bismuth is quite scarce, and also it can become cam active under neutron flask. Bismuth can parties in a reaction like this. The Bi 209, which is the most common isotope can absorbs a neutron to produce Bi 2 10. And then it can go through a beta decay to produce polonium 210. But sodium if we compare with that that can also participate in such reaction. Like, sodium to sodium 23 which is the most common isotope of sodium which is available in the nature in the form of natural salt also sodium chloride. That can absorbs the neutron to produce sodium 24 which is highly reactive and immediately goes through a beta decay process to form magnesium 24. And you can see the half-life value for and sodium 24. It is half-life is quite small it is just about 15 hours

therefore, from the point at which the sodium 24 is formed, almost within about 15 minutes half of those new nucleus or new nuclei will break down or will participate in the beta decay into form magnesium and it is expected that this or we can visualize this conversion of sodium 23 to magnesium 23 we almost direct because of this small half-life. And magnesium 24 is a stable isotope. So, the radioactive effect of sodium 23 inside the reactor is not their significant.

But if we compare that with bismuth 209 then half-life of bismuth 210 is more than 5 days. So, some more time is required to remove the radioactive waste from the reactor no, and also the radioactive waste or the products like polonium or etcetera which remains inside the reactor, that or I should not polonium I should say this is a Bi 210 now has more time inside the reactor to participate in the radioactive decay, thereby emitting or thereby causing the probability of more radioactive hazard.

So, in a nutshell whatever you are getting from this slide in the previous slide sodium has it is own issues. But still it is the most suitable coolant that we can identify at the moment and that is why through the liquid cool fast breeder reactors whatever we have at the world, at the commercial level at the moment they all work with liquid sodium. So, we come to the sodium cooled fast reactors SFR it is characteristics or discuss to the part of the previous module.

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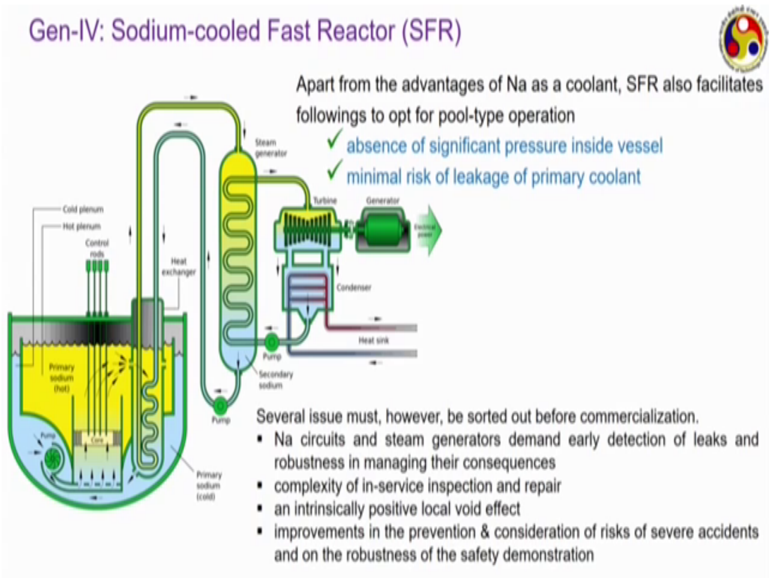

Now, I discuss about some issues that it may have. The sodium has it is own advantages as we have mentioned, but SFR also facilitates for couple of advantages because of which it goes for the pool type operation. Pressure we pressure inside the pressure vessel is can be quite low. Sodium has a low melting point are reasonably high boiling point and therefore, we can operate this in unpressurized situation. And pressure vessel can remain at the atmospheric condition.

Another problem that or another advantage whether SFR processes is a minimal risk of leakage of the primary sodium. Because the way it has been designed the primary coolant will not leak out the core, but there are several issues which also need to be sorted out before full commercialization actually, out of this 3 SFR MFR and GFR. SFR is the one whose development is at the most advanced stage, the trial runs all are completed and it is presently gone for the power testing. And once the power testing is successful, then probably it can go for pool scale commercialization.

But the issues that sodium circuits and steam generators demand early detection of leaks and robustness in managing in their consequences because even a smallest amount of leak of sodium out of the reactor will bring it in contact with the atmospheric here, which can lead to fire inside the plant. The complicity in inser service inspection and repair sodium is opaque in nature, and also, we should never allow the sodium to come open to the atmosphere, and that is why in-service inspection or when the run is going on the when the reactor is operating that time any kind of inspection and repair is impossible.

SFR can offer an intrinsically positive local void effect. As it is liqui using a liquid fuel if temperature fluctuates inside, then there may be small void of sodium appearing or small sodium vapors may start to appear. And if we are having a positive local void effect, then that can lead to a failure of the reactor. So, that is something that needs to be managed generally by optimizing the design of the core and finally, the improvements in the prevention and consideration of risks of severe accidents and on the robustness of the safety demonstration which also needs to be a certained for this SFR.

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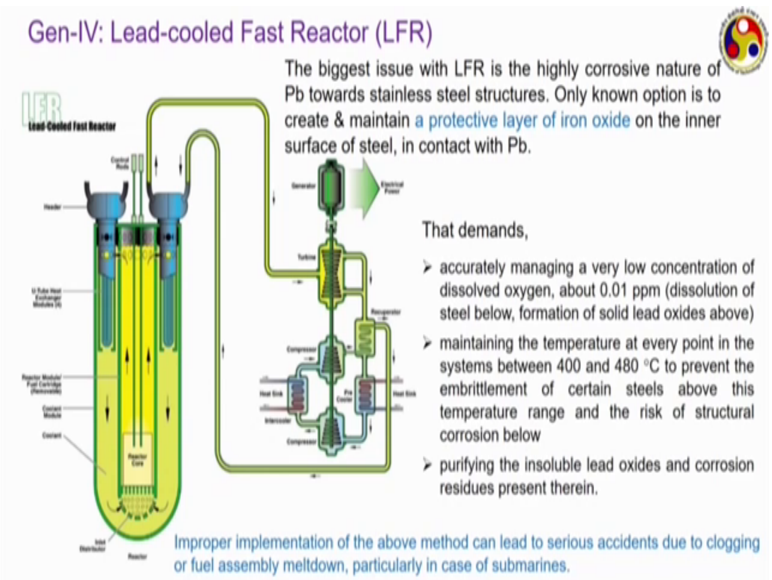

Next, we have the LFR liquid sorry lead cooled fast reactor. The biggest issue with LFR is it is highly corrosive nature. Lead has it is own advantage over sodium like I have mentioned it has much higher boiling point and it has a higher heat capacity. But it is melting point is also high, and it is also corrosive nature compared to sodium. So, sodium lead as a fuel has or rather as lead as a coolant, has it is own advantages and disadvantages. And along with that, the LFR itself also generally because of the high temperature involvement we like to use stainless steel as a material. And this lead is highly corrosive to stainless steel, which is the biggest issue LFR immediately phases.

Only reasonable option to prevent such kind of corrosion is to use a protective layer of iron oxide or the inner surface of the stainless steel. The surface which is in contact with lead, that we put a protective layer of iron oxide. So, that the lead is not coming in contact with the steel , but this particular technology can require quite a few factors like accurately managing a very low concentration of dissolve oxygen about 0.01 ppm. Maintaining the temperature at every point in the system between 400 and 480 Celsius it is quite a narrow band. But we have to maintain this because if the temperature falls below this 400 degree Celsius, then there will be risk for structural corrosion whereas, when it goes above 480 degree Celsius, then certain steel may become quite brittle.

And also purifying the insoluble lead oxide and corrosion is residues present there in. That is another thing that we have to consider. in this iron oxide layer current properly we implemented, then there can be serious accidents like those 2 sub Russians submarines that I mentioned earlier ; which are using lead bismuth eutectic kind of materials coolant. Because of the clogging or fuels only meltdown, the entire reactor performance may get affected.

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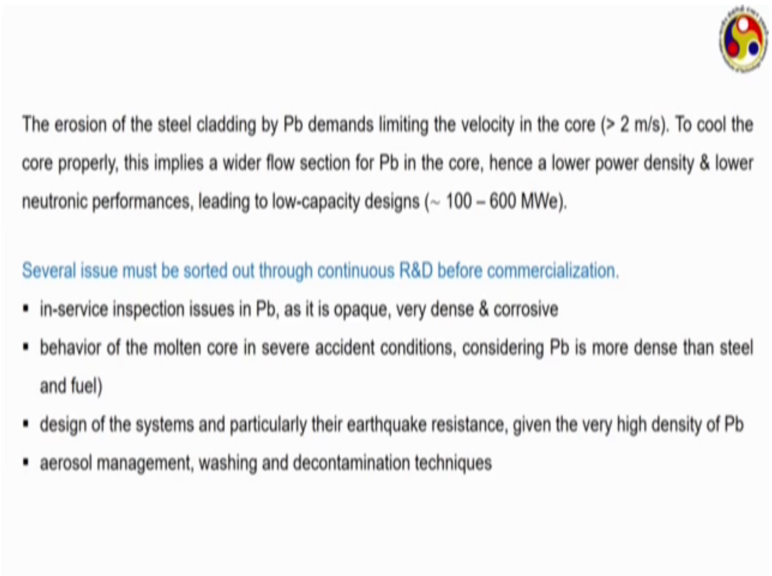

The erosion of the steel cladding by lead can be limited if we keep the velocity small, something less than 2 meter per second. But also the if we reduces the velocity that will reduce the total flow rate of the lead, but once the flow rate reduces for a given power output the temperature rise on lead also will increase across the core, and that will that is also not desirable. And therefore, to cool the core properly, we need to go for a much wider flow section. And as I going for a wider flow section in order to allow the required amount of mass flow rate of lead so that it can take the power output, the total power density and this is a neutronic performance becomes poor leading to low capacity designs compared to PWRs and BWRs , that this capacities is quite low. Or I should say mostly compared to SFRs these capacities a bit low.

Also, there issues related to LFRs. LFRs itself like in service inspection against, because lead is opaque and both sodia and both cases. So, in sodium and both cases this in-service inspection may become difficult. The corrosive environment is another issue, because of this in-service inspection. Behavior of molten coal in severe accident situation that is something that has not been studied at all the limited data which is very limited, and therefore, we have to study that particularly you have to consider that the lead is much denser compared to both the fuel and steel which is the cladding material.

The design of the systems and particularly earthquake resistance given again the very high density of lead can be the affected there. And finally, aerosol management washing and decontamination techniques need to be considered.

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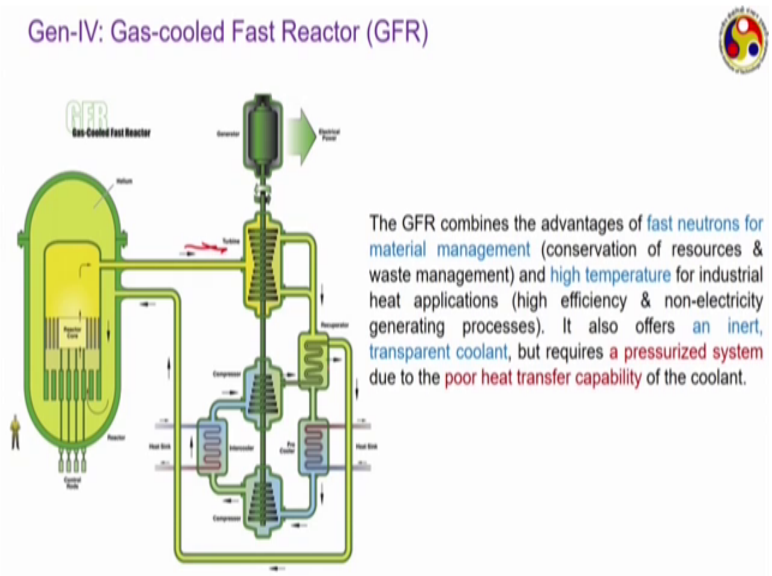

Finally, the gas cooled reactors the GFR it combines, the advantages of the fast neutron technology because the material management in fast neutron technology is very high resources can be conserved. And so, it is a owest neutrons once here going for fast neutrons, the we can facilitate breeding. Therefore, resources can be conserved the we shall be having much less amount of waste. So, waste management becomes easy, but also GFR allows to us to go for very high temperatures. As we are using a gas commonly helium, in certain cases carbon dioxide as working medium we do not need we never have to bother about any kind of boiling temperature limit.

Unless the, this any kind of chev stability issues or chemical stability issues that elevated temperatures we can keep on increasing the temperature level. And at high temperature level thermal efficiency keeps on increasing, and also non-electricity generating processes can also be facilitated, that is we can go for some kind of cogeneration as well. Like you can look at this diagram there are hot gas that hot helium gas that is coming out of this that generally goes through the turbine.

And from the turbine it goes to the recuperator, I mean, the turbine after doing the expansion work it goes through the recuperator. And from that recuperator it goes back. But the gas that we have in this recuperator or I can say the material or the fluid which is taking the heat in a recuperator can also be used for other purposes, like such as for cogeneration.

And also, another advantage is with helium as the field is a we are having an inert and transparent coolant. So, inside inspection or any kind of maintenance is very easy it is an inert environment. So, no problem with any kind of corrosion or any kind of real chemical reaction when it comes in contact with water or air, but the heat transfer performance of course, will be poor because the thermal conductivity is significantly lower almost negligible compared to that of sodium or lead.

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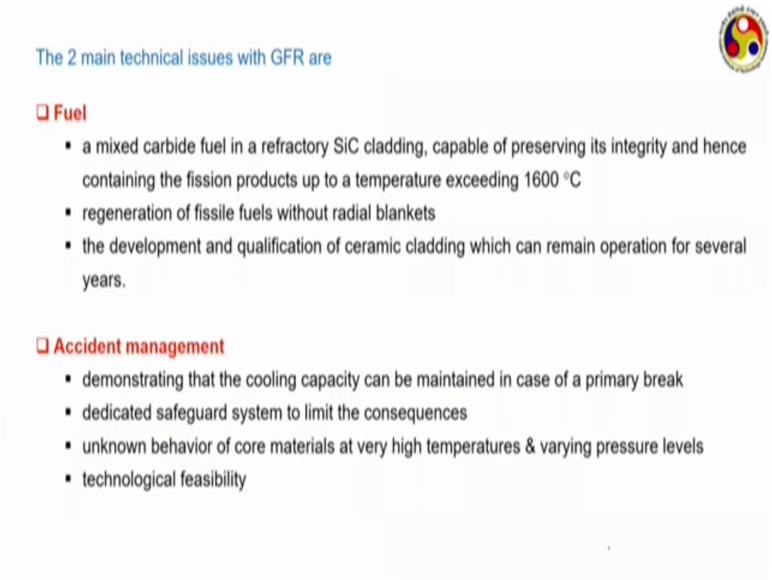

There are 2 main technical issues with GFR, one with the fuel and other is accident management. Related to fuel we need to find a proper mixed carbide fuel; which will be put in a silicon carbide cladding and that should be capable of sustaining up to 1600 degree Celsius without any buckling. So, that the fission products can be maintained other is the regeneration of fissile fuels without any kind of radial blankets. And fall and finally, is the development and qualification of ceramic cladding, which can remain operational for several years, which is not possible with the present-day material science knowledge.

And with accident management GFR should demonstrate that the cooling capacity can be maintained in case of a primary break, also dedicated safeguard mechanism is required to limit any kind of consequences of such cooling related accident. And also, the how the core material is going to behave at very high temperatures also varying pressure that is unknown. So, that is something that also we should look into. So, in and finally, the technological feasibility of GFR should be ascertained before commercialization.

So, in a nutshell we can see that all these 3 fast breeder technologies that SFR LFR and GFR all of them show immense possibility, and future and can be the solution for power production requirement in future, but still there is some way to go because we have to sort out quite a few issues

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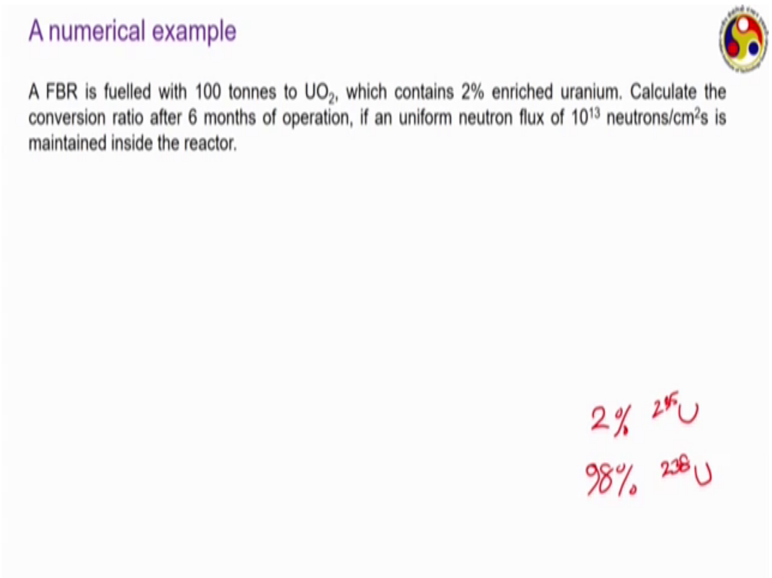

That brings us towards the end of this module, but I would like to finish with a small numerical example related to this breeding ratio. Let us consider we have a breeding reactor which is filled up with uranium oxide as a fuel a certain quantity of uranium oxide, which is has 2 percent of enriched uranium. And you have to calculate the conversion ratio after 6 months of operation if it is subjected to the uniform neutron flask.

Now 2 percent enriched uranium means, the fuel contains 2 percent of sorry the fuel contains 2 percent U 235 and 98 percent 238. Other isotopes of uranium like U 234 etcetera can be neglected. So, what are the isotopes that we have inside the reactor of course, when you have starting with we are having U 235 U 238. U 235 will go for fission reaction thereby produce fission fragments, and U 238 will participate in the breeding reaction.

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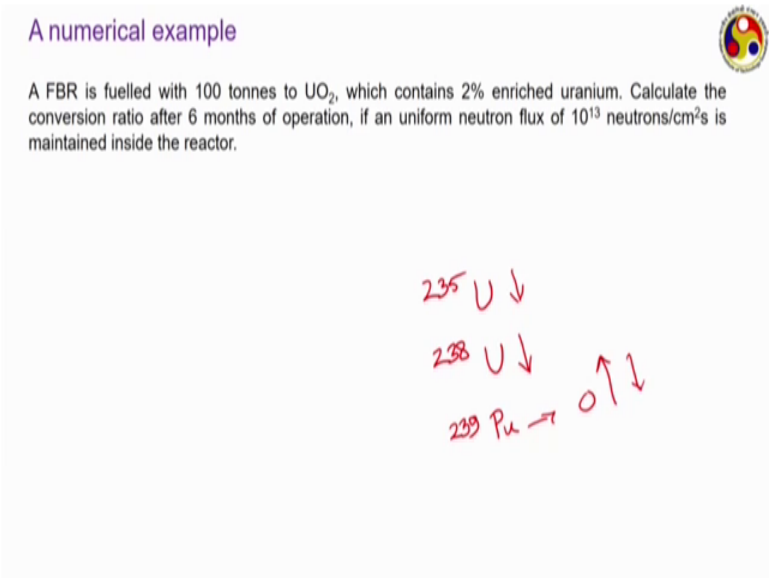

So, as time goes on we shall also be having Pu 239 produce inside the reactor.

So, initially Pu 239 concentration is 0 to start with, but a time goes on it will keep on increasing. Whereas, concentration for both U 235 because of fission, and U 238 because of this breeding reaction will keep on coming down. And actually, plutonium concentration you are not sure that will continue to keep on increasing. Because it will increase because of the breeding, but it will also decrease because of it is own fission decay. if you just go back to the module number 6, there we made a small mathematics to discuss about the control issues.

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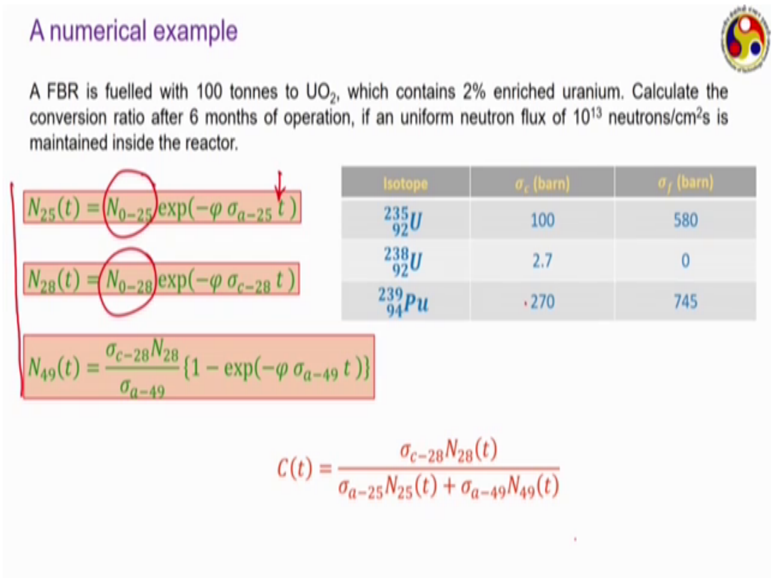

And there we identified this expression, N 25 refers to the concentration of uranium 235 nucleus, and how it changes with time this one beings the initial concentration. Then N 2 28 refers to uranium 238 concentration this is again the initial 1, in this case this is 98 percent. And plutonium concentration is initial 0. So, this N 49 refers to Pu 2 the 40 239. And these are the corresponding cross section values.

So, using this or time period this t is referred to as 6 months in this case, and as we already know the molecular weight or the mass number for all these 3 isotopes or. So, we can always calculate the value of this N naught 25 and N naught 28, and phi and all the sigma values are given. So, at the end of 6 months of operation we can calculate the values of these 3 quantities. And now conversion ratio at any time is given to be like this. So, using this you can calculate the conversion ratio. I am leaving this to you, please try to solve this problem and if you face any issue, then you can get back to me.

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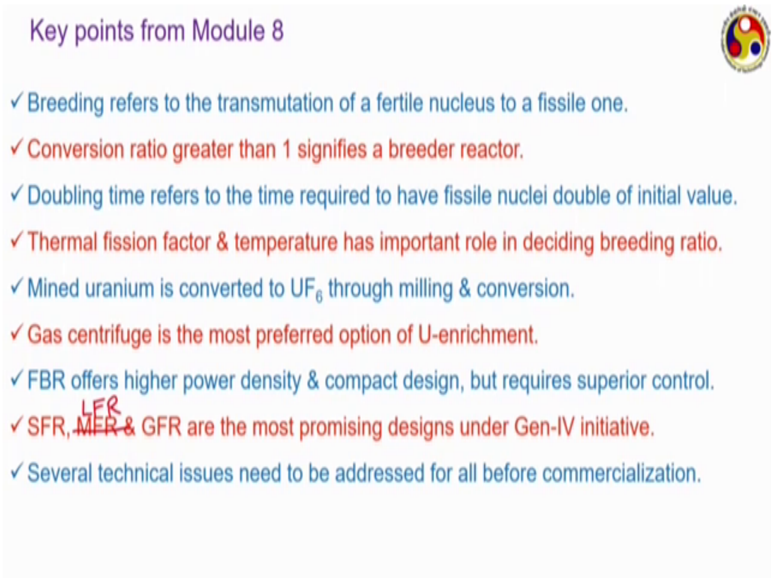

So, to summarize our observation from this module, we know now that breeding refers to the transmutation of a fertile nucleus to the fissile one which can act as a fuel for another reactor or maybe in the same reactor. Conversion ratio greater than one signifies a breeder reactor whereas, it is less than one we can early get burners or converters and doubling time is the time which is required to make the number of fissile nucleus double then whatever we had initially.

Then we have disc and we have also discussed about the thermal fission factor and temperature. The role they play on deciding this bleeding ratio. Then we discussed about the fuel cycle. And we have seen that in all the processes, generally the mined uranium is converted to uranium hexafluoride gas through milling and conversion, and then we go for the individual process gas centrifuge is the most preferred method of uranium enrichment.

Then FBR offers much higher power density and compact designs compared to the thermal reactors, but it requires much superior control you have discussed in detail about the pros and cons on FBR and also it is comparison with the PWRs or thermal reactors in general SFR mfr and GFR actually instead of a MFR, I should not write mfr here, it should be LFR. The lead cool fast breeder reactor or if we write properly it should be LFR. SFR LFR and GFR are the most promising designs under gen 4 initiative because the other 3 designs have their own issues. But all of them had to solve certain technical issues before final commercialization. So, that brings us towards the end of the module number 8, please go through all the lectures and solve the assignments, which is also available with you. And whenever you have any issue have any doubt please drop a line to me.

So, thanks a lot in the next lecture, in the next week, we are going to discuss about the other type of nuclear reaction possible, about which we have never talked about since our first module, which is fusion power generation.

So, thank you.