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NPTEL
National Programme on Technology Enhanced Learning

NUCLEAR REACTOR AND SAFETY AN INTRODUCTORY COURSE

Module 11 Lecture 01
Engineered safety Systems

Dr. G Vaidhyanathan
School of Mechanical Engineering
SRM University

Good morning in the last few lectures we brought out the various principles of safety that are imbibed into the design operation of all systems in a nuclear power plant. We also got out what lessons we have learned? From the different events, which have happened in different nuclear power plants? One of the most important aspects, which we consider in the design of all power plants, is to follow the principles of redundancy diversity and independence remembers redundancy diversity and independence.

These three now so we have to engineer our system such that these principles are followed in total. So, in this and the next lecture I will take you through how the safety principles have been implemented in the nuclear power plants. Now let us look! at how we can assure safety of a nuclear or plant.

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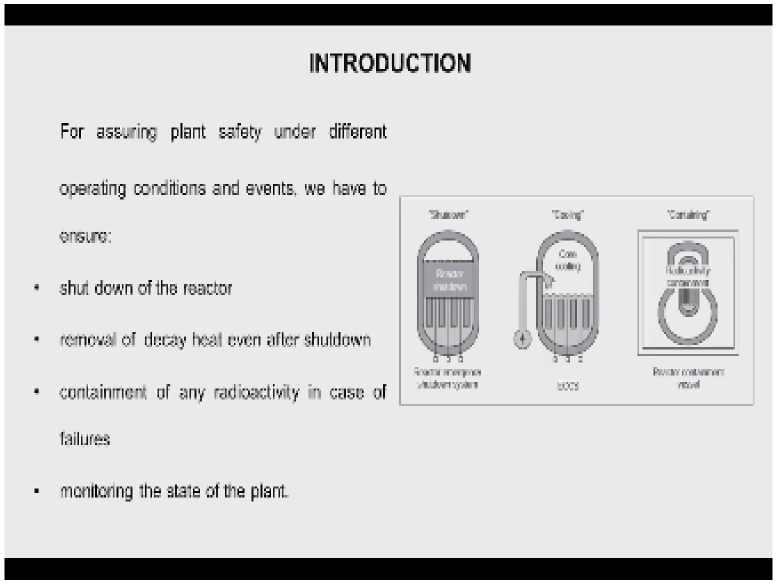

First in case, of an event we must be able to shutdown the plant. Maybe we should assure a safe shutdown of the plant. When, we do this shutdown we have stopped the fission reaction. The chain fission reaction has been stopped. But still heat is getting produced in the reactor due to the decay of the fission products.

That has been generated during the fission. So, as I have already mentioned you many times this heat is of the order of six to seven percent immediately after shutdown and this grows Down Goes Down very gradually. So, we need to cool the reactor that means we need to have flow of the coolant through the core not to the full level a partial level so that we can keep the clad and the fuel temperature within limits.

Should we not be able to do it then, the clad will fail and the fission particles will come out of the clad mix with the coolant. And of course, it has all you know consequent effects nothing is going to happen reactor. Is channel but still contamination and activity so the next aspect after shutdown is cool? So here, is what we have represented shut down using the control rods and cool by normal way or emergency core cooling system.

As, we have been talking about then the third most important aspect is contained should there be any missing link in the core cooling or something shortfall. And if, there is are lease or efficient products it should be contained. So these are the three main, not only that! last but not the least we must know what is the state of the plant.

So, we must be able to monitor the plant so that is the fourth on so let us look what? does the design of a nuclear power plant in wall.

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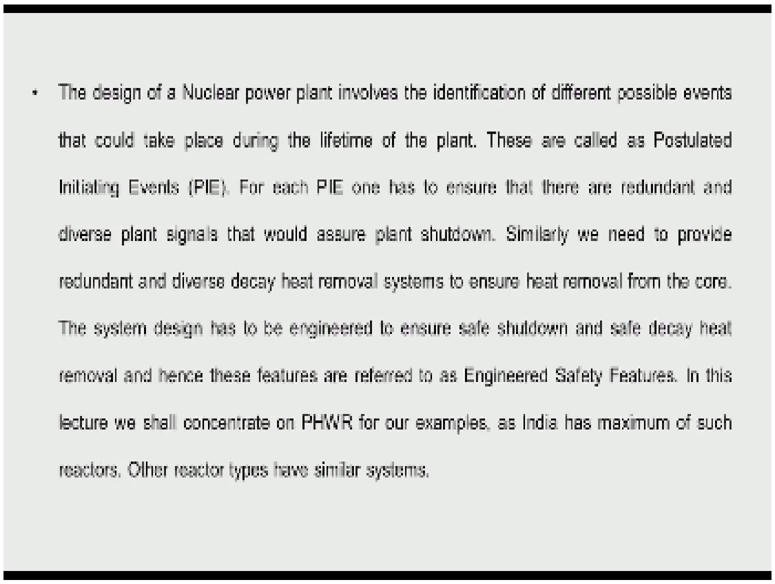

First we need to postulate the events in the plant. What are the different events that can occur in the plant? Of course, we call them as the postulated initiating events. Then having said that for every event we would plan a set of safety actions. That need to take place so let us start let us say my pump has tripped primary pump which cools. The reactor one of the pumps has tripped.

So the flow would go down temperature will, go up so I must have the means of detection of this event through redundant raise. Let us say, I take temperature I must not have one temperature measurement I must have two or three temperature measurements. So that even if one fails the other channels would be able to give me the temperature. So this is what you call redundancy like that if we had taken flow, we take flow there also we should have two to three channels of flow measurement. Now the temperature and flow are diverse signals even if the one does not give the signal the other will give the signal. So here we say for every event there must be redundant and diverse signals that can actuate the shutdown of the plant.

Shadow of the plant means the control rod should go into the core and stops the chain reaction. Having said that the first step to shut down we must have redundant and diverse signals. Next I want to remove the decay heat cool. The reactor so Indeed redundant and diverse decay heat removal systems.

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- The design of a Nuclear power plant involves the identification of different possible events that could take place during the lifetime of the plant. These are called as Postulated Initiating Events (PIE). For each PIE one has to ensure that there are redundant and diverse plant signals that would assure plant shutdown. Similarly we need to provide redundant and diverse decay heat removal systems to ensure heat removal from the core. The system design has to be engineered to ensure safe shutdown and safe decay heat removal and hence these features are referred to as Engineered Safety Features. In this lecture we shall concentrate on PHWR for our examples, as India has maximum of such reactors. Other reactor types have similar systems.

Then this safe shutdown and the safe decay heat removal are in fact called as the engineered safety features. That is we engineer them such that we have multiple systems diverse systems. So that things do not happen and mind you independence of each one such that there is no chance of a common cause failure or a common mode failure.

So this is where we are ensuring the cool surround. I'm sorry Shannon and then cool the reactor now we will go with some examples. I will try to be giving examples more of the pressurized water reactors which are the mainstay of our nuclear power program. Today surely other types of reactors also would have similar systems. Now shutdown systems now shut down systems what we need to do?

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SHUTDOWN SYSTEMS

Shutdown is one of the most important safety functions in a reactor. It is usually accomplished through rapid insertion of a neutron-absorbing material into the core. These would absorb the neutrons in the core leading to sub-criticality and finally stopping of the chain reaction. Another way is to dump the moderator. If **moderator is removed**, the neutrons will remain at the higher energy levels and the probability of fission reaction would come down drastically, resulting in stopping of the chain reaction, thus leading to **shutdown** of the reactor. For design of a Shutdown system we need to specify the **negative reactivity of the system and rate of reactivity insertion**. We also need to limit the reactivity worth of a single control rod and ensure that redundant, diverse and independent signals are available to actuate the shutdown system.

They should be having Neutron absorbing materials so the moment you put these control rods containing neutron absorbing material. The neutrons would be absorbed by the control rod and finally a stage will come there will be no neutrons available for fission. Continuing the chain reaction At least, we said for every vision one Neutron must remain to be cross fission.

So the absorber rods which are made of boron or cadmium will absorb and stop the chain reaction. This is one way of shutting down another way let us look at you know you have a moderator in a pressurized hey what reactor this moderator. What it does it reduces the speed or velocity of the neutrons. When the velocity is reduced they have a better probability of a fusion reaction but if the velocity is high.

The probability of fission reaction is less. So, if I remove the moderator from the system that also will result in the shutting down of the reactor. Of course, we do not resort to this moderator removing cannot remove do that in the pressurized. Water reactor or the boiling water reactor because the moderator and the coolant are the same they are the same not different whereas in a pressurized a boat reactor the moderator is separate system and coolants a separate system. So for now how much should be the worth of the control rods.

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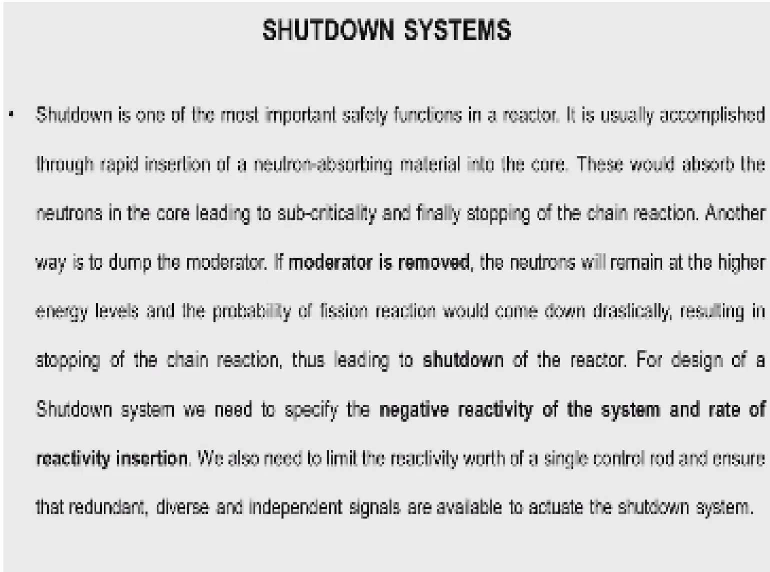

As, I mentioned earlier we always use the term reactivity and what is reactivity it is the deviation from the critical condition. Delta K by K where you know KX called as the multiplication factor. So how much should be the worth of the rod so that it can shut down the reactor, So this is one thing should be specified. And at what rate? We should go in what rate is the reactivity insertion rate is very important. If, you recall in the Chernobyl accident one of the findings was even though the control rods had enough worth of reactivity.

It was felt that the rate of reactivity insertion was slower had it been faster maybe the reactor would have shut down an accident may not have happened this is one of the important things. So these two aspects are important. In the design of a shutdown system.

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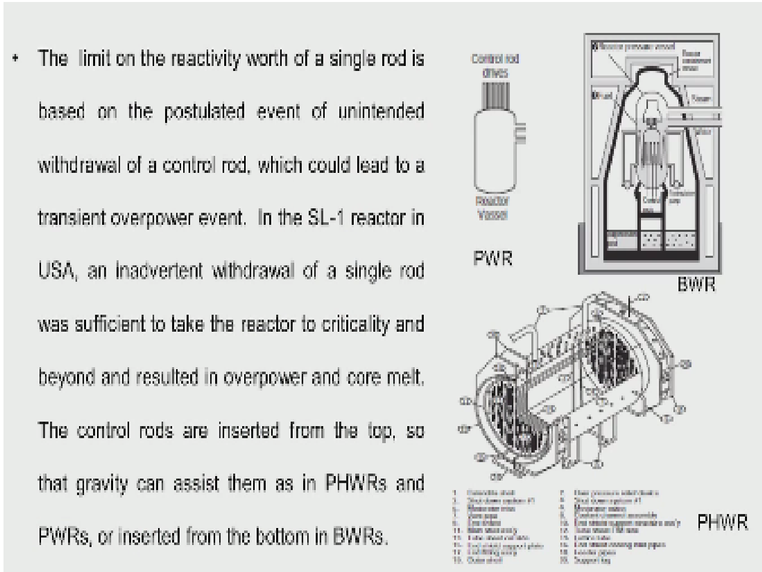

Now not only that, we have multiple number of rod there is redundant number of control rods in any reactor. How then it comes what should be the worth of a single rod? So, here were call one of the accidents which happened in the sl1 reactor where inadvertently a control rod was taken out continuously through and it resulted in taking the reactor to criticality and even beyond.

So over power was there and the fuel melted so the reactor control rod should be such that even if you take one control rod completely from bottom to top the reactor must not become critical. That means it requires some more rods to be raised to become critical and this rod movement there should be what calls? Limit on which you can move rod in a particular besides. That if we have a single control rod it will have more effect in the region around the control dot.

So we needed to spread out the control rods. Then the control rods you see in the case of a boiling pressure.

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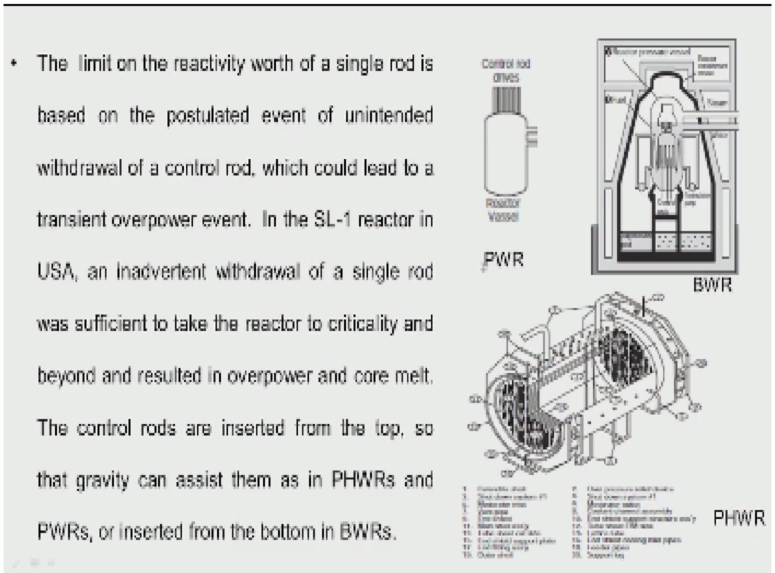

Is what? Reactive they are driven from the top whereas in the case of a boiling water reactor they are driven from the bottoms. As, I mentioned to you earlier the control the in the case of a boiling water reactor the steam water mixture boiling is there in the core so steam water mixture comes out. And here you have the moisture separator which is on the top. So, there is going to be an obstruction in case you put the control rods from top so we put the control rods from the bottom.

Of course, here gravity eights here gravity does not date we must have a hydraulic pressure to push the control rods. Then let us come to the pressurized water reactor unlike the pressurized water reactor or the boiling water reactor the core is horizontal but the control rods are from the top. So this is how the control rods are located in the different reactors.

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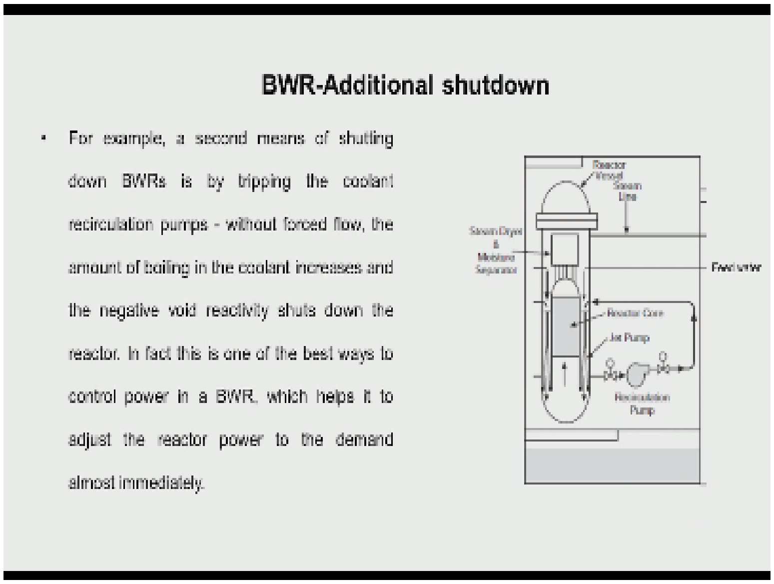

In the case of the boiling water reactor it is you know it is very sensitive to temperature the reactivity. Is very sensitive to temperature and if the inlet temperature through the reactor. Increases then your wide generation will be more and you know most of the designs. We have negative reactivity worth of the boiling water reactors while because of boiling there is a negative reactivity and the power comes down.

So in fact in the case of boiling water reactors this is one feature which is automatically coming in that the temperature rise itself could control. So this is also one way I trip this pump recirculation pump so the water mixing will not be there you will not have so the temperature should go up so you have here shutting down of their actor.

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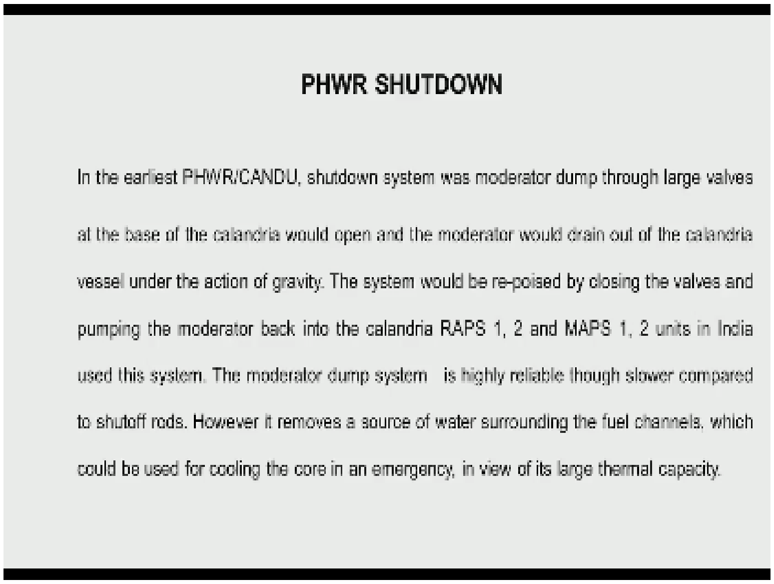

PHWR shut down there is pressurized water reactor surround system. First of course, the control rod which you saw then the other I mentioned something about the moderator dump system. Just let me show you where the moderator dump system is.

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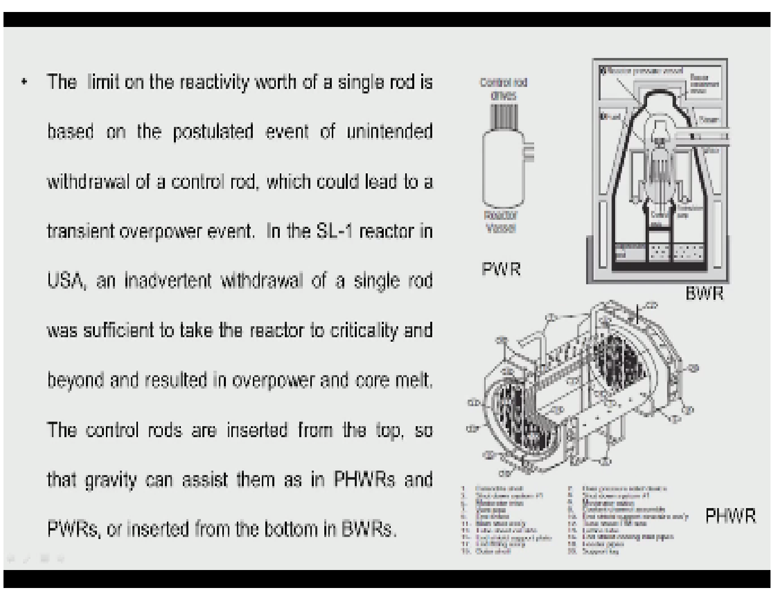

See these are the rods these are kelentria the fuel rods are put in a tube pressure tube which is again covered. With the kelendria tube and the whole thing is in a vessel which contains the moderator heavy water at the bottom. Of few of the reactors which we have built we have dumping ports by which the moderator comes out if you open those ports the water would come down moderate would come down and thereby shut down the reactor.

So this feature we did have in the earlier fury at two reactors plants at Rajasthan at maps means units Rajasthan unit one you need to and maps that is colored kalpak am unit one and you need to have this feature. Now this dumping is quite are liable process but then it was felt that when this moderately surrounding the land area tubes it also offers a big thermal capacity for a heat source that is heat sink in case there is an event and the heat is not removed this itself would act like a heat sinks in the future designs we do not dump the moderator as again as a increased safety measure so we keep the moderator and its thermal capacity helps us in minimizing the rate of temperature rises what in more other plan new plants what sort of a system we have let us see.

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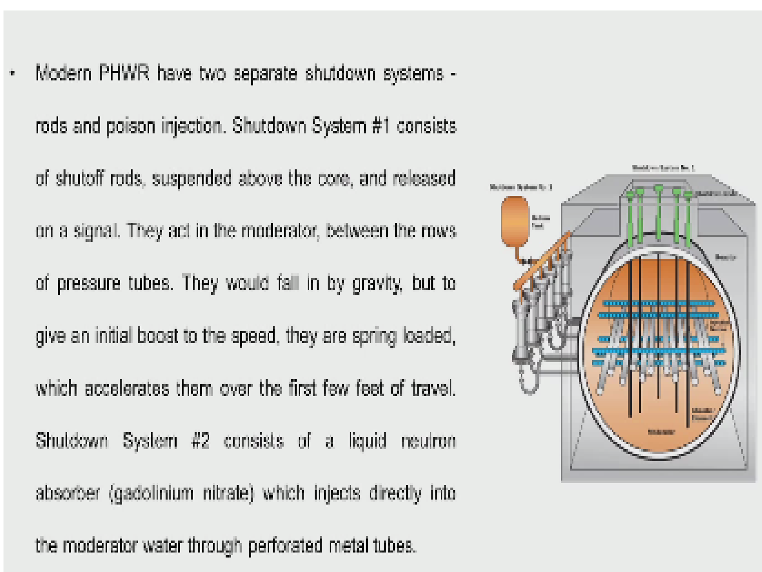

We have the shutdown system one which has these control rods here you can see some control rods moving then we have the other shutdown system which consists of gadolinium nitrate poison it's just like boron or cadmium it is a neutron absorber one of the reasons. Why we put gadolinium nitrate instead of boron is that we require very little amount of governing of nitrate then boron to have the same reactivity.

Worth to negative reactivity for Sharma and this is in connection with the moderator system so this guttural rhenium nitrate gets injected to the moderator through injection nozzles and it gets completely into the moderator there by the moderation when the earth neutrons come for moderation they can absorb but still the thermal capacity of the moderator is other for you to take up the heat so you have to shut down systems and you see they are based on different principles.

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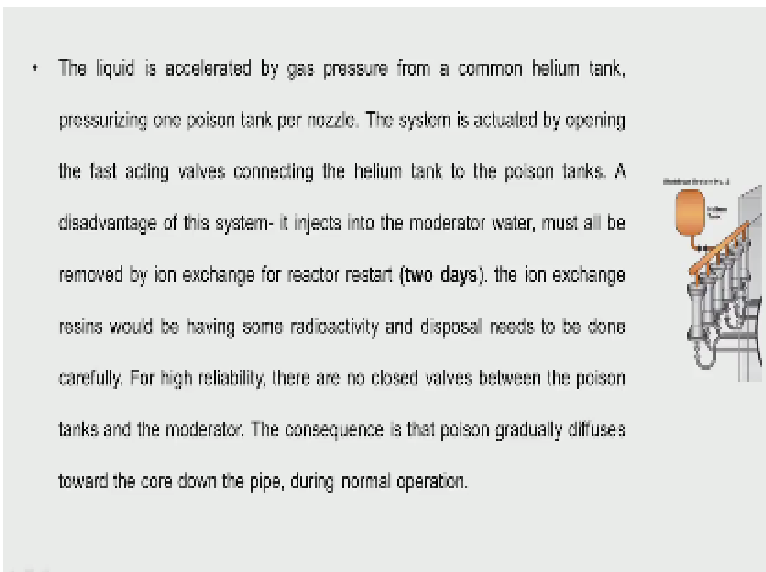

Now how does the second shuttle system act first surround system okay it has got a control rod drive system.

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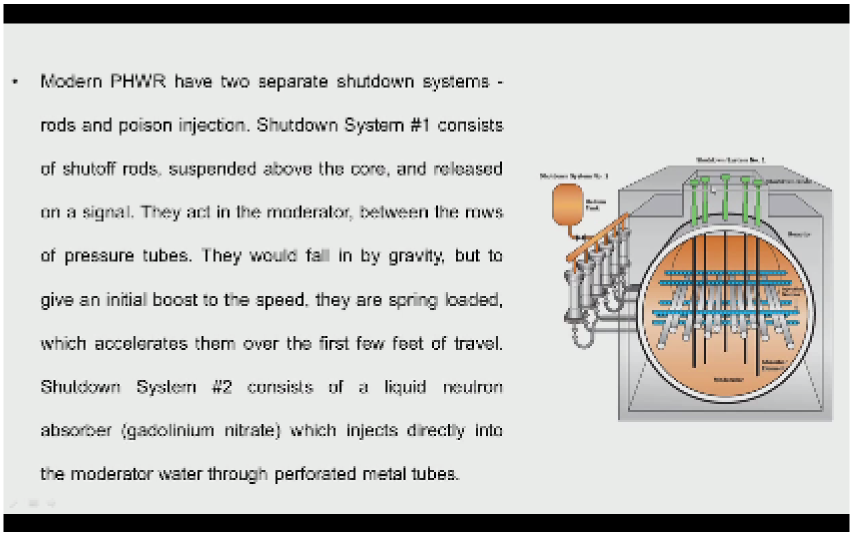

It can be driven down or you can release it the control rods would drop them into gravity but then what about this system here we have a helium tank.

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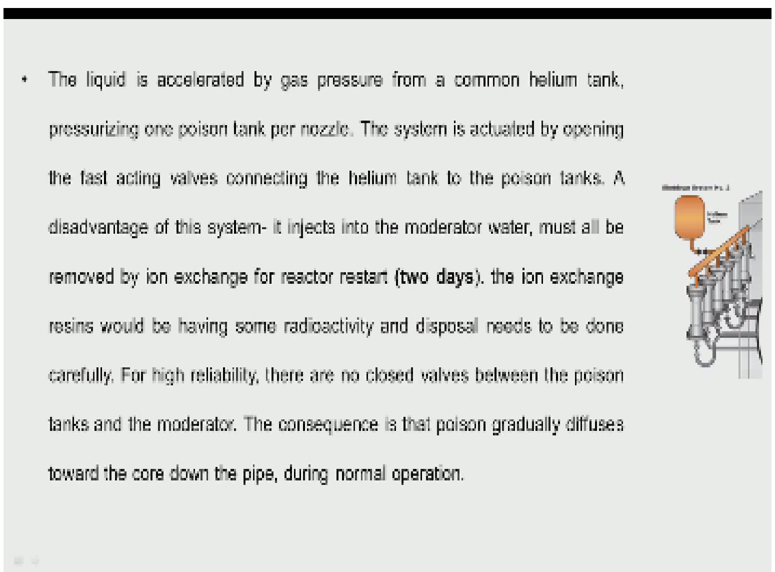

And these are poison tanks we have many boys and tanks and this valve is aghast-acting valve which is connected and the moment. This valve opens the pressure of the reactor and this here I am sorry the helium pressure of the helium in this tank would force. The gallium nitrate into the moderator okay but it has got a disadvantage suppose you have the moderator food of gadolinium nitrate.

Okay reactor has been shown but then you have to remove the gadolinium moderate from the moderator otherwise you will not be able to restart the reactor you will not get the moderation so this process is done through an ion exchange method and this racine should absorb the gutter. Lyn ham nitrate and moderator will get purified this process takes about two days now you see here this gutter lingam nitrate.

Is always in contact with the moderator these walls are these walls do not operate all are in contact these walls are only for isolation during some maintenance etcetera otherwise this is only well now they are in contact with the moderator so even though it is not flowing there will be a slow diffusion of the ghettolyneham nitrate. The reason is if you have too many valves to be open the reliability of the system comes down. We can't afford to have a low reliable system whereas, If you have one or two walls it is easy the reliability would be better just to make it safe you keep on increasing the components. Now let me tell you if one component has a reliability of ninety percent and you put to such components the reliability will come down.

To eighty-one percent 9.9 22.9 so remember just by putting many systems you are also increasing the chance of failure now the speed of the control rod.

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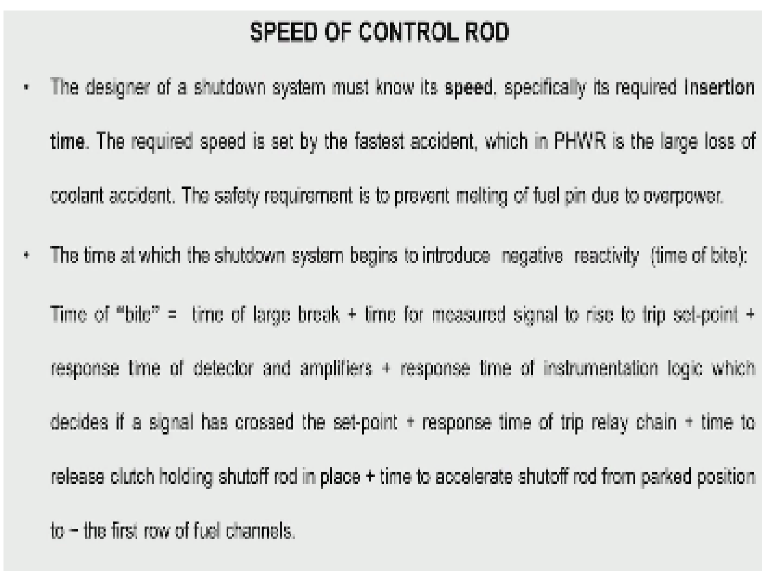

SPEED OF CONTROL ROD

- The designer of a shutdown system must know its **speed**, specifically its required **insertion time**. The required speed is set by the fastest accident, which in PHWR is the large loss of coolant accident. The safety requirement is to prevent melting of fuel pin due to overpower.
- The time at which the shutdown system begins to introduce negative reactivity (time of bite):

  Time of "bite" = time of large break + time for measured signal to rise to trip set-point + response time of detector and amplifiers + response time of instrumentation logic which decides if a signal has crossed the set-point + response time of trip relay chain + time to release clutch holding shutoff rod in place + time to accelerate shutoff rod from parked position to ~ the first row of fuel channels.

Now after all we are using the controller to shut down the plant in case of events. We must find out which is that event which requires the maximum reactivity. In the minimum type- reactivity in the minimum time now in the case of a pressurized water reactor is a large loss of coolant accident means a big pipe rupture primary header rupture in which in the tender or the outer head. Of rupture would be the one and that causes the need for a maximum reactivity. So that the fuel pins do not melt they are safe their integrity is maintained it is different that you cannot operate the reactor further but then integrity is maintained ok so now one is we saw the reactivity worth. We have to decide also the speed we have to decide but then also the time we need to design time at which it is to take place things do not happen you just push a button and things do not happen immediately. Let us see what sort of delays are involved in this that is a time at which you're shadowing system has started introducing reactivity into the reactor.

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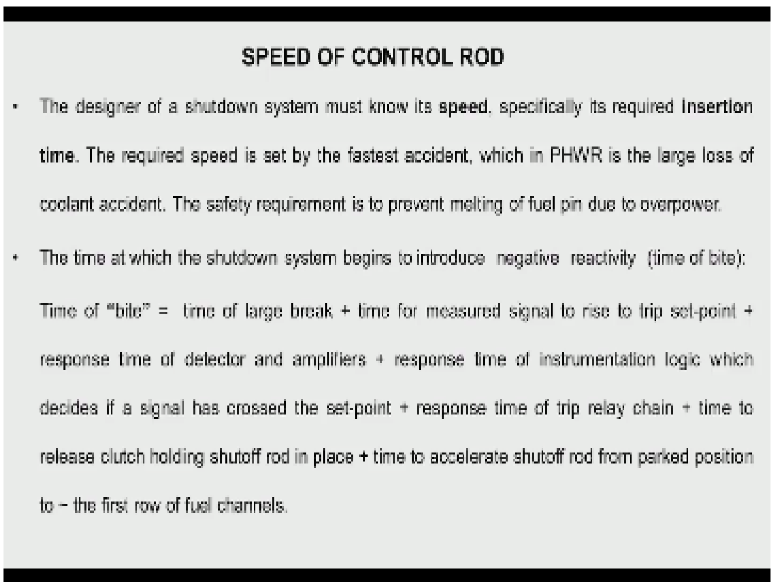

We actually call it as a time of bite it is of course, a terminology that is equal first is the time of the break how much time it has taken for the break to happen then having broken it is detected by some. Event some monitoring the plant how much time it has taken the measured signal. It measures and it takes some time to give the set point that means it involves a response time of the instrumentation system response time is that time.

Which take time taken to reach sixty-six percent of the changed value? So that time you have to consider if you take a thermocouple you may have a four second response time or a two second response time. Then you it is not set up so having said that so it reaches the trip set point then the detector then your amplifiers electronics in the circuit they would have some time time constants so that you need to add. Okay, then you have logics there will be many in signals coming for trip So the safety logic has to ascertain whether it is a required trip or it is a spurious condition all those things. We need, Of course! that some more ideas you will get when I talk about the logics for the time being you take that the safety logic needs some time to diagnose and give a signal for the tip so that is what is the response. Time of the logic then the trip relays you have given a signal to trip the motors that relays and change and then there is a time which taken for the clutch to release in some cases. Here the magnet so it could be the magnet response time and then one the rod false it is initial velocity.

Zero it will take some time to accelerate depending on the height and reach the first row of the elements so all these times together only then your negative reactivity would start insulting now this is about the control rods now let us look at the time of white of the other poison injection system.

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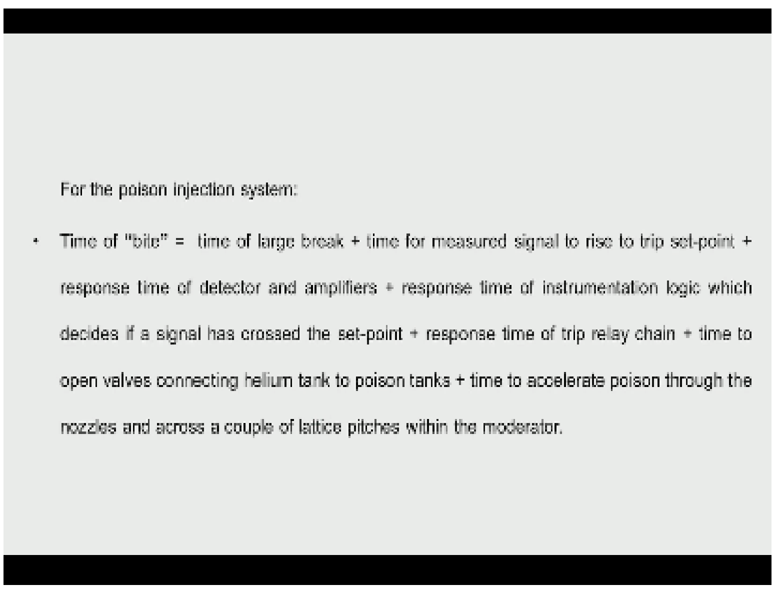

So again time for the break to happen time for the measured signal to reach the set point that remains same set bond response time of the detector and amplifiers then instrumentation logic. Then the relay chain here comes difference time to open the valve connecting the helium tank to the moderate this one this one time to open this valve.

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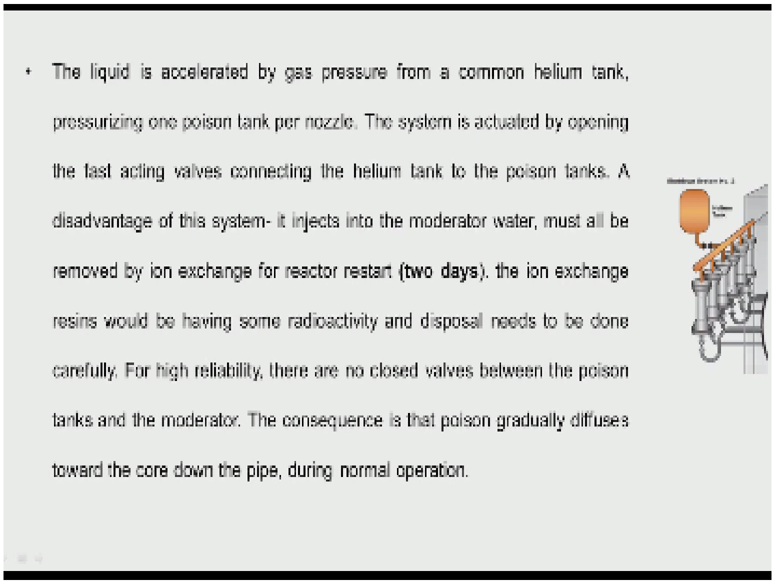

So these things need to be considered and how much time it takes to accelerate into the code or the accident to the moderator so these to define these considering this you have to design or engineer the system.

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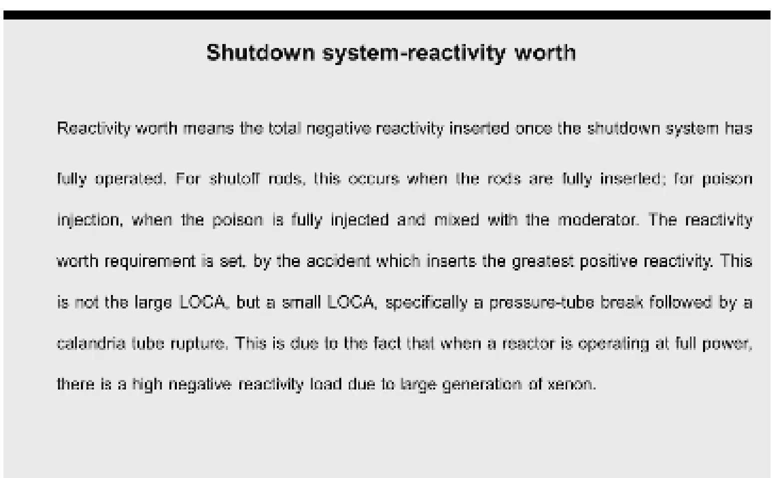

Now shutdown system reactivity worth that means the total reactivity which needs to be inserted. For the poison injection system we will say when the poison system has-been fully injected and makes you the moderator what is the amount of reactivity it will contain here we are not talking about the rate we are just talking about the amount of reactivity negative reactivity.

Now it is found that while the large local sets you the rate of reactivity insertion the total reactivity is not set with the large local. But way a small local means a small loss of coolant accident. There is a reason when there is a small local means your reactor is operating let us say at a smaller flow or a small at a full smaller power. So the flows are less.

So here what happens when the power is less you know in any fission reaction it produces xenon which is a poison if there is a higher power the xenon production is more poison production by the as a consequence the fission reaction is more so the xenon worth it would aid in case of a large local but the the amount of support it gives incase of a small local is small so the amount of reactivity worth is decided more by the small loss of coolant accident just to give you.

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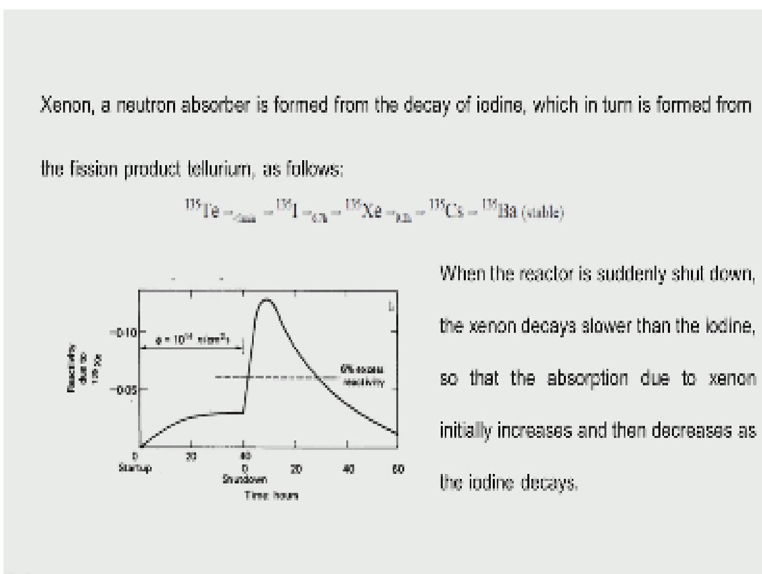

How this xenon is produced of course tellurium one of the fission products it decays with the one minute time constant or decay constant becomes iodine 135 again with the 6.7. Our decay constants becomes xenon 135 which after a decay of 0 is the concept of 19.2 hours. Become cesium and finally barium so there is a always when the reactor starts there is an increase of the xenon then after sometime. There is an equilibrium situation and when you shut down again it comes down.

So here, if you see when you start up there is any increase in the xenon then you see it increases once there is a shutdown the xenon contribution increases because xenon discontinuing producing the fission reaction has stopped. So, it can no more nullify so the negative reactivity is increases then after sometime it comes down so here this portion independent upon how much of the fission products.

Were left behind and this would become less when I have a lower power so in short you can see when the reactor is searched around suddenly the xenon is decaying slower than the iodine so the xenon absorption initially increases you see there is a difference between the time constant of generation decay concept generation and decay of xenon so it increases xenon increases instead increases and then decreases this is again related to the iodine decay and the xenon decay now let us come to the safety system design we talked about the surround.

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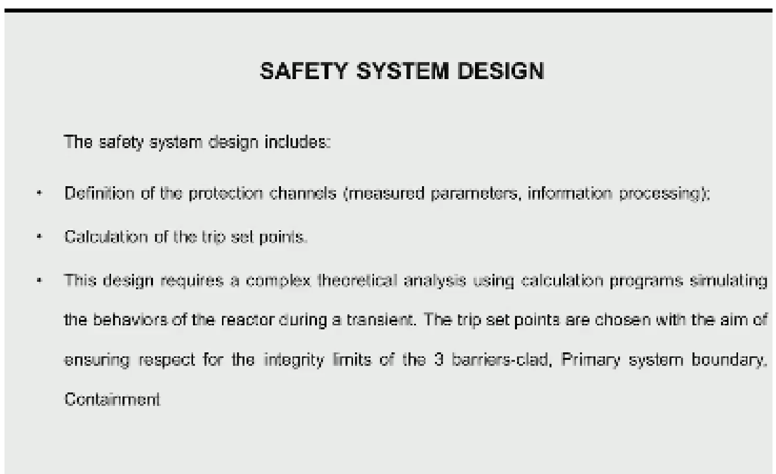

System so we have to define what all the parameters which need to are shut down the plant. We need to tell how the processing of these signals need to be done then we have to set the trip signals for example let me say that I would not like the coolant to reach a maximum temperature of say 300 degree centigrade under any circumstance. I cannot keep the trip threshold as 300because should there be a measurement error and there could be a measurement response.

There is a measurement response time so even though when the actual temperature crosses 300 by the time the signal is strip signal is given the actual temperature would have crossed300 so my desire is that under no circumstance the rib signal should cross 300 so I would keep something lower say 290 so like that using such things.

We have to set that rip point trip set points and how we do that if you recall with reference to the first reactor a BTR at kalpakkamI was telling you that we have a we have developed computer codes which or digitized model of the reactor and whole plant reactor nuclear power plant where we study the effect of different events and how the temperature changes there in the model we put all these time delays into the models and then find out we set the trip points and all the trip points are set so that we do not cross the limits of temperature on the clad.

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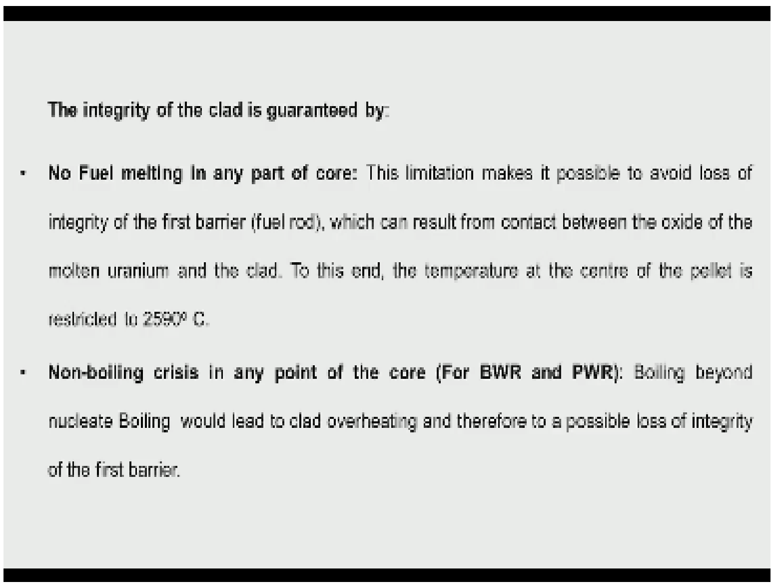

This is very important other one is the primary system boundary and last but not the least the containment. Whatever, limits under no circumstance this should be crossed so when I do not want the integrity of the clad to be affected so it is done in two ways one is my fuel should not melt because if fewer melts then. It could react with the client so fuel should not melt so that means the fuel temperature should always be less than the melting point again i repeat the melting point cannot be measured.

So the only thing which is measured is the temperature of the coolant so we link the temperature of equivalent with the melting point of the fuel because we know the we have the models we link them put the uncertainties in them and then fix the we deduce we derived whether the melting point has crossed or not that is with reference to the fuel.

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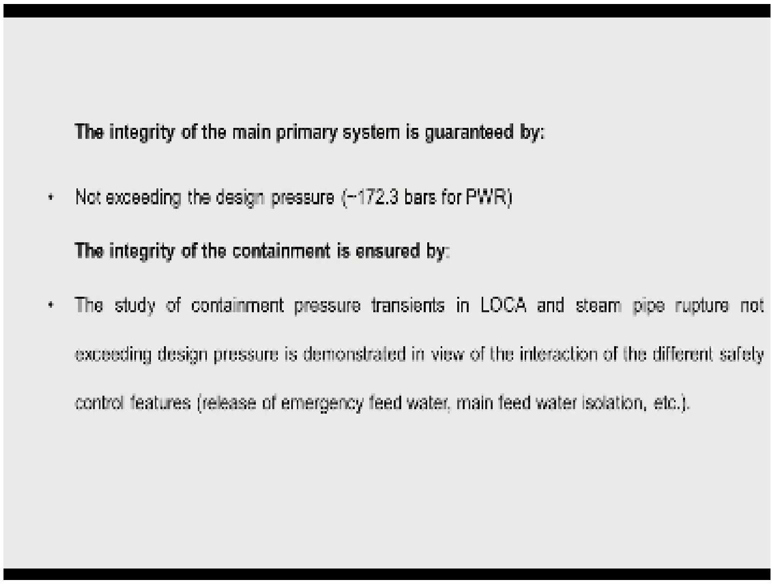

But what about the clad you take a any reactor we should not overheat. So here again we have a linking of the clad temperature so the equivalent temperature with a clad temperature also we have in case of the pressurized. Water reactor where we do not foresee boiling under normal conditions the neutronic signals do give us signals whenever there is a void and we can detect if there is boiling in the core or not or in the boiling water reactor and the pressure is water reactor.

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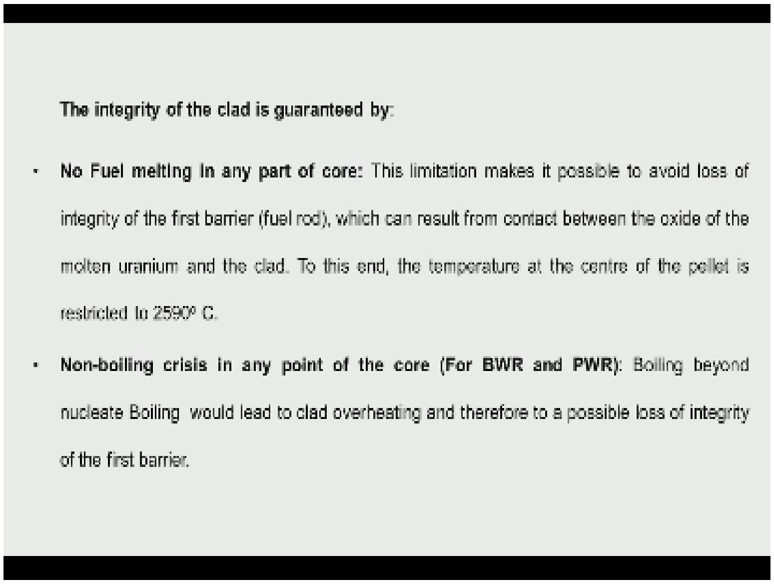

We actually have another restriction that it should not cross nucleate boiling so we have a correlation of the tells you under what quality condition. It would change it would become cross nucleate boiling and this is calculated and compared. With the design and that ratio we keep limit. Then the integrity of the primary boundary we see to it that the pressure should not cross under any circumstances.

We have the pressure measurements and here again as I said we do not put the limit as the maximum pressure with something less so that in the pressure measurement itself if there could be an error we do not get into problems. Then the containment integrity the containment means it should not fail under any conditions so we have to keep it cool so that it will give the shielding always and it should not leak because in case of leaks any failure has happened inside the activity would go out so we do this leak testing continuously for the containment.

The reason is we have many pipes penetration until the containment we have tried to minimize them but still wherever containment comes we have to see that they are that those penetrations are leaked right now first is an even to be detected we must have enough time to detect an event and ensure the signal for safety.

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SIGNALS and SAFETY LOGIC

For a shutdown system to be effective, it must detect an event soon enough and initiate signals for safety action. Practice is to sense an accident with at least two diverse trip parameters on each shutdown system. It is not always practical to do so. Manual trip is permitted if the time-scales are long - typically fifteen minutes from the first clear signal of the accident in the Main Control Room

EVENT	SYMPTOM	DETECTION
Loss of Reactor Power Control	Reactor power & system Pressure rise	High Neutron Flux, High Log rate of Neutron Flux, High PHT Pressure
Loss of Forced Circulation	Coolant Flow Drops	Low Flow, Low Core Pressure drop, High PHT Pressure, High Neutron Flux

So as I mentioned two divers strip parameters are required one could be temperature other could be flow one could be Neutron flux other could be pressure so here i have given you some signals which come in the case of two events one is loss of reactor power control that means it is an over power somehow the reactivity insertion is there my controller I am continuously taking out in that case the reactor power and system pressure rice would be the things which will increase and they are detected by two things high Neutron flux and high log rate of neutron flux and high PHT pressure here mind.

You we do not consider high Neutron flux and high log rate of neutron flux as the same because the law great of neutron flux is derived from the high Neutron flux. so we do not this these are two signals only two divers signals similarly coming to the flow loss of for circulation coolant flow will drop so I have either a low flow or low core pressure drop in case of PWR or a high temperature in case of a fast breeder reactor and then again PHT pressure because the heat is not getting removed so the pressure rises in the system.

And one thing as I mentioned earlier we do not take any allowance for manual trip we do not consider as a safety measure at least for minimum of15 to 30 minutes in the control room the first clear signal comes after that 15minutes we do not take any credit everything should be automatic in most of the reactors it is 30 minutes now then this is the called as a two out of three logic.

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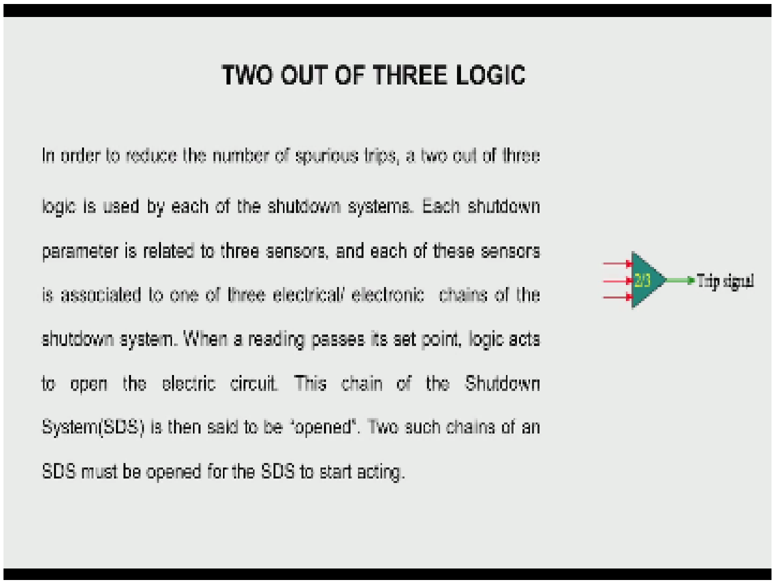

I mentioned to you we have redundant measurements let us say three temperatures or three pressures so then there is a logic with checks whether two out of three are giving my trip signal if they give then the reactor is stripped so in other words it tries to satisfy if one alone goes one of the three goes it does not consider because it feels it could be a spurious but if two are giving it is the logic say so surely something is wrong so and each shutdown system is related to the sensors and each sensor or they are also connected.

To independent channels electronics etc and when this trip signal comes then only we say p shutdown system signal has come and once a trip signal comes the shadowing system will stop start acting Let now we get into the surround system so why this 2 by 3logic how it has evolved now one is any channel.

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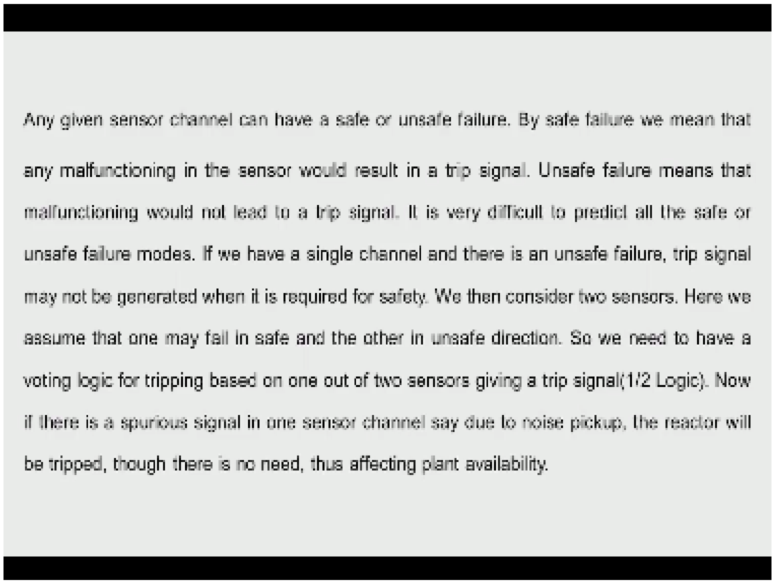

Can fail in the safe direction when I say fair in the safe direction maybe when there is no signal it could give a signal that something is wrong so it is failing in the safe direction but what do you mean by unsafe something has happened my temperature has crossed but it does not give you a signal so but in any reactor can you be checking whether it is a safe failure or an unsafe failure signal so we do not take if one channel is safe no problem react this trip should it become unsafe and you do not have the reactor trip you had it so we consider that way on single channel never we make any trip signal.

Then let us take whatever we will put two sensors and two channels and let us consider one fails in unsafe direction the other fails in the safe direction so that means if suppose I have a 2 by 2 logic that is I say both the channel should give me trip signal then only I will trip then what happens once one of the channels gives you unsafe for is I have an unsafe fault it would not give you signal only once one of the channels will give you in case actually my temperature has crossed only one channel is giving it would not trip okay, then let me say I will put one out of two.

So in case of an actual temperature increase surely I am assured but should I say there is a spurious signal then what will happen I have got a one out of two and it has failed in the unsafe direction it may give a trip and me trip the reactor when I do not want their actor to trip it has stripped so that means my plant availability is affected, so I do not go for a one by one one by two or two by two I have one more channel I go for a 2 by 3 so that is how we have evolved this 2 by 3 logic off late there are providing four channels.

So that one channel they could take for maintenance and still have a logic which does not affect availability and safety so this is way now spurious signal you may ask how can a story a signal happen it could be some noise pick up in the electronics as simple as that even though you put shielded cables somewhere the shielding is not there it has come up it could pick up a nice but we presume that it does not happen in althea channels so another advantage of two by three logic is I want to test these channels.

I can give a trip signal to one of the channels a simulated signal and it won't trip but I will check up by giving a signal here whether I am getting signal here it won't come but I know whether it this whole system is working or not so this gives me their testability so not only operability maintainability testability all are equally important in summary we have really looked at a very very important safety of the reactors how we engineer the safety to carry out the three important functions.

One is shut down there actor that is topped the fission reaction cool reactor to remove the decay heat and the third one to see the containment integrity is maintained last but not the least I mentioned monitoring is always essential we had a look at the shutdown systems how they are placed in pressurized water reactor a boiling water reactor and pressurize heavy water reactors we also got a idea how that there is need to decide the reactivity worth how much total worth and the rate of worth they are not decided by the same even there by two different events.

Then how the trip signals are arrived at we gave example of a to diverge signals for a heavy water reactor and we also talked about the to shut down systems then the safety logic how it has got evolved how we awarded the two by three safety logic thank you.

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R. Selvam
S Subash
F Soju
S Pradeepa
M Karthikeyan
T Ramkumar
R Sathiaraj

Video Producers
K R Ravindranath
Kannan Krishnamurty

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