Industrial Safety Engineering
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Lecture – 19
Bow – Tie: Cut – Sets for Accident Scenarios

Hello, welcome to this class. Today's discussion will be on Cut Sets for Accident Scenarios which is a part of Bow Tie; you can say it is basically the event tree site.

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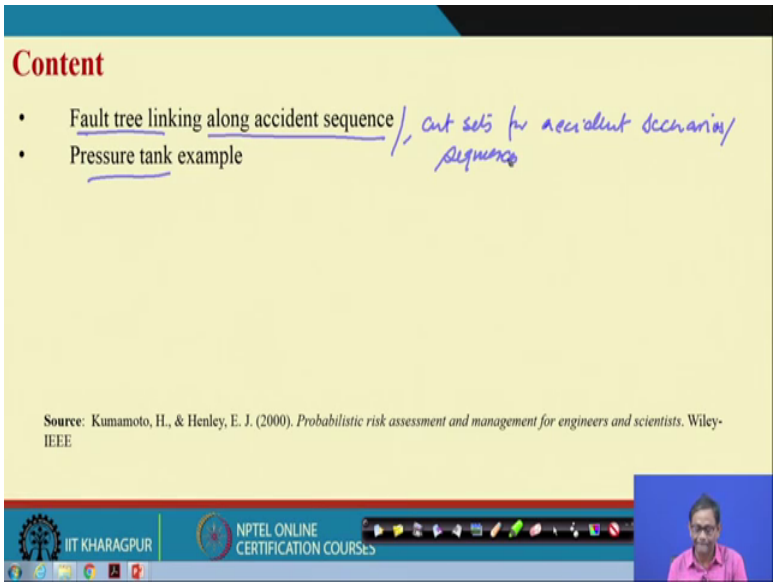

So, let us see what we will discuss. We will discuss two things. In the event tree will be different pivotal events actually these are nothing, but the protection configuration against the initiating event in terms of event tree and top event in terms of fault tree occurs.

So, then when the top event in terms of fault tree occurs or initiating event in terms of event tree occurs then the system behaves against this fault in such a manner that the recovery will be maximized. So, now depending on the system configurations, there will be different layers of protection. So, each of the layer can fail. So, if you want to know that how this layers fail.

So, ultimately you required to develop fault tree. So, that is why we, we are saying that fault tree linking with accident sequence. Accident sequence will be developed using

event tree and at each of the node of the event tree the success and failure of the protection measure which are basically known as pivotal events. So, those will be understood using fault tree. So, that is the first part.

Then what we will do? We will first discuss a general example and then we will go for the pressure tank example because this pressure tank example, we have discussed in previous lectures. And we are trying to bring that pressure tank example in all the lectures as much as possible. So, that there will be the common trade that how the different concepts methodologies and tools and techniques are employed and this can be done for a particular with reference to a particular example.

In this process we will develop the along the accident scenario or sequence the cut sets. So, cut sets for accident scenarios or sequences. So, every sequence gives one scenario. So, accident scenario is the end state of the event tree. So, these are the things we will be discussing today by 30 minutes of time. And thus, resource is basically the same book probable PRA actually PRAM for engineers and scientists by Kumamoto and Henley. And by this time you are familiar with this book and you will get that most of the materials I have taken from this book.

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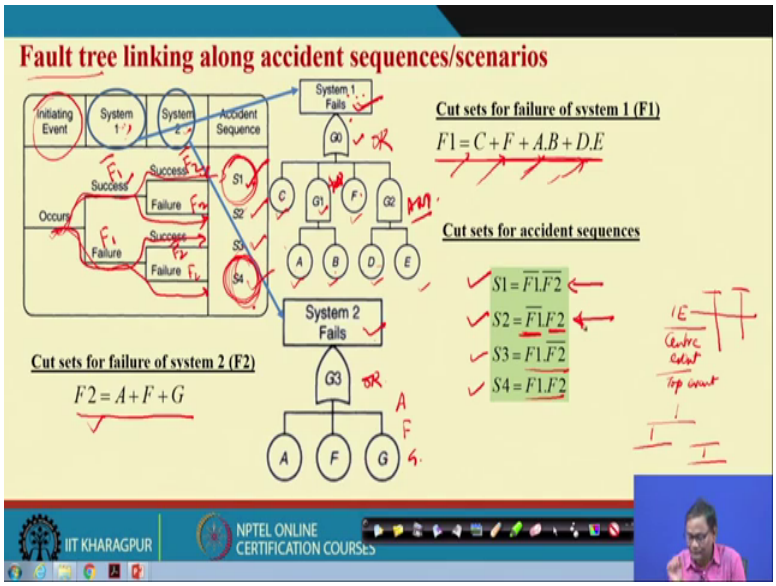

Let us understand it fully. So, initiating event; in event tree the starting point is even is initiating event, initiating event should occur. If you go back to bow tie then you will find out this is the event which is the top event in the fault tree. So, that is the linking

point and in bow tie these event is also known as centre event, actually in bow tie this is centre event.

So, in fault tree it is top event and in event tree it is initiating event. And ultimately what happened in even tree we progress along this depending on the protection configuration here. And in fault tree we try to find out the, we try to find out the root causes. So, whatever may be the we are, we are starting with initiating event, let it maybe the centre event. So, if it occurs, so, immediately you have seen in with earlier examples that the system behaves in such a manner that the occurrence can be the, effect of this occurrence can be minimized.

So, let there in this particular example, let there are two systems one after another. And ultimately both are independent, they do not depend on each other. So, given this initiating event the success and failure of the two systems are known, let it be or you have to find out. By success we means that if this event occur then the system will be able to fight against this wrong thing. And then some kind of accident sequence or scenario will be generated and if it is not then what will happen, another kind of situation will generate or scenario will generate.

Now, question is that depending on if system 1 the successful or failure then system 2 will be activated. Many a times what happens, if system 1 is sufficient enough to recover to mitigate the effect, then system 2's action is not required. But many times it is also required because layer 1 now system 1 may not be sufficient enough. So, here in this particular case we have branched the system 1 and system 2 in terms of success and failures. So, even if system 1 is successful, but system 2 will also act and when system 1 is failure and system 2 also act.

So, as a result there are four accident sequences means initiating event occurs then success, success this is one sequence initiating event occurs then system 1 success, system 2 failure, second sequence, initiating events occurs first system failure second system successful third sequence, initiating event occur first system failure second system failure this is the fourth sequence. So, if we say that these are basically protection against the initiative mechanic initiating event then; obviously, when both the protection fails. So, that S 4 that will be the most harmful whereas, the both the system is successful this will be safe or least harmful.

So, in accidents scenarios, we means these states. S 1 is scenario 1, S 2 scenario 2, S 3 scenario 3, S 4 scenario 4, ok. Now our job here is that link the fault tree with the sequence. So, how do you link? The failure of system 1 or failure of system 2, these are dependent on some other sub system component or some other root causes. So, as a result you can develop the fault tree for failure of system 1 as well as fault tree for failure of system 2.

So, we have given hypothetical fault tree here because this is just for understanding purpose, it is not a case, it is a demonstration of the concept. So, for the time being let system 1 fails and there are C A B FD and E, these are the basic events which ultimately leads to system 1 failure. And this is the fault tree, here G 0 is one get or gate and G 1 is and gate or gate and, and gate and this is another and gate, ok. And similarly, when system 2 fails so, there is 1 or gate and there are three basic events any one of these leads to system 2 fails.

Now, what is our job? We want to find out the cut sets along the accident paths, the along the accident paths or cut sets accident scenarios. Now, if I consider S 1 then this is first cut set, S 2 this is the cut set, S 3 and S 4 like this. So, you may be wondering that how the, what is it happening here. What is S 1? S 1 is basically initiating event occurs system 1 and system 2 are successful, ok. So, if we consider system 1 failure is F 1 then its success will be F 1 bar, if system 2 failure is F 2 then its success will be F 2 bar. So, then this is basically F 2 and this one F 2 bar, ok.

Now, if I considered that this, this occur, these are exist, then this F 1 bar and F 2 bar these and these, these two is occur then the S 1 will occur. And, and in terms of cut set we, we will in terms of scenario, we will write like this. So, now, for S 2 you see that S 2 will be F 1 bar, this successful system 1 successful system 2 failure. So, first one successful and second one failure, these two happened then only the sequence will be create it.

So, in this manner S 3, F 1, F 2 bar and S 4, F 1, F 2, ok. Now this is in terms of the system pivotal events like you know pivot element 1 and pivotal element 2 or system 1 failure and system 2 failure, you are writing. But what we are interested to know, we are interested to (Refer Time: 12:36) know how the basic events here with reference to

system 1 and system 2 failures, basic events are linked with this, with this sequence, these four sequence that is basically linking fault tree with the accident sequences.

In order to do so, you require to find out the cut set for the system 1 as well as system 2. So, all if you know that what is cut set, cut set basically is a set where is all the basic events of that set occurs, then the system event top event occur. Now, if I considered the first one that system 1 failure, then what is happening here, system 1 failure if C occurs system will 1 will fail, if F occur system 1 will fail because of or gate, but A and B simultaneous occurrence also lead to system failure and D and E simultaneous occurrence lead to system 1 failure.

So, as a result how many sets you will get? You will get because or gate increases the number of sets so, 1, 2, 3, 4. So, the first one is C, second one is F, third one is G 1 basically A into B, fourth one is G 2 G into E. So, this is in Boolean expression web read. This is basically the failure of system 1 which we can be in terms of cut set, cut set for failure of system 1, it can be written like this, this plus symbol is nothing, but union. Now, similarly for system 2, you can write because it is a, it is basically or gate. So, A F and G; that means, the three cut sets are there, and in Boolean probe we can write like this F equal to A plus F plus G.

Now, let us see that how are we will get the sequence using this, this basic events AFG C F A B, something like this, ok. So, that is what is your job, what is your job then? We want to link the fault tree with the accident sequences. By accident sequences we understand basically the path, by accident scenario the end state like S 1, S 2, S 3, S 4. So, S 1, S 2, S 3, S 4 these end states, it these are all basically will result, if initiating event occurs. And, depending on the behavior of the system against the initiating event what will happen different scenarios will be developed with maybe with higher level of severity.

If the protection system or the pivotal events are successful; so, then successful means basically able to fight against initiating event, the severity will be low less or there will be completely safe situation or other way that situation will severity wise it will increase. Now, we want to link these accidents sequence or scenarios with the basic event of the protection systems failures or that configuration for the protection configuration. By protection configuration with reference to this example we understand system 1 and

system 2, other way you can say layer 1 and layer 2, layer 1 protection layer 2 protection like this. And then our ultimate job is that find out the suppose the value of SI, I equal to 1 to 4 with reference to this basic events. So, we if we want this event this event to occur, this one to occur then, then what are the basic events in terms of system 1 and systems 2 that should occur, that will ultimately again result in cut set. So, we will find out next the cut sets.

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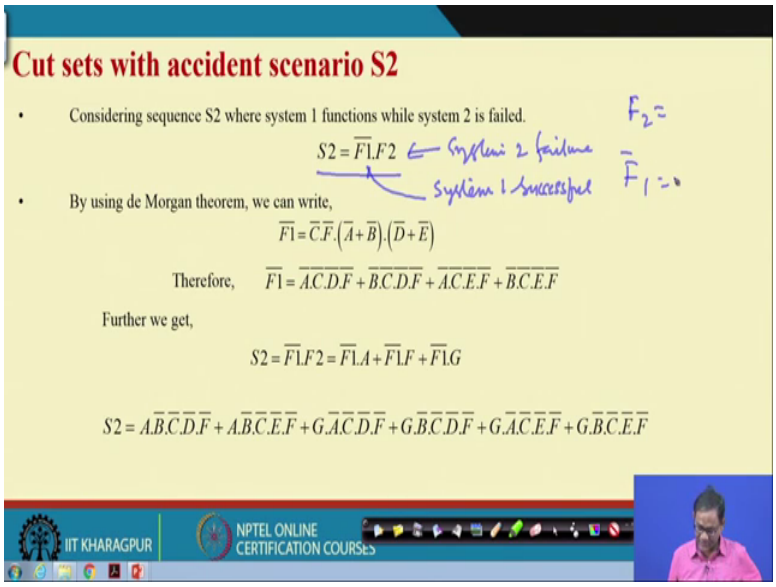

Let us understand for the S 2. So, let us see. So, you all know that what is S 2 when F 1 mean system 1 successful, system 2 failure, ok. Now system 2 failure F 2, what is the cut set and F 1 cut set, if I ok, it is already there, fine.

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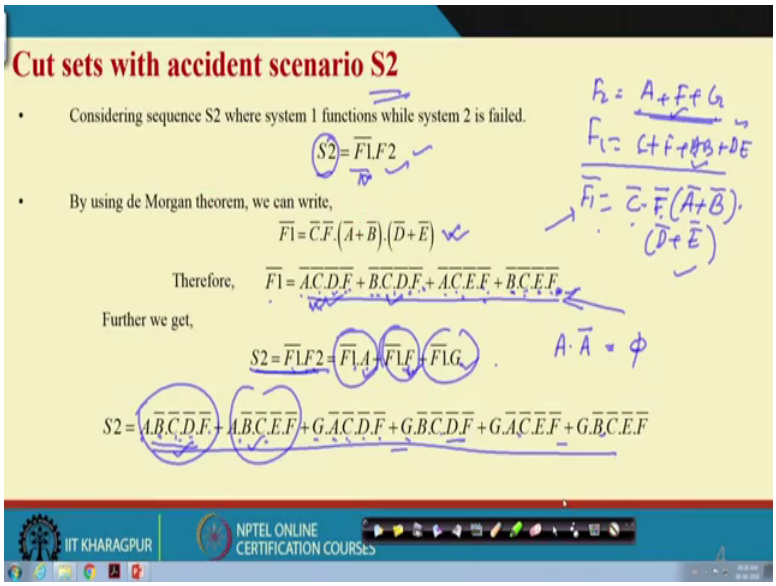

So, sorry suppose S 1, what is F 1, F 1 is C plus F plus A B plus DE and F 2 is A plus F plus G, that is what we know. Now, S 2 is F 1 bar and F 2, F 1 bar means the success of the system 1. So, from here we want to know F 1 bar. So, if you use the De Morgan principle what will be the F 1 bar? F 1 bar will be C bar intersection bar then intersection will be union A bar plus B bar into that is again intersection B bar plus E bar. So, C will be converted to when you are writing the F bar success of the system 1, C will be bar, F will be F bar, A bar, B bar, B bar, E bar like this, but this union will become intersection, intersection will become union. So, that it is written here, ok now, if you expand this then will be getting this one, ok, if you expand you will be getting this.

So, then F 1 bar is A bar, C bar, D bar, F bar B plus B bar, C bar, D bar, F bar plus A bar, C bar, E bar, F bar plus B bar, C bar, E bar, F bar, ok. Now what is the sequence? Sequence is S 2 which is F 1 bar into F 2. So, we are writing like this here, F 1 bar into F 2. So, what is F 2? F 2 is A plus F plus G. So, if you write here F 1 bar F 2. So, then F 1 bar into A plus 1, F 1 bar into F plus F 1 bar into G, ok.

Now, we have seen that what is F 1 bar here, this is F 1 bar. So, if you multiplied A intersection A and A bar, what will be the value, this will be 0 because A and its complement there is no intersection. So, as a result in the in F 1 bar wherever A is there, all those terms will vanish if we multiplied F 1 bar with A. So, this will vanish, this will vanish, what is remaining B C D E F bar and B C E F bar which will be multiplied by A.

So; that means, A B bar, C bar, D bar, F bar this one, then B bar, C bar, E bar, F bar here these two.

Now, F intersection F bar will be 0. So, everywhere F is there. So, no term will be available for this all in becomes 0. Now F 1 bar G in F 1 bar there is no G, so all the terms will be multiplied by G. So, that is why G A bar, C bar, D bar, F bar and like this 1, 2, 3, 4, 5, 6. So, you get this one is basically the cut set basically for S 2. So, that mean if this situation will occur, S 2 will occur the situation will occur S 2 will occur. something like this with reference to the basic event of the two system level fault tree system 1 and system 2. So, that is what is known as cut sets with accident scenario, this scenario is S 2.

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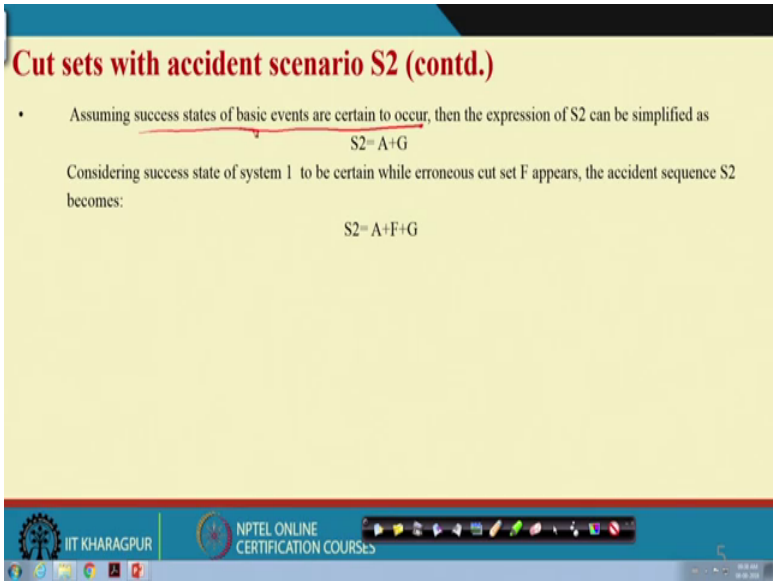

So, what will happen? There are two situation: situation 1, If we considered that situation 1, you are considering that basic events are certain to occur success states of basic events are certain. Sure, what does it mean? This means what are the success state for basic given A, C, D, E, F, A, B, D, E, F bar, these are all success events for the basic event ABCDEF bar. So, if we assume that that all success events are certain to, certain to occur because that is of that is obvious for high these plant and that is that much reliability should be there. Then what will happen this B bar, C bar, D bar, F bar, all bars that item will become 1.

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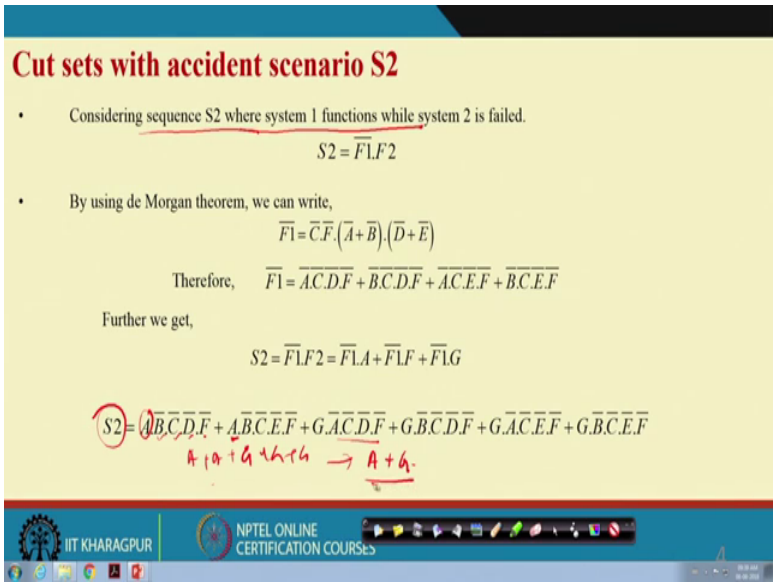

So, as a result what will be the H 2 value? Here A, here also A plus A is A only and then ultimately this all G, G plus G plus G. So; that means, A plus A plus G plus G plus G, but these are nothing, but in Boolean form this is basically A plus G. So, if we consider all the basic events, all the success of the basic that components, they are certain occur. Then the sequence S 2, sequence is A plus G, I mean failure of A and failure of G. So, that is what we have written in the first. So, your cut set will be this.

Now, you may think differently also that the you instead of considering the basic events certain to occur, you may consider that the system 1 is certain to occur, in the same system success of system 1 is certain to occur. Then what will happen, then F 1 bar will be 1 and you will get S 2 A plus F plus G. So; that means, A plus G there, but one more F is coming, one more cut set is coming. So, this will not, this is not correct. So, it is recommended that you please do not consider, you please do not consider this type of assumption that system 1 will occur because when you have the cut sets, ok. So, then let us see another one.

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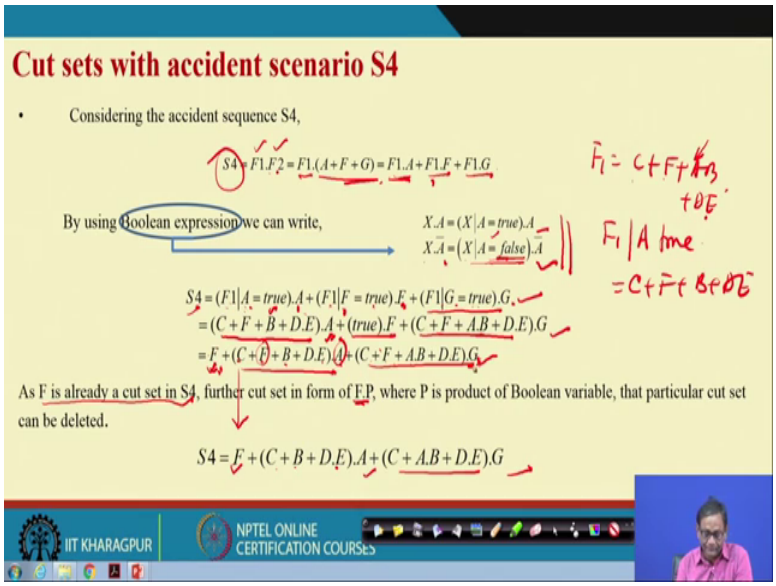

Let us go for sequence 4, in sequence 4 both the system fails. So, you will you know F 1 and order the cut set for F 2 A plus A plus F plus G. So, write down F 1 A F plus F 1 dot F plus F 1 dot G. So, you, you can multiply and finally, go forward and you will may, you will ultimately land up with some cut sheets which will be definitely correct cut sets. But here we are showing some Boolean expression to make the mathematics simpler or it will reduce the number of steps.

So, what are the method Boolean expression, when you say X, you mean intersection A, we can write that X given A equal to three intersection A AX intersection A bar, you can write X given a equal to falls intersections A bar. If you follow this and then simplify this one what is going to happen you see S 4 that mean F 1 A, F 1 given A true into A, second one F 1 given F 2 into F, third one is F 1 given G true into G.

Now, F 1 given A true so, all of you know, what is F 1, C plus F plus A B plus D E. Then if 1 given A true; that means, this will always happen. So, this will become C plus F plus B plus D E. So, as a result you are writing the F 1 given A true it is C plus F plus B plus DE and into A. Now F 1 given F true into F, this is basically true F. So, you are writing true F because here F is there F 1 F is also true.

Now, third one what will happen, F 1 giving G equal to 2 into G. So, here you see C plus F plus FB plus DE, there is no G the same thing is there multiplied by G. So as a result what is happening this true F, this coming as a cut set F, C plus F plus B plus DE is

coming like this and this one becoming this. Interesting thing is there that already F is A cut set. So, if you another one FA and FG is coming another cut sets. So, already as the minimum cut set is F. So, that mean FA and FG will not be, will not be required. So, that is what is written here as F is already in the cut set that further cut set from FP where P maybe here A B, all those things it is not required.

So, that mean this results into this, what will happen? F then C plus B plus DE, C plus B plus DE into A because this intersection, this is not require. Similarly, C plus AB plus DE into G, so, this is not required. So, if you proceed in this manner, what will happen further you see that you are getting F now C ok, ok, let it be like this.

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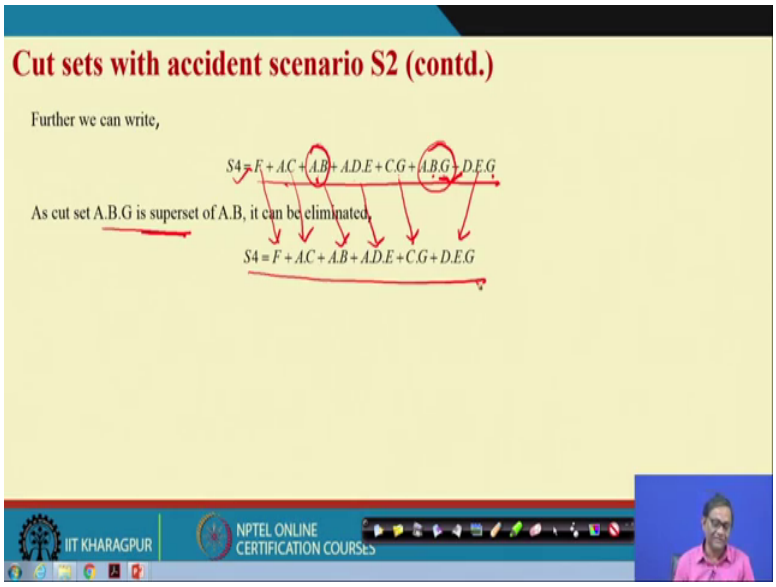

So, finally, if you expand this you will be getting this A plus AC, AB, ADE, CG, ABG, DEG. Now, you see AB is there, again ABG is there. So, AB is cut set. So, what is the need of ABG, it is not required. Similarly, maybe DEG, DEG, AC, I think others are not there. So, that mean what will happen, ABG will be not required. So, these become F, this AC, AB find, ADE find, CG find, this is not required, DEG is coming. So, that is basically the resultant cut set for S 4, sequence 4, this is what is linking cut sets with accident scenario.

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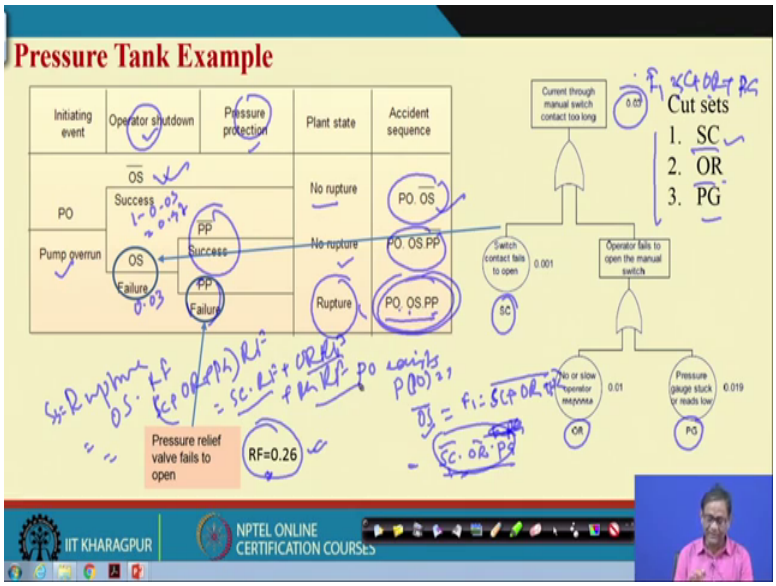

Now, let us see one example that is the pressure tank example and you all know this example we have discussed several times. So, you here the situation is like this, when there is pump over run. So, under this situation to protect the tank from over pressure situation, what will there? There will be operator shut down and there will be pressure protection operator shut down given the some other features of the system.

So, as a result what happen when operator shut down will take place? There will be a fault tree for operator shut down and the operation will maybe successful maybe failure and depending on the fault tree we will get the probability. So, with reference to pressure tank example, we found out that this, this is 0.03, that operator value that is 0.03.

Then what will be the success? 1 minus 0.03 that is basically 0.97 and in pressure protection what is there, we have the relief valve. So, relief valve should work. If relief valve fails to open what will happen, overpressure situation will also arise. So, now the relief valve that failure probability that mean fails to open, we consider 0.26, it is a very high value we consider, but it should not be that high value.

So, what will happen then the scenarios, there are three scenarios, see the first scenario is basically pump overrun exist operator shutdown successful. So, pressure protection this is not important here. So, no rupture, this is the scenario. Second one is that operator shutdown failure, but pressure protection successful this is the no rapture case scenario 2

and third one is the pressure operator shut down fail pressure protection also fail then rapture will take place, this is the third scenario.

Now as we have discussed earlier, in the same manner what happened you just find out the fault tree for this, fault tree for this. Here, in this particular example that operator shutdown fault tree when we are developing, we are finding out the three basic events, they are linked with linked or gate. And as a result you are getting cut sets like this three cut sets. So, if I say the failure here, this is F 1 then F 1 is that is SC plus or plus PG. Here, in the second system that is the, it is basically the basic event relief valve failure. So, pump failure means relief valve failure, there is, there is only that is RF is the, is the failure event, ok its properties like this.

Now, for the time being you just think of that you want that what is happening here, that scenario three. So, if we say PO exist, PO exist; that means, Probability of PO equal to 1. Now what is the OS? OS you will see that what we are saying S 1 or we can write this OS equal to F 1 which is basically SC plus, plus OR plus PG. Then what will be that OS bar that, that will be the total bar plus PG, total bar which will be SC bar intersection, OR bar intersection PG bar. So, using the same philosophy what we have discussed earlier. So,, ultimately what happened, you just you can find out OS bar, but here OS bar is not require, where is OS bar required? OS bar will be required here.

So, in this case you use this formula find out the sequence. In this case we require OS and PP that is, that is SC plus OR plus PG which will be multiplied by PP, which is basically RF. So, as a result the rapture scenario, rapture scenario if I want to the get the fault tree which is S 3 in this case. So, this be your OS into PP is nothing, but RF where OS is SC plus OR plus PG into RF. So; that means, SC into RF plus OR RF plus PG RF. So, three different cut sets you are getting here.

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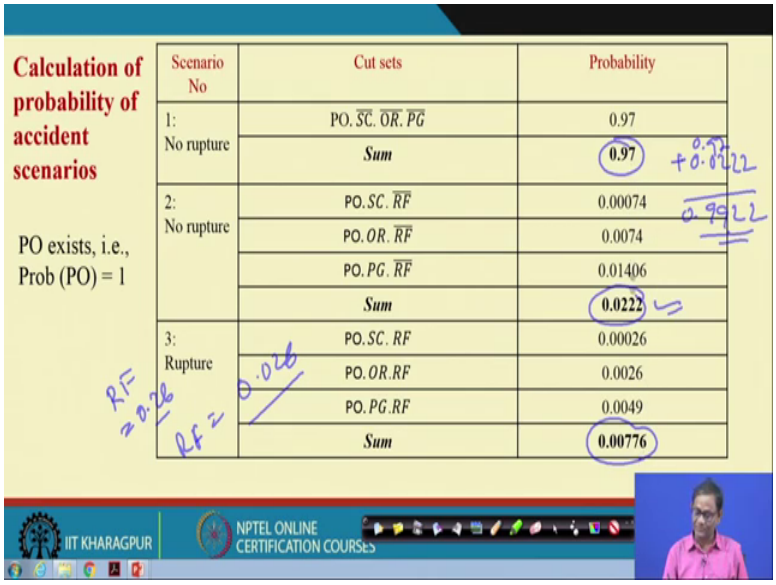

So, that is what we have discussed in next slide. What is there? So, you will get for different scenarios, this is the cut sets and as PO, we are considered it is 1. So, given the probability already given in last slide; so, you are getting probability of for the first scenario no rupture probability is this, second case there are three different cuts sets. So, ultimately you are getting the three probability, then they will be summed up. Third case rupture also three different cut sets, there are three different probability that will be summed up. So, then in thus in this case your pressure protection as well as the operator shutdown or I can say the system configurations against PO exist.

So, that the tank rupture will not take place, that is 0.97 plus 0.0222, so and here it is 0.97. So, how much it is? 0.9922, it is a more than 99 percent chance that thing will happen. But if we considered the case if the severity is very high because rupture is high severity case. So, it should not be this much, it should be even much, much lower than this, ok. But this has happened because we have considered that RF failure is very frequent 0.26. If you consider RF failure is very less suppose 0.026, what will happen? This, this will the probability value, this probability will further reduced, this probability of success will (Refer Time: 37:03), ok.

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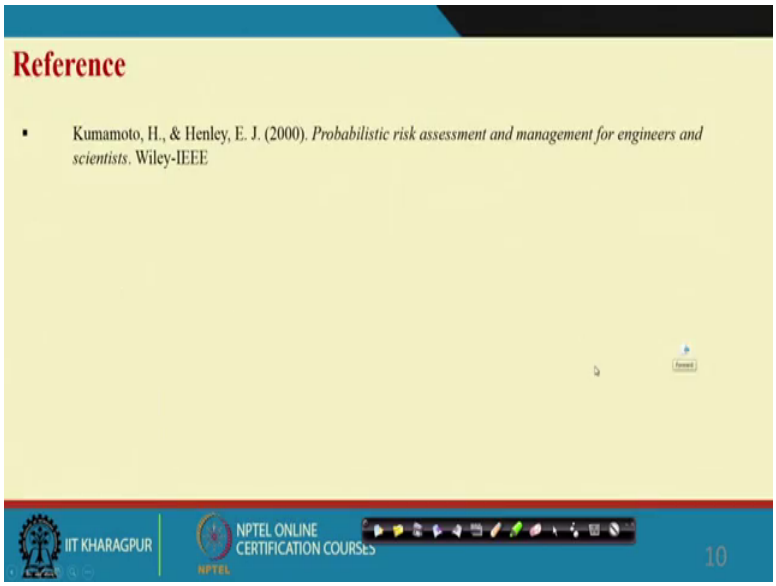

So, this is what is the in nutshell that our topic on that linking fault tree with your event tree. Or other way, I can say the accident sequences and finding out the cut sets of the accident sequences. So, this is subjective, it very simple one. But, please remember you required to know the Boolean algebra because, when you have complex fault tree so, that time manually in this manner the way we have explained it is not possible, ok.

Thank you very much. Hope you have enjoyed it.