Indian Institute of Technology Madras
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NPTEL
NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

NUCLEAR REACTOR AND SAFETY
AN INTRODUCTORY COURSE
Module 07 Lecture 01
History of Events in Nuclear Power Plants and Radiation Facilities

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Good morning, everybody. In the last two lectures, I gave you some ideas about the safety principles which are followed in the design of all nuclear reactors and nuclear establishments. I also talked to you about the approaches why how the safety is really gone into a very large depth, what is meant of the defense in depth approach wherein we find out what are all the events which can happen, how it can happen for a particular design, what sort of events can happen and then we see that the effect of those events are minimal. But now how do you know what events can happen. One is from the design, we can try to postulate failures, but besides this, there is a wealth of data which is available based on the operating experience of different nuclear power plants and radiation facilities.

Here it is very important that we take duo note of all such events which have happened in the other plants and then see that such an event cannot happen. Okay, should such an event happen, can I take some approaches in the design by which the consequences could be mitigated, all such thoughts need to be given to your design.

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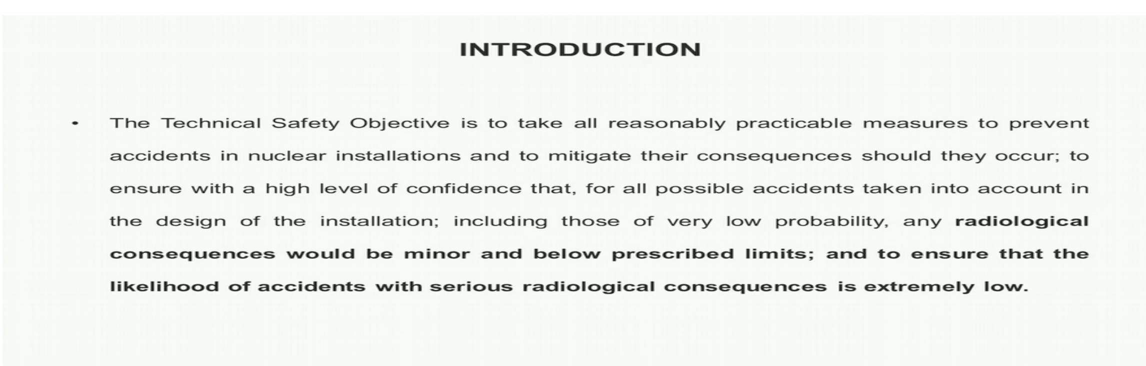

Now, let us look at what sort of events have been there. As I mentioned in the lecture on safety principles that we have to have a technical safety objective that we take measures to prevent accidents and in the case accidents happen, we should be able to mitigate their consequences to a very large extent, such that any radiation release is of a very low probability and that in any radioactive release is within the prescribed limits. So essentially we are looking at any event should have minimal radiological consequence.

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- The study of the **operating experience** available on similar installations is one of the principal sources to identify the events that must be considered in the safety design of the plant. Unless we have an idea of the likely events, we cannot make provisions to assure safety. The following question should be asked about the occurrence of an event at a plant: Could it happen in the plant we are designing? If the answer is 'yes' then appropriate **measures of prevention/mitigation** should be taken, within the minimum technical times but without unjustified haste. Various sets of design and safety criteria require that, during the important phases of a plant's life, the collection and recycling of experience are systematically performed within the responsible organization.

So let us look, one is as I said the operating experience on similar installations need to be considered. So we have to ask ourselves a question, can it happen in my design. If yes, then how to prevent or mitigate. So this approach needs to be that.

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- Thanks to the safety conventions present in different countries, any deviation from normal events are reported as unusual occurrences, unlike in other energy sectors. The major source of data besides **IAEA**, are the World Association of Nuclear Operators **(WANO),** Failure Data Base of Japanese Atomic Energy Agency **(JAEA) and the** Licensee Event Report (LER) from the **USNRC**. In India the Atomic Energy Regulatory Board **(AERB)** is the agency monitoring and reviewing all unusual occurrences. This lecture is devoted to the history of events that have occurred in different nuclear plants. Few of these are detailed out to bring out the causes that led to these events.

Now, thanks to the safety approaches, we have safety conventions under the auspices of the IAEA and there is a method of reporting any deviation from the normal. So any unusual occurrences happening in the plant, they may not have had any consequences, but any occurrence which is not in the design is called as an unusual occurrence.

As I mentioned, we have data which are reported from different countries and it is a practice in all the nuclear establishments to report any unusual occurrence, there is any deviation from the normal to the IAEA and so you have the data bank, you have the data bank of the World Association of Nuclear Operators, you have the Failure Data Base of the Japanese Atomic Energy Agency and USNRC. In India we have the Atomic Energy Regulatory Board which monitors all such unusual occurrences in all the radiation establishments.

This lecture finally would look into different events which have happened, but not all the events, some events. Whenever we look at an event, the severity of the event is important and public must get an idea what is the level of that event.

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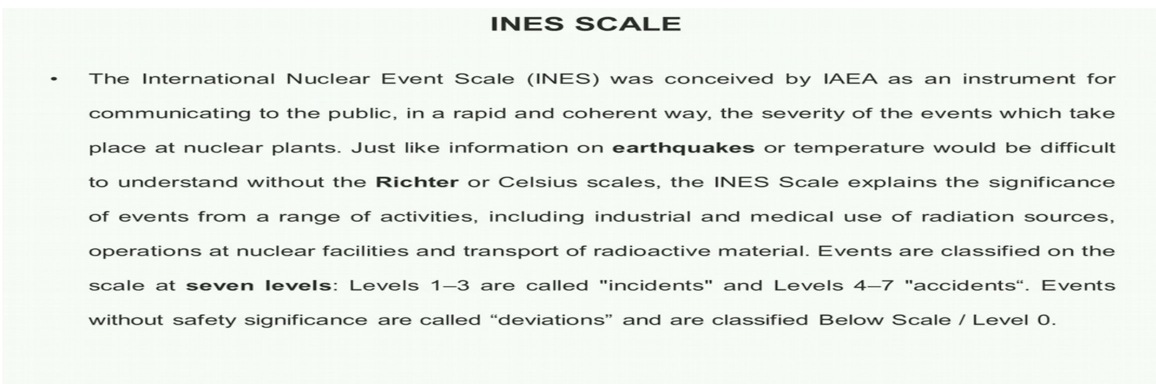

For example, you take an earthquake, whenever there is an earthquake, it is said it is 6.2 on the Richter scale. When you talk about temperature, you say it is 34 degree centigrade that is on the Celsius scale. If it is Fahrenheit, it is a Fahrenheit scale. So there is a scale; here we have the International Nuclear Event Scale which explains the significance of the event. It could be from different activities, but the significance is known by the level and how the levels are classified, we have seven levels.

Levels 1, 2, 3 are called as incidents and 4 to 7 are accidents, and which is below level 1 that is 0, they are just deviations, minor deviations. From this, you can easily conclude that level 7 would be the maximum accident, you are right.

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- Level 7 –Major Accident, external release of Radioactivity(thousand terra bequrels), significant damage
- Level 6 – serious Accident, external release of radioactivity(Thousand to tens of Bequrells),
- Level 5- Accident with offsite consequences(hundred to Thousand Bequrels), severe damage
- Level 4- accident without significant offsite risk , damage to installation
- Level 3- serious accident
- Level 2- incident
- Level 1-Anomaly

Let us just see what is level 7. It is a major accident with large external radioactivity release of the order of thousands of terabecquerels and a good amount of damage to the plant. Level 6, again a serious accident but the radioactivity release is less, something like thousands to tens of becquerels. Coming to level 5, the accident has good amount of offsite consequences. Again, it is related to the radioactivity release of the order of hundreds to thousands of becquerels and severe damage.

Then level 4 talks to you about events wherein the site, the plant site has the problems issues, that is activities only restricted to the plant site. So there is no offsite risk. Of course, installation has damaged. Level 3 would be a serious accident but not with release of radioactivity. Level 2 would be an incident and Level 1, an anomaly.

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EVENTS AT NUCLEAR FACILITIES

- There have been many incidents in nuclear power plants and fuel cycle facilities ever since the nuclear power plants came into being. In view of the fact that designers were aware of the bad consequences of radiation, there was always a safety aspect associated with every design. However, in spite of this some accidents have occurred but the lessons learnt from them has been put to advantage in future designs, through the IAEA, which has acted as a nodal agency.

Now, as I mentioned to you, the different incidents cover not only the nuclear power plants; they also cover the fuel cycle facilities also, all the fuel cycle facilities where radiation is involved, like reprocessing, fuel fabrication, and all such areas.

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YEAR	REACTOR	INES SCALE	COUNTRY	IAEA Description
2011	Fukushima	5	Japan	Failure of Emergency cooling after Earthquake and Tsunami,Causing explosion
2011	Onagawa		Japan	Fire after Tsunami
2006	Fleurus	4	Belgium	Worker at irradiation facility gets high dose of radiation
2006	Forsmark	2	Sweden	Degraded safety function due to CMF in emergency power supply
2005	Sellafield	3	UK	Release of radioactive material from installation
2005	Atucha	2	Argentina	Overexposure above ALI at NPP
2003	Paks	3	Hungary	Spent fuel rod rupture and fuel pellets spill
1999	tokaimura	4	Japan	Fatal Overexposure of worker after criticality accident in reprocessing facility
1999	Yanangio	3	Peru	Radiation burns due to radiography source

Just to give you an idea of different events which have happened in different scales, topmost you see the Fukushima reactor accident. It is IAEA scale 5. It happened in Japan after the emergency core cooling failed after a big earthquake and tsunami.

Then near about the same place called Onagawa in Japan nothing happened; there was a fire only after tsunami. Then in an irradiation facility in Belgium in 2006, worker has got a high dose of radiation. If you then move down in the Hungary in the Paks nuclear power station, spent fuel rod ruptured and fuel pellets split, bringing out the radioactivity. Then we have the famous Tokaimura event in Japan in 1999; it is IAEA 4 where there is a fatal overexposure that means overexposure of so much after a criticality accident in a reprocessing facility and the worker died, two or three workers died. I will give you the details later.

Before this, of course, you had the Chernobyl accident which was placed at level 7. We will look into all these accidents one by one.

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Ines Scale	Environment	Radiological Barriers	Defence in Depth
7	Chernobyl 1986, External release of a significant fraction of core inventory		
6	Kshytm, Russia 1957 Significant release of Radioactivity from explosion of a high activity waste tank		
5	Windscale Pile, UK, 1957, Release of Radioactivity after fire in reactor core	Three Mile Island, USA, 1979, Severe damage to Reactor Core	
4	Tokaimura, Japan, 1999, Fatal Overexposure of workers following criticality accident	Saint Laurent, France, 1980, melting of one fuel channel without release of activity to environment	
3		Sellafield,UK, 2005,Release of large quantity of radioactive material from installation.	Vandellos, Spain,1989, Loss of safety system in NPP
2	Atucha, argentina,2005, Overexposure of worker above ALI at NPP	Cadarache, France, 1993, Spread of contamination not expected in design.	Forsmark, Sweden,2006, Degraded safety function due to common mode failure in Power Supply
1			Breach of operating limits at NPP

Oh, we already have; Chernobyl which really had an impact on the environment. Then level 6, we have an event from a reprocessing facility where an explosion occurred and radioactivity split out. Then the Windscale event, I will describe to you, Tokaimura, then radiological barriers. The next set of events like Three Mile Island, the environment was not affected, but the radiological barrier, the final barrier was intact. Then we had the other events like you know Saint Laurent, France where one fueled channel melted, but there was no activity release.

There have been some other activities, actions or events which had taken place but they really they have not affected the environment because the defense in depth approach had been followed.

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- The TMI, Chernobyl and Fukushima incidents became very important because of the radiation exposures to the workers and public. There have been near miss events like the David Besse reactor head Corrosion, USA and the fire at Narora Atomic Power station in India, which have given important corrections for future designs. In some cases, it has been a design error, in some operators have flouted procedures and in some combinations of events not thought off have led to the accident.

Of course, to the common man, common public, TMI, Chernobyl, and Fukushima are the most important events which will be remembered for a long time and there have been some events like a near-miss event wherein it could have become a larger event had it not been carefully watched. There is one event in the David Besse nuclear plant in USA and also we had a fire in the Narora Atomic Power station in India. So from all these things, we have learnt a lot of lessons which we have already implemented into our power plant designs.

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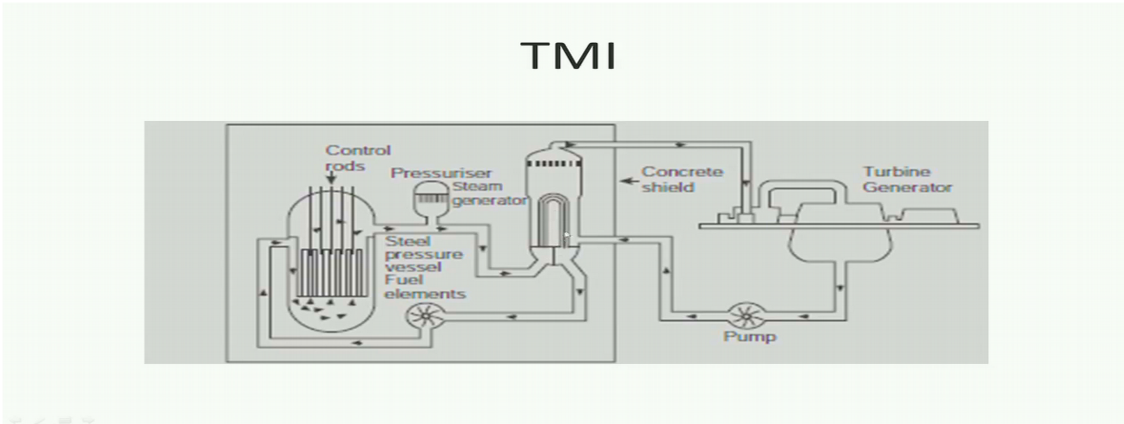

TMI, Three Mile Island is a pressurized water reactor. So you have the core here, the steam comes out, goes like this. It is not steam, I am sorry, it is pressurized water. It goes like this, exchanges heat to light water in another steam generator, and comes back and pumped back. Now there is a pressurizer which maintains the pressure of this system. We want to have the higher pressure so that boiling is avoided in the reactor core that is uniqueness of the pressurized water reactor.

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Three Mile Island Accident

- The accident at the Three Mile Island Unit 2 (TMI-2) nuclear power plant near Middletown, Pa., on March 28, 1979, was the most serious in U.S. commercial nuclear power plant operating history, even though it led to no deaths or injuries to plant workers or members of the nearby community. But it brought about sweeping changes involving emergency response planning, reactor operator training, human factors engineering, radiation protection, and many other areas of nuclear power plant operations. It also caused the U.S. Nuclear Regulatory Commission to tighten and heighten its regulatory oversight. Resultant changes in the nuclear power industry and at the NRC had the effect of enhancing safety.

So what happened? This accident was a quite serious accident in the US commercial history. So lot of changes were subsequently brought in the training of operators, in the response planning. Really it was, it happened in 1979 and really opened the eyes of many of the designers and many of the operators to improve, not that things were bad, but how to improve and you know, always there is chance or there is a scope for improvement at every stage and that is what. Not that there was something very badly done, everything was okay, some thoughts into some type of events which could have caused were not you know effectively put it.

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- The accident began about 4:00 a.m. on March 28, 1979, when the plant experienced a failure in the secondary, non-nuclear section of the plant. The main feed water pumps stopped running, caused by either a mechanical or electrical failure, which prevented the steam generators from removing heat. First the turbine, then the reactor automatically shut down. Immediately, the pressure in the primary system (the nuclear portion of the plant) began to increase due to the production of steam. In order to prevent that pressure from becoming excessive, the pilot-operated relief valve (a valve located at the top of the pressurizer) opened. The valve should have closed when the pressure decreased by a certain amount, but it did not. Signals available to the operator failed to show that the valve was still open, water continued to pour out of the stuck valve, affecting cooling of core and caused overheating.

What happened? The accident happened in March 28, 1979, and there was a failure in the non-nuclear section in the steam water system of the plant. The main feed water pumps stopped due to some fault. Because of that the flow to the steam generator was not there. So the turbine tripped automatically, the reactor tripped. Of course, for the reactor to trip the pressure in the primary system increased and the pressure in the primary system increased beyond a certain level, the reactor tripped. After some time the pressure started relieving through a pressure relief valve in the pressurizer. After some time when the pressure had fallen down, normally the relief valve should have set back into the position. However, even though the operator felt that the valve would have closed, it was still open and no signals were available to the operator to really confirm that the valve has closed.

So what happened, water steam was going out through the pressure relief valve outside not to the core and this caused overheating of the core. Now, to have an idea of the level of water in the core, there is no instrument which shows the level of water in the core, but the level in the pressurizer was seen by the operator.

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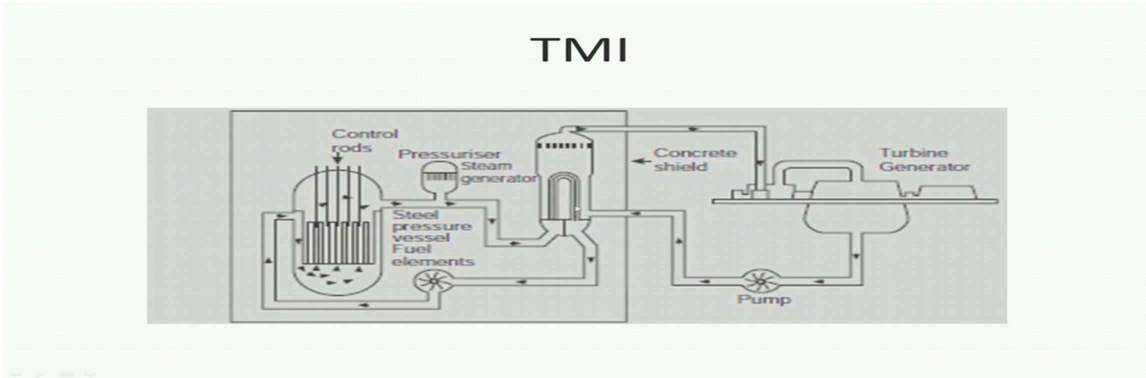

Now, let us look back what would have happened. See here because of the loss of cooling the temperature increased and here the temperature increase finally resulted in steam production and this steam production lifted this mass of water, whereas it was getting released continuously. So looking at the pressurizer level rising, the operator thought, oh, it is full of water. The core is full of water. So what he did?

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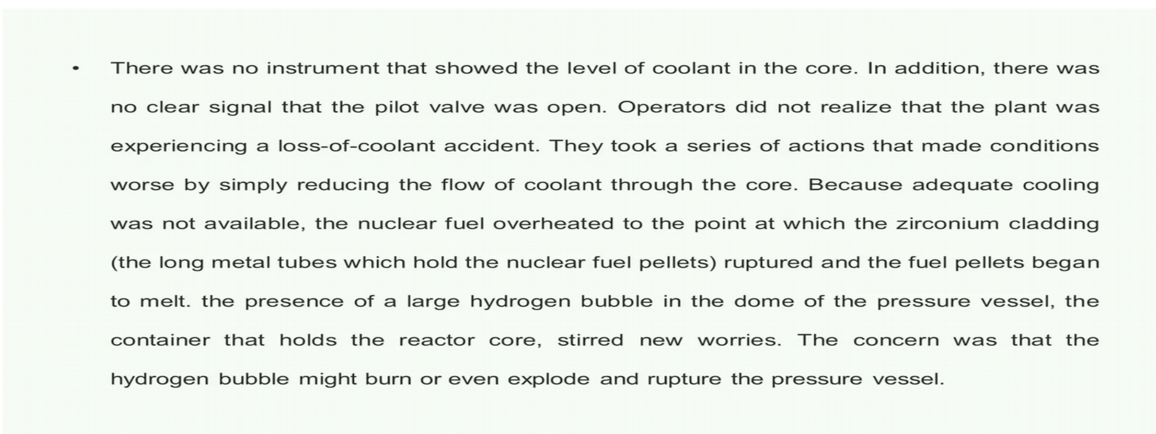

The emergency core cooling pumps, he really tripped the pump so finally there was cooling still absent to the core. The fuel pins ruptured, some of the fuel periods belted. In fact, the hydrogen generated due to the reaction of the zirconium clad and the water came out, but luckily for us nothing happened. It didn't reach explosion levels.

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Impact of the Accident

The accident was caused by a combination of personnel error, design deficiencies, and component failures. Issues Addressed were;

- Upgrading and strengthening of plant design and equipment requirements
- Identifying human performance as a critical part of plant safety, revamping operator training and staffing requirements, followed by improved instrumentation and controls for operating the plant.
- initiatives by licensees in early identification of important safety-related problems, and in collecting and assessing relevant data so lessons of experience can be shared and quickly acted upon

So effectively, you can look at there have been design deficiencies, no proper signals were available instrumentation signals are available to the operator to assess the state of the plant. Then personal error in the sense that the person, the operating personal could have looked at some other aspects really before turning off the cooling to the core, because removing the cooling to the core is a very, very important step before which they should have done.

So what was the effect? Upgrading was done, the plant design was strengthened, and operator training was improved by a very good amount so then identification of more problems and sharing of the information more and more. Apparently some similar event that happened in another plant quite some time back, but unfortunately that information was not shared. So maybe if it had been shared during the training period apparently the operators may have been better, put to save the situation.

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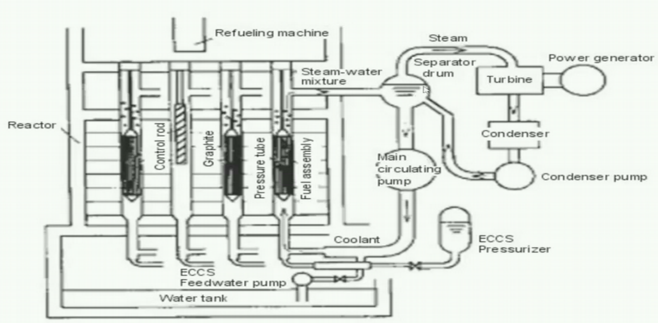
CHERNOBYL REACTOR



Next, so we have seen the American contribution, now let us go to the Russian reactor, Chernobyl. This Chernobyl is a boiling water reactor, but it is a pressure tube boiling water reactor. So there is a tube, pressure tube, it is not a pressure vessel. So pressure tube in which you have the fuel, you have the fuel assembly and steam is produced at the outlet the steam water mixture goes here, get separated, steam goes to the turbine, and then runs, and then this is the circulating pump. This is a boiling water reactor.

Now what happened? There is a feature in all the Russian plants that should there be a power failure and the turbine would trip but the turbine would be coasting down, turbine has got a large mass. So it has got inertia so it will coast down. So their idea is to generate power from that mechanical energy, variable frequency, variable voltage power and see whether you could run the main circulating pumps or let us say auxiliary feed pumps to cool the core. In fact, they say that this can cool core for nearly few minutes. This feature is present in most of their plants.

But here, in this Chernobyl reactor, they just wanted to perform a test to see whether this feature is existing and up to how much time it can take in this particular plant. Idea is good, but unfortunately a series of mistakes happened which really resulted in a big accident.

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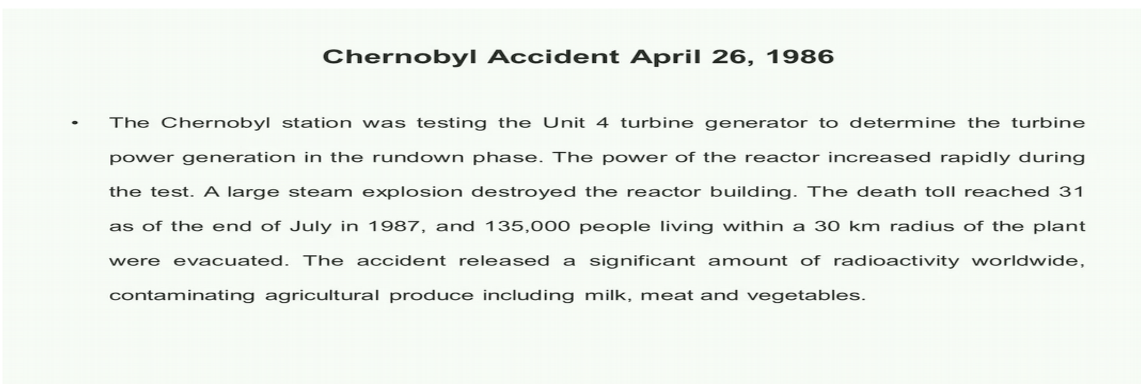

So at the end of the accident, there was a big explosion, 31 people died and the 31 people who died, most of them were firefighters and people around 30 kilometers were evacuated and significant amount of radioactivity was released to the environment.

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- The aim of the test was to determine the ability of the reactor's turbine generator to generate sufficient electricity to power the reactor's Emergency Core Cooling System (in particular, the water pumps) in the event of a loss of external electric power. The experiment started after connecting the main circulation pumps and the turbines and deactivating ECCS so that it would not respond to the reactor's low power output during the experiment . The reactor operators reduced the power level too rapidly, close to the maximum scale of the power drop allowed by safety regulations. Then, the control rods were pulled out of the reactor somewhat farther than normally allowed by safety regulations to raise the power output . Then there was hardly any margin left to safely control the reaction in the reactor. Nevertheless, the operators shutdown the steam supply to the turbine to continue the test , and the turbines slowed down to coast.

So as I mentioned, the aim of the test was ability of the reactor's turbine generator to generate electrical power to power the emergency core cooling system in the case of loss of external electric power. So what happened? The main pumps everything was started, but the emergency core cooling system which normally would have come up by itself was deactivated, so that when the reactor is at a very low power at that time it should not come. But when they were reducing the power to do the test, unfortunately, they pushed the rod too much so the power became very small. Now when the power was very small, it is not good because this type of design below about 7-10% of power level, it has got a positive coefficient, positive reactivity coefficient in that means that in case the temperature increases, there will be a positive reactivity.

So normally this reactor is not supposed to be operated at that power. So the operators try to take out the control rods but in spite of their control rods taking everything, they couldn't really come back to a higher power. But of course, the operators were not aware that this positive coefficient exists and we must not do tests at that power. Now the operators what do you called closed the valve to the turbine and the turbine started coasting down.

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- The recirculation pumps that were receiving power from the generator then slowed down and the cooling water flow dropped. The reactor then gained reactivity and the power started to rise. Automatic control rods were inserted in an attempt to lower the power, however, their slow speed failed to suppress the reactivity rise. Soon a nuclear burst started further raising the fuel temperature and they ruptured. It was only 40 seconds after the experiment had started. Sudden steam generation stopped the coolant water circulation and the fuel temperature reached 3,000 – 4,000 degrees C.

The recirculation pumps got the power from the generator, but they are also slowing down, the cooling water flow stopped, and as I mentioned, this was a region in which any rise in temperature would cause a positive reactivity, means it would go to increase the neutron chain reactions, and the power started to rise. At this stage operators tried to put in the control rods but the speed of the control rods was not very good; they were not able to suppress the reactivity rise and there was a burst, fuel temperature's increased, fuel ruptured and within 40 to 44 seconds after the experiment started, we had the explosion of the reactor building and lot of radioactivity plume coming out. So everything was over in less than a minute. So the fuel failed due to increased -- pressure tubes failed, water steam came out, and high temperature steam coming in contact with a graphite, the graphite also caught fire, the fire again increased the explosive force, upper part of the reactor was taken off, and the reactor building was really not a containment building. That is another reason, that was really not a good containment building; it was just a reactor building that also exploded and brought everything all the radioactive materials to the public.

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Cause

- Reactor without self controllability; This nuclear reactor was designed to have a positive reactivity coefficient during lower power operation. The management and the operators were not informed about the reactor's unstableness and danger during low-power operation. The pressure tubes were made of 4mm thin pipes. They were not strong enough to hold against pressure increase in abnormal circumstances. The reactor core had neither a steel pressure vessel nor containment for pressure-proof.

So one of the learned thing was this is a reactor without self-control ability. So in fact, no other country has this design. That is one thing; it's a good thing for us. These were basically plutonium producing reactors for the Russians, however, this reactor had the maximum availability in the Russian nuclear power plants. So the thickness of the pipes or the pressure tubes was also less; they were not strong. So the containment was also not pressure proof. S o this is basically a large thing in the design. Then of course, other mistakes that cutting off the emergency core cooling system was also another mistake by the operator, all compounded, but basic design had the flaws.

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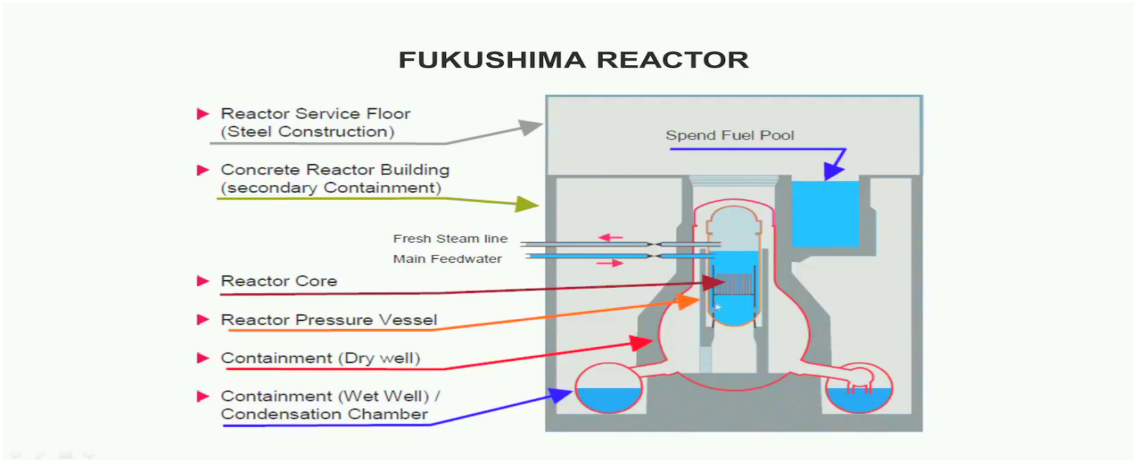

Now, let us go to the Fukushima reactor. Fukushima reactor is a boiling water reactor. So it is a pressure vessel boiling water reactor unlike the Chernobyl reactor, here all the core elements are there, steam is produced, so then that is goes to the turbine, and here at the top, they have got the spent fuel pool that is the fuel which has seen enough burn up in the core is kept in this tank which is full of continuous cooling water so that its temperature is kept low. Of course, we have the different containments; the reactor pressure vessel, you have the dry well, the wet well and of course, the concrete building, etcetera.

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FUKUSHIMA ACCIDENT,JAPAN (2011)

- At 14:46 Japan standard time on March 11, 2011, Earthquake— rated a magnitude 9.0— occurred at a depth of approximately 25 kilometers , 130 kilometers east of Sendai and 372 kilometers northeast of Tokyo off the coast of Honshu Island. This earthquake resulted in the automatic shutdown of 11 nuclear power plants at four sites along the northeast coast of Japan (Onagawa 1, 2, and 3; Fukushima Dai-ichi 1, 2, and 3; Fukushima Dai-ni 1, 2, 3, and 4; and Tokai 2). The earthquake precipitated a large tsunami that is estimated to have exceeded 14 meters (45 feet) in height at the Fukushima Dai-ichi Nuclear Power Plant site. The earthquake and tsunami produced widespread devastation, resulting in approximately 25,000 people dead or missing, and significantly impacting the infrastructure and industry in the northeastern coastal areas of Japan.

Here let us see what happened. In 2011, March 11th, there was an earthquake, had a magnitude of nearly 9 on the Richter scale and apparently the epicenter was in the depth in the ocean, somewhere 25 kilometers depth, near east of a place called Sendai and 372 kilometers of Tokyo. So this resulted, the movement by earthquake was there, the seismological signals, vibrations were this thing, all 11 nuclear plants at four sites, they shut down, all, everything went off well. But then this earthquake resulted in a large tsunami because it was in the sea, it pushed up the water and it is estimated that it should have gone to something like 14 to 15 meters height. So it flooded the place, lot of people were dead, in fact, because of the tsunami and lot of infrastructure was damaged.

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- As a result of the earthquake, offsite power was lost to the entire facility. The emergency diesel generators started at all six units providing alternating current (ac) electrical power to critical systems at each unit, and the facility response to the seismic event appears to have been normal.
- Approximately 40 minutes following the earthquake and shutdown of the operating units, the first large tsunami wave inundated the site followed by multiple additional waves. The estimated height of the tsunami exceeded the site design protection from tsunamis by approximately 8 meters . The tsunami resulted in extensive damage to site facilities and a complete loss of ac electrical power at Units 1 through 5, a condition known as station blackout (SBO).

Okay, so what happened to the plant? The offsite power was lost because of the snapping of the towers, so there was no offsite power. So immediately the emergency diesel generators started. So they provided the power supplied to all the important systems of the plant, including the cooling of the core and the spent fuel storage. Then 40 minutes after everything had practically settled down, at that time, there was another tsunami, large tsunami, it inundated the whole place and the design of the place of the whole establishment was for a tsunami of eight meters height based on the data available to them, based on the previous tsunamis. But this tsunami was of a higher height. So finally what happened? It resulted in the loss of AC electrical power to all the units because the diesel generators, everything goes underwater. So we have a situation called no offsite power and no onsite power so that is called as station blackout. In the nuclear reactor terminology, we call it as SBO, station blackout.

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- Cooling was lost to the fuel in the Unit 1 reactor after several hours, the Unit 2 reactor after about 71 hours, and the Unit 3 reactor after about 36 hours, resulting in damage to the nuclear fuel shortly after the loss of cooling. Without ac power, the plants were likely relying on batteries and turbine-driven and diesel-driven pumps. The operators were likely implementing their severe accident management program to maintain core cooling functions well beyond the normal capacity of the station batteries. Without the response of offsite assistance, which appears to have been hampered by the devastation in the area, among other factors, each unit eventually lost the capability to further extend cooling of the reactor cores.

So cooling was lost in unit 1; unit 2 again also it happened after 71 hours and unit 3 after 36 hours. So without the AC pumps, the plant was relying only on the battery. There were some diesel driven pumps but they also got submerged and finally the cooling was lost to the plant.

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- The Unit 1, 2, and 3 explosions were caused by the buildup of hydrogen gas within primary containment produced during fuel damage in the reactor and subsequent movement of that hydrogen gas from the drywell into the secondary containment. The source of the explosive gases causing the Unit 4 explosion remains unclear. In addition, the operators were unable to monitor the condition of and restore normal cooling flow to the Unit 1, 2, 3, and 4 spent fuel pools.

Then what happened, the zirconium water reaction resulted in hydrogen built-up, the built-up of hydrogen was so much that it damaged the first and second level of containments and then it exploded. Unit 1, 2, unit 1, of course, the expression was there. Not only that, even in the spent fuel bay, lot of fuel pins had failed because of lack of cooling and hydrogen generated.

So one point is very clear in the plant design everything was okay but for the fact that the diesel generators should have been kept at a bigger height. In fact, when this accident happened normally we have a review of all our reactors whether such things can happen and we just looked at our own facilities and we found and basically those facilities which are around near the sea because this happened due to a tsunami earthquake in the sea, so we looked at the Kudankulam power plant. We had already put the diesel at about 15 to 20 meters height from the sea level. So apparently we had based on our margins built in, it was there so we concluded that such an accident cannot happen. But we did have a tsunami in 2004 during which there was a flooding of the Kalpakkam plant which we shall see, of course, nothing happened, which we shall see later.

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WINDSCALE ACCIDENT (UK in 1957)

- Technicians overheated Windscale Pile No. 1 because poorly placed temperature sensors indicated the reactor was cooling rather than heating. An unexpected release of 'Wigner' energy from the graphite of a reactor which used this material as a moderator, caused the fire of the graphite itself Graphite stores energy in its lattice at temperatures <100 deg C. but releases it at higher temperatures releasing energy and raising temperature to~ 100 deg.c. The excess heat lead to the failure of fuel. The resulting fire burned for days, damaging a significant portion of the reactor core.

Then there was a Windscale accident in UK. See the Windscale Pile or you can call as what do you call, any reactor you called as a pile. Graphite was being used as a moderator. Then this graphite has a property of storing energy when temperatures are low. At room temperature, it stores some energy and then beyond a certain temperature, maybe 500 or 1000 it would release that energy and that energy will come with a burst. This actually is called as Wigner energy. Now this Wigner energy was there and in this case, when the operator was raising the power, the temperature was not sensed properly because it was not located in the correct place. So apparently, the operator overshot the temperatures and the Wigner energy got released and it burnt the graphite, the fuel failed, and it burned for several days and damaging the portions of the core.

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- An effort to cool the graphite core with water eventually quenched the fire. The reactor had released radioactive gases into the surrounding countryside, primarily in the form of iodine-131. Milk distribution was banned in a 200-square-mile area around the reactor for several weeks. Explosions didn't happen and the reactor fire was extinguished, but the story goes that the engineer's hair suddenly turned white!

Of course, operator was very, very thoughtful, immediately he put in water and quenched the fire. However, radioactive gases basically Iodine-131 had got released and the they took care that milk which was distributed within about a 200 square mile area they didn't use it, but otherwise nothing specific. But there is a story, they said no explosion happened, reactor fire was extinguished but the engineer’s hair turned white in the control room.

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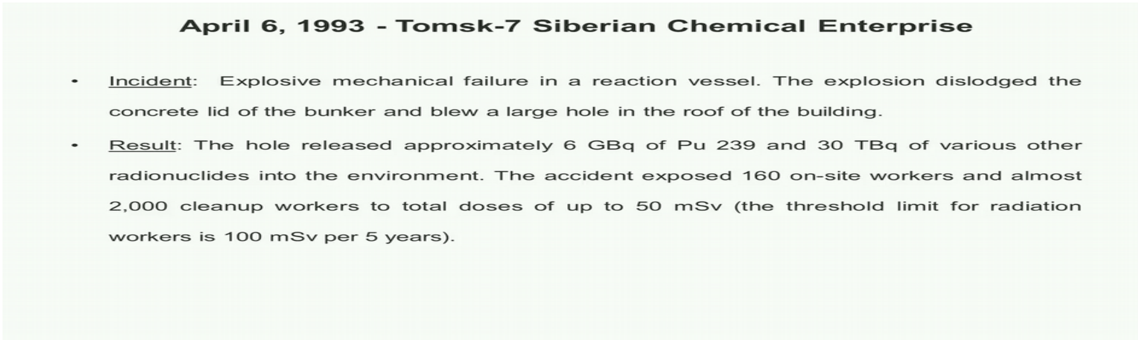

Then we had an accident which is again related to release of radioactivity in Siberia in the Tomk-7. Some reprocessing experiments were going on and there was an explosion, so whatever was the fissile material, everything came out that contained plutonium and this release was approximately six gigabecquerel of Pu-239 and 30 terabecquerels of other radionuclides and nearly 160 onsite workers were actually exposed to this radiation. However, the total dose was 50 millisieverts only, we have a limit for 100 millisieverts in five years. So that way it was not much but it did create a radioactivity release.

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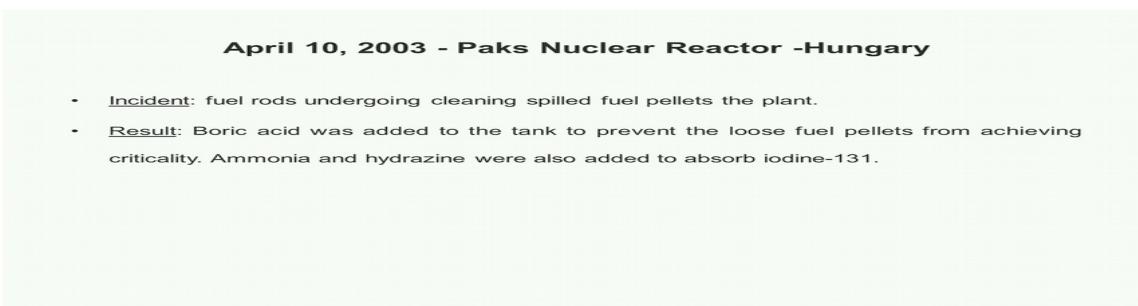

Then the Hungary Paks plant which I mentioned. While the fuel rods were undergoing cleaning, it fell down and the fuel pellets came out and the thoughtful operator added boric acid so that they don’t become critical because if we put boric acid it will absorb the neutrons and there will be no chance of any situation becoming critical.

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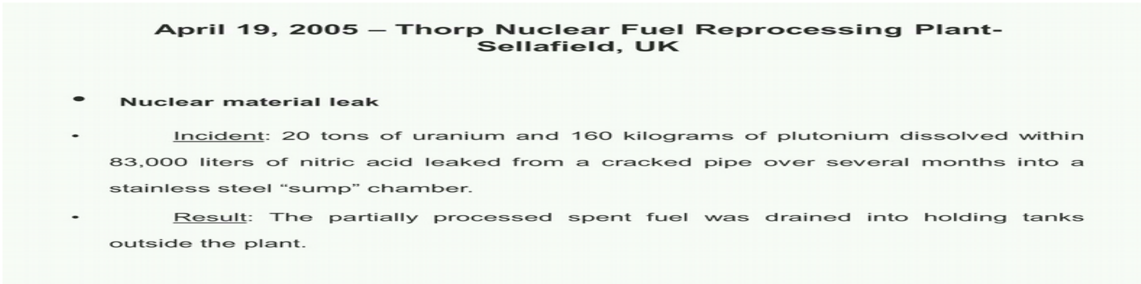

Then the reprocessing plant at Sellafield, here see the incident 20 tons of uranium and 160 kg of plutonium dissolved in a large amount of nitric acid, but there is a pipe which was leaking for several months, it was within a stainless steel sump, and that there was getting into another some outside the plant. So when the reactivity increased people realized that something has happened inside the plant, but nothing much to worry about.

Now, let us see the accidents which will happen with a lesser degree that we will take care in the next lecture. Thank you.

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