PDHonline Course E438 (3 PDH)

Nuclear Accidents

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Table of Contents

Nuclear Accidents

1. Introduction

The accidents at Three Mile Island (TMI) in the United States, Chernobyl in the Soviet Union (now Ukraine), and Fukushima Daiichi (Fukushima) in Japan are the ones most widely known in the nuclear power industry. All plants were designed for production of electricity. To understand the accidents and the differences between each several aspects will be reviewed and compared.

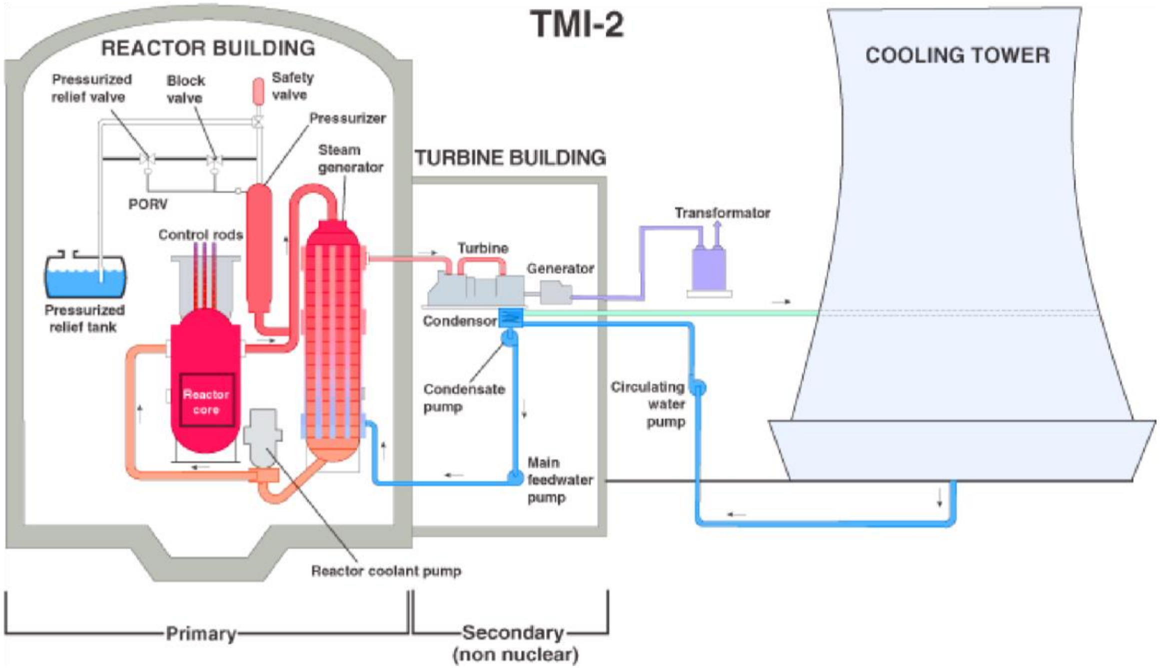
One important aspect is the design and if the design was conservative. This will be looked at from both the reactor design and containment building. The physics of how each reactor was operated will be examined. Another aspect will be the emergency planning involved. How was the public and local governments notified of the accident. And most important, what were the health consequences to the plant workers and general public?

Next, an overview of the accidents will be discussed.

2. Accident Overview

Three Mile Island

There are two pressurized water reactors (PWR) at the TMI site. The 30th anniversary of TMI2 was March 28, 2009. On that day at 4:00 am, a failure occurred in the secondary side (steam side) causing the main feedwater pumps to stop pumping feedwater to the steam generators. This prevented the steam generators from removing heat from the primary side (reactor side). This caused the plant's turbine-generator and then the reactor itself to automatically shut down. To remove the decay heat from the primary side the auxiliary or emergency feedwater system should have started but did not. The primary began to heat up causing relief valves on the pressurizer to lift. One of the relief valves stayed open and was not recognized as being open for some time. This resulted in the primary side continuing to be depressurized and allowing formation of a steam bubble in the reactor vessel. The reactor continued to heat up and increased radiation levels were observed in the containment building. The accident and fuel damage had occurred.



Chernobyl

There are four reactors at the Chernobyl site. The reactors are pressurized water-cooled reactors using a graphite moderator. The accident at Chernobyl Unit 4 occurred on April 26, 1986. A test was being conducted at low power. There was a concern that if power was lost from the electrical grid then power would be lost to the reactor coolant pumps for a period of time until the backup diesel generators could start and become fully loaded. The generators required 15 seconds to start but took 60 to 75 seconds to reach full load. The test was to see if the turbine generator residual momentum or spinning without steam could provide electrical power to the coolant pumps during this time gap. As the turbine generator spun down the resultant decrease in coolant flow caused a power spike due to a positive void coefficient (explained in the reactor design section). A reactor trip (rapid insertion of control rods) occurred but it was too late. Power increased in an uncontrolled fashion resulting in a steam explosion and resultant fire. The graphite moderator caught fire and increased the emission of radioactive particles carried by the smoke. The building that housed the reactor was damaged resulting in the large scale release of radioactive material into the environment.

Fukushima

There are six boiling water reactors (BWR) at the Fukushima site. On March 11, 2011, a 9.0 magnitude earthquake struck Japan just off shore on the northeast coast. Eleven reactors at 4 different sites automatically shut down. At the Fukushima site three were operating (Units 1-3) and three were shutdown (units 4-6) for a refueling outage. The three operating reactors shutdown automatically as designed when the earthquake occurred. The normal electrical connection to the grid was lost. Emergency diesel generators started on all six units providing power to critical cooling systems. After 40 minutes, a tsunami of 14 meters height caused extensive damage to the site and diesel generators. The plant was originally designed for a tsunami of 3 meters. The design was modified in the year 2000 to 5.7 meters. The tsunami exceeded the design. Only unit six retained one diesel generator used to keep units 5 & 6 in a safe shutdown condition. Units 1-4 overheated causing fuel damage and release of radiation.

3. Reactor Design

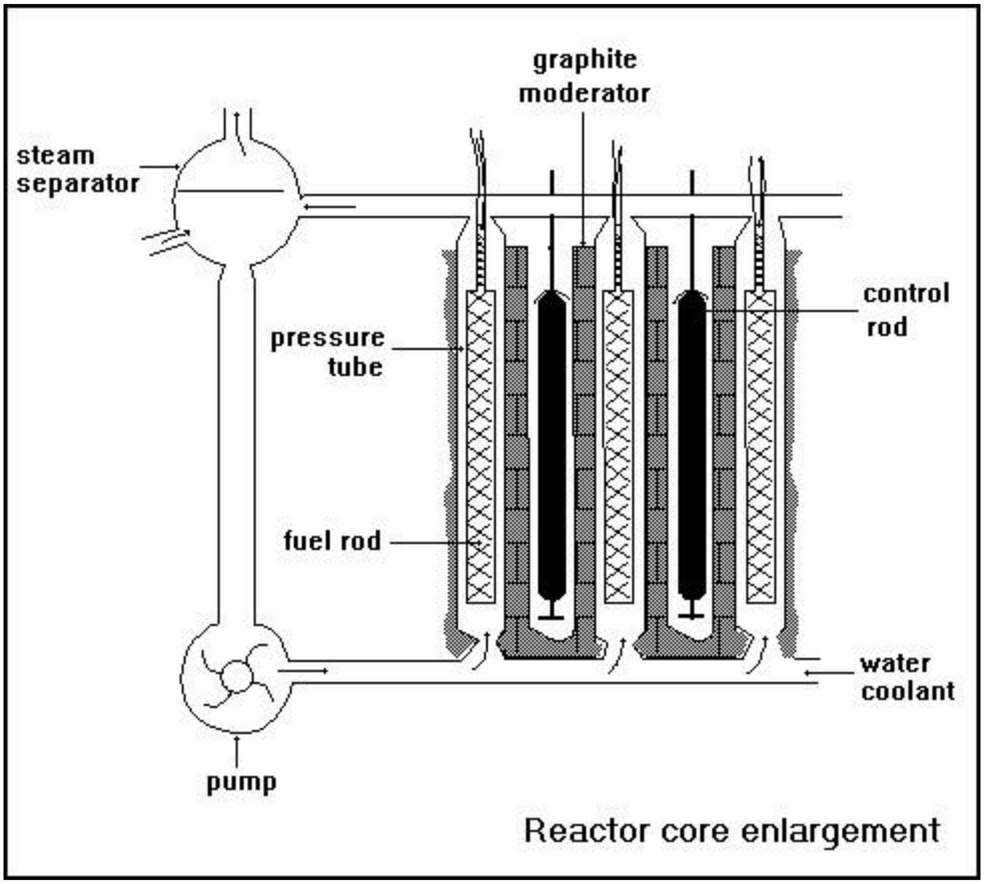
Three Mile Island

Commercial power reactors built in the United States typically use water as both the coolant and moderator. This applies to both PWRs and BWRs. The coolant carries the heat away that is produced by the reactor. The moderator is what slows down neutrons produced from fission. Neutrons born from fission are prompt neutrons and to successfully interact with U-235 to cause fission must be slowed down. The hydrogen atom in water is about the same size as a neutron and interacts with neutrons in an excellent way, similar to billiard balls striking each other, to slow them down. These neutrons can interact with the U-235 to cause fission. These reactors are said to be inherently stable. This is because as power is increased the water heats up and becomes less dense. Therefore, there is less interaction with the neutrons and some may escape the reactor. This provides a negative feedback to decrease power. The regulation controlling the design of United States reactor can be found in the Code of Federal Regulation (CFR). It is located in Title 10 CFR Part 50 Appendix A, General Design Criteria. Criterion 11, Reactor Inherent Protection, applies. A link to the NRC website for 10 CFR is given below:

http://www.nrc.gov/reading-rm/doc-collections/cfr/

Chernobyl

The reactor at Chernobyl used water as a coolant but graphite as a moderator. Chemical elements with a low atomic number are effective in slowing down neutrons. Graphite (carbon) like water has a low atomic number and is used to slow down neutrons. Water absorbs neutrons as well as slowing them down. Water is less efficient as a moderator then graphite. With a more efficient moderator the enrichment of U-235 used in the fuel can be less. Chernobyl used pressure tubes containing fuel rods with water around the fuel. The pressure tubes were placed in blocks of graphite. As power increased some of the water surrounding the fuel rod would boil. These voids resulted in less neutron absorption in the water and better moderation by the graphite. This caused power to increase. The reactor had a positive void coefficient. This resulted in a positive feedback to increase power. Something else must be done such as inserting control rods to turn power.



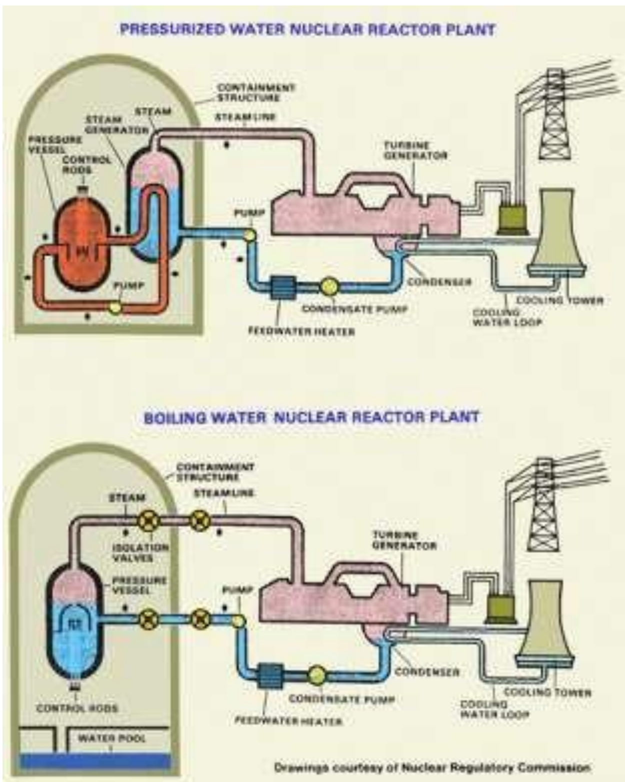
The change in reactivity per percent change in power is called the power coefficient. For Chernobyl the reactor had a positive power coefficient. The power coefficient is the summation of the moderator temperature coefficient, fuel temperature coefficient, void coefficient, and anything else that temperature affects power. Different type of reactors may have one the coefficients as the dominant contributor to the power coefficient. The values of the coefficient vary as conditions change in the reactor.

Currently, a reactor with a positive power coefficient is not allowed to be licensed in the United States for commercial use. Why would the Soviet Union choose a reactor design like Chernobyl? The Chernobyl design had a dual purpose of power production for electricity and plutonium production. Plutonium is used in nuclear weapons. Plutonium does not occur in nature but can be produced in a nuclear reactor. The U-238 in the fuel can adsorb a neutron and decay to plutonium. Having the fuel located in pressure tubes, the reactor can be partially refueled while operating. After about a month of operation the fuel can be removed to recover the plutonium. The plutonium can fission also by fast neutrons and is not left in the reactor longer than necessary for the production of plutonium from U-238. The plutonium is recovered from the fuel by a chemical separation process.

The United States back in 1943 as part of the Manhattan Project built a reactor at Hanford, Washington for plutonium production. It was a water cooled and graphite moderated reactor also. Plutonium from this reactor was used in one of the first atomic bombs. Several plutonium reactors were built at Hanford but all have ceased operation.

Fukushima

The six reactors at Fukushima were BWRs. They are similar in design to BWRs licensed in the United States. Water boils in the reactor and steam is supplied to the turbine generator without the steam generator used in a PWR. As long as water can be supplied to the reactor vessel the fuel can be protected from overheating.



In a sense, BWRs are thought to be simpler to protect in an accident situation. The reactor can be depressurized and as long as water can be pumped into the vessel core cooling is maintained. If the water boils in the core this helps remove heat. However, a source of power is necessary to run a pump. The two sources of power by design are offsite power or the electrical gird connection and onsite power from the emergency diesel generators.

4. Containment

Three Mile Island

One of the big differences between TMI and Chernobyl was that TMI had a containment structure. At TMI the primary side was enclosed in a concrete steel reinforced containment. This structure was designed to withstand the effects of a loss of coolant accident. The internal design pressure for containment was around 60 pounds per square inch. The design requirement for reactors built in the United States is located in Title 10 CFR Part 50 Appendix A, General Design Criteria 16, Containment Design.

Criterion 16--Containment design. Reactor containment and associated systems shall be provided to establish an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment and to assure that the containment design conditions important to safety are not exceeded for as long as postulated accident conditions require.

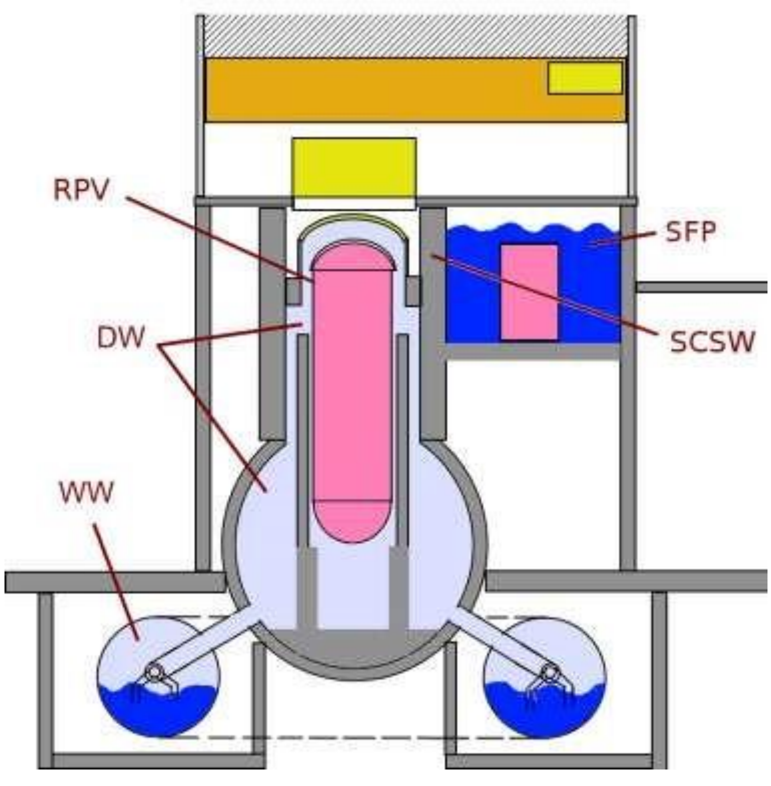
Another way of thinking about this is probabilistic risk assessment. Two terms that are used are core damage frequency (CDF) and large early release frequency (LERF). CDF relates to the probability of damage to the reactor. LERF relates to the probability of a radioactive release. The accident at TMI did damage to the reactor core but it was contained inside the containment building. At TMI, CDF was a factor but not LERF.

Chernobyl

Chernobyl was inside a building enclosure but it was not designed for an accident. The explosion and fire at Chernobyl destroyed a part of the building over the reactor resulting in a direct release path of radioactivity to the air. This type of reactor could not be licensed in the United States without a containment structure.

Fukushima

The reactors at Fukushima were BWRs designed by General Electric. The containment for Units 1-5 were Mark 1 containments with Unit 6 having a Mark 2 containment. The Mark 1 containment looks like an inverted light bulb called the drywell (DW). The reactor pressure vessel (RPV) is contained inside the drywell. The drywell is connected to a suppression pool or wetwell (WW). The spent fuel pool (SFP) containing used fuel is located in the building called the reactor building.



After the tsunami caused the loss of the backup emergency diesel generators, there was no electric power to supply the emergency core cooling water pumps. The only available source of water to the reactor was from the Reactor Core Isolation Cooling (RCIC) system. RCIC is a small steam driven turbine pump that takes steam from the vessel and pumps water into the vessel. However, this system needs battery power for control. After about eight hours battery power was lost and RCIC stopped supplying water to the vessel. The reactor began to overheat. The fuel rods have a cladding on the outside made of Zircaloy. At high temperatures there is a Zirconium fuel cladding water reaction that produces hydrogen. Without electrical power for ventilations systems to operate the hydrogen began to build up resulting in explosions in several of the units causing damage to the external structure of the reactor buildings.

Additionally, there were concerns that water had leaked out of the spent fuels pools and the spent fuel was possibly damaged. The spent fuel pools are located on the refueling floor inside the reactor building.

5. Emergency Notification

Three Mile Island

The accident at TMI occurred around 4:00 a.m. on March 28, 1979. At 7:45 a.m. the same morning the Nuclear Regulatory Commission (NRC) Regional Office at King of Prussia, PA was informed. At 8:00 a.m. the NRC headquarters in Washington D.C. was notified. Within a few hours the facts that an accident had occurred was well known. The requirement for an emergency plan for a nuclear plant in the United States is in 10 CFR Part 50.47, Emergency Plans. Likewise, immediate reporting requirements are in 10 CFR Part 50.72.

Chernobyl

On the other hand, the accident at Chernobyl occurred the morning of April 26, 1986. It was not known outside the Soviet Union that a major release of radioactive material had occurred until workers at the Forsmark nuclear plant in Sweden about 680 miles away detected radioactive particles on their clothes around noon on April 28, 1986. No problems were found at the Forsmark plant which caused the search for the source.

A Soviet Union government team arrived at Chernobyl the evening of April 26, 1986. They found that two workers were dead and 52 were in the hospital. The evidence of extremely high levels radiation and a number of cases of radiation exposure was acknowledgement of the reactor destruction. On April 27, 1986, the community of Pripyat of 50,000 residents located next to Chernobyl was told to evacuate. This occurred 36 hours after the accident but was kept silent outside the Soviet Union.

If an accident of the magnitude as Chernobyl had occurred in the United States, prompt implementation of the emergency plan including notification and protective actions such as sheltering and evacuations are required by federal law to be quickly implemented.

Fukushima

The magnitude of the earthquake and resulting tsunami on March 11, 2011 made this event quickly know worldwide. The United States Nuclear Regulatory Commission (NRC) staffed its Emergency Operations Center the day of the event. Days later some NRC personnel were sent to Japan to assist.

The damage at Fukushima evolved over several days as the reactors overheated and hydrogen explosions occurred. The ability to cope with the accident was hampered by the large loss of life and infrastructure damage of the surrounding community.

6. Radiation Release

To understand this section a term for the amount of radiation releases will be reviewed. Curie (Ci) is a term used to describe the amount of radiation released. The Ci is anything that produces 3.7×10^{10} disintegrations per second. In the SI system one Ci equals 3.7×10^{10} Becquerel (Bq).

Three Mile Island

At TMI the release was estimated to be 15 to 17 Curies. Much of this release came from systems that connected to the primary side. These systems were located in the auxiliary building which is adjacent to the containment building. The auxiliary building is vented to the atmosphere. The radioactive gases such as xenon and krypton leaked out of these systems into the atmosphere. It is important to realize that the damaged fuel remained inside the reactor vessel which is housed inside the containment building.

Chernobyl

While at Chernobyl, the release was estimated to be 5.2 million TBq. One TBq is equal to 27 Curies. Chernobyl released 140.4 million Curies which is about 5% of the core. There is a range of estimates of the radiation released. However, this is several million times more than was released at TMI. As a result of the initial explosion and fire part of the building containing the reactor was destroyed leaving a direct path to the atmosphere. The fire was a difficult fire to put out. A graphite fire is similar to a charcoal fire. Radioactive gases as well as radioactive elements of iodine, strontium, cesium, and plutonium went into the atmosphere.

Fukushima

The amount of radiation released at Fukushima was about 900,000 TBq. Like Chernobyl, there is a range of numbers for the estimate. This converts to 24.3 million Curies. Compared to Chernobyl the amount was about 17.3 % of the amount released at Chernobyl.

7. Health Effects

Next, Rem is a unit of absorbed dose. The name comes from Roentgen Equivalent in Man. It is a unit for measuring amounts of radiation, equal to effect that one roentgen of X-rays or gamma rays would produce in a human being.

While there is not a correlation between Rem and Curie, there is an estimating tool or rule of thumb. It is called the Curie-Meter-Rem rule. It is based on cobalt, Cobalt-60. It states that for a one Curie point source of Co-60 at a distance of one meter gives one Rem in one hour. It can be seen from this rule of thumb that a large Curie release could result in large exposure of radiation to a person.

The effects of radiation on people are considered in two groups. One is high doses and is called acute effect. The other is low dose and is called chronic effect. The annual limit for radiation workers is 5 Rem per year. Most workers never come close to this limit. For the general population about 20% of the people will die from cancer. Out of 10,000 people 2,000 will die from cancer. If a radiation worker receives one Rem over a year there is a slight increase in the cancer death rate. There would be an additional four deaths out of 10,000 for radiation workers.

Three Mile Island

At TMI, it is estimated that there was only 1 to 2 additional cancer deaths to the general population which could be attributed to the radiation release.

Chernobyl

If a worker exceeds the annual limit in a short time then the worker may experience acute radiation syndrome. The initial signs are nausea, vomiting, fatigue, and loss of appetite. Below a dose of 200 Rem these may be the only signs of radiation exposure. About 50% of people die if they receive 400 Rem. With medical treatment, it can only be effective if the dose is below 1,000 Rem.

At Chernobyl 134 plant workers and fire fighters received from 800 to 1,600 Rem. Of these 28 died within three months. Two died within the first days from injuries from the fire and radiation.

There was widespread contamination from the Chernobyl accident. A large number of children received substantial radiation doses in the thyroid after drinking milk contaminated with radioactive iodine. There have been about 4,000 cases of thyroid cancer of which 99% were successfully treated. In addition, it is estimated that there has been about 4,000 cases of radiation related cancer deaths to the emergency workers and people who lived near the plant. The health effects of Chernobyl have been studied extensively since the accident in 1986.

Fukushima

There were two workers found dead in the plant days after the disaster. They were found in the basement of the Unit 4 turbine building. They most likely ran during the tsunami. The tsunami itself resulted in an estimated 20,000 casualties. Nearly 600 deaths were disaster related. These were the result of injured people, especially elderly people, being evacuated from the emergency zone.

There were no direct deaths from radiation exposure. At least six workers exceeded their legal lifetime limits. Another 300 workers received significant radiation doses. The estimates for predicted future cancer deaths vary widely. A range of 100 to 1,000 will be used to compare to the other nuclear accidents. This range correlates to the 4,000 deaths from Chernobyl when considering the amount of Curies released.

8. International Nuclear Event Scale

The International Nuclear Event Scale is established by the International Atomic Energy Agency (IAEA).

The ratings are as follows:

7 – Major Accident

6 – Serious Accident

5 – Accident with Wider Consequences

4 – Accident with Local Consequences

3 – Serious Incident

2 – Incident

1 – Anomaly

Chernobyl was classified as a 7 for being a major accident.

TMI was classified as a 5 for an accident with wider consequences. The core was partially melted and the TMI-2 was decommissioned. Sweeping changes came to the nuclear industry because of TMI.

Fukushima was not initially classified as a 7. Units 1, 2, and 3 were classified as 5. Collectively, Fukushima was classified as a 6 but later raised to a 7.

There are other accidents at military or research facilities with accident level classifications which are not discussed in this course.

9. Aftermath

Three Mile Island

After the TMI accident studies were conducted by the NRC, nuclear industry, and an independent study for the U.S. President. The Kemeny Commission was the study conducted for President Carter. The commission was critical of the plant designer, the utility, and the NRC. The commission report indicated a number of equipment failures. However, a number of human failures contributed to the accident. The report was critical of the utility and NRC regarding resolution of safety issues.

The NRC conducted several studies of the accident. Probably the document that most nuclear plant personnel are familiar is NUREG 0737, Clarification of TMI Action Plan Requirements. It contains all the new requirements for plant equipment, changes to operator training and staffing, improved instructions, improved instrumentation and controls, enhancement of emergency preparedness. There was also improvement in regulatory oversight.

The nuclear industry formed the Institute of Nuclear Power Operations (INPO) to promote excellence in the industry and provide a unified approach to nuclear issues.

TMI-2 is permanently shut down and defueled. All the radioactive water was decontaminated and evaporated. All reactor fuel and radioactive waste has been shipped to a Department of Energy facility. TMI-1 had its license temporarily suspended. In 1985 it was permitted to resume operation. It is in operation today.

Chernobyl

The number of short term and long term deaths from the accident has been discussed. About 130,000 residents within a 30 mile radius of the plant were permanently relocated. There have been numerous studies about Chernobyl and the long term health effects.

The focus of activities at the site has been building a structure to safely shelter the damaged unit 4 and bring an end to operation of the other three units. The current day status of the units is given below:

Unit 4 – destroyed in the 1986 accident.
Unit 2 – shutdown in 1991 after a serious turbine fire.
Unit 1 – closed in 1996.
Unit 3 – closed in 1999.

With the 25th anniversary of Chernobyl efforts have started to build a giant shelter over Unit 4 and the original sarcophagus. This plan is called the Shelter Implementation Plan (SIP). These projects are funded by the United States and other members of the G7, the European Union, and other donor countries.

The NRC reviewed the Chernobyl accident for lessons learned. It concluded that there no change in design of United States plants required due to the accident.

Fukushima

There is an active large cleanup effort at the Fukushima site. Units 1-4 which were severely damaged were decommissioned in April 2012. Units 5-6 which were slightly damaged were decommissioned in December 2013. Presently the units are stable and seawater is being pumped through the reactors to cool them. Some of the water is leaking out into the buildings.

This water is being pumped out, filtered, and returned to the reactor. Plans are to remove the spent fuel from the fuel pools in two years and remove fuel from all the reactors in ten years.

Weekly reviews of the Fukushima cleanup can be found on websites of World Nuclear News (www.world-nuclear-news.org) or Nuclear Street (www.nuclearstreet.com).

Fukushima implications have been worldwide. In the United States, the NRC had ordered changes because of the disaster. The changes and present status can be found on the NRC website (www.nrc.gov). There is a link on the left under "Spotlight" that takes one to Japan Lessons Learned. A three-tiered prioritization of the recommendations was taken by the NRC. The tier one activities are summarized below:

> Mitigation Strategies – to enhance the capability to maintain plant safety during a prolonged loss of electrical power
>
> Containment Venting System – to provide a reliable hardened containment vent system for BWRs with Mark I or Mark II containment designs
>
> Spent Fuel Pool Instrumentation - to provide a reliable wide-range indication of water level in spent fuel storage pools
>
> Seismic Reevaluations - to reanalyze potential seismic effects using present-day information to determine if safety upgrades are needed
>
> Flooding Hazard Reevaluations - to inspect existing plant protection features against seismic and flooding events, and correct any degraded conditions
>
> Seismic and Flooding Walkdowns - to inspect existing plant protection features against seismic and flooding events, and correct any degraded conditions
>
> Emergency Preparedness Staffing and Communications - to evaluate potential strategies that may further confine or filter radioactive material if core damage occurs

Looking at these tier one activities provides a good general understanding of the activities the plants in the United States are actively undertaking.

In Japan all the operating reactors were ordered shutdown by the Japanese government after Fukushima. Each plant must pass a series of stress tests prior to restart. Some 50 reactors provided about 30% of Japans electricity. Attempts to restart some of the plants have been challenged in court and none have restarted as of May 2014.

TOP

Table of Differences

Topic	Three Mile Island	Chernobyl	Fukushima
Date of accident	March 28, 1979	April 26, 1986	March 11, 2011
Reactor Design	PWR, Inherently stable	Graphite moderated, Positive Void Coefficient	BWR, Inherently stable
Purpose	Power production	Power & Plutonium production	Power production
Containment	Yes	None	Yes
Public notification	Yes	Delayed	Yes
Radiation release	Minimal 15 to 17 Ci	5% of the core 140.4×10^6 Ci	Several reactors 24.3×10^6 Ci
Deaths (radiation) Immediate Long term - cancer	 None 1 to 2	 30 4,000	 None 100-1000
Present status	Unit 1 – operating Unit 2 - decommissioned	Unit 1 – closed in 1996 Unit 2 – closed in 1991 Unit 3 – closed in 1999 Unit 4 – destroyed in 1986	Units 1 - 4 decommissioned in April 2012 Units 5 - 6 decommissioned in December 2013