Lesson 2: Plant Stability

Lesson Overview

The purpose of this lesson is to examine the events during a reactor accident that could potentially cause public radiation exposure. This lesson also covers components of plant systems designed to control the threat of exposure.

Upon completion of this lesson, you will be able to:

- Describe what failures must occur to cause major off-site consequences.
- Describe the components of plant systems designed to control the threat of major off-site consequences.

Remember you can access the glossary in one of two ways throughout this course. You can select the glossary button in the top right hand corner of each main content screen. In addition, on content screens you can select underlined words to access their definitions in the online glossary. Selecting an underlined word will take you directly to its definition in the glossary.

This lesson should take approximately **35 minutes** to complete.

Radioactivity of Fission Products

In Lesson 1, you learned that when a neutron strikes a U-235 atom, the U-235 atom absorbs it. This makes the nucleus of the U-235 atom unstable and causes it to split into two or more lighter atoms called fission products.

Fission products are radioactive and must be kept inside the reactor. The fission process must be stopped and the reactor shut down if there is an accident. When the reactor shuts down, heat is still being produced by fission products. Even when the reactor is shut down, the accident is not yet over and damage could continue.

Exposure Prevention Systems

During a reactor shutdown, the plant must keep the radioactivity in, but let the heat out. Heat causes pressure to build up. To protect the containment, heat must be removed.

The plant's safety systems begin operating after the reactor is shut down.

There are two types of exposure prevention systems:

- Passive systems that contain the fission products
- Active systems that keep the barriers cool and control decay heat

Next you will learn what occurs after a reactor shutdown.

After Reactor Shutdown

Within the first hour after shutdown, heat decreases rapidly. There is a 25% drop in temperature. This is the most critical period of an accident and the one in which the most stress is placed on safety mechanisms.

One month after the accident, heat decreases level off, and a further drop in temperature occurs. This is still an area of concern because heat must continue to be removed over the long term and fission products may still be unstable.

Next you'll learn about the main source of radiation exposure to the public.

Radiation Exposure to the Public

The only location in the plant that contains enough radioiodine to pose off-site health risks is the core. It contains enough radioactive iodine (radioiodine) to cause deterministic health effects. Releasing 1 or 2% of the radioiodine within the core directly into the atmosphere creates the possibility of early health effects off-site.

Therefore, severe reactor core damage is the main event that can lead to radiation exposure of the public. This is what occurred at Three Mile Island. A combination of operator error and equipment malfunction permitted the core to become uncovered, overheat, partially melt, and release large quantities of radioactive material into the containment. While there was severe core damage at Three Mile Island, offsite exposures were very low due to the fact that the containment did its job and did not fail.

Containment Failure

After core damage has occurred, the containment structure must be protected. There are four general areas of containment failure:

- Overpressurization
- Bypass
- Direct containment heating
- Containment venting

In the next section of this lesson, you will learn about these four types of containment failure.

Overpressurization (1 of 2)

If decay heat from the core is being released into the containment and is not being removed, the pressure could cause containment failure. This decay heat must be removed for several days to weeks after reactor shutdown.

U.S. commercial reactor containments have a design leak rate of 0.1–0.25% per day at design pressure.

Most containments fail at two to three times the pressure at which they were designed to operate. It takes over 20 hours for overpressure failures due to decay heat to occur. Decay heat can be removed by:

- Sprays or containment coolers.
- Venting to release pressure.

Overpressurization (2 of 2)

Hydrogen (H2) may be produced during core damage and must be controlled by preventing the Zircaloy-water reaction. Containments at very high pressure have insufficient oxygen to allow an H2 burn. This is called inerting. In some accidents, the inerting could be lost through containment leakage. Steam can also inert a containment until the sprays come on and remove the steam. The containment can also be vented to release the excess H2.

Containment Bypass

Bypassing allows a release of radioactive materials directly from the reactor coolant system into an area outside the containment. Releases may be monitored or unmonitored. The releases may also be unfiltered, allowing iodines and particulates to escape along with krypton and xenon (noble gases). The following would cause the containment to be bypassed:

- A steam generator tube rupture (SGTR) in a PWR
- Failure to isolate the main steam lines in a BWR
- Loss-of-coolant accident (LOCA) outside of containment

Direct Containment Heating

Direct containment heating (DCH) is the collective term for everything that can happen if the core melts through the bottom of the reactor vessel—a large increase in pressure and the production of large amounts of hydrogen. Direct containment heating is possible for hours after core damage. Although this did not happen at TMI, some models indicate that the reactor vessel should have failed during the accident.

Containment Venting

Power plants have procedures for venting the containment to remove hydrogen and to release pressure. Containment venting does not consider the radioactive dose that the population may have received from any previous release that may have taken place. To prevent a very large dose due to containment failure, a smaller dose through venting may present an acceptable risk to those making the decision. Consequently, venting could result in a substantial dose off-site.

As you learned earlier in the lesson, there are many ways in which the containment can fail. Venting is predictable; however, failure is not.

Select this link to access a chart with detailed information about the types of containment failure.

Now that you know how radiation exposure can occur, let's review the barriers designed to protect the public.

Fission Product Barriers

You just learned about the four general areas of containment failure.

Next, you will learn about the three main fission product barriers designed to keep nuclear fission products away from the population:

- Cladding (fuel rods or pins)
- The reactor coolant system (RCS)
- The containment structure

On the next screens, you will learn about each of these fission product barriers.

Cladding (1 of 2)

Cladding around the fuel rods or fuel pins is the first and most important barrier. Fuel rods are made of zirconium alloy (Zircaloy) and the material from which the tubes are made is known as cladding.

Once filled with uranium fuel pellets, the tubes are pressurized with helium gas and sealed. As the reactor operates, gaseous fission products are generated and collect in the fuel rod.

Cladding (2 of 2)

Approximately 5% of the cesium, iodine, and noble gases created by fission are contained in the top of the fuel rod, an area referred to as the gap. If radioactivity in the gap is released into the reactor coolant, a gap release has occurred.

From time to time, cladding imperfection may occur resulting in the release from that particular rod. A major gap release is evidence of a serious reactor accident. The probability of a reactor undergoing a major gap release is in the order of 1 in 1,000,000 over its lifetime.

To prevent the fuel rods from failing and releasing radioactive materials into the coolant, always keep the fuel covered with water. Water transfers the heat away from the fuel rods. Excessive heat can damage the rods.

Reactor Coolant System (1 of 2)

The reactor coolant system (RCS) or primary system is the plumbing that goes around the fuel and acts as the second barrier against a release of radioactive products. This system holds the water that cools the core. Core damage can occur only if it fails. In the event of a reactor failure, this system is not 100% reliable because it has many possible failure points.

Reactor Coolant System (2 of 2)

The location at which an RCS fails provides indicators of the type of release that can be expected. It also indicates how you can keep the core covered in water. All RCSs have pilot-operated relief valves (PORVs) and safety valves that are designed to open during an accident.

Containment Structure

The containment structure encases the rods, plumbing, and water and acts as the third barrier against radioactive release. It should capture any release that makes it past the first two barriers. It is designed to:

- Withstand the large increase in pressure resulting from a break in the RCS (called a blowdown).
- Reduce the amount of fission products released into the environment during an accident.
- Remove the long-term heat generated by fission products as they decay.

If the containment structure does not fail or leak abnormally, there will be very low dose off-site in the event of an accident, even if the reactor sustains very severe core damage. This was observed at Three Mile Island (TMI).

Let's examine containment designs for pressurized water reactors (PWRs) and boiling water reactors (BWRs).

Pressurized Water Reactor (PWR) Containment Designs (1 of 2)

There are several types of containment designs.

PWR containments are large, strong concrete rooms that contain the reactor plumbing. Their size and strength, as well as other features, such as sprays, suppression pools, and ice vats, that wash fission products and remove heat, enable them to withstand blowdowns. The heat removal process occurs on a long-term basis.

Pressurized Water Reactor (PWR) Containment Designs (2 of 2)

Some PWR containment designs use ice to condense steam, thereby keeping the containment pressure low during an accident. This may also be accompanied by containment sprays (a feature found in PWRs and BWRs), which are also used to condense steam.

Boiling Water Reactor (BWR) Containment Designs

Older boiling water reactor (BWR) containments are very small and have suppression pools where the steam is condensed and fission products are filtered. Later-generation BWR containments resemble PWR high-pressure containments—large and robust. BWR containments also have sprays to reduce pressure by condensing gases. Some BWR containments employ hydrogen igniters near the top of containment to control-burn hydrogen, which may be generated by a Zircaloy-water reaction during an accident.

Three major containment types were created during the evolution of BWR containments. Select the following links to access detailed diagrams of each of these containment types:

- BWR Mark I Containment Design
- BWR Mark II Containment Design
- BWR Mark III Containment Design

Predicting containment performance is difficult. You won't know when containment will fail until it does.

Critical Safety Function (CSF) Overview

You just learned about fission product barriers. In the next section of the lesson, you will learn about critical safety functions (CSFs).

CSFs are actions that were developed to:

- Protect the integrity of the fission product barriers.
- Allow emergency operations during accident conditions.
- Outline what has to be done, independent of the nature of a failure, to protect the containment and the core.

The following questions should be asked in this order to ensure that CSFs are adequately maintained:

- Is the reactor shut down?
- Is the core covered with water? How? How do you know?
- How is the decay heat being removed? To where? How do you know?
- What is the status of the vital auxiliaries (AC and DC power) and how do you know?

CSF #1: Shut Down the Reactor

Shutting down the reactor is the first and most important CSF.

The reactor protection system (RPS) is used to shut down, or scram, the reactor. This is accomplished by the rapid insertion of control rods to stop the fission. Control rods are materials that are neutron poisons; they absorb neutrons. Boron may also be injected to absorb neutrons.

It is crucial that the reactor be shut down during an accident because the safety systems are not designed to perform their functions while the reactor is operating, the reactor must be shut down.

If the reactor fails to shut down, you must rely on its emergency cooling systems. Failure of the automatic system to shut down is called anticipated transient without scram (ATWS).

CSF #2: Keep the Core Covered and Cool (1 of 3)

The second CSF is to keep the core covered and cool. Water is used to remove the heat generated by the fission within the core. Failure to remove the heat can lead to fuel pin damage and RCS failure.

A break in the RCS will lead to water loss, which will cause the core to be uncovered if the water is not replaced. An uncovered core will heat up at 1°–2° F per second (0.5° -1° C/sec) and eventually cause fuel clad failure and release of fission products.

When the core temperature rises to between 1,400 and 2,000 degrees, between 15 and 20 minutes after the core is uncovered, the zirconium metal of the fuel rods reacts with the water cooling the core. This reaction produces hydrogen, which accelerates the temperature increase in the core. This is known as the Zircaloy-water reaction.

CSF #2: Keep the Core Covered and Cool (2 of 3)

Select this link to access a table that describes the time frame of possible damage to the core in the event of a failure in the cooling system.

To summarize this table, if there is no injection of coolant into the containment structure, after 15 to 45 minutes, there could be:

- Cladding failure.
- Hydrogen gas generation.
- Gap release.
- Local fuel melt in the uncovered core.

After 30 to 90 minutes of being uncovered, the core may be uncoolable and:

- There may be rapid release of volatile fission products.
- The molten core may also slump to the bottom of the vessel.

After one to three or more hours, the core may melt through the vessel. There may also be

- Maximum core melt and hydrogen gas formation.
- Maximum in-vessel release of fission products.

CSF #2: Keep the Core Covered and Cool (3 of 3)

The emergency core cooling system (ECCS) is utilized to keep the core cool and covered. In the early phase of an incident, high- and low-pressure injection pumps supply coolant to the reactor. Water is initially supplied from storage tanks and then from recirculation of water from containment. The heat is removed from the core and released into containment.

CSF #3: Remove Decay Heat

The third CSF is removing decay heat. For long-term cooling, hot water (potentially containing radioactive material) is pumped from containment to heat exchangers, releasing the heat to the environment.

CSF #4: Maintain Vital Auxiliaries

The last CSF is to maintain vital auxiliaries. AC and DC power and console control must be maintained in order to read instruments, to operate pumps and valves to inject water, and to allow other safety features to function. Emergency diesel generators and batteries are vital auxiliaries.

As you will learn in this course, the loss of vital auxiliaries was critical in the Fukushima nuclear incident.

Other CSFs

Other CSFs include:

- Controlling the containment pressure through use of sprays, ice, and venting
- Controlling hydrogen buildup in containment through the use of igniters and recombiners
- Maintaining containment integrity
- Preventing direct containment heating from reactor vessel melt-through by such means as containment flooding

Lesson Summary

Let's summarize what you have learned in this lesson:

- Severe reactor core damage is the main event that can lead to radiation exposure of the public.
- There are four general areas of containment failure:
  - Overpressurization
  - Bypass
  - Direct containment heating
  - Containment venting
- There are three main fission product barriers designed to keep nuclear fission products away from the population:
  - Cladding (fuel rods or pins)
  - Reactor coolant system
  - Containment structure
- There are four main critical safety functions (CSFs): Shutting down the reactor
  - Keeping the core covered and cool
  - Removing decay heat
  - Maintaining vital auxiliaries

The next lesson will cover core damage assessment and release assessment.