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Basic Nuclear Reactor Safety — Part 1


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All energy forms have upsides and downsides. Nuclear energy is no exception.

Its upside is the enormous amount of energy produced by uranium-235 (U-235) fission — about 1.5 million times more energy per gram of fuel than that of hydrocarbon fuels.

The downside is that energy from the decay of radioactive fission products continues to produce heat in the reactor fuel even after the fission reaction is terminated. Fission products have half-lives ranging from seconds to millions of years. At reactor shutdown, the power generated by fission product radioactive decay is about 7.5 percent of reactor operating power. While decay heat generation drops off as shorter **half-life** radioisotopes disappear, one week after reactor shutdown, decay heat power is still about 1.5 percent of reactor operating power. This radioactive **decay heat** must be removed from the reactor fuel to prevent overheating, fuel melting, and release of radioactive material.

This is Part 1 of a two-part series that will address nuclear power plant safety objectives and the associated safety measures designed to achieve those objectives.

Nuclear Power Plant Safety Objectives

There are three operational safety objectives associated with ensuring the integrity of the nuclear reactor fuel and of the multiple radioactive fission product retention barriers:

1. Reactor core **reactivity control** (i.e., neutron population control)
2. Reactor core **heat removal** capability
3. **Fission product containment**

These safety objectives are accomplished by means of a three-level defense-in-depth approach. Level 1 is focused on **prevention**, which seeks to avoid completely those operational occurrences that could result in system damage, loss of fuel performance, and abnormal releases of radioactive material.

The goal of Level 2 is **protection**, which seeks to terminate unlikely, low-probability incidents and operational occurrences that cause reactor shutdown and could lead to minor fuel damage and small releases of radioactivity.

The emphasis of Level 3 is **mitigation**, which seeks to limit the consequences of accidents if they occur despite the intervention of prevention and protection measures.

Prevention measures include reactor design features that provide inherently stable operating characteristics and safety margins, operational instrumentation and automatic controls, plant personnel training, operating procedures, risk-informed maintenance, and periodic component/system testing and inspections.

Protection measures include automatic reactor shutdown, automatic monitoring and safety-system initiation, and guidelines and procedures for managing operational upset conditions.

Mitigation measures include emergency reactor core cooling and heat removal systems, emergency electrical power systems, radioactivity containment barriers/structures, emergency operating procedures, and an emergency plan to control and minimize the consequences of potential accidents.

Normal Operational Safety

Normal plant operational safety is accomplished by means of defense-in-depth Level 1 (prevention) measures that maintain reactor core reactivity control, provide decay heat removal capability, and assure fission product retention barrier integrity.

Reactivity Control

Reactor reactivity control (i.e., neutron population control) is assured by reactor design features that provide negative feedback for positive reactivity changes in the reactor core. This control is independent of reactor operator action and operates on very short time scales to ensure a controllable rate of change for reactor power level increases.

A redundant Reactor Protection System that can be manually actuated by a reactor operator or automatically actuated by numerous reactor trip signals ensures that neutron-absorbing control rods can be inserted quickly into the reactor core to terminate the reactor core fission chain reaction.

Decay Heat Removal

Following reactor shutdown, the decay heat load continues to decrease as the shorter half-life radioisotopes decay away. However, the longer half-life radioisotopes continue to generate heat for many years. A nuclear power plant shutdown heat removal system consists of redundant pumps to circulate cooling water to remove heat from the reactor core, and redundant heat exchangers that transfer the heat to a plant component cooling water system.

Even after used fuel is removed from the reactor it needs to be placed in a tank of circulating water to remove decay heat for a few years until the generated heat load has been sufficiently reduced such that air cooling is adequate to keep the fuel rods from overheating.

Fission Product Retention Barriers

There are four fission product retention barriers. The first barrier is the uranium oxide fuel pellet. Most fission products are retained within the fuel pellet ceramic matrix.

The second barrier is the fuel rod that contains the nuclear fuel pellets. All fission products are retained within the fuel rods as long as they remain intact.

The third barrier is the reactor primary coolant system piping and components, which provide a physical barrier to fission-product release in the event of fuel rod damage.

The final barrier is the reactor containment building structure. This is the ultimate barrier to preventing fission-product release to the environment in the event of nuclear fuel damage.

Continue reading Part 2 here.

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