Energy Engineering and Systems Analysis

Nuclear Fuel

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Fuel Type and Composition

Nuclear fuel is the source of energy production in a nuclear reactor and it is manufactured in different forms depending on reactor type. Fuel used in most operating commercial nuclear reactors, including both pressurized (PWR) and boiling (BWR) water reactors, is in the form of uranium oxide (UO_2) pellets that are typically about 1 cm in diameter and 1 cm long. Manufacturing of this form of uranium fuel starts with mined uranium that passes through processes of conversion and enrichment before it is made into a final form of solid dense pellets. Typically UO_2 fuel is enriched in the fissile isotope U-235 to about 3-5% (U-235 fraction in natural uranium is about 0.7%) compared to the fertile isotope U-238.

Fuel Rod and Fuel Assembly

A fuel rod consists of a number of pellets that are stacked (about 4 to 5 meters long) into a metallic zirconium alloy (zircalloy) thin tubes (or cladding) that are 0.4-0.8 mm thick and sealed from both ends. A thin gap between the pellets and cladding is filled with helium gas (pressurized to about 3 atmospheric pressure) to improve heat transport from the fuel pellets to the reactor coolant.

A number of fuel rods are arranged in a grid *assembly* which restricts fuel vibration and movement in all directions (see figure). The typical number of fuel rods per assembly varies by reactor designs and can be between 49 to over 300 rods per assembly. The number of assemblies in a reactor core and the frequency of loading and discharging assemblies in and out of the reactor depends on reactor type and power production. For example, a 1100 MWe pressurized water reactor may contain 193 fuel assemblies composed of over 50,000 fuel rods and some 18 million fuel pellets.

Typical reactor refueling intervals vary from 12 to 24 months, after which the reactor is shutdown for a few weeks to a month for refueling and maintenance operations. The current average fuel burnup (energy per unit uranium mass) achieved in reactors is up to about 50,000 MWd/t (Mega-Watt-day/metric ton of initial uranium), with future goals of increasing the burnup to 70,000 MWd/t or more.

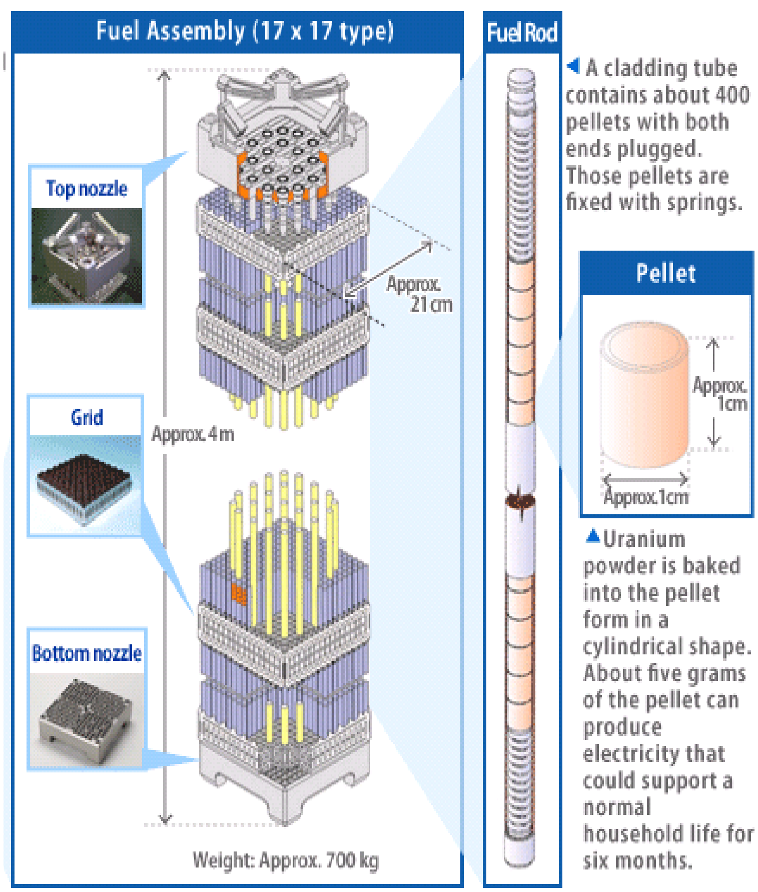

Diagram of a pressurized water reactor assembly (©Nuclear Fuels Industries, Ltd)

Defense Barrier

A fuel rod consisting of fuel pellets and surrounding cladding tube provides a barrier against release of radioactive materials to the outside under the extreme reactor operating conditions. The first barrier against the release of radioactive fission products that are produced during the fission process is the fuel pellet. Fuel cladding is the second barrier that separates radioactive fuel from the rest of the reactor system. Although fuel fabrication procedures are stringent and require high quality assurance procedures to minimize manufacturing defects, fuel failures can take place during reactor operations. In addition, limited fuel failures can take place due to other operational phenomena such as pellet cladding interaction and crud deposition. Small amounts of fuel leaks (due to rod failure) are allowed during normal operations and anticipated off-normal conditions. Those failures do not affect reactor safety and rather affect reactor operations. The nuclear industry has set a goal of eliminating those leaks aiming at zero fuel failure operations in the near future.

Operating Conditions

Although the melting point of UO_2 is over 2,800^oC, fuel is usually operated at a much lower peak centerline temperatures (less than 1,400^oC). This provides enough margin to fuel melting and to loss of fuel integrity. In general, pre-specified design criteria and limits for nuclear fuel operating conditions are aimed at ensuring fuel integrity during normal reactor operations and off-normal conditions.

Design Criteria and Limits

Design criteria for fuel rods are such that fuel integrity is maintained during normal operations and during off-normal events. Even under off-normal conditions fuel design criteria requires maintaining fuel integrity, ability to cool the fuel, ability to shutdown the reactor, and ability to maintain specified acceptable design limits.

Temperature Limit: Fuel design limits are prescribed to ensure cladding integrity under the severe reactor operating conditions and during off-normal conditions. There are design limits set by the NRC for cladding temperatures and heat fluxes, in addition to limits on cladding oxidation and hydrogen generation from chemical reaction between water/steam with cladding. The cladding temperature limit is 2200^oF (1204^oC) for zircalloy cladding of LWR fuel. This outer cladding temperature limit is related to the instability of water and two-phase boiling that can lead to runaway heating of the cladding, and eventual hydrogen release as a result of cladding oxidation and interaction with generated steam. Scenarios when such a high temperature limit is exceeded include a loss of coolant accident (LOCA) with possibility of evaporation of the water cooling the fuel rods, as the water temperature rise while heat generation in the fuel continues (even if the reactor is shut down, heat generation from decay heat, at the rate of a few percents of the fission heat generation, can lead to overheating of the cladding under those accident conditions).

Heat Flux Limit: The other important design limit is related to the critical heat flux (CHF) which is a major factor in limiting the outer cladding temperature to slightly above the saturated temperature. Approaching CHF leads to a sudden reduction in heat transfer capability of the coolant and associated increase in cladding temperature. It is important that those temperature and heat flux limits are maintained to assure fuel integrity and prevention of release of radioactive materials to the outside of the reactor system.

Limits in Spent Fuel Pool: Heat generation in fuel continues after its removal from the reactor core due to decay heat production. Consequently, spent fuel is cooled and stored in a water pool near the reactor where it remains covered by about 20 feet of water (per NRC regulations) for a number of years until decay heat generation is reduced. About 50^oC limit is usually set for water temperature in the pool to prevent fuel degradation and limit changes in water chemistry. Increase in water-pool temperature beyond this limit or drainage of water in the pool and exposure of fuel rods to the atmosphere can compromise spent fuel integrity.

Limits in Dry Storage: After cooling in wet storage pool for 10 to 20 years, spent fuel can be sent to interim dry storage facility on the nuclear plant site. Again, there are design limits for spent fuel cladding temperature to prevent cladding failure during storage. Possible failure is mainly caused by cladding creep rupture and mechanical strength degradation combined with hydride re-orientation. The United States design limit for cladding temperature in dry storage is 40^oC.

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