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The Fukushima accident sequence

The earthquake and the subsequent tsunami that devastated part of Northeast Japan on March 11th, 2011, led to a series of accidents in the Fukushima Daichi nuclear plant, constructed and operated by Tokyo Electric Power Company (TEPCO). Only three of the six units of the plant (all of them boiling water reactors, BWR) were operating at that time. The sequence of events followed roughly the same pattern for the three operating reactors. During the earthquake, the reactors were automatically halted by the insertion of the control rods. The residual heat removal system, requiring power supply, provided cooling during nearly one hour, until the tsunami (far beyond the design basis of the plant) rendered the diesel generators inoperative. These generators had started up automatically when external supply from the electricity grid failed because of the earthquake. In these conditions, a passive system is able to evacuate the core thermal power into the containment; the drawback of this operating mode is that containment pressure builds up and after a time the water level in the reactor vessel shrinks to the point that partial dry-out of the fuel rods can occur. Steam venting into the upper floor of the reactor building, in order to reduce the pressure of the primary containment, resulted in a large hydrogen explosion. The presence of a large amount of hydrogen accompanying the steam is a symptom that core dry-out has caused an overheating of the fuel rods to the temperature of clad oxidation. Indeed, taking into account both the difficulties of maintaining a proper core cooling and the evidences of high radiation levels and fission product release, it must be assumed that a partial melt occurred in the core of the three reactors. This fact makes heat extraction from the fuel even more difficult, as the amount of accessible surface becomes smaller. Furthermore, molten fuel accumulates in the lower plenum of the reactor vessel which might break because of the heat. The cooling of the pools containing the spent fuel was also affected by the loss of electricity supply. Water evaporation because of residual heat eventually resulted in exposition of the spent fuel rods to air, with subsequent overheating, cladding degradation and release of fission products. Activity in the plant is now focused on restoring and maintaining the cooling capacity in the three units, to cool the core down and to maintain the integrity of the reactor vessel and of the primary containment in order to confine radioactivity, but also on keeping a sufficient water level in the spent fuel pools.

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HOW DOES A NUCLEAR PLANT WORK?

Francisco Calviño

In a nuclear power plant, heat is produced by a chain fission reaction in the reactor core. Fission is a nuclear reaction where the nucleus of a heavy atom (normally uranium) breaks into two pieces when hit by a neutron. In this process energy is liberated and carried away by the fission fragments, and neutrons are also emitted and propagate the chain reaction. In a boiling water reactor (BWR), fission energy is transferred to boiling water, and the produced steam is directly used to drive a turbine connected to an electrical generator. Steam is condensed at the turbine's outlet and returned to the reactor, closing the loop. Fission fragments are radioactive elements that decay at a fast rate into the so-called fission products. The decay of the radioactive fission products produces decay heat even after all fission reactions are stopped. When the nucleus of a radioactive atom decays, it emits radiation, which can be harmful in large doses. To avoid the release of radioactive elements into the environment multiple barriers are provided in the plant. The innermost barrier is the metal cladding of the fuel rods. The set of the thousands of fuel rods and the water surrounding them is known as the reactor's core. A steel-made vessel contains the core and acts as the second barrier. The reactor vessel is located inside the primary containment building, made of concrete and an inner lining of steel and designed to sustain strong earthquakes and other natural phenomena. This building is the third barrier. A secondary containment, the external building, is used in the BWRs.

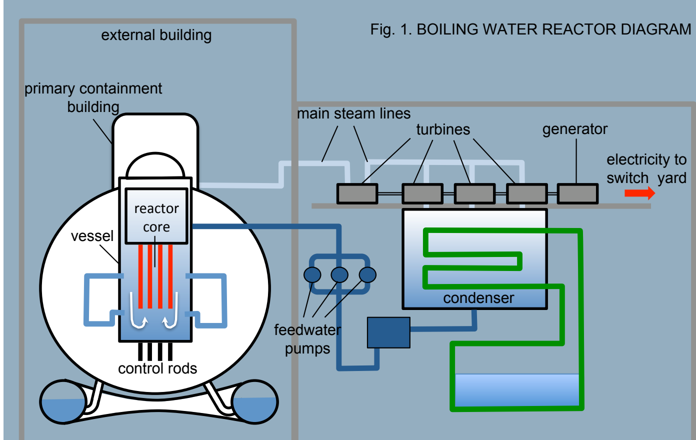

Fig. 1. BOILING WATER REACTOR DIAGRAM

SAFETY FUNCTIONS IN NUCLEAR ACCIDENTS

Three safety functions are crucial in dealing with the progression of a nuclear accident. The first one is keeping the reactor in a subcritical condition (i.e., preventing the fission reaction chain). In Fukushima, this was completed by automatic insertion of neutron-absorbing control rods into the reactors' cores and by adding neutron-absorbing boron to the cooling water.

Cooling water is needed for the second function: extracting heating power. Safety systems and operating procedures are designed to do so. Decay heat, produced even after the reactor shuts down, never becomes zero but is always decreasing, fast during the first hours and then more slowly. During days it is of the order of megawatts. Safety systems are designed in a robust way, but while passive third generation reactors will use gravity or natural circulation to inject cooling water, reactors designed in the 1970s (such as the ones in Fukushima) use electrical pumps to perform the same function. When cooling systems do not work properly, water is still a good cooling fluid because it takes a large amount of heat when it boils and transforms into steam; but steam fills a larger volume and makes the pressure rise.

This leads to the third safety function: keeping radioactivity confined. Integrity of the primary containment building must be preserved, so steam venting is necessary to avoid excessive pressure. In Fukushima, pressure also built up due to the production of hydrogen by the oxidation of zirconium cladding with water at high temperatures. Primary containment gas spaces do not contain oxygen, so that hydrogen explosions cannot occur inside. But hydrogen was inevitably vented as well into the external building. Electrical power is needed for handling accidents, and thus it is ensured by the plant design, which takes into account external events -like earthquakes and tsunamis. It is clear that in this case events surpassed the design basis. Regarding the performance of the safety systems, it is worth mentioning that some otherwise simple operations like refilling a water pool or a diesel fuel tank at atmospheric pressure, or reconnecting electrical wires, were not simple at all in the aftermath of the tsunami in the Fukushima scenario. *Francesc Reventós*

Monitoring emissions

Steam venting from a nuclear reactor, and indeed any effluent from the containment, implies the emission of radioactive airborne particles and gases into the atmosphere, forming the so-called *radioactive cloud*. Dispersion of these substances depends on the meteorological conditions. Radioactive particles in the cloud can be deposited by dry or wet (i.e. with rain drops) deposition processes, whereas noble gases are not subject to any sink process apart from their radioactive decay. To follow the cloud, there exist emergency surveillance radiological networks that contain two components: first, dose-rate monitors, which measure the radiation dose rate from the cloud and from the substances deposited on the ground, and second, monitors of particles and gas, which measure the concentration of radioactive substances in order to address their possible inhalation. In addition to these measurements, the use of atmospheric transport models is necessary in order to predict where the cloud is going to, and to inform appropriately the decision makers.

Arturo Vargas (INTE), Delià Arnold (INTE)

Decontamination

When large areas are significantly contaminated by radioactive deposition, optimized remediation measures should be applied, if justified, to prevent or reduce the internal contamination of individuals. In urban areas, open surfaces are the most affected, although wind and rain can reduce the contamination significantly. Street washing, removal of the upper soil level and removal of trees and vegetation are specific decontamination techniques that could be applied. In agricultural areas, the most effective measure is to exclude some vegetables from commercial distribution, feed animals in clean pastures, and set up a milk and meat monitoring system. In forest environments, the most effective countermeasure is to apply restrictions on the harvesting of food products, hunting practices, and collection of firewood, because applying specific decontamination techniques could harm the ecosystem even more. Similarly, in aquatic environments the main effort consists in restricting the consumption of contaminated water and fish.

Maria Amor Duch (INTE)

Health effects

Radiation dose is defined as the energy deposited by radiation per unit mass of the irradiated body. The unit of dose in humans is the sievert (1 Sv = 1 J/kg). Radiation effects on human health may be classified into two categories, stochastic (or probabilistic) and non-stochastic (or deterministic). Non-stochastic effects have a dose threshold (beyond a few Sv) that must be exceeded before the effect is observed, the severity of the effect increasing with dose. On the contrary, stochastic effects occur randomly below the mentioned threshold, carcinogenesis being the most important effect. The probability of occurrence increases with dose, but its severity is independent of dose. Studies of bomb survivors in Hiroshima and Nagasaki show a linear relationship between carcinogenesis and dose at high doses, but epidemiologic data at low doses are inconclusive.

Maria Amor Duch (INTE)

What can be learnt

The nuclear plant in Fukushima was not prepared to resist a 9.0 earthquake and a 7 to 9 meter wave tsunami. Two main lessons can be learnt from this accident. First, radioactive spent fuel ought to be removed from the nuclear plant pools, and taken to a centralized interim storage facility, where cooling systems are passive and shields are much more resistant. Second, new reactors should rely on passive safety systems in which electricity is not required to evacuate the residual heat of the nuclear reactor during an emergency. This feature is implemented in third generation reactors such as the AP1000, now in construction in China.

Javier Dies