The Japanese nuclear disaster

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On 11 March 2011, Japan was ripped apart by a devastating natural disaster, which began with a massive magnitude 9 earthquake. The events that followed led to the loss of nearly 16,000 lives and thousands were left homeless. The tsunami that occurred as a direct result of the earthquake caused a serious nuclear disaster at the Fukushima I Nuclear Power Plant, the effects of which are still being felt in the region.

The plant had six boiling water reactors. In such a reactor, the energy released by the nuclear reaction is used to heat a water vessel that in turn powers a turbine to generate electricity. Due to the nature and location of the Fukushima power plant, a protective seawall, designed to withstand 5.7 m high waves, was installed. However, 51 minutes after the earthquake struck, a tsunami measuring 13.1 m high hit the power plant. Fires broke out at the facility and all of the reactors suffered a series of failures.

So, what exactly happened? Let’s examine the chemistry behind the news…

Isotopes

This word seems to appear from mouths with fear and dread: isotopes. But isotopes of an element are simply atoms with the same atomic number but a different mass number; essentially, they have the same number of protons and electrons but differ in the number of neutrons in the nucleus. Take carbon. It has three well-known isotopes. $^{12}$C is the most abundant isotope of carbon, but the other two isotopes have some rather useful and interesting chemistry.

$^{13}$C makes up of 1.1% of naturally occurring carbon, and due to the number of neutrons in its nucleus, unlike $^{12}$C it can be used for nuclear magnetic resonance (NMR) studies to identify compounds. Radiocarbon dating is a term used for the measurement of $^{14}$C in order to date things (such as archaeological finds), as it is a radioactive isotope that decays at a predictable rate.

Radioactive isotope

$^{14}$C is just one example of many radioactive isotopes. Radioactive isotopes can decay by alpha and beta decay, examples of which can be seen below:

Alpha decay: $^{238}_{92}$U → $^{234}_{92}$Th + $^{4}_{2}$He$^{2+}$, emitting alpha particles (an alpha particle is essentially a helium nucleus)

Beta decay: $^{137}_{55}$Cs → $^{137}_{56}$Th + $^{0}_{-1}$e, emitting beta particles (electrons released from the nucleus)

The reactor vessels of the Fukushima I Nuclear Power Plant have fuel rods containing uranium oxide. These fuel rods contain significant proportions of $^{235}$U. When this isotope is bombarded with neutrons, nuclear fission can occur. To aid the efficiency of the reaction there are moderators in the nuclear reactor vessel, which slow down neutrons to allow the uranium to capture them (fast-moving neutrons
are less likely to be captured by uranium nuclei). Unlike other radioactive decays, the products of nuclear fission reactions cannot be predicted. In a nuclear reactor, $^{235}\text{U}$ takes in a neutron, turning it into its $^{236}$ isotope. This isotope then decays into two other isotopes plus neutrons, releasing energy that heats the reactor vessel. One example of a fission reaction of $^{235}\text{U}$ is:

$$^{235}_9\text{U} + ^1_0\text{n} \rightarrow ^{236}_9\text{U} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3^1_0\text{n} + \text{Energy}$$

The three neutrons produced in this reaction could go on to react with three more $^{235}\text{U}$ atoms in a chain reaction, which could lead to a nuclear explosion. To prevent the reaction running away, control rods are introduced to absorb most of the neutrons, maintaining the reaction at a steady rate.

**Spent fuel rods**

Once a number of fission reactions have occurred, fuel rods no longer have any $^{235}\text{U}$ in them or they have so little that the process is inefficient. This means that nuclear fission of uranium can no longer take place. These are termed *spent fuel rods*. Spent fuel rods still give off heat as other fission products decay and hence they are stored in the reactor contaminant structure in deep (usually around 12 m) baths of water. Once the rods have cooled they are processed and disposed of.

**Explosions**

This casing of a fuel rod is made from zirconium (Zr), as this transition metal is able to let neutrons through, making it a perfect material for this purpose. When the tsunami struck the Fukushima I Nuclear Power Plant it flooded and disabled the back-up diesel generators that had kicked into action when the earthquake had cut the main power supply. A secondary back-up power system (a set of batteries) was deployed in order to maintain the temperature of the reactor, but once these batteries had run down, the reactor grew hotter and hotter. In order to prevent too high a pressure, steam was allowed to escape (this already presented a risk, as the steam may have contained low levels of radioactive material). Zirconium reacted with the steam and was oxidised, producing hydrogen gas:

$$\text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2$$

A hydrogen–steam mixture is safe, but as the steam cools and forms liquid water, the hydrogen is free to react with oxygen in the air. Any spark will ignite it and this is what caused the fires and explosions in reactors 1 and 2 in the initial days of the disaster.

**Meltdown**

Once a reactor vessel reaches approximately 2500°C, a meltdown can occur. Fuel rods melt and sink to the bottom of the vessel and can burn a hole, leading to contamination of water that is desperately pumped in to try and avoid this. In June 2011 the Japanese government confirmed that the Unit 1 reactor vessel containment was breached. The true repercussions of this are still not known.

You can find out more about earthquakes and keep up with news from the Fukushima Power Plant at the BBC News Japan Earthquake website (http://tinyurl.com/4trnn8g).