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History review of nuclear reactor safety

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ABSTRACT

With the occurrence of the three major nuclear accidents, nuclear safety issues have become the lifeblood for nuclear power development in the world. Understanding the history of nuclear reactor safety is of great significance to improve the safety of the future nuclear power. In this article, the histories of nuclear reactor safety development are reviewed in terms of the "birth of atomic energy", "birth of nuclear reactor safety", "development of nuclear reactor safety", "dilemma of nuclear reactor safety", "rebirth of nuclear reactor safety".

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1. Introduction

Nuclear energy plays an important role in the world electric supply. There are 448 units in operation and 58 units under construction by the end of 2017 (International Atomic Energy Agency, https://www.iaea.org/pris/). Although the three-major nuclear accidents in the history severely damage the confidence of nuclear power development for most countries, and especially have great influence on the short-time development of nuclear power. However, in the long run, the future of nuclear power is still bright enough. Basing on the prediction of International Energy Agency (IEA), nuclear power of the world will increase by more than one time under the 2DS plan by 2050s when the nuclear power proportion in the world electricity supply will arrive at 17% (Houssin et al., 2015).

The "3S" is a noted safety terminology involving nuclear regulation. The nuclear safety, nuclear security and nuclear safeguard. The International Atomic Energy Agency (IAEA) defines nuclear safety as "the achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards". While, the IAEA defines nuclear security as "the prevention and detection of and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities" (IAEA I., 2016). Nuclear safeguards indicate countermeasures to verify that countries obey their international obligations of no using nuclear materials for nuclear explosives.

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This article only involves the nuclear safety and the one only for nuclear power plant (NPP).

The world nuclear reactor technology development experiences four stages, namely Gen-I, Gen-II, Gen-III and Gen-IV reactors. However, the nuclear reactor technology widely used today still rests on the Gen-II level (Goldberg and Rosner, 2011). With the occurrence of the three major nuclear accidents, namely the Three Mile Island (TMI) accident, Chernobyl accident and Fukushima accident, safety defects and problems of the Gen-II nuclear reactor technology, especially the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) technologies, have being exposed. Each nuclear accident has identified the weaknesses of the NPP and challenged the nuclear safety of nuclear power. The TMI accident just proves the possibility of severe accident with core damages, the Chernobyl justifies the possibility of the large releases of radioactive materials to the environment, and the Fukushima accident indicates the possibility of Beyond Design Basis Accident (BDBA). Every nuclear accident just promotes the development of nuclear safety. Unfortunately, the history has proved that the nuclear accident did not happen again with the same reason. Just as Murphy's Law go "anything that can go wrong will go wrong". For the future, the only certain thing is that the next nuclear accident will happen definitely. However, we have no ideas with what will cause this nuclear accident. The only choice we have is doing our best to improve the nuclear reactor safety revolutionarily and thoroughly. Nowadays, nuclear reactor safety has become the lifeblood for NPP development in the world. Thus, it is very important to understand the history of nuclear reactor safety.

Thus, in this particle, the history of nuclear reactor safety is reviewed in terms of the "birth of atomic energy", "birth of nuclear reactor safety", "development of nuclear reactor safety", "dilemma of nuclear reactor safety", "rebirth of nuclear reactor safety".

2. The history of nuclear reactor safety

2.1. Birth of atomic energy

In the early time of ancient Greeks, the notion of atomic conception just stayed on a subjective level that matter consisted of minute, indivisible particles. Until the 17th century, scientists proved the existences of atoms. In 1783, Antoine Lavoisier firstly proposed the concept of elements. In the early 19th century, British chemist John Dalton developed the ancient Greek ideas on atoms that it was just a minute solid sphere particle which could not be split further (Van Melsen, 2004). As science was widely accepted by human beings in late 19st- and early 20st-century, Europe initiated the research on nuclear physics and many famous scientists with great contributions to the nuclear physics developments appeared here.

In the late 1895, Wilhelm Rontgen discovered a new type of ray, which he called x ray for the lack of a better name to it. His discovery instantly stimulated the scientific world and the popular press as made public in early 1896. Rontgen's discovery opened the door to medical imaging technology and earned him the first Nobel Prize in physics (Glasser, 1993). Stimulated and motivated by the discovery of X rays, in 1896, Antoine Becquerel discovered the phenomenon of radioactivity after his detection of the radiation discharged from uranium salts (Myers, 1976). In 1897, Joseph Thomson discovered the electron when he was doing experiments with the gas discharge tubes. After Becquerel, Marie Curie discovered radium and lead the scientific community in the study of theory behind the uses of radioactivity (Pasachoff, 1996). In 1904, after the discovery of electron, Thomson raised the famous atomic structure model of "Plum Pudding Model" that each atom was regarded to be a sphere structure filled with a positive charged fluid, known as the "pudding", and with negatively charged electrons scattered in the fluid, known as "plums" (Compendium, 2009). In 1911, a famous experiment conducted by Ernest Rutherford called "Rutherford's Gold Foil Experiment" overturned Thomson's "Plum Pudding Model" and put forward a new atom structure model named "Planetary Model". For this new model, Rutherford held that the atoms contained a small dense center carrying all the positive charges. He called this center the nucleus. While the negatively charged electrons scattered around this positively charged dense center. He thought that the negatively charged electrons were restricted in a certain orbit by the electrical forces between the nucleus and electrons. The road to the atomic energy started in 1919 when Rutherford achieved the first artificial transmutation reaction that he split the nitrogen into oxygen with a release of high-energy particle named proton in his alpha particle bombardment experiment (Geiger, 1910). In 1932, James Chadwick, Rutherford's colleague at Cambridge, discovered and identified another new particle, named by neutron as it had no charge (Chadwick, 1932).

With the first artificial transmutation test carried out by Rutherford, many particle accelerators were fabricated to bombard the nuclei of various elements to disintegrate atoms. As protons and alpha particles are positively charged, they would meet substantial resistance resulted from the positively charged target nucleus when they attempted to penetrate the atoms. For an interview in 1933, Rutherford called such expectations "moonshine". Einstein compared particle bombardment with shooting in the dark at scarce birds. Beginning in 1934, the Italian physicist Enrico Fermi began bombarding elements with neutrons instead of protons, theorizing that Chadwick's uncharged particles could enter the nucleus without resistance. Just as other scientists at that time, Fermi paid little attention to the possibility that mass could disappear during bombardment with the release of large amounts of energy from the atom in accordance with Einstein's formula, $E = mc2$, which was proposed in 1905, indicating that the mass and energy were transformable. With his colleagues, Fermi bombarded sixty-three stable elements and produced thirty-seven new radioactive ones (Shea, 1983).

During the activities of bombarding elements with neutron, the radiochemists Otto Hahn and Fritz Strassman made an unexpected discovery that the uranium nuclei changed greatly and broke into two pieces having similar mass with much energy discharged from the atom. Borrowing the terminology of cell division Frisch named this process by fission. It soon reached an agreement that the process of fission could not only generate large amounts of energy but also 2 to 3 secondary neutrons. These 2 to 3 neutrons might further collide with other uranium atoms and generate more neutrons and more energy, and so on. This spontaneous process was called the "chain reaction" which completely changed the prospects of utilizing the energy stored in the nucleus. Obviously, a self-sustaining reaction under control could steadily produce a large amount of energy for heat and power, while an uncontrolled reaction could turn into disastrous explosions due to the energy amplification exponential order. News of the Hahn-Strassman experiments and Meitner-Frisch calculations propagated with extreme rapidity. From then on, Americans led the way in producing equipment for nuclear physics and high-energy physics research later (Andersen, 1996).

2.2. Birth of nuclear reactor safety

In 1939, Albert Einstein wrote a letter to President Franklin D. Roosevek, reminding him of the importance of research on chain fission reactions which contributed to the development of powerful bombs (Einstein, 2013). In 1942 the Manhattan project aiming at nuclear weapon development initiated by the United States with

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