Centrum Rzeczoznawstwa Budowlanego

Open Access Journal
Modern Engineering 3 (2020) 92-99
journal homepage: https://mengineering.eu/

Overview of the safety systems used in generation III and III+ of reactors

Michał STĘPIEŃ*[1], Grzegorz NIEWIŃSKI[1], and Aleksej KASZKO[1]

[1]Warsaw University of Technology, Warsaw, Poland

Abstract

Generation III and III+ of nuclear reactors are most often operated in the world. Reactor safety issues are the most important part of designing nuclear power plants. This article presents the current accident protection systems in power plants. Among other things, the so-called "defense in depth" was presented, which minimizes the risk of the spread of nuclear fission products and the associated passive safety and reactor protection systems.

Keywords: safety systems, gen III+ reactors, nuclear energy

1 Introduction

Nuclear power plants belong to the group of conventional power plants, in which the thermal part is a nuclear reactor, generating energy from the fission of heavy nuclei of elements such as U-233, U-235, Pu-239 and Pu-241. The first nuclear power plant started operating in the 1950s in Obninsk, in the Union of Soviet Socialist Republics. The reactor was designed to produce plutonium, and the generation of electricity was only a side effect. In addition, nuclear reactors also appeared in the west, in the USA (Shippingport, 1957) and Great Britain (Calder Hall, 1956). Their main feature was the possibility of reloading fuel while the reactor was in operation without having to shut it down.

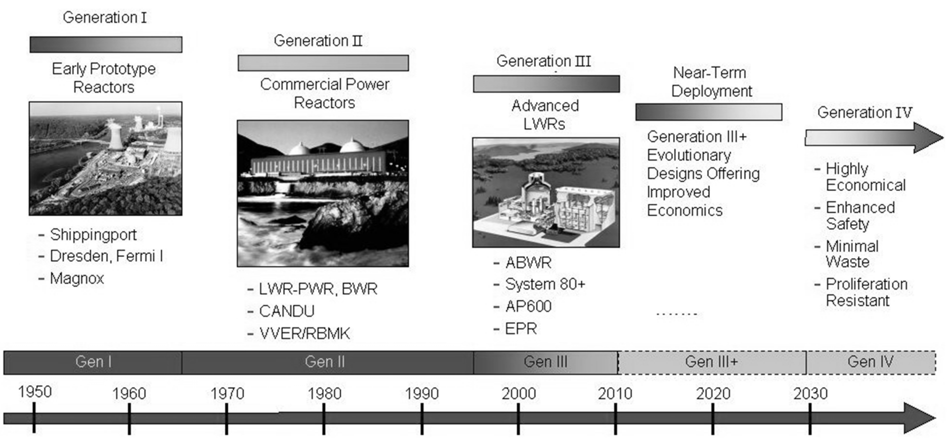

Figure 1. The evolution of nuclear power plants [11]

The second generation of reactors are the most popular light-water reactors of the PWR and BWR type, in which the reactor's cooling fluid and moderator was light water (H_2O). Work on Generation III (Gen III) reactors began in the mid-1980s. The most important changes that were introduced in the Gen III Reactors were the increase of operational safety, resulting in lowering the possibility of serious damage to the reactor core, and increasing the economic efficiency. Currently, work on generation IV reactors is carried out in the world. Gen IV reactors are characterized by openness to new concepts and significant changes in the operation of reactors compared to those

*Corresponding author: E-mail address: michal.stepien@itc.pw.edu.pl (Michał STĘPIEŃ)

Received 02 February 2020
Available online 16 September 2020
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

currently operating. The use of plutonium or thorium-based fuel, or duplicating or gas-fired reactors is contemplated [17]. This group of reactors includes: SMR (Small and Medium Reactors), very high-temperature VHTR (Very High Temperature Reactors), supercritical SCWR (Supercritical Water Cooled Reactor) reactors, cooled with MSR molten salt (Molten Salt Reactor) and Fast Breeding Reactors (FBR) gas-cooled Fast Reactor (GFR), sodium-cooled SFR (Sodium-cooled Fast Reactor) and lead-cooled LFR (Lead-cooled Fast Reactor) (Figure 1) [3, 16].

2 Concept of reactor safety

Nuclear reactors are designed in accordance with the principle applied in facilities requiring the highest trust, i.e. the so-called "Defense in Depth", which consists in introducing many independent layers of security, as shown in Figure 2.

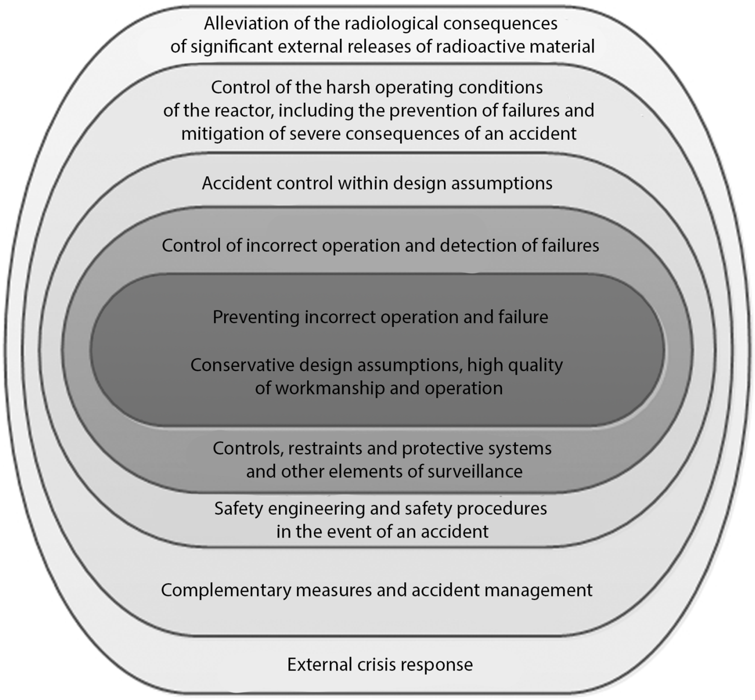

Figure 2. The defense in depth concept: purposes, methods and means

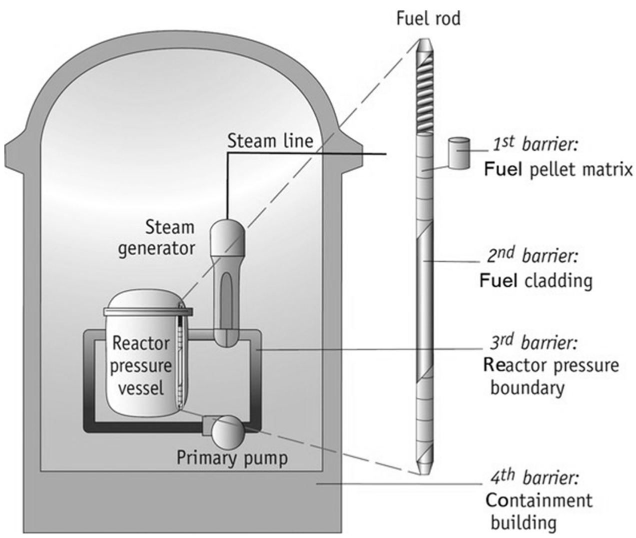

Figure 3. Typical barriers confining radioactive materials in nuclear power plants [6, 12]

The concept of "defense in depth" consists of five concepts that produce specific effects. The basic one is the so-called "Inherent Safety", which in relation to nuclear facilities consists in designing the reactor in such a way that it is a self-regulating system (eg negative reactivity coefficient, natural convection cooling). Further concepts are Precaution and Prevention during normal reactor operation. Control and regulation systems as well as security systems are used for this. The last two terms - Mitigation and Beyond Design Basis Accidents - are the presence of safety systems and severe failure systems to reduce the risk outside the installation. The above rule is graded. The WASH-1400 report showed that the greater probability of a given failure, the smaller its effects on the environment. Diversification and redundancy (multiplication) significantly increases the level of security, thus reducing the effects of errors and failures [2, 4].

The essence of "defense in depth" is perfectly illustrated by the multiplication of barriers against the escape of radioactive substances. These are, in turn: the fuel sleeve, the fuel rod, the primary cooling circuit of the reactor and the building of the reactor casing (Figure 3) [6].

3 Reactor protection systems (RPS)

The safe operation of the reactor is essential for the safety of a nuclear power plant. In order to achieve this, a number of key parameters of the installation are monitored, ensuring that they are kept within certain specified intervals. These limits are determined by careful analysis of the individual failure scenarios and have been selected in such a way as to ensure an appropriate margin between the safe operating limit and the actual safety limit [15]. The systems responsible for ensuring that the occurring deviations of parameters from normal operating conditions do not cause a failure, or in the event of its occurrence, initiate an action aimed at limiting its effects, are defined by the reactor protection systems (RPS).

The reactor protection system must therefore consist of measurement systems and limit value control for the monitored parameters and automatic reactor trip system (RTS) by dropping control rods and flooding the reactor with boric acid. In terms of limiting the effects of an accident, the role of the security system is to start specially installed safety systems or systems (SS).

Currently used reactor protection systems consist of two independent and autonomous subsystems: primary (PPS - Primary Protection System) and secondary (SPS - Secondary Protection System). Each of them performs the same function, but works on the basis of different components (eg PPS is a digital system, and SPS - an analog system) with different measuring systems. For a better illustration, an example of the control of the circulation pump operation in the primary circuit of the reactor is given. The PPS system measures the pump supply voltage and sends a signal to switch off the reactor if the voltage measurement drops below a predefined value. At the same time, the SPS system measures the current supplying the pump, in the event of a drop below the limit value, the SPS system will send a signal to switch off the reactor regardless of PSP.

The reactor protection systems are designed according to the principle of logical selection 2 out of 3 or 2 out of 4. This means that the protections will trip when two independent signals from different measuring systems appear, which indicate a defect or failure. The selection of control parameters and the limits of which, when exceeded, will cause the activation of the protection systems, is made due to [1, 14]:

- breaking the uncontrolled chain reaction and increasing the reactor's power,
- ensuring the required safety margin from the state of the film boiling crisis and the melting of the fuel in the core,
- limits of the pressure load on the primary circuit components.

4 Security systems

In the situation that the safety systems do not work, or the reactor or its components are damaged despite their operation, the security systems are activated. The role of safety systems is to minimize the effects of the resulting failure. In modern nuclear reactors, generation III / III + their multiplication is used. Usually these are three or four systems, whereby the operation of a single system, depending on the type of failure, should lead to the radioactive material not escaping outside the reactor or containment.

In modern nuclear power plants, the multiple secutiry systems are separated from each other and placed in separate buildings so that the failure of one of the systems or the complete destruction of the building as a result of an aircraft impact does not result in the loss of functionality of other systems [5, 7, 13].

Security systems can be divided into two basic groups: active and passive. Active systems are activated in response to malfunction or failure of the reactor and require external power (e.g. operation of pumps requires electricity or emergency diesel aggregates). Passive protection systems do not require an external power supply, and their operation results from the operation of natural laws of physics (e.g. flow caused by gravity or pressure difference).

In this article, the authors decided to focus only on passive systems, which seem to be safer solutions and do not require human intervention in their operation.

4.1 Passive core cooling system in AP600 and AP1000

Standard operating conditions of the reactor are considered to be full-time operation at full power and are designed for such thermohydric conditions.

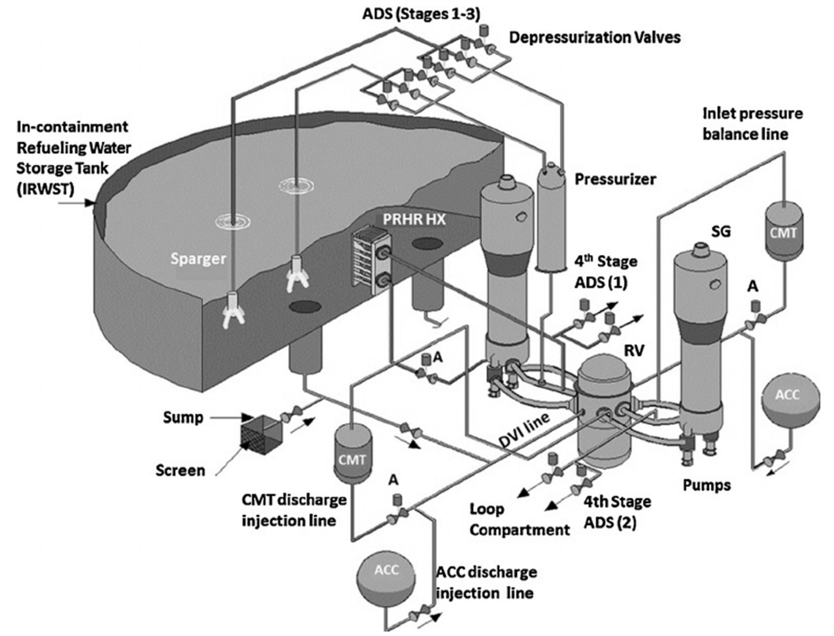

Figure 4. AP600 Passive Core Cooling System [9]

In the event of a failure, the heat is removed to the environment from the primary circuit by passive cooling of the reactor containment. The system uses gravity, natural convection and the energy of compressed gases. It works automatically and the presence of circulation pumps is not required, and the factor driving circulation is the heat of nuclear reactions in the core. The passive core cooling system and PCCS ensure the safety of the reactor for approx. 72 hours without operator participation and no power supply.

4.2 Passive core catcher in the EPR

The passive molten core catcher in the EPR reactor is an off-design accident containment system used to avoid the release of radioactive materials outside the containment without losing its tightness.

As a result of the lack of heat reception from the fuel, the core melts, which can melt the bottom of the reactor tank, destroying it. The molten core leaks into a specially designed room covered with a thick layer of concrete at the bottom of the reactor well, i.e. the core catcher. Rapid solidification and cooling of the molten core are accomplished with the aid of a cooling structure. It also prevents concrete erosion. The passive valve system floods the hot material with water from the internal backup tank, and after 12 hours - the heat removal system from the containment housing cools the leakage area.

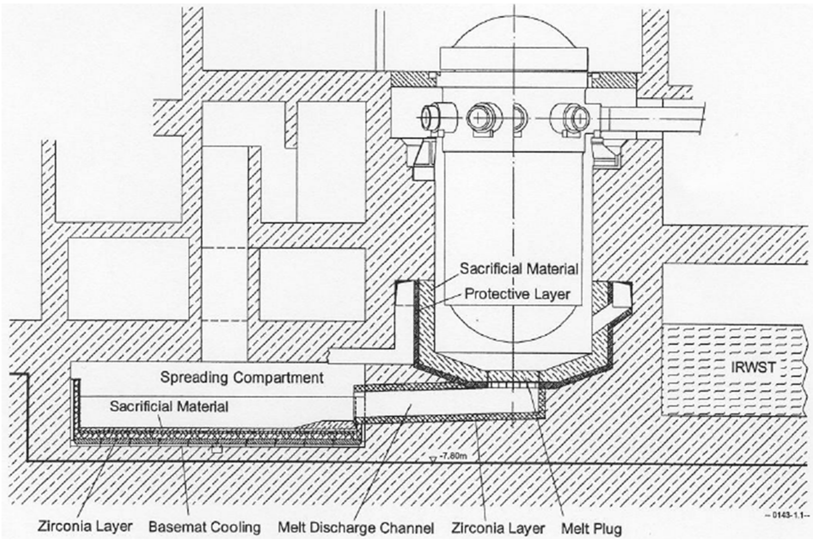

Figure 5. Core catcher [10]

4.3 Passive containment cooling system (PCCS) in AP600 and AP1000 reactors

PCCS (PCCS, Passive Containment Cooling System) is a system ensuring effective discharge of generated heat outside the containment in the event of a failure, when the internal pressure does not exceed the design pressure. As a result of the LOCA type failure (Loss of Cooling Accident), in which the reactor coolant (hot water at a pressure of 150 bar) expands to the containment, and turns into steam by increasing the pressure. The role of the cooling system is to reduce the pressure in the housing by condensing the steam (receiving heat from it).

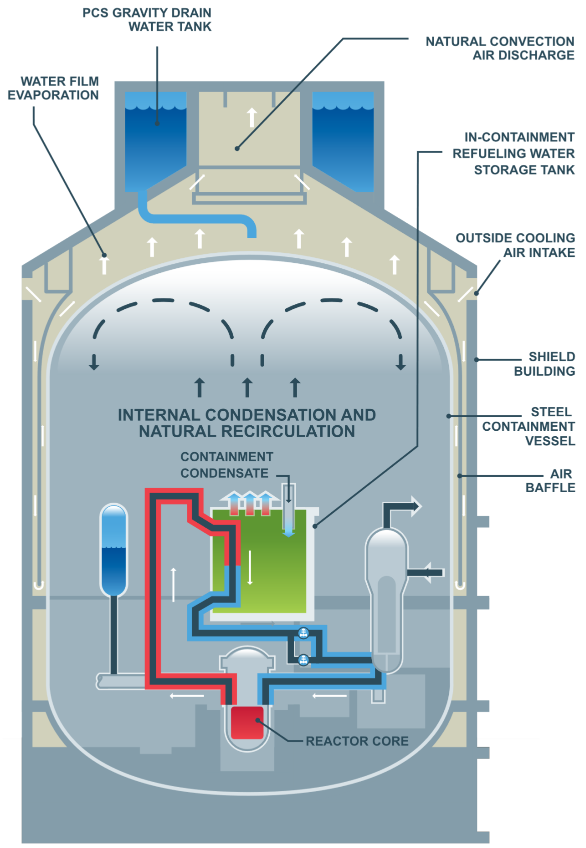

Figure 6. AP1000 Passive Containment Cooling System, PCCS [7]

Water vapor in contact with the steel inner surface of the containment condenses, which causes a rapid reduction in pressure. The condensation heat is collected by a stream of cold water spray from the tanks located at the top of the security building. Water cooling is combined with the natural air circulation inside the housing, creating the so-called the chimney effect [7].

The cooling water tank is calculated for 72 hours of operation with the refill option, however, in the absence of water supply, the pressure in the housing begins to gradually increase (according to simulations - after 14 days it reaches 90% of the design.

4.4 Passive Residual Heat Removal System (PRHR) in AP600 and AP1000 reactors

The main function of PRHR (Passive Residual Heat Removal) heat exchangers is to provide a long-term period of residual heat removal, while it is impossible to receive this heat via steam generators (Fig. 7). Heat is transferred through the natural cycle. The exchanger system is under pressure during the standard operation of the reactor and can start operation at any time. The liquid flow is started by opening the shut-off valve located at the bottom of the PRHR heat exchanger. The residual heat removal system includes: PRHR HX heat exchangers, IRWST (In Containment Refueling Water Storage Tank) acting as a heat receiver.

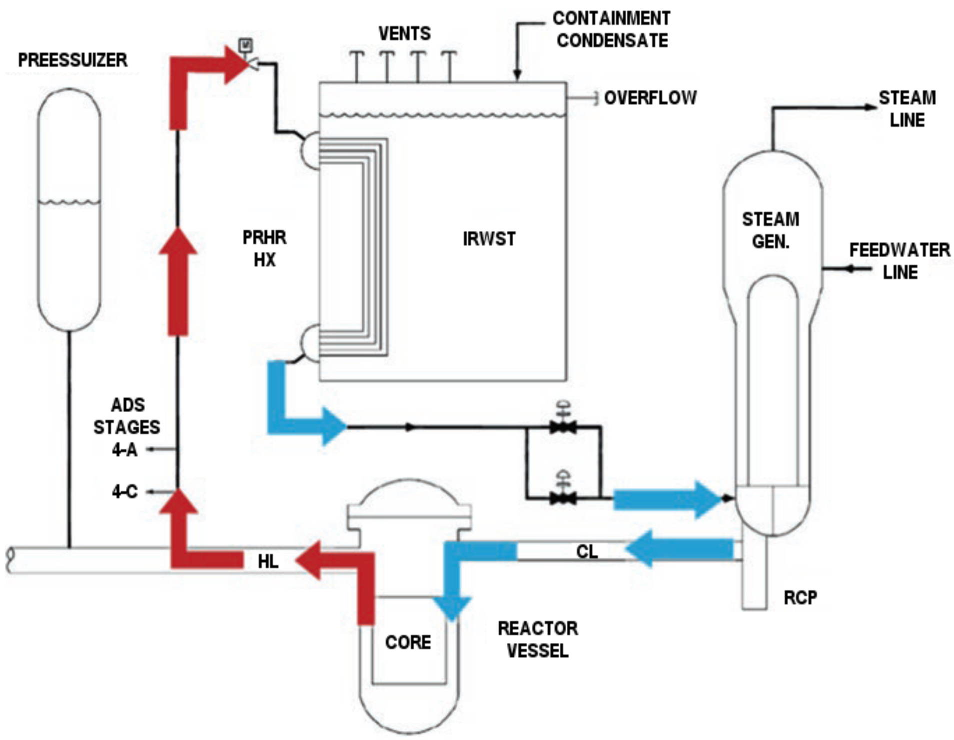

Figure 7. Passive residual heat removal (PRHR) system [8, 9]

4.5 Emergency Boric Acid Core Flooding System

The Emergency Boric Acid Flooding System (EBS) is present in the British PWR-type reactor. As a result of a failure or the necessity to shut down the reactor, a mixture of water and boric acid is introduced into the primary cycle, the role of which is to "shut down the reactor" by absorbing thermal neutrons. During normal operation of the installation, the EBS system is in standby mode. The shut-off valves on all four injection loops are closed, the lines to the outlet tank are open and the system is under low pressure and low temperature. If a high water level is detected in the upper section of the tank, the two in-line shut-off valves in the piping are automatically closed. This results in a loss of coolant from the primary cooling circuit, which may occur due to failure or accidental opening of the EBS main shutoff valve.

The system is equipped with pneumatic and hydraulic energy storage devices, having their own gas (nitrogen) tank, independent of the air supply station and oil pumps. The slight drop in nitrogen pressure is compensated by replenishing the air cylinder with remote charge lines running through the second shell wall. The hydraulic fluid stops the valve, and upon receipt of the initiation signal, two solenoid operated pilot valves vent the fluid. It enables the opening of the main valve under the influence of gas pressure in the nitrogen accumulator [14].

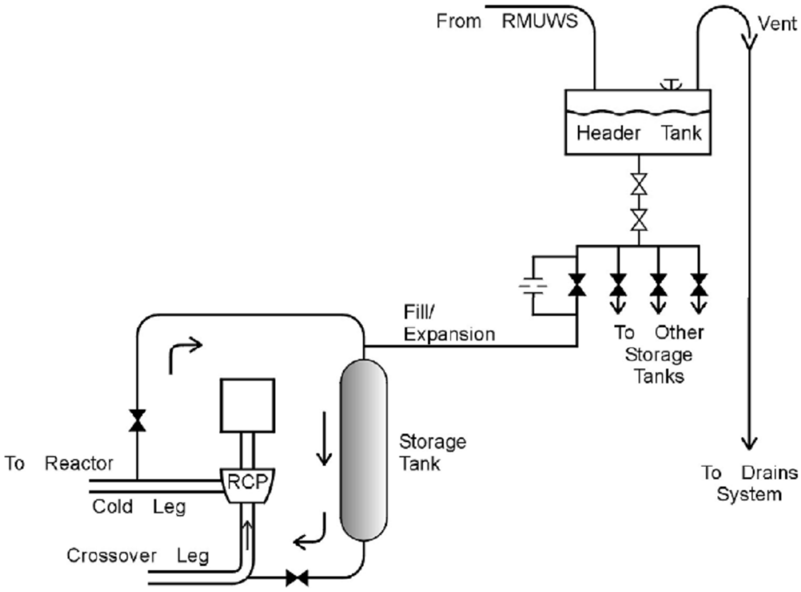

Figure 8. Emergency Boration System (EBS) [14]

4.6 High Pressure Safety Injection in PWR type reactors

High Pressure Safety Injection (HPSI) is used in all pressure reactors. It is part of the Emergency Core Cooling System (ECCS) which performs emergency injection and recirculation of the coolant. Its purpose is to maintain the coolant supply of the reactor core and to properly remove heat after a failure caused by the loss of cooling accident (LOCA). The coolant injection function is performed a relatively short period after the failure has started and then adapted to the recirculation mode to maintain long-term cooling of the core.

The system starts automatically at low pressure in the pressure stabilizer, high pressure in the containment, or when a flow irregularity is detected in the primary cooling circuit. Therefore, apart from LOCA, other events may lead to the activation of the HPSI system [7].

5 Conclusions

The development of nuclear power is constantly related to the issue of improving the safety of operation of a nuclear power plant. This is done in two ways, first of all through a design solution ensuring internal stability of the fission reaction (reactors cooled and moderated with water). In the past, constructions were developed which, due to the occurrence of undesirable phenomena, e.g. a sudden increase in reactor power, increased the intensification of the fission reaction and deepened the changes that could lead to serious reactor accidents. The second factor contributing to the improvement of safety is the use of safety systems only found in nuclear power plants. The increase in the safety of generation III / III+ reactors takes place through the development of the diversity of the systems used and their multiplication. Particular emphasis was placed on passive systems that operate according to the natural laws of physics and do not require external power.

Current nuclear reactors are designed so that core failure should occur no more than once every 100,000 years, and a large release of fissile material into the environment no more than once every 10,000,000 years. All this makes modern nuclear power plant solutions very safe and even in the event of a severe reactor failure, the local population is not fenced off.

References

1. Ackermann, G. *Eksploatacja elektrowni jądrowych* (Wydawnictwo Naukowo-Techniczne, Warszawa, 1987).

2. *Assessment of safety* (27.06.2017). International Atomic Energy Agency. https://www.iaea.org/ns/tutorials/regcontrol/assess/assess3213.htm.
3. Celiński, Z. Foreseen Development of the Nuclear Power. Generations of Power Reactors. Part II. *Energetyka* **3,** 137–144. ISSN: 0013-7294 (2004).
4. *Considerations of the performance and reliability of passive safety systems for nuclear reactors* INSTITUT DE RADIOPROTECTION ET DE SURETE NUCLEAIRE, 2016.
5. Marques, J. Environmental characteristics of the current Generation III nuclear power plants. *WIREs Energy Environment* **3,** 195–212. ISSN: 2041-840X (2 2013).
6. *Nuclear Energy Today* (27.06.2017). OECD Nuclear Energy Agency. http://dx.doi.org/10.1787/9789264103306-en.
7. *Nuclear Safety – Unequaled Design. Passive-safety systems. Multiple levels of defense. Advanced controls* (22.06.2017). WESTINGHOUSE. http://www.westinghousenuclear.com/New-Plants/AP1000-PWR/Safety.
8. Oka, Y. & Bittermann, D. in *Reflections on the Fukushima Daiichi Nuclear Accident: Toward Social-Scientific Literacy and Engineering Resilience* (eds Ahn, J. *et al.*) 223–258 (Springer International Publishing, Cham, 2015). ISBN: 978-3-319-12090-4.
9. *Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants* Vienna: International Atomic Energy Agency, 2009.
10. Pikkarainen, M., Laine, J., Purhonen, H. & Kyrki-Rajamaki R. Sairanen, R. *Heat Transfer Analysis of the European Pressurized Water Reactor (EPR) Core Catcher Test Facility Volley* Interlaken, Switzerland: IYNC, 2008.
11. *Reaktory III generacji* (27.06.2017). http://www.nuclear.pl/energetyka,genIII,reaktory-iii-generacji.html.
12. *Safety of nuclear power reactors* (27.06.2019). WORLD NUCLEAR ASSOCIATION. http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx.
13. *Safety related terms for advanced nuclear plants* Vienna, 1991.
14. *Sizewell B Plant Systems Training Student workbook: Emergency Boration System* (EdF ENERGY, Gloucester, 2012).
15. *Sizewell B Plant Systems Training Student workbook: Reactor Protection System* (EdF ENERGY, Gloucester, 2012).
16. Stępień, M., Niewiński, G. & Kaszko, A. Safety systems in Gen III i III+ reactors. *Aparatura Badawcza i Dydaktyczna* **22,** 180–190. ISSN: 2392-1765 (2017).
17. Trojnar, K. SAFETY OF EMBANKMENTS WITH ANTHROPOGENIC A RUBBER FILLING MADE OF RECYCLED TYRES. *Inżynieria Bezpieczeństwa Obiektów Antropogenicznych* **4.** ISSN: 2450-1859 (2019).