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DEPARTMENT OF FOREIGN LANGUAGES

ÚSTAV JAZYKŮ

NUCLEAR POWER PLANTS DESIGN AND SAFETY: A CASE STUDY OF THE TEMELÍN NUCLEAR POWER PLANT

DESIGN A BEZPEČNOST JADERNÝCH ELEKTRÁREN: PŘÍPADOVÁ STUDIE JADERNÉ ELEKTRÁRNY TEMELÍN

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

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Bakalářská práce

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NÁZEV TÉMATU:

Design a bezpečnost jaderných elektráren: případová studie jaderné elektrárnyTemelín

POKYNY PRO VYPRACOVÁNÍ:

Popište návrh, provozní vlastnosti a bezpečnostní opatření jaderné elektrárny Temelín. Porovnejte tuto jadernou elektrárnu s jinými jadernými elektrárnami a vyhodnoťte její výhody a nevýhody.

DOPORUČENÁ LITERATURA:

1) International Nuclear Safety Advisory Group. (1999). Basic safety principles for nuclear power plants. 75-INSAG-3 Rev. 1. Vienna: International Atomic Energy Agency.
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Vedoucí práce: Mgr. Ing. Eva Ellederová, Ph.D.

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Abstract

The bachelor's thesis is a case study of the Temelín nuclear power plant. It aims to describe the design, operating principle, and safety measures of the Temelín nuclear power plant, compare the design and safety measures of selected nuclear power plants in and outside the Czech Republic and discuss the advantages and disadvantages of the Temelín nuclear power plant compared with other selected nuclear power plants. The thesis is based on a literature review of different sources to ensure its maximum validity. The sources included scholarly books, articles, brochures, online lectures, virtual tours, and internal learning materials. It can be concluded that the Temelín nuclear power plant is maintained at a high safety standard by the State Office for Nuclear Safety and its operators. Although the design has many advantages, there are some minor disadvantages that, however, do not have any significant influence on the nuclear power plant safety.

Key words

Nuclear power plants, safety, safety systems, design, operating principle, Temelín, Dukovany, Chernobyl, Fukushima Daiichi, comparison

Abstrakt

Bakalářská práce je případovou studií jaderné elektrárny Temelín. Jejím cílem je popsat projekt, princip provozu a bezpečnostní opatření jaderné elektrárny Temelín, porovnat projekty a bezpečnostní opatření vybraných jaderných elektráren v České republice i mimo ni a diskutovat výhody a nevýhody jaderné elektrárny Temelín ve srovnání s ostatními vybranými jadernými elektrárnami. Práce je založena na rešerši literatury z různých zdrojů, aby byla zajištěna její maximální validita. Zdroje zahrnovaly odborné knihy, články, brožury, online přednášky, virtuální prohlídky a interní výukové materiály. Lze konstatovat, že jaderná elektrárna Temelín je Státním úřadem pro jadernou bezpečnost a jejími provozovateli udržována na vysoké bezpečnostní úrovni. Přestože má projekt mnoho výhod, existují i určité nevýhody, které však nemají na bezpečnost této jaderné elektrárny zásadní vliv.

Klíčová slova

Jaderné elektrárny, bezpečnost, bezpečnostní systémy, design, princip činnosti, Temelín, Dukovany, Černobyl, Fukušima, porovnání

Rozšířený abstrakt

Bakalářská práce se zabývá bezpečností a designem jaderné elektrárny Temelín. Jejím cílem je popsat design, provozní vlastnosti a bezpečností opatření dané jaderné elektrárny, porovnat ji s dalšími vybranými jadernými elektrárnami a vyhodnotit její výhody a nevýhody. Dané téma bylo vybráno z důvodu stále rostoucí spotřeby elektrické energie a snahy Evropské unie o snížení počtu „nečistých" zdrojů elektrické energie. Zavíráním a rušením uhelných elektráren a rapidním nárůstem počtu elektrických vozů je potřeba budovat nové „čisté" zdroje. Evropská komise v roce 2022 dočasně schválila zařazení jaderných elektráren mezi čisté zdroje energie. Naneštěstí havárie jaderných zařízení v minulosti stále budí strach v obyvatelích některých evropských zemí. Tato práce tedy hodnotí bezpečnost jaderných elektráren na území České republiky a porovnává bezpečnostní opatření s některými z nejznámějších jaderných elektráren v zahraničí, ve kterých nedostatek bezpečnostních prvků nebo chyba v připravenosti zařízení a personálu vedly k havárii. Z těchto důvodů byly pro porovnání vybrány jaderné elektrárny Černobyl, Fukušima I a Dukovany.

Jaderná elektrárna Temelín používá jako zdroj tepla tlakovodní reaktor typu VVER, který se řadí mezi reaktory II. generace. Porovnávat její parametry s nejnovějšími a typy reaktorů by pro cíl této práce nebylo vhodnou volbou, proto byly zvoleny další elektrárny s reaktory druhé generace. Jaderná elektrárna Dukovany pracuje na velice podobném principu, jelikož stejně jako jaderná elektrárna Temelín využívá tlakovodní reaktor VVER. Jaderné elektrárny Černobyl a Fukušima I používaly varné reaktory. Ačkoli princip výroby elektrické energie je u obou těchto elektráren podobný, konstrukce jejich varných reaktorů se značně odlišuje.

Je zajímavé pozorovat, jak se koncepty elektráren se stejnými nebo podobnými typy reaktorů postupem času mění a vylepšují na základě předešlých provozních zkušeností. Tím se i prodlužuje životnost již postavených a provozovaných jaderných elektráren. Životnost jaderné elektrárny s reaktory druhé generace je kolem čtyřiceti let. Díky udržování elektrárny, opatrnosti a důslednosti se může životnost prodloužit až o dalších dvacet až čtyřicet let.

Při zpracování tématu práce bylo potřeba rozeznat spolehlivé zdroje. Informace byly čerpány nejenom z tištěných knih a jejich online dostupných verzí, ale také z článků na odborných webových stránkách, z oficiálních webových stránek Skupiny ČEZ i učebních materiálů určených pro přípravu personálu jednotlivých jaderných elektráren Skupiny ČEZ. Ke

zpracování bakalářské práce významně přispěly i virtuální prohlídky elektráren, kde je možné získat mnoho zajímavých informací. Ověřování informací o zahraničních jaderných elektrárnách bylo podstatně náročnější. Mnoho zdrojů uvádělo rozdílné informace a některé informace nebyly zcela dostupné. Velmi důležité bylo vždy ověřit pravdivost informací ~~od~~ u dozorčích orgánů. Nejvhodnějším zdrojem ověřování informací týkajících se havárií jaderných elektráren jsou odborné zprávy misí organizovaných Mezinárodní agenturou pro atomovou energii.

Po vysvětlení základního principu zvolených jaderných elektráren, vyjmenování a popsání jejich bezpečnostních prvků a vzájemném porovnání vyplynulo z rešerše literatury, že výhody jaderné elektrárny Temelín převažují nad nevýhodami, celková bezpečnost elektrárny je na vysoké úrovni a patří ke světové špičce. Jako výhody jaderné elektrárny Temelín lze uvést její dvouokruhové provedení (rozdělení primárního a sekundárního okruhu) a inherentní fyzikální vlastnosti reaktoru. Dalšími velkými výhodami pro Českou republiku jsou vysoký výkon každého bloku a umístění elektrárny. Pro stavbu jaderné elektrárny je zapotřebí splnit řadu různých kritérií. Elektrárna se nachází na kopci, v blízkosti zdroje vody a je umístěna na velmi stabilním podlaží. Stav technologie ale není tím jediným ukazatelem bezpečnosti jaderného zařízení.

Neméně důležitý je přístup vlády České republiky a provozovatelů jaderné elektrárny Temelín k její bezpečnosti. Jejich přístup je dostačující, v některých případech převyšuje celosvětové standardy a je patrné, že opatrný přístup a zacházení s technologií, kterou mnozí považují za nebezpečnou si získal náklonost veřejnosti. Elektrárna již přes dvacet let splňuje podmínky bezpečného provozu a doufejme, že pod přísným dohledem Státního úřadu pro jadernou bezpečnost bude vyrábět elektřinu ještě mnoho let.

Marečková, K. (2023). *Design a bezpečnost jaderných elektráren: případová studie jaderné elektrárny Temelín.* Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií. 44 s.

Vedoucí bakalářské práce: Mgr. Ing. Eva Ellederová, Ph.D.

Prohlášení

Prohlašuji, že bakalářskou práci na téma *Design a bezpečnost jaderných elektráren: případová studie jaderné elektrárny Temelín* jsem vypracovala samostatně pod vedením vedoucí bakalářské práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne 25.5. 2023 ....

Kristýna Marečková

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Introduction

Society's view on nuclear energy in the Czech Republic can be compared to a roller coaster. At first, the interest in nuclear energy and a new way of producing electrical energy was considerable. The Nuclear Research Institute was established in Řež in 1955, thus making Czechoslovakia the ninth country in the world to successfully start up its own nuclear facility (Knápek, Efmertová & Mikeš, 2011). The institute in Řež has been in operation ever since.

Then, the accidents at the nuclear power plant in Jaslovské Bohunice happened in 1976 and 1977 (INES[1] level 4 – accident with local consequences) and, finally, the accident of the Chernobyl power plant (INES level 7 – Major accident) in 1986. Due to these accidents being so close to home and kept in secrecy from the public for a long time, public distrust gradually grew. People did not believe the nuclear power plants were safe anymore and their distrust led to public resistance against the nuclear power plants, which resulted in many issues and problems during the potential construction of additional units and new power plants in Czechoslovakia (later also in the Czech Republic and Slovakia respectively).

Nowadays, there are two nuclear power plants in the Czech Republic (Temelín, Dukovany) owned by ČEZ Group Plc. and two nuclear power plants in Slovakia (Jaslovské Bohunice, Mochovce) owned by Slovenské elektrárne, a.s.

One of the most modern nuclear power plants in Europe is in Temelín. ČEZ, a.s. (2004) says that the construction of the Temelín nuclear power plant began in 1987, but it faced adverse circumstances related to the outbreak of the Velvet Revolution in 1989 and the consequent change of regime. Therefore, only two units out of the four planned units were built.

This thesis aims to describe the design, operating principle, and safety measures of the Temelín nuclear power plant, compare the design and safety measures of selected nuclear power plants in and outside the Czech Republic and discuss the advantages and disadvantages of the Temelín nuclear power plant. The Dukovany nuclear power plant was selected for comparison because both power plants are in the Czech Republic, the same company operates them, and they both have pressurized water reactors. The construction of

[1] INES stands for the International Nuclear Event Scale. It is a tool for communicating the safety significance of nuclear and radiological events to the public. Events are rated at seven levels. The scale is logarithmic – that is, the severity of an event is about ten times greater for each increase in the level of the scale. (IAEA, n.d.)

the Temelín nuclear power plant had to undergo several adjustments based on the standards of Western countries. Its design and safety measures are compared to the Chernobyl and Fukushima Daiichi nuclear power plants which were selected because of the impact of their accidents on nuclear safety.

The topic was selected because nuclear energy is the only possible step forward since it can be deployed on a large scale and directly replace fossil fuel plants, thus avoiding the combustion of fossil fuels for electricity generation. Moreover, the electricity consumption significantly increases, but no new highly efficient energy sources are built, and coal and nuclear power plants are closed, so energy sources gradually disappear without compensation. The European Union supports the production of environmentally friendly electric cars, but no one seems to realize there will not be enough power to drive them. Renewable sources are not always 100% effective and reliable. The public is becoming more open to nuclear energy, and the support for nuclear energy is high, so it is necessary to show how, when operated properly, a nuclear power plant is nothing to fear.

The basic operating principle of a nuclear power plant is explained in the first chapter. Next, the operating principle of the Temelín nuclear power plant is described, followed by the operating principle of the Dukovany nuclear power plant, the Fukushima Daiichi nuclear power plant and the Chernobyl nuclear power plant in subchapters respectively.

In the second chapter, different types of safety systems are described, from the most important safety barriers that prevent the leakage of radioactive substances into the environment to the safety systems of the primary circuit (e.g. the control rods). Then the chapter addresses the issue of losing offsite power and discusses additional safety measures. Besides, it lists organizations responsible for nuclear safety and emphasizes the importance of international cooperation.

Lastly, in the third chapter, the advantages and disadvantages of the Temelín nuclear power plant are discussed and compared to the other selected nuclear power plants.

1 Basic Operating Principle

In this chapter, the basic operating principle of a nuclear power plant will be described. Chapter 1 is divided into subchapters, which will be needed to explain the operating principle of selected types of power plants respectively.

Nuclear power plants are very similar to coal power plants because both use heat as a driving power and a source of energy. That is why they are both considered as thermal power plants. The main difference between thermal power plants is the fuel used to generate the heat. Nuclear power plants use nuclear fission to generate electricity. As stated by Energy Education (n.d.), the most dominant fuel for nuclear power plants is uranium as thorium is not currently in use. The heat generated inside the reactor converts water into steam using the so-called Rankine cycle (Energy Education, n.d.). The steam then spins the turbine and the generator, thus generating electricity. The simplest operating principle is as follows – inside the reactor, nuclear energy transforms into thermal energy because of the fission reaction, thermal energy in the form of steam starts to rotate the turbine, thus transforming thermal energy into mechanical energy. As the turbine rotates, the rotor of the generator also rotates and produces current due to electromagnetic induction, thus transforming mechanical energy into electrical energy (ČEZ, a.s., 2019a). Usually, the machinery (the turbine and the generator with the shared shaft) as a whole is called a turbogenerator or a turboalternator. This is the basic operating principle of nuclear power plants. Energy cannot be "made" or "created", it can only be transformed, as the law of conservation of energy[2] states.

This thesis focuses on the design and safety measures of the Temelín nuclear power plant and its comparison with the concepts of the selected nuclear power plants as there are different ways of implementing the nuclear power plants projects. In the next subchapter, the operating principle of the Temelín nuclear power plant will be described. In Chapter 1.2, the operating principle of the Dukovany, Chernobyl and Fukushima Daiichi nuclear power plants will also be described to show the differences and similarities between the concepts and designs.

[2] The law of conservation of energy states, according to ČEZ, a.s. (1999a), that "energy cannot be produced or destroyed, only transformed into another type of energy".

1.1 Operating Principle of the Nuclear Power Plant Temelín

Even though both nuclear power plants in the Czech Republic are based on very similar operating principles, there are differences. Each year, new experience gained from operating nuclear power plants is shared by the operators of the power plants, who try to improve or modernize the power plants to achieve the maximum safety standards and potential. Therefore, each nuclear power plant and even each unit can be slightly different.

This thesis studies the most modern nuclear power plant in the Czech Republic, the Temelín nuclear power plant. The construction began in 1987, the design of the power plant had to be adjusted to fit western standards, as the whole project was made in the Soviet Union and, as already mentioned, the Soviet nuclear technology created growing public distrust. As the two units (Unit 1 and Unit 2) of the Temelín nuclear power plant are almost identical, only one will be described. The Temelín nuclear power plant has a containment building, a two-circuit design, and there is only one turbine and a generator for one reactor.

As stated by ČEZ, a.s. (n.d.a), Temelín uses two pressurized-water reactors VVER 1000/V-320, which are the "heart" of the power plant. Reactors in the Temelín nuclear power plant use slightly enriched uranium (approx. 4% of fission isotope U^{235}) as fuel. The fission of the uranium nuclei in the core (the active zone) transforms nuclear energy into thermal energy and heats up the coolant flowing through the reactor. Light demineralized water is used as a coolant and a moderator[3]. The cooling water, heated up to 320°C, flows through the pipes of the primary circuit to four steam generators. It does not boil because it is kept under high pressure of 15.7 MPa (Svět energie, 2020a). Inside the steam generator, there is a point of contact between the primary and secondary circuits. There are heat transfer surfaces (little tubes) that serve as a heat exchange system that prevents mixing the water from the primary circuit and the secondary circuit. After transferring the heat, the coolant is pumped by a main circulating pump back to the reactor and the process repeats. One of the main components of the primary circuit is the pressurizer, the over-pressure relief system (Nuclear Power, 2022), and the emergency discharge of the steam-gas mixture. These systems will be described later in Chapter 2. The whole primary circuit is hermetically sealed inside a reinforced concrete building – containment, as illustrated in Figure 1.

[3] A moderator is a material used in a reactor to slow down high-velocity neutrons, thus increasing the likelihood of fission (U.S.NRC, 2021).

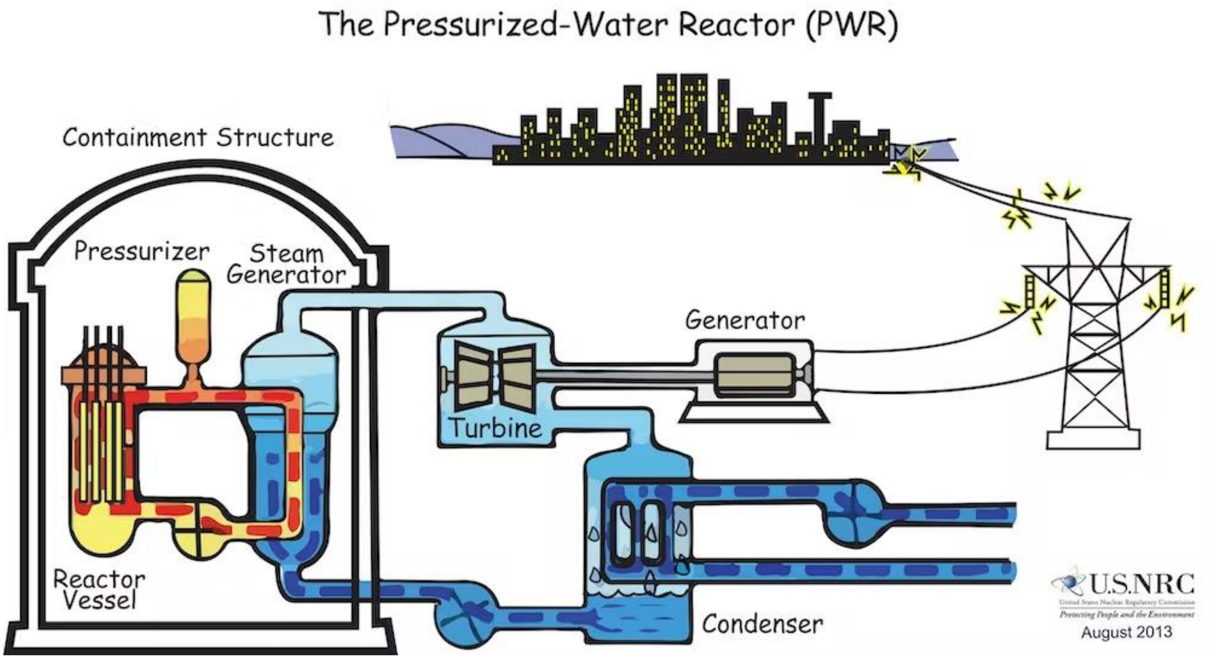

Figure 1. PWR principle of operation.
Reprinted from US Nuclear Regulatory Commission (2013, August).

The secondary circuit starts in the steam generators. Heat transfer surfaces are submerged in water on the secondary side of the steam generator. There is lower pressure (6.3 MPa), so demineralized water can boil here at the temperature of 278.5°C (Svět energie, 2020a). Water evaporates and transforms into steam. The steam from all four steam generators must be brought together to one pipeline to equalize (even out) the parameters before it can go to the turbine. The turbine consists of four main parts – one high-pressure part and three low-pressure parts. The steam flows to the high-pressure part and passes on around 40% of its energy to the turbine (Svět energie, 2020a; ČEZ, a.s., 2019a). Afterwards, steam flows to the moisture separators, which are along both sides of the turbine. They improve the parameters of steam to heat it up with electric heaters and separate moisture. Standard rotations of the turbine are 3,000 rotations per minute (rpm). Moisture must be separated because at these rotations, even a drop of water could damage the turbine. Steam from separators flows to three low-pressure parts and passes on 20% of its energy to each part (Svět energie, 2020a). The steam then continues to flow to the condensers.

The whole principle of the nuclear power plant is transferring heat, so it is no surprise the heating transfer tubes are a recurring system. There are three condensers in total in each unit because each of them is directly under the low-pressure part of the turbine. In each condenser, there are around 32,000 heat-exchanging titanium tubes (Svět energie, 2020a). Steam constantly flows around these tubes since they create lower pressure to "pull" steam from the turbine to the condenser and cooling water circulates inside them.

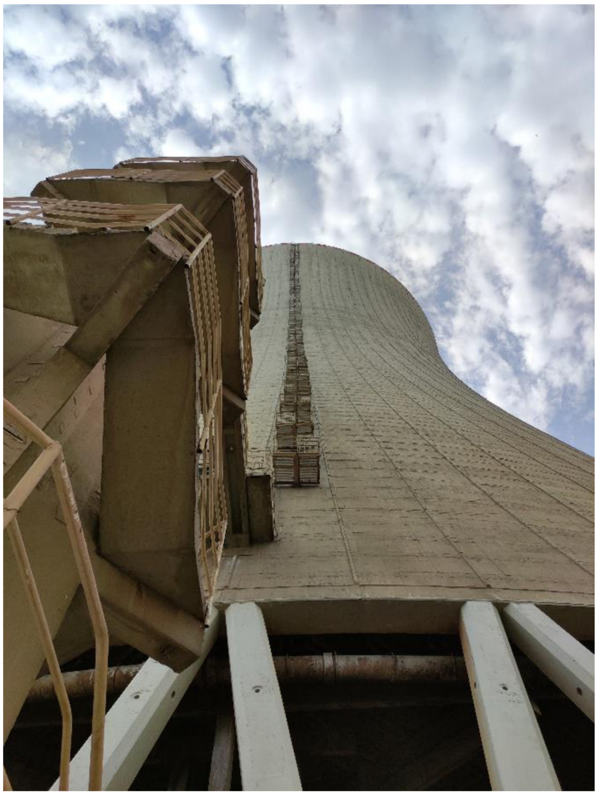

Figure 2. The cooling tower.

Cooling water inside the tubes takes on (absorbs) the heat from the steam, thus forcing steam to condensate. Cooling water then runs into cooling towers. Nuclear power plants without access to the sea typically use cooling towers to cool down circulating cooling water. One of the Temelín nuclear power plant's cooling towers is shown in Figure 2. Usually, there are two cooling towers per unit. Plastic nozzles spray water brought from the condenser. Cooling towers of a specific shape called rotational hyperboloids provide a "chimney effect" (ČEZ, a.s., 2019a), thus cooling the water that is pumped back to the condensers to repeat the process of cooling down the steam.

The newly transformed water is called a condensate (ČEZ, a.s., 2019a). Condensation pumps pump the condensate through low-pressure heating systems (low-pressure regeneration), they heat up the condensate to prepare it for the other parts of the secondary circuit, the thermal degassers, and the supply tank (see Figure 3).

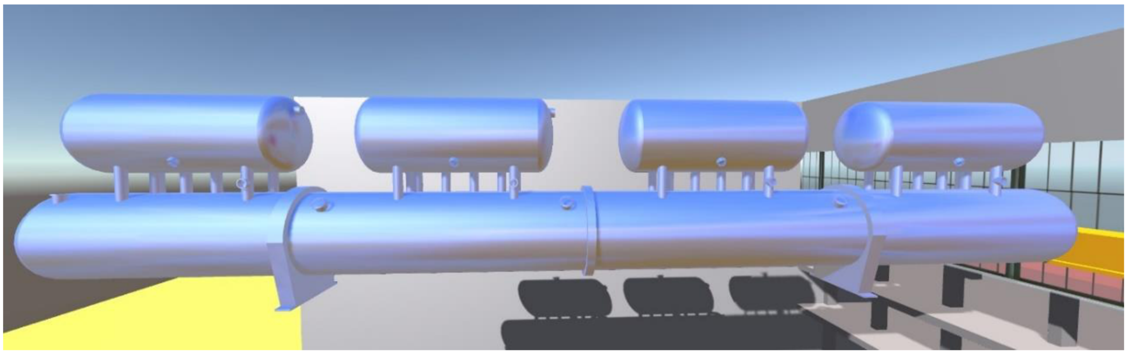

Figure 3. The supply tank with degassers. Reprinted from Jaderné elektrárny 3D (2017).

There should always be a supply of demineralized water (condensate). The condensate then flows from the supply tank through high-pressure regeneration, heating up to the temperature of 220 °C, and the electrically supplied turbines pump the condensate to the steam generator (Svět energie, 2020a). These pumps are called feedwater pumps, as they "feed" the water back to the steam generators; therefore, the condensate is called the feedwater. The whole process of water turning to steam and flowing into the turbine repeats.

The turbine shaft is attached to the generator (ČEZ, a.s., 2019a). If the turbine spins, the rotor of the generator also spins at the same speed. The generator is a synchronous non-salient pole machine with two poles. As stated before, the generator and the turbine spin at 3,000 rpm. This is given by the frequency of the power grid with which the generator needs to be synchronized (it is 50 Hz in the Czech Republic). Because of electromagnetic induction, the rotating magnetic field of the rotor interferes with the magnetic field of the stator, thus inducing a voltage of a magnitude of 24 kV (Simopt, 2017). The generator circuit breaker is located directly underneath the generator and three isolated-phase buses lead to transformers located right outside the unit (ČEZ, a.s., n.d.b). The voltage gets transformed from 24 kV to 400 kV and flows through the transmission towers to a nearby electrical substation in Kočín (ČEZ, a.s., 2019a).

Water is essential for the operation of nuclear power plants, so naturally, one of the main criteria when building a nuclear power plant is a sufficient source of water. The Temelín nuclear power plant has the river Vltava as its water source. As the area of the power plant was considered for four units in total, there is plenty of water for additional units. Approximately five kilometres away from the power plant is the pump station Hněvkovice located on the river Vltava. Two underground pipelines lead to the power plant and supply it with river water which flows into two tanks inside the power plant where it serves either as cooling water or is chemically processed and used in the secondary or primary circuit as the demineralized water (Svět energie, 2020d, ČEZ, 2019b).

1.2 Operating Principle of Selected Nuclear Power Plants

For the purpose of comparing the design and operating principle of the Temelín nuclear power plant, the infamous nuclear power plant in Chernobyl and a slightly less infamous Fukushima Daiichi were chosen. The second nuclear power plant in the Czech Republic operated by ČEZ Group Plc., the Dukovany nuclear power plant, is also included because it is the oldest nuclear power plant operated by ČEZ Group Plc., where the requirements for safety measures given by the regulators are the same but executed through different technology. It is a very good example of comparing safety measures of similar reactor types run by the same country.

1.2.1 Dukovany

Operating principle of the nuclear power plant in Dukovany is only slightly different from the Temelín nuclear power plant. The whole cycle was described in the previous chapter, so in this chapter, only the parts with differences will be mentioned. The Dukovany nuclear power plant was selected as another concept because the nuclear power plants in Slovakia follow the same (or very similar) original design despite being constructed in different years by different companies.

The Jaslovské Bohunice, Mochovce, and Dukovany nuclear power plants have reactors VVER 440/V-213 (EP Power Europe, n.d.; ČEZ, a.s., 2022). As mentioned above, I chose to describe only one of these nuclear power plants because of the similarities in their design. The Dukovany nuclear power plant is made into a dual-unit design, which means inside one reactor hall, there are two reactors. For each reactor, there are two turbines with generators, making it four turbogenerators inside each turbine hall (Svět energie, 2020b).

Slightly enriched uranium is also used in the Dukovany nuclear power plant as fuel with light water as the coolant and the moderator. The difference is only in the final form of a fuel assembly and the number of assemblies inside one reactor. The coolant is heated up by the fission reaction to 297°C, kept under pressure of 12.11 MPa, and flows to six steam generators (ČEZ, a.s., 2022). The primary circuit is located inside a containment building with a bubbler. The heat exchange happens in steam generators and steam flows to turbines. Steam flows to two separate turbines with generators, and spins them (3,000 rpm), thus inducing 17.75 kV voltage in stator windings (Slabák, 2020, December 10). The electrical substation for the Dukovany nuclear power plant is Slavětice.

The turbine consists of one high-pressure part and two low-pressure parts. Underneath the low-pressure parts are located the condensers. The Dukovany nuclear power plant has eight cooling towers in total, making it four for one dual-unit.

1.2.2 Chernobyl

In the Chernobyl nuclear power plant, there were four nuclear reactors RBMK-1000 (six planned in total). The English abbreviation for RBMK reactor is LWGR, which stands for light- water cooled graphite moderated reactor. Plokhy (2018) states that "RBMK reactors were designed to run on almost natural uranium-238, with enrichment level of a mere 2 to 3 percent of uranium-235." (p.51). RBMK reactors (called High Power Channel Reactors in English) use graphite as the moderator and water as the coolant. He explains that these reactors were chosen by the Soviet Union because of higher power and cheaper costs than VVER (Plokhy, 2018). Plokhy (2018) also mentions that due to beliefs that RBMK reactors are perfectly safe, Chernobyl, in favour of further decreasing the costs, has no containment structure.

RBMK is a boiling reactor. As illustrated in Figure 4, the reactor consists of an enormous number of channels (1693 in Chernobyl's reactors) surrounded by graphite bricks. The coolant is heated up to 280°C by fuel rods situated inside these channels. The water boils, turns into steam and under the pressure of 6.9 MPa flows to moisture separators (Energy Encyclopedia, 2022). Because of the "low" pressure, the reactor does not have to be in a pressure vessel (Plokhy, 2018). Afterwards, the steam flows directly to the turbine because RBMK reactors are built in single-circuit design, making them even cheaper for construction. The steam spins the turbine; condensers underneath the turbine turn steam into feedwater and feedwater flows back to the reactor. Chernobyl does not have cooling towers because it has "a cooling pond, which is an artificial water reservoir that was created to cool down the heat exchangers." (Voitsekhovych, et. al., n.d.). The generator spins with the turbine, thus creating electricity.

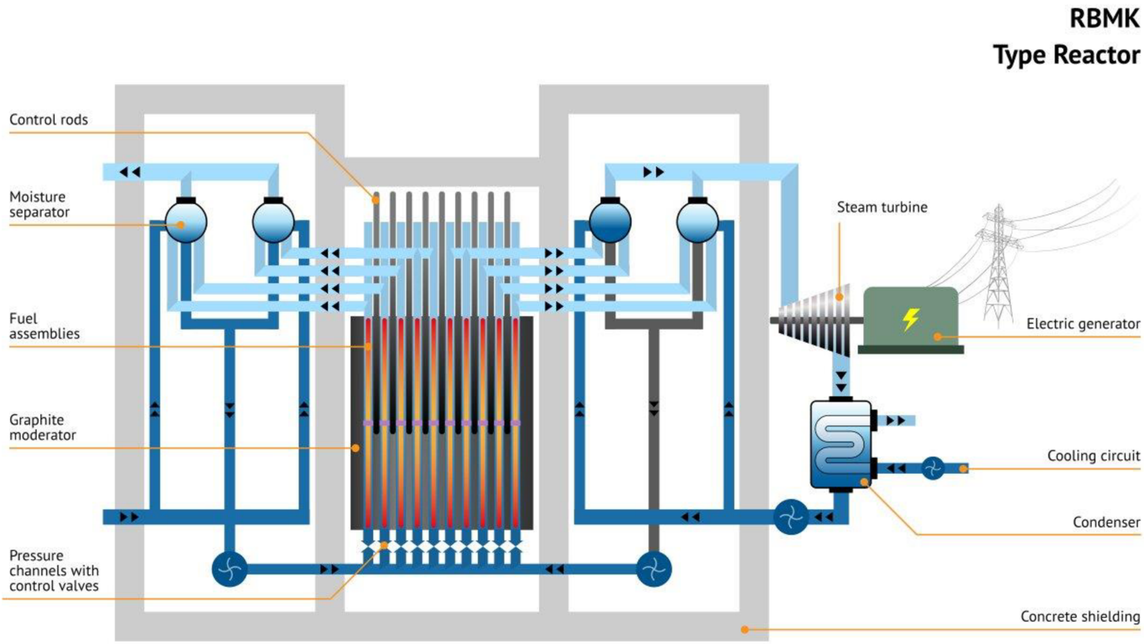

Figure 4. RBMK. Reprinted from Energy Encyclopedia (2022).

1.2.3 Fukushima Daiichi

The operating principle of the Fukushima Daiichi nuclear power plant is similar to the Chernobyl nuclear power plant as they both have boiling water reactors and single-circuit design. The main difference is the reactor design. The pressure and temperature inside the boiling water reactor (BWR) in the Fukushima Daiichi nuclear power plant approx. 7 MPa and 286°C (TEPCO, n.d.; Denk & Kačena, n.d.). As illustrated in Figure 5, the Fukushima Daiichi nuclear power plant has a pressure vessel for the reactor, a primary containment (drywell) and a pressure suppression pool (wetwell). For cooling inside the condensers, seawater is used. Additionally, the Fukushima Daiichi nuclear power plant's reactors do not use graphite as the moderator, but demineralized water (Denk & Kačena, n.d.).

The core located inside the reactor vessel heats up the cooling water, creating a steam-water mixture. The mixture flows to the moisture separators, and the dry steam flows to the turbine and spins it, generating electrical energy inside the generator (U.S. NRC, 2015). The condensation process is the same as in the previous power plants. The cooling is ensured by seawater – no cooling towers are needed.

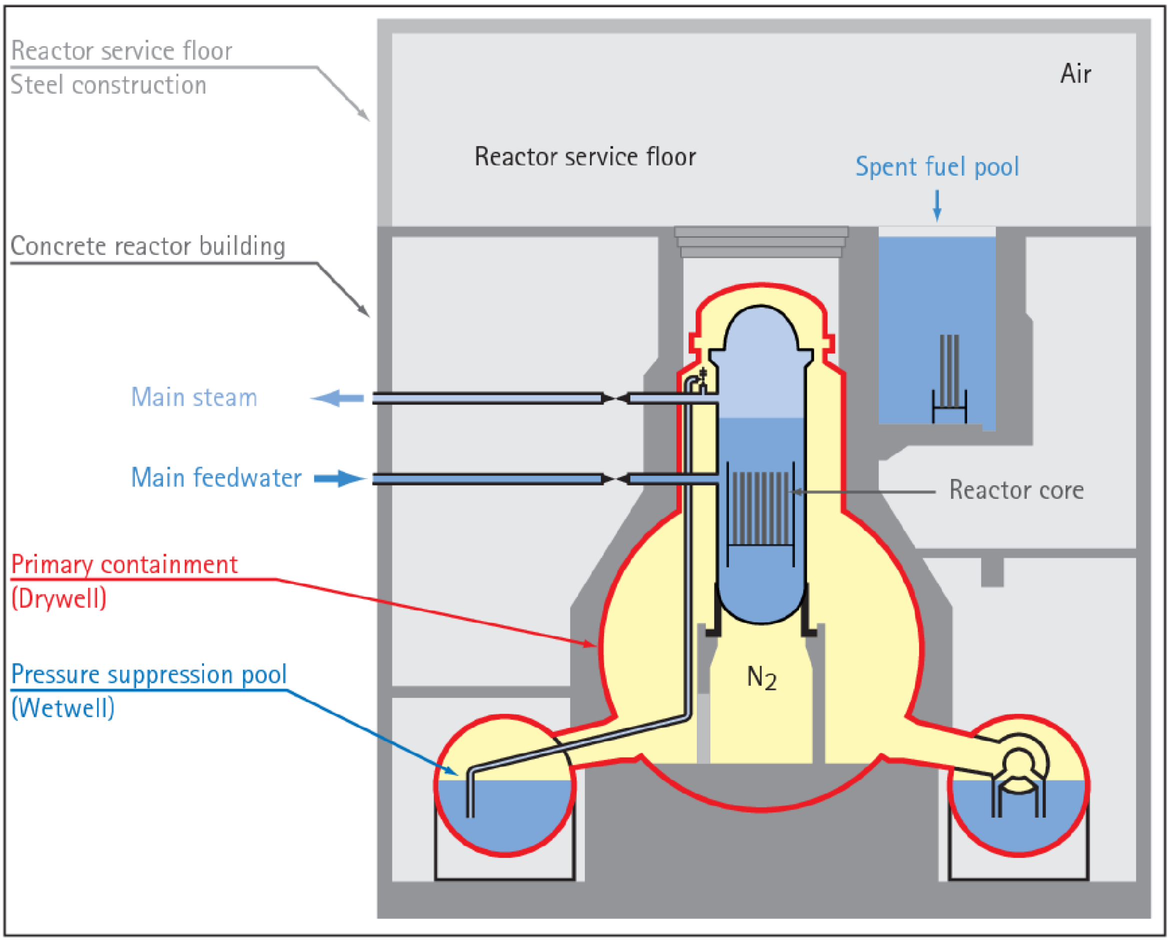

Figure 5. BWR-3 Fukushima Daiichi. Reprinted from Mohrbach (2011).

As the basic operating principles of the selected nuclear power plants were described, the differences in the individual principles became visible. Thus, the following chapter will cover both the key and additional safety measures of the selected nuclear plants.

Chapter 1 covered the basic operating principle of a nuclear power plant, specified the operating principle of the Temelín nuclear power plant and afterwards described the operating principle of the selected nuclear power plants. The chapter also examined and highlighted the differences in individual designs.

2 Safety Measures

The general nuclear safety objective is "to protect individuals, society and the environment by establishing and maintaining in nuclear power plants an effective defence against radiological hazard." (International Nuclear Safety Advisory Group, 1999, p. 8)

In this chapter, the main safety measures of the selected nuclear power plants will be described. Some of the safety measures were already briefly mentioned in the previous chapter. In the Czech Republic, the government places great emphasis on nuclear safety. The safety is overseen by authorities for each state and even authorities that represent the Europe Union and the world. Each year, nuclear power plants are improving thanks to the joint effort of the inspectors, operators and workers of various organizations and nuclear power plants respectively. The main points of nuclear safety include the ability to safely shut down the reactor, the ability to cool down the active zone of the reactor and the ability to limit and lower the release of radioactive substances below permitted limits (ČEZ, a.s., n.d.b).

This chapter will be divided into several subchapters, each discussing one safety issue. The chapter will conclude with a list of the organizations for nuclear safety as they play a crucial role in deciding whether or not a nuclear facility can start or continue operation. Most safety measures are based on previous experience, so it is important to share the experience between the operators of nuclear power plants and facilities. According to Spinrad and Marcum (2023), "the nuclear industry in the United States created a design philosophy referred to as 'defense in depth'," which means that "all safety systems are required to be functionally independent, inherently redundant, and diverse in design". The following chapters will show that the Czech Republic, among other countries, has also adopted this philosophy.

2.1 Preventing the Leakage of Radioactive Substances into the Environment

The most basic safety measures are physical barriers against the leakage of radioactive substances into the environment (Slabák, n.d.; ČEZ, a.s., 2020). The first barrier is the matrix of the pellet. Swiss Federal Nuclear Safety Inspectorate ENSI explains that "the solid radioactive substances (and part of the radioactive noble gases) are trapped in a matrix in the pellets during the normal operation of the reactor" (2018, November 7). The second barrier is the cladding of the fuel rods made from zirconium alloys. Zirconium alloys are used because of their low capture cross-section to thermal neutrons and their good corrosion resistance (Slabák, n.d.). The next physical barrier, the pressure vessel (see Figure 6), is absent from the Chernobyl nuclear power plant design. The reason for the absence, as mentioned in the previous chapter, was lowering the cost of the power plant and the trust put into the design of the reactor.

Figure 6. Pressure vessel. reprinted from ČEZ, a.s. (n.d.b).

Another physical barrier can be the whole primary circuit if it is separated from the secondary circuit (Slabák, n.d.; ČEZ, a.s., 2020) and absent from the boiling water reactors with the single-circuit design, such as in the Fukushima Daiichi and Chernobyl nuclear power plants. The last physical barrier is the hermetic (airtight) structure - containment. As the International Nuclear Safety Advisory Group (1999) notes, "a containment structure is designed to withstand the internal pressure that can be expected to result from the design basis accident for this structure, calculated using substantial safety factors." (p. 59). For the Temelín nuclear power plant, it is the containment with 1.2 m thick concrete walls and pre-tightened ropes inside these walls (ČEZ, a.s., 2020; Svět energie, 2020a). The ends of the pre-tightened ropes are shown in Figure 7. The Dukovany nuclear power plant has a bubble condenser containment system. In case of an accident, the radioactive steam would flow to water trays filled with demineralized water and boric acid and would need to bubble through the water, thus condensing and decreasing pressure (Blinkov, et. al., 2000; Svět energie, 2020b). The Chernobyl nuclear power plant did not have any containment structure, only a standard concrete building. The Fukushima Daiichi nuclear power plant has the Mark I containment. The containment consists of a condensation chamber (wet well) and a concrete shell (dry well). The wet well is a torus-shaped container made of steel, located under the pear-shaped pressure vessel (Federal Office for the Safety of Nuclear Waste Management, n.d.). The pressure vessel is connected to the wet well by a series of pipes. The pipes are submerged in water, thus forcing the water vapour to condensate.

Figure 7. Ends of the pre-tightened ropes. Reprinted from Sviták (2020, November 13).

2.2 Safety Systems of the Primary Circuit

Every nuclear reactor mentioned needs a neutron absorber for control of the chain fission reaction. For the nuclear power plants Temelín, Dukovany and Fukushima Daiichi, the absorber is Boron constantly present in the coolant in the form of boric acid. Boric acid is used for small and long-term changes in the power output of the reactor (ČEZ, a.s., 2020).

For immediate regulation of the fission reaction, solid boron carbide in the form of control rods is used. Control rods made from solid boron carbide were also used in the Chernobyl nuclear power plant, however, they had tips made from graphite (Slabák, n.d.).

The Temelín nuclear power plant has sixty-one control rods divided into ten groups. The control rods must shut down the reactor (stop the chain fission reaction) in a few seconds. Each control rod is controlled by a linear stepper motor (see Figure 8) and held in position by an electromagnet. The Dukovany nuclear power plant has 37 control rods divided into six groups (Brounková, 2020). Each source lists a different number of control rods for the Chernobyl nuclear power plant Unit 4 (179–205 rods). Unreliable sources state the number of control rods in the Fukushima Daiichi nuclear power plant is thirty-nine.

Figure 8. Linear stepper motors.

Both the Temelín and Dukovany nuclear power plants have a volume compensation system (ČEZ, a.s., 2022). This system must check the temperature, pressure and volume of the primary circuit. The volume compensator is the only point in the primary circuit where the primary water boils because of the electrical heaters inside. The water vapour creates "a steam pillow" which can put more pressure on the primary circuit in case of low primary circuit pressure. It also can work in reverse. In case of too high pressure, there is a shower system that sprays the steam pillow, making it condensate and relieve the pressure (ČEZ, a.s., 2020). The Temelín nuclear power plant has a bubbler tank as a part of the pressure compensation system.

Nuclear power plants must have hydrogen recombinators to prevent hydrogen-caused explosions. Figure 9 displays one of many recombinators in the Temelín nuclear power plant. The recombinators dilute the hydrogen with liquid nitrogen to enable mixing hydrogen with oxygen at lower than 4% concentrations as this concentration of the elements is not explosive (ČEZ, a.s., 2020; Svět energie, 2020b).

Figure 9. Recombinator.

The safety systems of the primary circuit can be further divided into two groups – systems for cooling the active zone and systems for decreasing pressure inside the containment. The systems for cooling the active zone can supply the active zone with coolant and dissipate heat from it even in case of a damaged primary circuit (leaking of the primary pipes) in sufficient amounts (ČEZ, 2020).

To lower pressure inside the containment structures, there are emergency spray systems (ČEZ, a.s., 2020). The spray system inside the containment building of the Temelín nuclear power plant is shown in Figure 10. In the Dukovany nuclear power plant, the spray systems are also part of the containment structure. In case of an accident, the leaked steam would be sprayed with demineralized water with a concentration of boric acid (ČEZ, a.s., 2020).

Figure 10. The spray system in the Temelín nuclear power plant.

Since the spray system does not affect the reactor's active zone, an additional safety system must be introduced. There is a passive safety system that, in case of coolant loss in the active zone, pours demineralized water out of tanks to the active zone and floods it. The passive safety systems are called hydro-accumulators. The tanks are pressurized with nitrogen; therefore, they can react to the loss of pressure without electricity (ČEZ, a.s., 2020; Svět energie, 2020c). The hydro-accumulators are not the only safety system that ensures the cooling of the active zone during an accident; however, the other main systems will not be described here because there is no way to compare them to designs of the nuclear power plants outside the ČEZ Group Plc. Besides, it is rather difficult to obtain much detailed information about the safety measures of nuclear power plants abroad.

2.3 Loss of Offsite Power

Nuclear power plants must be prepared for a number of situations that can happen during normal operation including a total blackout. In case of loss of offsite power, there must be onsite power sources. The Temelín nuclear power plant is able to start up from a complete blackout of the power grid. There are thirteen possible power sources for the nuclear power plant Temelín (ČEZ, a.s., 2015). These sources are divided into three categories: operational sources, reserve sources and emergency sources. The thesis does not discuss operational sources because they are used for standard operation when safety measures are not considered.

The Lipno I hydroelectric power plant was built to balance energy spikes; therefore, it can start up very quickly. Within 150 seconds, it can be fully operational providing the power output of 120 MWe (ČEZ, a.s., 2023), making it the ideal reserve source of electricity for the Temelín nuclear power plant. The self-consumption of the Temelín nuclear power plant is approximately 50 MWe (ČEZ, a.s., n.d.b). Electricity is led to Temelín through the Dasný and Kočín electrical substations. This connection must be tested annually.

The safety systems of the reactor cannot be disconnected from a power source for longer than fragments of seconds (ČEZ, a.s., n.d.b). The emergency sources of electricity are diesel generators (ČEZ, a.s., n.d.b). They must be ready to start up and power the first systems in a few seconds and must be regularly tested.

Main Emergency Diesel Generators

The main emergency sources of power for both units of the Temelín nuclear power plant are the emergency system diesel generators. Each unit has three emergency system diesel generators ready. One emergency system diesel generator, as illustrated in Figure 11, is enough to power the appliances necessary to ensure nuclear safety. However, the other two must always be in reserve in case of some problems (Svět energie, 2020b). In nuclear safety redundance of safety systems is very important. These diesel generators are kept in a "hot" state, which means they are ready to start up at any moment. They start up without human intervention and can operate without refuelling the tanks for 72 hours of continuous usage each (ČEZ, a.s., 2019b). The power output of one system diesel generator is 6.3 MW (ČEZ a.s, 2019b, ČEZ, a.s., n.d.b).

Figure 11. Diesel generator. Reprinted from ČEZ, a.s. (2012).

The diesel generators must be cooled, which is provided by so-called essential service water. This service water is considered essential because it ensures the operation of main emergency diesel generators that are essential for nuclear safety. Figure 12 shows pools with spraying fountains (sprinkle pools) visible from around the power plant that serve as a cooling system for the essential service water. This water is also used for cooling the spent fuel pool inside the containment building.

Figure 12. Sprinkle pools. Reprinted from ČT24 (2019).

Common Diesel Generators

There are two additional diesel generators located directly between the two units in the Temelín nuclear power plant. Despite being kept in a hot state, they are not responsible for nuclear safety. They supply expensive machinery that could be damaged by suddenly losing all power. The technical parameters of these diesel generators are the same as the emergency diesel generators, i.e., their start-time delay is 10 seconds and their power output is 6.3 MW, but they are both connected to both units. One is enough to supply both units simultaneously (ČEZ, a.s. 2019b).

Accumulator Batteries

As stated above, some of the appliances, mainly emergency systems of the primary circuit, are allowed the loss of power for only fragments of seconds. The starting sequence of the main emergency diesel generators takes around 10 seconds (ČEZ a.s., 2019b). These appliances-need another emergency source, so the power supply is provided by accumulator batteries regularly charged and discharged to be in the best possible condition.

2.4 Additional Safety Measures

The previously discussed safety measures are crucial in case of a loss-of-coolant accident (LOCA) which is assumed as a guillotine rupture of the primary circuit pipelines. They are carefully implemented for the worst possible accident scenario. LOCA is considered the maximum credible accident, also called the "design basis accident" (European Nuclear Society, 2019). Additional safety measures are adopted to prevent beyond design-basis accidents[4].

Operators of nuclear power plants must carefully observe the situation around the whole world, e.g. global and local opinions on nuclear energy, war conflicts, accidents and emergencies that occur in different types of power plants. Many aspects must be taken into consideration when operating a nuclear power plant. And unfortunately, they gradually increase over time. The response to these events must be immediate. Not only is it essential to adjust the equipment and regularly test and modernize it, but it is also very important to have the operating personnel ready for all kinds of situations. Nowadays, most power plants,

4 Beyond design-basis accidents are accidents that are outside the realm of what the plant was designed to withstand (e.g. the Fukushima nuclear accident). They are difficult to predict either because they have never occurred or have a low probability of occurring (Energy Education, n.d.).

no matter the type, are fully automatic or can operate without much human intervention. However, in case of technological failure, the human aspect can be very important in managing the situation. Some additional safety measures following an accident as well as the function of the emergency response centre and its team with other shelters will be mentioned in this chapter.

Station Black Out Diesel Generators

Following the accident in the Fukushima Daiichi nuclear power plant, nuclear power plants all over the world had to undergo a series of stress tests. To respond to the stress tests, the nuclear power plants Temelín and Dukovany had to build additional emergency power sources (Slabák, n.d.; Svět energie, 2020b). Two additional diverse alternating current diesel generators had to be built in each of the power plants. The diesel generators are often called station blackout diesel generators (SBO DGS) (ČEZ, a.s. 2019b). Another safety systems that needed improvement were the hydrogen recombinators. The improvement included increasing the number of recombinators inside the containment structures in the Temelín and Dukovany nuclear power plants (Slabák, n.d.).

Auxiliary Gas Boiler Room

Some can argue that the auxiliary gas boiler room is not a safety measure, but I disagree. The Temelín nuclear power plant supplies heat to its own area and nearby objects. Additionally, it supplies heat to the nearby town Týn and Vltavou and in the near future, it should supply a part of České Budějovice. This heat is extracted directly from the turbine (steam extraction) and transferred to the heat exchange building.

If both units must be shut down due to an emergency or other factors, the heat can be supplied by five steam boilers located inside the auxiliary gas boiler room, so the people living there are not left without heat. Also, these boilers can serve as a warm-up to the units. It can supply enough heat to start up the units and it can be used for various tests (ČEZ, a.s., 2019b). Both units are connected to each other, so they can help each other, but if one unit enters a refuelling outage and the second must be shut down because of an emergency, there will not be enough heat to warm up the equipment to start it up. That is why I consider the gas boiler room a safety measure.

Shelters and Emergency Response

When discussing safety, it is also very important to mention the shelters inside the nuclear power plant. There are four in total in the case of the Temelín nuclear power plant and six in the case of the Dukovany nuclear power plant (Admin, 2017). They are marked with a yellow sign on the building under which the specific shelter is located. Inside the area, there need to be pointers, so everyone always knows where to go in case of an emergency. Locations of the shelters are taught to every worker before they are given access to the power plant. The shelters in the Temelín power plant have the capacity to cover 1775 people (Admin, 2017). The introduction training handbook is accessible online from ČEZ Group Plc. website. Once every year every worker who has access to the nuclear power plant has to take a test (Kantor, 2017). This test focuses on the operating principle of the power plant, radiation protection, layout of specific objects and also emergency response.

One of the shelters in the Temelín nuclear power plant is designed for a special purpose. It is called the emergency response centre. It is a room where the emergency response team meets and manages the situation. The team consists of several people working in the power plant, and it is divided into four shifts. For example, one of the members of the emergency response team is always the manager of the power plant. However, there can be a situation, where the emergency response team cannot occupy the emergency centre. In this case, there is a simple solution – a tent that can be built on a field. The backup emergency centre is mobile and distributed to both nuclear power plants in the Czech Republic (Šuleř, 2015).

Workers at the site must undergo regular medical check-ups and must be psychologically tested periodically. A well-trained staff is a prerequisite for safety (ČEZ, a.s., 2019a). Tests allowing entry to the guarded area of the power plant are repeated annually with no exceptions. All workers must exactly know how to behave in certain situations. These situations are not only tested theoretically but also practically through exercise. There are several different kinds of exercises in nuclear power plants. The number of exercises done in the Temelín nuclear power plant increased to twice the number because of the accident in the Fukushima Daiichi nuclear power plant (Admin, 2017). Some exercises are only for certain parts of the power plant, whereas others apply to the whole site. Sometimes the exercise is kept secret and other times it is announced in advance. However, the manager of the power plant can decide from one day to another that there will be additional exercise. Usually, the exercise is for the workers only – simulation of self-evacuation, evacuation by buses, going to the shelters and using protection against radiation. Once in a while, there must be an exercise that includes the Czech army. There is an extinction zone around both nuclear power plants in the Czech Republic. A breach of this area is also part of the exercise due to the breaches in the past (Kubeczka, 2003).

2.5 Organizations for Nuclear Safety

All safety measures must be monitored, regularly tested, and even improved. The State Office for Nuclear Safety is the most important authority to the operators of nuclear power plants. It issues permits for activities, sets the conditions for operation and is subordinate to the government (Slabák, n.d.). The Czech Republic's State Office for Nuclear Safety is called Státní úřad pro jadernou bezpečnost (SÚJB). SÚJB performs state administration and supervision of nuclear safety, radiation protection, physical protection and emergency preparedness for all nuclear facilities in the Czech Republic (SÚJB, n.d.a). The Atomic Act[5] is available in its updated form on SÚJB website. However, to ensure the maximum possible safety of the nuclear facilities, the government of the Czech Republic decided to be part of additional international organizations, allowing cooperation between the nuclear power plants in the world.

The first international organization is the International Atomic Energy Agency (IAEA). IAEA's three basic tasks: promotion of Safeguards and Verification, supervision of Safety and Security and the support of nuclear Science and Technology for peaceful purposes (Slabák, n.d.; SÚJB, n.d.b). IAEA regularly sends Operational Safety Review Team (mission OSART) at the request of the government. OSART compares the activities of the selected nuclear power plant with safety standards and recommendations of IAEA. OSART focuses on the documentation, not the operation of the power plant as a whole (Slabák, n.d.). That falls under a different organization.

The World Association of Nuclear Operators (WANO) was created as a response by the nuclear community and industry to the Chernobyl accident. WANO's task is to maximize the safety and reliability of nuclear power plant operations by exchanging experience (Slabák, n.d.). The membership is voluntary. WANO (2022) explains that "to maximise the safety and reliability of nuclear power plants worldwide by working together to assess, benchmark and improve performance through mutual support, exchange of information, and emulation of best practices."

The Western European Nuclear Regulators Association (WENRA) brings together the supervisory authorities of the European Union and Switzerland. Applies only to countries of

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[5] The Atomic Act is the law on the peaceful use of nuclear energy. This Act regulates all matters relating to the peaceful uses of nuclear energy. These include, for example, the obligations and rights of legal and natural persons in the use of nuclear energy, the conditions for the management of radioactive waste, the conditions for nuclear safety, the scope of state supervision of nuclear safety and others. (ČEZ, a.s., 1999b).

the European Union with a nuclear programme.

The European Nuclear Safety Regulators Group (ENSREG) was created by European Commission in 2007 (ENSREG, n.d.). ENSREG is an independent, expert advisory group and it decides the stress tests of nuclear power plants in the European Union.

The European Atomic Energy Community (EURATOM) wants to raise living standards by growing the nuclear industry. It supports nuclear research with an emphasis on preventing the misuse of nuclear material (Slabák, n.d.).

This chapter was divided into five subchapters, each covering a different safety issue and describing the corresponding safety measures. It was also important to mention the organizations responsible for nuclear safety and the safe operation of nuclear power plants. As this thesis is the case study of the Temelín nuclear power plant, the focus was on the safety measures of this nuclear power plant. The level of safety measures of the other three nuclear power plants was also considered and discussed when this information was publicly accessible.

3 Advantages and Disadvantages

In this chapter, the advantages and disadvantages of the Temelín nuclear power plant design will be discussed and it will be compared to the design of the Dukovany nuclear power plant, the Fukushima Daiichi nuclear power plant and the Chernobyl nuclear power plant. The focus will be on the similarities and differences between the Temelín nuclear power plant and the Dukovany nuclear power plant as they both have a pressurized light water reactor, but they were built in a different regime and according to different standards.

The most important fact is that both nuclear power plants with pressurized water reactors have passive safety features and "inherent safety", which is a significant safety advantage. Inherent safety means using basic physical principles inside the reactor to prevent an accident. An example of an inherent safety feature is a negative reactivity coefficient[6] (Slabák, n.d.). If there is an increase in temperature inside the reactor, the ability of water to moderate neutrons decreases, thus reducing the probability of fission. This is not true for the nuclear power plant Chernobyl, which has positive reactivity coefficients, so if there is more steam inside (less neutron-absorbing water), the reactivity of the reactor increases (INSAG, 1992). The Chernobyl nuclear power plant used unenriched uranium as fuel, so according to Marshall (2011, March 17), "the reactor was designed in a way that made it easier for the nuclear reaction to accelerate". The Fukushima Daiichi nuclear power plant has a boiling reactor, which is the same as in the Chernobyl nuclear power plant, however, the Fukushima Daichi also has a negative reactivity coefficient because it uses slightly enriched uranium as fuel (Marshall, 2011, March 17).

One of the passive safety measures was already mentioned in Chapter 2.2 – the use of the hydro-accumulators. Hydro-accumulators are shown in Figure 13. In the Temelín nuclear power plant, there are four hydro-accumulators that passively react to a decrease in pressure inside the reactor pressure vessel. Two of them connect to the reactor pressure vessel above the active zone to flood it from above. The other two under the active zone fill the reactor pressure vessel from below (ČEZ, a.s., 2020). Having more safety systems that react to the change of pressure and are therefore considered passive (do not need electricity to function) is an advantage.

[6] Reactivity coefficients provide a measure of the way in which the neutron multiplication, or reactivity, of a reactor core changes as a function of other reactor variables, such as temperature and pressure, and hence indicate the reactor's inherent stability (Risley, 1987).

Figure 13. Hydro-accumulator.

Another passive safety measure that both the Temelín and the Dukovany nuclear power plants have are the control rods (Slabák, n.d.). In case of loss of power, electromagnets holding the control rods will let them fall to the active zone. Every nuclear power plant has a different number of control rods or regulation cartridges, as they are called in the Dukovany nuclear power plant (ČEZ, a.s., 2020b), made of boron carbide. The advantage of control rods being a passive safety measure is that electromagnets hold the rods in their set position, thus in the event of a power failure, rods are no longer held in position and fall to the bottom of the active zone.

Both nuclear power plants in the Czech Republic have emergency pumps and emergency spray systems. All nuclear power plants should have emergency pumps, but unfortunately, there is no access to specific information about those pumps from the power plants abroad. The spray system "showers" the steam inside the containment building, forcing it to condensate. The water then flows to the bottom of the containment, where it collects in emergency tanks, and emergency pumps pump it back to the emergency sprays creating a loop, which is another advantage.

The difference is in the containment structure. The functions of each containment structure were described in Chapter 2.1. It is hard to say which design is more beneficial and efficient because every type of nuclear power plant has different requirements for construction. The advantage of the structure can be its cost, as the reinforced concrete structure with pre-tightened ropes and steel lining can be quite expensive. According to Mitchell (n.d., as cited in Madsen, 2021), strong safety standards and safety changes can have a positive impact on the reliability of the nuclear power plant, which ultimately improves cost-effectiveness. The containment of the Temelín nuclear power plant is the newer, more modern solution to the containment with a bubbler because the function of the bubbler is already provided by the volume compensation system with the condensation tank

Another advantage, especially in warmer weather, is having two cooling towers per unit. The operators in the Temelín nuclear power plant can switch all four cooling towers to cool one unit (during a refuelling outage in the second unit). Some nuclear power plants that use only one cooling tower have faced problems in summer due to the drop in the river level. Nuclear power plants that use cooling water from rivers must return the water to the river. When the river level drops, it can heat up faster; therefore, the nuclear power plant must lower the power output to reduce the usage of cooling water. A very similar situation is with seawater-cooled nuclear power plants. According to Hersher (2018, July 27), "cooling issues at nuclear power plants may get worse in the future. Climate change is causing global ocean temperatures to rise and making heat waves more frequent and severe in many parts of the world".

The disadvantage of the Temelín nuclear power plant is having to shut down the reactor, i.e. the whole unit, for any manipulation with fuel. The containment must remain hermetically sealed during operation. Therefore, no spent fuel can leave the building during operation, only during the planned refuelling outage. The refuelling outage takes approximately two months, which can also be longer than other nuclear power plants. The Chernobyl nuclear power plant allows refuelling during operation.

The disadvantage of the dual-unit design is that every accident of one reactor or one turbine in the Dukovany nuclear power plant can possibly affect the rest of the equipment inside the same building. The Dukovany nuclear power plant has four turbogenerators inside one turbine hall. In case of a fire, it could possibly affect the other equipment directly. The same applies to the reactor hall for two reactors. In case of an accident, both reactors can be affected. However, the dual-unit concept has a lot of advantages. The reactor hall only needs one refuelling machine (Svět energie, 2020b). Additionally, if there is a problem with one of the turbines, the other one can continue operation, while there are repair works done on the affected one. It is very beneficial if the operator of the unit does not have to shut down the whole unit because of a small problem with one machine.

The disadvantage of the Temelín nuclear power plant's mono-unit concept is that in case of a problem with the turbine or the generator, the whole unit must be shut down. Additionally, the big turboalternator inside the Temelín nuclear power plant faces problems with vibrations. Workers must precisely put the turbine together and connect it with the precision of hundredths of a millimetre after each outage. The smaller turbines in the Dukovany nuclear power plant are more stable (ČTK, 2019, November 11). The vibrations of the machinery can be felt when standing near the turbine. It stands on its own baseplate that must be sprung. The advantage is the power output of 1125 MWe per unit. Another advantage is the layout of the diesel generators.

Both power plants have the advantage of having a separate circuit for the non-active part of the unit. The two-circuit design allows the secondary circuit to stay non-radioactive, thus reducing the risk of leakage (Nuclear Asia, 2017, June 12). Also, after the nuclear power plant is shut down for good, the decommissioning is much simpler, because of the non-active equipment.

Chapter 3 discussed the advantages and disadvantages of the Temelín nuclear power plant and simultaneously compared them to the advantages and disadvantages of the Dukovany nuclear power plant, the Fukushima Daiichi nuclear power plant and the Chernobyl nuclear power plant. The advantages of the Temelín nuclear power plant include the two-circuit (two-loop) design, the inherent safety of the reactor, the possibility to connect all four cooling towers to one unit, the strict supervision of the State Office for Nuclear Safety and the capability of its management. The high output power is a considerable advantage for the Czech Republic. Moreover, the power plant's location is also an advantage as it is located on a hill, close to the water source and on very stable ground. The large area of the power plant gives many working opportunities; thus, the power plant contributes to a lower unemployment rate. The disadvantages are the inability to manipulate nuclear fuel during operation and facing problems with vibrations due to the size of the turbogenerator.

Conclusion

The bachelor's thesis aimed to examine the nuclear power plant Temelín. It described the design, operating principle, and safety measures of the Temelín nuclear power plant, compared the design and safety measures of selected nuclear power plants in and outside the Czech Republic and discussed the advantages and disadvantages of the Temelín nuclear power plant compared with other selected nuclear power plants. The thesis framed a theoretical concept of the issues based on a literature review of relevant sources.

The design and operating principle were described in Chapters 1 and 2. Even though some safety measures were outlined in Chapter 2, most of them were discussed in Chapter 3. The advantage of the Temelín nuclear power plant is its location, power output, containment building, and the fact that most equipment and machinery is made in the Czech Republic, so the know-how is not abroad.

Disadvantages of the Temelín nuclear power plant are the vibrations of the turbine, the necessary shutdown procedure every time there is a problem with the turbine or the generator (compared to the dual turbines in the Dukovany nuclear power plant), and not being able to move the spent fuel from the spent fuel pool inside the containment to the spent fuel repository located inside the guarded area. The literature review revealed that the advantages of the Temelín nuclear power plant outweigh the disadvantages. There is still room for improvement, and the management of the power plant tries hard to modernize the power plant and keep it in the best possible condition, which is praiseworthy. They use the project reserves to get the most from the power plant. Hopefully, one day the Temelín nuclear power plant will have the Units 3 and 4 it needs. The area of the Temelín nuclear power plant is large enough to be used for different projects.

In my opinion, the Czech government's approach to nuclear safety is appropriate and sufficient. A cautious approach to nuclear safety is always a good choice. The Temelín nuclear power plant meets safe operating conditions and hopefully would be producing electricity for years to come under the supervision of the State Office for Nuclear Safety. Nuclear safety does not depend only on the state of the equipment, but also on the awareness, education and responsibility of individual workers. From my own experience working at the nuclear power plant Temelín, management tries to motivate workers to always be cautious, no matter how experienced the worker is, and pay attention to his/her work as well as their surroundings to prevent even minor injuries. The State Office for Nuclear Safety emphasizes the training of the staff and the technical condition of the equipment. The safe operation of a nuclear power plant involves a high level of professional staff. The demands placed on nuclear power plant personnel in the Czech Republic are, on average, higher than those in Western countries. The Atomic Act is updated regularly and implemented in operation as soon as possible.

A prerequisite for a nuclear power plant's safety must follow regulations and standards that describe using nuclear power plant devices and procedures. Extensive analyses of the occurrence and development of project accidents are carried out to verify the implementation of the applicable safety standards. Moreover, technical, and organisational measures are established to deal with their possible consequences as a precautionary measure.

The only complication I faced while working on this thesis was the time-consuming resource authorisation process and gathering enough information about the topic to recognize false information online. Without the background knowledge of the operating principle of nuclear power plants and electrical engineering education, I would not be able to spot some of the mistakes and errors made by the writers on educational websites.

The number of safety systems in nuclear power plants is enormous because they are usually divided into several groups, each focused on a different aspect of the concept of safety. This thesis only covered some of the main systems for nuclear safety as it would be too time-consuming to name every single one of them and discuss them in great detail.

For anyone interested in nuclear safety, I would suggest reading the reports published online by nuclear safety organizations. Additionally, to anyone interested in the Temelín and Dukovany nuclear power plants, I would highly recommend visiting the information centres of these power plants where they can get additional information about their design and safety measures.

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