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NUCLEAR POWER PLANTS SECURITY

BEZPEČNOST JADERNÝCH ELEKTRÁREN

BACHELOR'S THESIS

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Bakalářská práce

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NÁZEV TÉMATU:

Bezpečnost jaderných elektráren

POKYNY PRO VYPRACOVÁNÍ:

Vymezte koncept bezpečnosti jaderných elektráren a diskutujte bezpečnostní opatření pro prevenci potencionální jaderné katastrofy a negativního vlivu na životní prostředí.

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Abstract

The concept of nuclear power plant safety and security is a complex one. The safe operation of nuclear power plants is crucial for reliable and harmless power generation. An accident linked with this type of facility could have a negative impact on the health of the public, wildlife, and it could cause pollution of the environment. The aim of this bachelor's thesis is to frame the concept of safety and security of nuclear power plants and discuss the means of preventing a nuclear catastrophe. The theoretical part of the thesis deals with defining the basic operational principles of nuclear power plants. Furthermore, the safety and security measures are discussed and illustrated. Moreover, the impact of the safe operation of nuclear power plants on the environment is examined. Lastly, the consequences of the failure of safety and security systems are described with historical examples. The practical part of the thesis realised by means of an online questionnaire survey is concerned with the level of awareness of nuclear power plant safety and their environmental impact among the general public.

Key Words

safety, security, nuclear power plant, accidents, hazards, radioactive waste, awareness, environmental impact, emissions, Chernobyl, Fukushima,

Abstrakt

Koncept bezpečnosti a zabezpečení jaderných elektráren je složitý. Bezpečný provoz jaderných elektráren má zásadní význam pro spolehlivou a neškodnou výrobu elektřiny. Nehoda spojená s tímto typem zařízení by mohla mít negativní dopad na zdraví lidí, volně žijících zvířat, a mohla by způsobit znečištění životního prostředí. Cílem této bakalářské práce je vymezit koncept bezpečnosti a zabezpečení jaderných elektráren a prodiskutovat způsoby prevence jaderné katastrofy. Teoretická část práce se zabývá vymezením základních provozních principů jaderných elektráren. Dále jsou diskutována a ilustrována bezpečnostní a zabezpečovací opatření. Následně je zkoumán dopad jaderných elektráren na životní prostředí za běžného provozu. V závěru jsou popsány důsledky selhání bezpečnostních a zabezpečovacích opatření na historických příkladech. Praktická část práce, která byla realizována prostřednictvím online dotazníkového šetření, se zabývá mírou povědomí veřejnosti o bezpečnosti jaderných elektráren a jejich dopadu na životní prostředí.

Klíčová slova

bezpečnost, zabezpečení, jaderná elektrárna, nehody, nebezpečí, radioaktivní odpad, povědomí, dopad na životní prostředí, emise, Černobyl, Fukušima

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Vedoucí bakalářské práce: Mgr. Ing. Eva Ellederová.

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V Brně dne ....

Jakub Štěpán

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1 Introduction

Times when electric energy was generated by fuelling steam engine and tending the fire are long gone. Since nuclear energy was discovered, it has become an essential part of modern civilization. It is used in a number of different industrial sectors, including agriculture, transport, pharmaceutical industry and medicine. Moreover, it significantly contributes to scientific research and plays a key role in the reduction of greenhouse gases. Arguably, the most publicly recognized and prominent use of nuclear energy remains in providing electricity. The first nuclear power plant started its operation in the Soviet Union on June 27, 1954. Today, there are more than 400 operating nuclear reactors. It is safe to assume that humankind relies on the reliable supply of electric energy and relatively economic operation of nuclear power plants. Nevertheless, “playing with fire” can be dangerous and nuclear energy is a formidable force that poses a great risk if security measures are inadequate or fail altogether.

The aim of this bachelor’s thesis is to frame the concept of vulnerability, and security of nuclear power plants as well as their impact on the environment and the potential ramifications of an accident during their operation. The thesis is divided into a theoretical and practical part. The theoretical part concerns the subject matter of nuclear power plants and their operation. In order to understand the underlying processes behind nuclear power plant operation, the complex topic of nuclear energy is discussed in the first chapter of this thesis. The process of nuclear reaction that takes place in the power plants is examined and explained in detail to better illustrate their operation. Once the operational principles are established, the focus is directed at the safety and security of nuclear power plants. Safety measures at different nuclear power plants and their sufficiency are discussed. Additionally, more possible safety measures and improvements of existing safety measures to prevent adverse impacts of nuclear power plants are investigated. Moreover, the radioactive waste and emissions, their contribution to air-pollution and other negative effects are covered. The impact and ways of dealing with carbon dioxide, radioactive waste and decommissioning nuclear power plants and reactors are investigated. To illustrate the importance of correctly working safety and security measures, the final chapter examines the horrific impact that past safety failures had on their locations.

The practical part of the thesis assesses the level of awareness of nuclear power plant safety and environmental impact among the general public. It is in the form of an online questionnaire survey and the respondents' overall attitude toward nuclear power plants is discussed in the closing chapter of the practical part of the thesis.

2 Nuclear power plant operation and nuclear energy

Nuclear power plants are an essential source of relatively clean energy. A certain part of the public might view this type of energy as extremely dangerous and harmful to the environment. They often argue against it and use power plant accidents to support their arguments. However, it is a common misconception that nuclear energy is extraordinarily harmful to the environment. Many claim that the energy produced by nuclear power plants is in fact green. In my opinion, both sides have valid and invalid points. Therefore, one of the aims of this thesis is to reach a conclusion which confirms that both proponents' and opponents' claims of nuclear energy are substantiated. This topic will be discussed in greater detail later.

Today, the fact that nuclear energy is merely a product of splitting atoms could be considered common knowledge. Nonetheless, the actual process of producing electricity at nuclear power plants that is used to power up home appliances is far more complicated than simply splitting an atom. The process of splitting atoms is called nuclear fission. Nuclear fission itself is the process of an unstable atom, called radioactive isotope, that falls apart into pieces creating other particles and energy (Woodford, 2018). Furthermore, Woodford explains the types of fissions that can occur: "nuclear fission can happen spontaneously, in which we case we call it radioactive decay (the conversion of unstable, radioactive isotopes into stable atoms that aren't radioactive)". However, uncontrolled, spontaneous splitting of atoms in nuclear reactors is extremely dangerous and undesirable. Woodford then continues to explain that nuclear fission can be controlled and made to happen on demand. That is the type of fission used at nuclear power plants. This controlled splitting of atoms is called a nuclear reaction. Simply explained, nuclear reaction produces atomic energy that nuclear power plants are equipped to harness and turn into electricity. Another important concept is chain reaction. Chain reaction, according to Atomic Archive (n.d.), is a process in which during fission another fission is induced in at least one other nucleus – atomic core (see Figure 1). It can become a self-sustaining process under the right conditions, this is identified as critical mass. Chain reaction can be either controlled or uncontrolled similar to nuclear fission. These two types represent the difference between a nuclear power plant and a nuclear bomb.

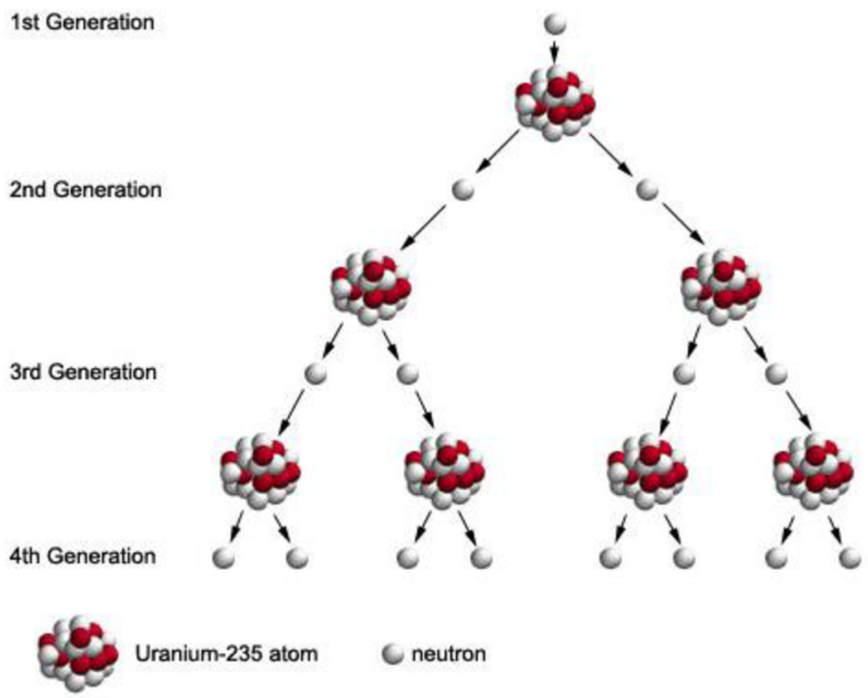

Figure 1. Illustration of an atomic chain reaction. Reprinted from Atomic Archive (n.d.).

The splitting of atoms during these reactions releases an enormous amount of heat. The heat is processed by the power plant and acts as fuel, similar to the manner in which solar panels use photons, to produce desired electricity. According to Woodford (2018), water is heated, and the resulting steam is used to drive steam turbines that are connected to generators of electricity. Woodford (2018) presents a simplified version of the entire process and divides it into individual steps (see Figure 2):

1) First, uranium fuel is loaded up into the reactor – a giant concrete dome that's reinforced in case it explodes. In the heart of the reactor (the core), atoms split apart and release heat energy, producing neutrons and splitting other atoms in a carefully controlled nuclear reaction.
2) Control rods made of materials such as cadmium and boron can be raised or lowered into the reactor to soak up neutrons and slow down or speed up the chain reaction.
3) Water is pumped through the reactor to collect the heat energy that the chain reaction produces. It constantly flows around a closed loop linking the reactor with a heat exchanger.

4) Inside the heat exchanger, the water from the reactor gives up its energy to cooler water flowing in another closed loop, turning it into steam. Using two unconnected loops of water and the heat exchanger helps to keep water contaminated with radioactivity safely contained in one place and well away from most of the equipment in the plant.
5) The steam from the heat exchanger is piped to a turbine. As the steam blows past the turbine's vanes, they spin around at high speed.
6) The spinning turbine is connected to an electricity generator and makes that spin too.
7) The generator produces electricity that flows out to the power grid—and to our homes, shops, offices, and factories.

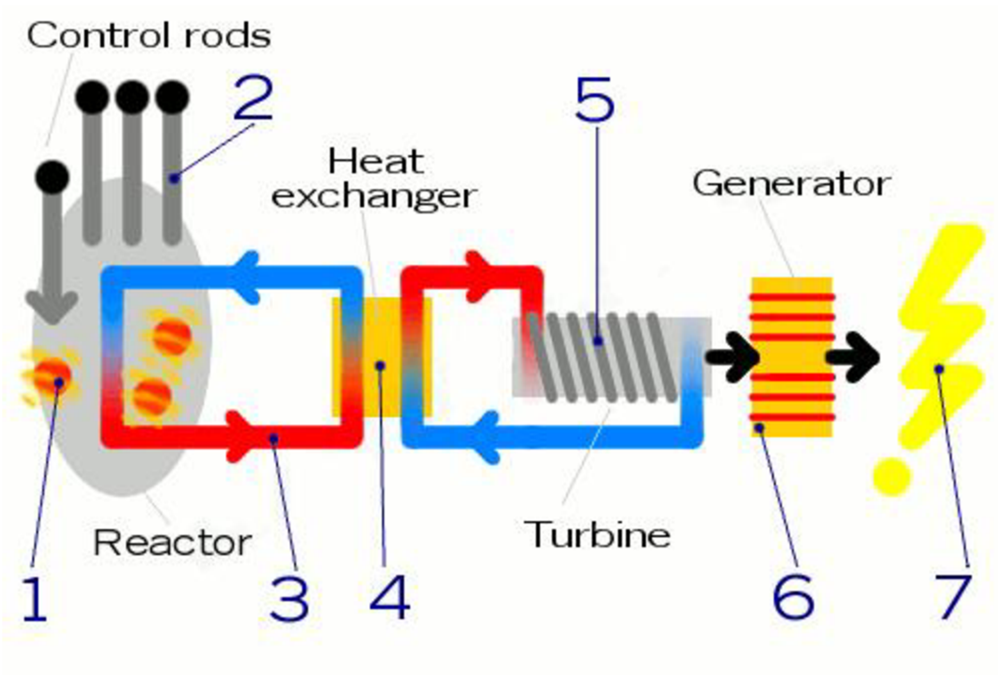

Figure 2. Illustration of nuclear power plant operation. Reprinted from Woodford (2018).

It is evident that the process of generating electricity through nuclear reaction is extraordinarily complicated. Precise and failproof procedures must be implemented to ensure proper and safe performance of the entire system. Therefore, the following chapter discusses appropriate safety and security measures that must be adopted.

3 Safety measures and security measures of nuclear power plants

Safety measures are an extensive subject that concerns every type of a power plant. However, in the case of nuclear power plants, ample security measures are vital, and their insufficiency may have long-lasting adverse effects on the workers, environment, and the general public living near the location of the reactor. Safety measures are closely linked with security[1]. The focus of this chapter is on unintended safety hazards and protection against them. Furthermore, the security design philosophy of nuclear facilities and potential security risks that could lead to intentional misuse of radioactive materials is covered here. Additionally, safeguards that prevent untrustworthy governments from obtaining and developing nuclear weapons are discussed.

3.1 International Atomic Energy Agency

Every type of a hazardous industry must adhere to regulations and specified procedures. Nuclear power plants are not an exception. The supervising international authority is the International Atomic Energy Agency (hereinafter referred to as IAEA). The organisation was set up in response to public fears and expectations resulting from the use of nuclear technology (IAEA, 2016). The main objective of the IAEA is to oversee and advocate the use of atomic energy. Its mission is defined in the organisation's Statute as follows (IAEA, 2016):

> The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose.

The member states are subject to the regulations and are responsible for the implementation of required procedures imposed by the IAEA. The organisation plays a key role in enforcing the Treaty on the Non-Proliferation of Nuclear Weapons (hereinafter referred to as NPT). The NPT is described in greater detail in chapter 3.4, which deals with the

[1] Safety focuses on unintended conditions or events related to radiological releases from authorised activities and it relates mainly to intrinsic problems or hazards, while security focuses on the intentional misuse of nuclear or other radioactive materials by non-state elements to cause hard and it relates mainly to external threats to materials and facilities (WNA, 2018a).

safeguard system.

3.1.1 The International Nuclear and Radiological Event Scale

The industry dealing with atomic energy is susceptible to accidents such as any other industry. Thus, the IAEA compiled the International nuclear and radiological event scale (hereinafter referred to as the INES scale). The scale works on a similar principle as the Richter magnitude scale. Each level on the scale represents the severity of a radiological event. A hazardous event represented by the scale is not limited to nuclear power plants. It also applies to radiological and nuclear events outside a facility.

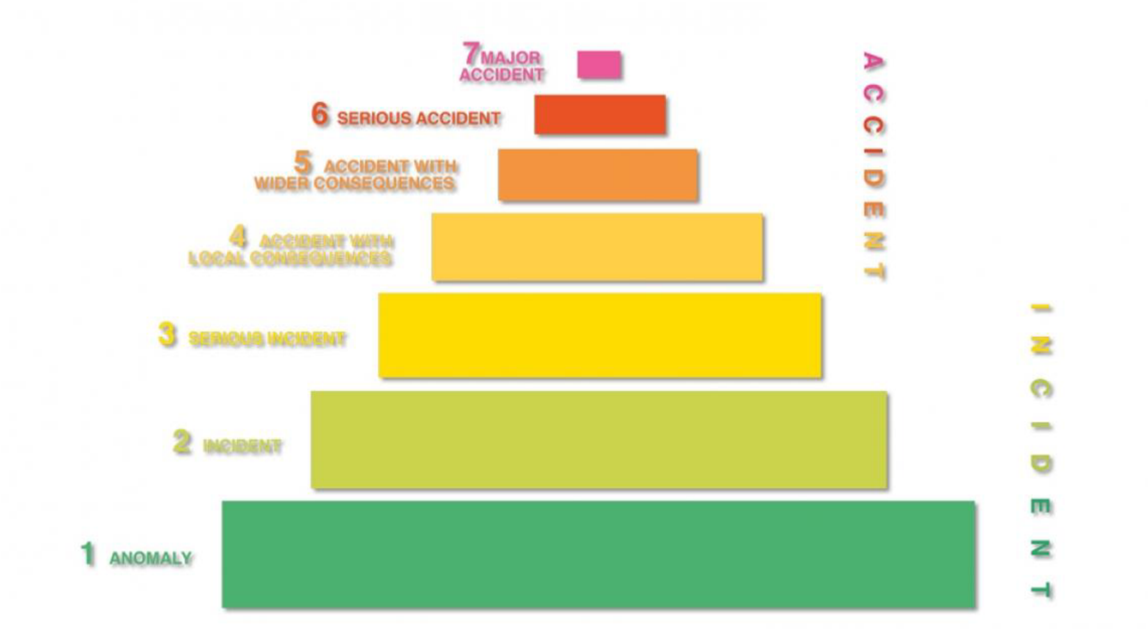

Figure 3. The International nuclear and radiological event scale. Reprinted from IAEA (2019).

There are defined seven possible levels of an event. The first three levels (1-3) are classified as only incidents and the following levels (4-7) are called accidents. A level zero events do exist, however they have no safety significance and are called deviations (IAEA, 2019). The severity is rated based on several criteria. According to the IAEA (2019) three main areas of impact are considered when rating an event:

- People and the Environment
- Radiological Barriers and Control
- Defence-in-Depth

The first category considers the radiation dose to the population and the environment from an event. The second area of impact deals with a release contained inside the affected location with no immediate impact on the population. The last category investigates the failure of security and safety measures.

The INES scale is used to present the severity of certain event to the public. This can help warn the population and help decide appropriate precautionary measures.

3.2 Safety measures

As mentioned above, sufficient safety measures are vital. An accident can occur anytime, anywhere. Adequate protection is necessary to prevent a catastrophe. The first nuclear power plant started its operation over sixty years ago. Since then, more than thirty larger incidents and accidents at nuclear power plants occurred (Rogers, 2011). And according to World Nuclear Association (2018a) (hereinafter referred to as WNA), only three of them were major. It is reasonable to assume that today with all the experience modern safety measures uphold a very high standard, but it is still impossible to make them perfect. Thus, it may well be argued that the layout and operation of these power plants are designed with the aim to reduce the likelihood and limit the severity of any potential accidents.

The WNA (2018a) states that the primary safety concern is the potential uncontrolled release of radioactive material into the environment outside of the power plant. A national regulator is appointed and they are responsible for the safe design and operation of the reactor by the licensee and for ensuring the safety of people and the environment. The WNA then explains that “nuclear reactor accidents are the epitome of low-probability but high-consequence risks”. It is safe to assume that the continually evolving safety measures significantly reduce the high risk associated with the operation of nuclear power plants. To achieve optimum safety the WNA (2018a) describes a “defence-in-depth” approach that is used in the Western world:

- high-quality design and construction,
- equipment which prevents operational disturbances or human failures and errors developing into problems,

- comprehensive monitoring and regular testing to detect equipment or operator failures,
- redundant and diverse systems to control damage to the fuel and prevent significant radioactive releases,
- provision to confine the effects of severe fuel damage (or any other problem) to the plant itself.

This approach can be summarized as: prevention, monitoring, and action. Additionally, three fundamental safety functions are described: reactivity control, fuel cooling, and containment of radioactive substances. It can be concluded that the safety measures are extensive and consider a human error in addition to issues with fuel and cooling. The companies, operating the aforesaid power plants, are responsible for monitoring the levels of radiation at the plant and surrounding environment. Thus, any leaks should be immediately identified and contained.

3.3 Security measures

Security of nuclear power plants is at the same level of importance as correctly functioning safety measures. Some might argue that they are perhaps even more critical. Radioactive material in possession of someone with malicious intent can potentially cause far more significant damage than a contained hazardous event at a nuclear power plant. What is more, an unauthorized person who acquires access to the plant can cause a profound crisis. In the current political climate, terrorist attacks throughout Europe are a common occurrence. It can be concluded that the objective of those attacks is to cause extended damage to the perceived enemy and to strike fear among the public. Sabotaging a power plant that uses nuclear material could lead to a widespread radioactive contamination. It may be regarded as certain that left unprotected this would be an attractive potential target of terrorism. To prevent this from becoming a reality, nuclear power plants are designed with great emphasis on security. That is what Physical Protection System (PPS) is used for.

The physical protection system can be summarized as a system designed to avert radiological theft or sabotage of nuclear materials. Each country has protection objectives that slightly differ. As an example, Whitehead, Potter and O’Connor (2007) claim that PPS designed for the United States power plants must meet core damage protection standards and must be able to prevent theft or sabotage of used fuel. Their publication deals with mainly design and evaluation of PPS (see Figure 4).

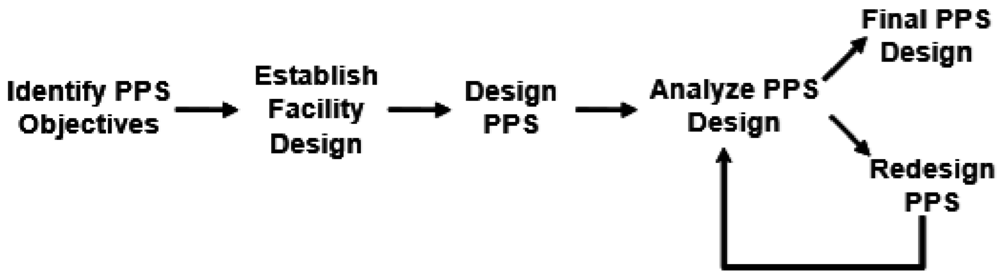

Figure 4. High-level description of a physical protection system design and evaluation process. Reprinted from Whitehead, Potter and O'Connor (2007, p. 17).

The entire simplified process of securing a nuclear facility can be observed in Figure 4. Firstly, the PPS objectives must be identified. This involves two main topics; threat definition and identification of protection objectives (Whitehead et al., 2007). According to Whitehead et al. (2007, p. 19), the establishment of a threat definition typically considers the following three questions:

- What class of adversary is to be considered?
- What is the range of the adversary's tactics?
- What are the adversary's capabilities?

Adversaries can be separated into three classes: outsiders, insiders and outsiders in collusion with insiders.

To conclude, the PPS is designed based on the consideration of the type of the attacker that might be encountered. Their experience, knowledge and potential access to the facility through permanent staff have to be evaluated. Additionally, the abuse of power by insiders has to be assessed. Generally, a potential attack from an insider should be considered among the most threatening. A member of permanent staff can become radicalized, be blackmailed, or potentially sell dangerous materials. Therefore, security measures at nuclear power plants cannot be taken lightly. Bunn (2017) explores a scenario involving an insider sabotaging a spent fuel pool:

> A radicalized insider at a nuclear power plant decides to take action by sabotaging the spent fuel pool, in hopes of causing a major radioactive release. The insider waits until hot, fresh fuel has recently been unloaded into the pool, with many of the hot assemblies in one area of the pool. Using tools that he had brought into the plant and hidden over the preceding weeks, he then damages the pump that would be used to add water to the pool, and also damages pool gaskets, causing a rapid leak. The pool water begins to drain, and the fuel is exposed. The water still in the bottom of the pool blocks air circulation, limiting air cooling of the exposed assemblies, and the assemblies overheat. The hot steam reacts with the melting zirconium on the hottest assemblies, and a spent fuel fire begins. The zirconium-steam reactions release a substantial amount of hydrogen, which builds up in the spent fuel building and ultimately detonates, damaging the building. Much of the radioactivity released in the spent fuel fire is therefore released into the environment.

The article supports the notion that the insider threat is perilous and should be prevented at all costs. Some of the suggested options of insider attack prevention are the screening and monitoring of the staff. Additionally, keeping the workers motivated and satisfied should contribute to trouble-free workdays. This colludes with facility design and ultimately the PPS design.

The PPS strives to prevent any possible attack. It does so by utilizing either deterrence or a combination of detection, delay, and response (Whitehead et al., 2007). Deterrence aims to make the facility a difficult target, hence a potential adversary will be discouraged from making an attempt to attack the power plant. If the adversary is not deterred and carries out an attack, then it must be detected and delayed for a sufficient amount of time for the security measures and personnel to respond. It is essential that the whole process of detection, delay, and a response is faster than the time the adversary needs to carry out the attack. Otherwise, the power plant is extremely vulnerable.

3.4 Safeguards

The idea of a rogue government developing nuclear weapons under the guise of harnessing nuclear energy for the purpose of providing electricity is an important topic that the first world leaders are undoubtedly concerned with. As was discussed above, one individual who gains access to a nuclear facility can cause immense harm. An entire hostile government in possession of a radiological weapon forms a terrifying image. To prevent such a scenario, the International Atomic Energy Agency conducts regular inspections and audits radioactive materials at nuclear facilities around the world. Moreover, according to the WNA (2018c), since 1970, there has been an international safeguard system in place that helps to prevent the transformation of nuclear materials into weapons. This system is further supported by the Nuclear Non-proliferation Treaty (NPT).

The WNA (2018c) affirms that the NPT "has been a conspicuous international success in curbing the diversion of civil uranium into military uses. It has involved in cooperation with developing nuclear energy while ensuring that civil uranium, plutonium, and associated plants are used only for peaceful purposes". The main objectives of the treaty are stopping the spread of radiological weapons and furthermore providing a sense of security for those states that are not capable of developing their own nuclear weapons as well as those that have condemned them voluntarily. One of the long-term goals of the NPT is complete nuclear disarmament. However, the WNA argues that the political situation in some parts of the world leaves some countries reluctant to dispose of their weapons of mass destruction due to security concerns in relation to their neighbours. This is one of the main issues that undermines the safeguard system.

The IAEA has been controlling and regulating the safeguard system since 1970 when it was implemented. If a country was to fail an inspection by the organisation it would face international condemnation and harsh sanctions (WNA, 2018c). In fact, the economic and diplomatic measures are one of the main pillars of the safeguard system. A country that agrees to the NPT accepts the safeguard measures required by the agency. As the WNA (2018c) reports, these include:

- Material Accountability – tracking all inward and outward transfers and the flow of materials in any nuclear facility. This includes sampling and analysis of nuclear material, on-site inspections, review, and verification of operating records.
- Physical Security – restricting access to nuclear materials at the site of use.

- Containment and Surveillance – use of seals, automatic cameras and other instruments to detect unreported movement or tampering with nuclear materials, as well as spot checks on-site.

These safeguard measures have to be adopted by all NPT non-weapon states. History proves that the measures listed above work and provide a compelling and safe system. However, the real danger is represented by the states which are not parties to the NPT.

Currently, there are five states that are signatories to the treaty in possession of nuclear weapons. These include the United States, Russia, China, France and the United Kingdom (Economictimes, 2016). They have signed the treaty, thus disclosing their nuclear programs and are subject to the revisions made by the IAEA. A complete dismantlement of the aforesaid programs would be ideal. In fact, it is one of the main objectives of the NPT. However, as was mentioned above due to politics and international relationships, the aforementioned countries are more than reluctant to dispose of their weapons. There are only five countries that have not signed the NPT: India, Pakistan, Israel, South Sudan and North Korea (Economictimes, 2016). These countries are not inspected by the IAEA and they can possibly be developing radiological weapons using the material from their nuclear facilities. The material is not audited by an impartial party, thus the government of such a nation could develop nuclear weapons. However, due to fear of economic sanctions and international condemnation, the programs are often executed in secret.

It can be concluded that the safeguard system is closely tied to safety and security. The total elimination of nuclear weapons is the ultimate solution; however, it is not possible at this time. The misuse and abuse of nuclear energy cannot be prevented entirely, considering the possibility of a rogue government. Nonetheless, the vast impact of the safeguards put in place almost fifty years ago and enforced by the IAEA and the Non-proliferation Treaty cannot be understated.

This chapter dealt with safety measures and security measures of nuclear power plants. The role and the contribution to the safe use of nuclear energy by the IAEA and the NPT were described. Despite the regulations, even a safely operating nuclear power plant does have a negative impact on the environment, which is discussed in the next chapter.

4 Impact of nuclear power plants on the environment

Nuclear power plants combine a number of complex processes. Any fuel powered object produces a particular type of waste in addition to the desired work or product. Considering the sheer complexity and magnitude of processes of a facility similar to a nuclear power plant, a high amount of varying waste and emissions is to be expected. This chapter deals with the topics most relevant to this thesis, such as indirectly produced carbon dioxide emissions and directly produced radioactive waste. Next, it focuses on division of radioactive waste into multiple levels of contamination. Additionally, the storage of spent fuel and reactor decommissioning are discussed.

4.1 Carbon dioxide emissions

Carbon dioxide (CO_2) is one of the greenhouse gasses. It is speculated that CO_2 is the main culprit of global warming. The increase of its volume in the atmosphere can be accredited to industrialisation and the use of fossil fuels.

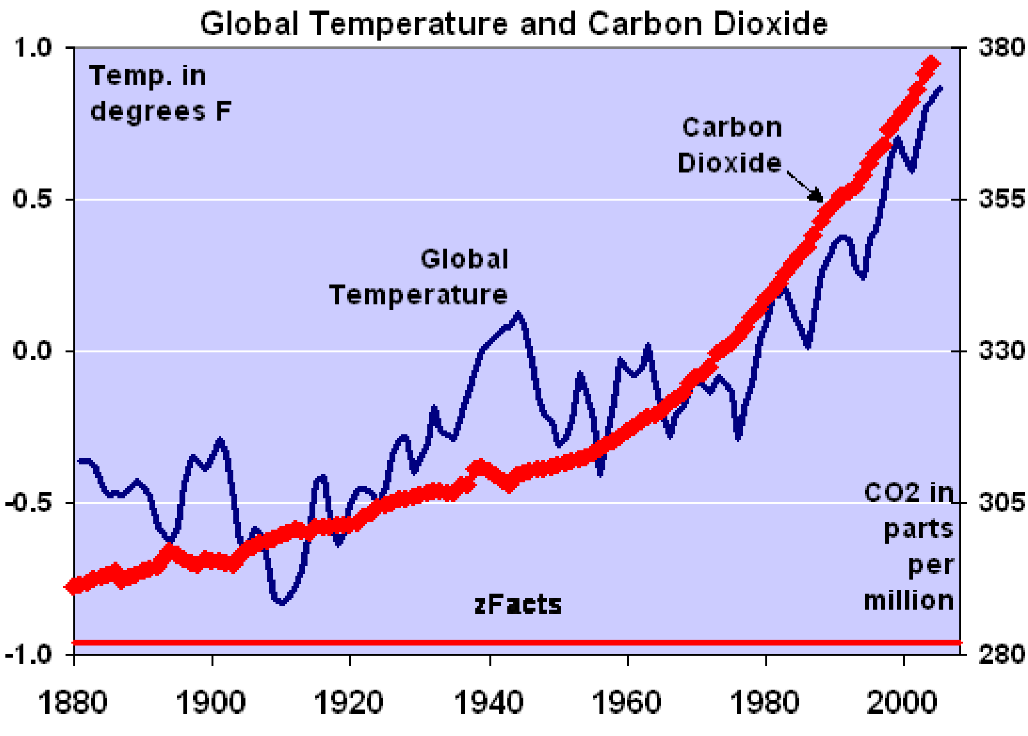

Figure 5. Correlation between CO_2 and temperature. Reprinted from Watts (2010).

As indicated in Figure 5, if the global warming studies are legitimate, an escalation of CO_2 production is highly undesirable. If the pattern continues, the temperature of the planet will eventually reach unsuitable values. Admittedly, nuclear power plants do not directly produce CO_2, however, countless processes linked with its operation and maintenance do. The U.S. Energy Information Administration (hereinafter referred to as EIA) reports that while nuclear reactors do not pollute air nor produce carbon dioxide by its operation, the gathering of fuel needed for its operation does. Uranium ore is mined and refined using machinery powered by fossil fuels. The process is complicated and requires a substantial amount of power, which subsequently results in CO_2 emissions. The EIA (2018) also indicates that the vast power plant complex requires an enormous amount of energy to build, resulting in additional emissions being released into the air.

In conclusion, nuclear power plants undoubtedly leave a carbon footprint on the environment as a result of their manufacture and operation. However, in contrast to power plants whose operation depends entirely on fossil fuels such as coal, nuclear power plants could be considered relatively environmentally friendly.

4.2 Radioactive waste

Radioactive waste is assuredly the most represented issue that concerns the general public. However, the amount of waste produced by nuclear power plants is relatively negligible compared to other types of power plant facilities. Moreover, spent nuclear fuel can even be further utilized (WNA, 2018). The radioactivity of nuclear waste, unlike the harmful effects of other hazardous industrial waste, diminishes with time. The WNA (2018b) further reports that "nuclear power is characterised by the very large amount of energy produced from a very small amount of fuel, and the amount of waste produced during this process is also relatively small". Considering this fact, it could be argued that electricity generated by nuclear power plants is more ecological than electricity generated by fossil fuel power plants. However, radioactivity cannot be seen and involves a great risk if radioactive materials are mismanaged. It is essential to understand that radionuclides have a half-life. Half-life is a process during which half of the radionuclide's atoms decay, hence it loses half of its radioactivity. This process continues until eventually, the material becomes non-radioactive. The IAEA (2018, p. 6) divides the types of nuclear waste into six categories:

1) Exempt waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.
2) Very short lived waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge.
3) Very low level waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control.
4) Low level waste (LLW): Waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities.
5) Intermediate level waste (ILW): Waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.
6) High level waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.

The disposal of nuclear waste is a complicated process. Higher levels of waste require geological disposition and can take decades or even centuries to completely decay. The HLW is the spent fuel, while other operations on the site such as cleaning of the reactor and storage ponds produce LLW and ILW (WNA, 2018b). It is essential to consider the volume of nuclear waste produced by nuclear power plants and the volume of waste produced by other means of generating electricity. Compared to traditional fossil fuel power plants the ratio of energy generated per amount of waste produced appears more favourable for nuclear power plants. Undoubtedly, solar power plants, wind power plants, and other more environmentally friendly options do exist. However, they possess their own technological limitations and a plethora of other problems.

4.3 Decommissioning nuclear power plants and reactors

Nuclear reactors have a limited lifespan that can last several decades. Continual use of a reactor at the end of its lifespan or following a severe incident undoubtedly increases the risk of a hazardous event. Thus, safe and successful decommissioning is necessary. In the event that the entire facility is required to be deconstructed and its location reused for other purposes, full decommission is mandatory. According to Gospodarczyk and Kincer (2017), a power plant is considered fully decommissioned when it is completely dismantled and the site is returned to greenfield status in order that "the site is safe for reuse for purposes such as housing, farming, or industrial use". Assuredly, deconstruction of a nuclear power plant as well as disposal of a radioactive reactor and material is far more complicated, time-consuming, and hazardous for the environment than deconstruction of an ordinary power plant. Gospodarczyk and Kincer (2017) describe three techniques that are primarily used in the United States for decommissioning nuclear power plants: Decontamination (DECON), Safe Storage (SAFSTOR), and ENTOMB.

Decontamination (DECON), is one of the fastest methods. The radiological materials and equipment are removed from the site and stored and decontaminated at a separate location. Thus, most of the irradiated material is absent, which allows relatively quick reuse of the land in approximately seven years.

Safe Storage (SAFSTOR), is considerably more time consuming than DECON. The entire process can last over sixty years. The first phase of SAFSTOR comprises of containing the site and monitoring it. The reactor and other radioactive material are left on the site until the radiation decays to safe levels. This can take over fifty years. The second part of the process is decontamination which can last approximately ten years. The advantage of SAFSTOR compared to DECON is the reduced decontamination cost. It is the result of a reduced amount of radioactive material on the site due to decay during the first phase.
ENTOMB, as the name suggests, means entombment of the entire site in concrete to prevent radiation leakage. This method is usually not used in the United States, but it has

been used in other countries, such as Ukraine where one of the Chernobyl reactors was entombed to help prevent radiation seepage.

According to Gospodarczyk and Kincer (2017), the chosen method depends on several factors. These include the amount of contamination, the terrain, and ease of removal of contaminated materials, and most importantly the cost. The operators tend to choose the more cost-effective method. It is also possible to combine the methods and use a different one for each part of the facility. The decommissioning process is considered complete when "the U.S. Nuclear Regulatory Commission (NRC) determines that the dismantlement has been performed according to the plan submitted by the operator at the beginning of the decommissioning process" (Gospodarczyk & Kincer, 2017).

If the method is to be chosen based on harmfulness to the environment, then there are several factors to be considered. ENTOMB of the whole facility is out of the question, as it would leave a sizeable portion of the site unsuitable for further use. Nevertheless, the impact of this method would not be as severe if only a small portion of the site was to be entombed. SAFSTOR takes a considerable amount of time and leaves the site unusable for more than half a century. DECON method is the fastest, it can be argued that the material is moved to another location where it could pose a threat to the environment. However, it can be assumed that these locations are adapted to handle the disposition of hazardous materials produced by demolishing a facility such as a nuclear power plant. Thus, in my opinion, the eco-friendlier solution is the DECON method, possibly in combination with the ENTOMB method. Furthermore, recycling and reusing materials leftover from decommissioning is a possibility. It is definitely desirable and considerably more environmentally friendly to further utilize the maximum amount of decommissioned material to eliminate or at least reduce the need for storage. This does not concern only irradiated materials but also the steel and concrete that originates as a result of deconstructing a nuclear facility. However, the level of radioactivity is an important factor in the reuse of such materials. The WNA (2018d) lists several options for recycling and reuse:

- Material which is essentially uncontaminated and unconditionally released.
- Material that can be melted in a regulated environment followed by metal recycle for consumer products (conditional clearance).

- Material with short half-life products that is melted and fabricated in a regulated environment and released for specific industrial applications (e.g. steel bridge).
- Material that cannot be released from regulatory control, but which may be recycled in the nuclear industry.

This chapter dealt with the environmental impact on nuclear power plants. The emissions of regularly operating nuclear power plants were discussed in addition to the disposal of nuclear waste. The complicated and lengthy process of decommissioning facilities and nuclear reactor were dealt with as well. However, the environmental impact of safely and correctly operating nuclear power plants cannot be compared to a catastrophe that is the failure of safety measures that the following chapter focuses on.

5 Historical failure of safety measures

Failure of internal safety measures and other possible accidents are not only undesirable but also unavoidable. Even state-of-the-art technology and software are prone to errors and malfunctioning. Additionally, possible outside influences and human error need to be considered. Moreover, natural disasters such as floods, earthquakes, and tornadoes are definitely a threat to high-risk facilities. An event like a plane crash is not very likely to occur but it still remains a possible safety concern. It is safe to say that there is a great number of safety concerns that are nearly impossible to address and history proves that. This chapter focuses on the most notorious accidents that occurred at nuclear power plants since their inception. Each disaster is dealt with separately detailing the cause, and the severity of impact on the local area. Additionally, safety measures that could help prevent specific failure are discussed.

5.1 Chernobyl

The nuclear catastrophe that occurred in Chernobyl in 1986 is probably the most infamous. It was a major accident, a level seven disaster on the INES scale[2]. A major accident means that there is a significant leak of radiation, immediate adverse effects on health, and there are long lasting effects on the environment. The accident occurred because the operators disabled the automatic safety control that prevents the plant from running at dangerously low power (Dufková 2011). The reactors at low power were unstable and in addition to other contributing factors resulting from the disabled automatic safety control an uncontrollable power surge occurred. The hot fuel particles and water caused a steam explosion. The thousand-ton lid was lifted by the explosion and the reactor core was exposed, causing a fire and radiation leakage into the atmosphere.

According to Dufková (2011), the wind spread the radiation to central Europe, Scandinavia and even to the Balkans. The Nuclear Energy Institute (2015) (hereinafter referred to as NEI) states that the reactor contained 190 metric tons of uranium fuel and other fission products. An estimated 13 to 30 percent was released into the atmosphere. Large areas in the Russian Federation, northwestern Ukraine, and Belarus were contaminated. The health

[2] INES refers to the International Nuclear and Radiological Event Scale that is a worldwide tool for communicating to the public in a consistent way the safety significance and radiological events (IAEA, 2019).

effects were most severe immediately after the incident and a large number of people suffered from thyroid cancer (NEI, 2015). The initial effect on health might have been less severe if the government had implemented sufficient safety measures sooner. As NEI (2015) reports, the following extensive measures to protect the public were deployed over the years following the catastrophe:

- decontamination of settlements,
- removal of substantial amounts of food from human consumption,
- treating pasture,
- provision of clean fodder to farm animals.

The immediate death toll was 31 plant workers and firefighters and thousands of other people were exposed to a dangerous amount of radiation (Dufková, 2011). Today, the affected reactor is entombed in a concrete structure that is slowly weakening. Ukraine and other nations plan to construct a new concrete tomb which should last over a hundred years (NEI, 2015).

It is obvious that the cause of the Chernobyl accident was human error on multiple occasions. Dufková (2011) points out that the decision to disable the automatic safety control was approved by supervisors. The disaster would not have occurred if the operators and supervisors had adhered to the correct technical procedure. A possible measure that could prevent such an error is to completely automatize the process. Another possible safety measure that could be implemented is to remove access of ordinary personnel and appoint a properly qualified technician. The qualified worker would then be able to disable the automatic control for maintenance and other necessary tasks while minimizing the danger of unqualified personnel causing a disaster.

5.2 Three Mile Island

In 1979, a nuclear accident occurred at the Three Mile Island power plant. It was an accident with wider consequences, a level five disaster on the INES scale. Level five means serious damage to the reactor, a considerable leak of radiation and the need to at least partially evacuate the local area. NEI (2014) reports that the cause was the combination of equipment failure and the incompetence of plant operators. After a water cooling pump stopped working a pressure relief valve was opened, however, it did not close as it was designed to do after the pressure stabilized. Thus, the cooling water escaped the system and the fuel began to overheat. The indicator incorrectly showed that the valve was properly closed and thus the operators did not replace the lost cooling water. They made the decision to stop the coolant pumps completely and the reactor overheated.

NEI (2014) states that “as a result of the TMI accident, approximately 2,6 million liters of radioactive cooling water ended up in the basement of the reactor building and in tanks in the auxiliary building, contaminating them”. Additionally, a small amount of radiation escaped into the atmosphere through one of the auxiliary buildings. Fortunately, the level five accident did not cause any injuries and had no apparent effect on the health of the population in the local area, but the media caused widespread panic and the incident had a negative effect on nuclear power programs in the United States (Dufková, 2011). Dufková also states that the clean-up of the affected unit lasted nearly twelve years and cost ten times more that the initial cost of the unit.

The cause of the accident was human error and malfunctioning equipment. The incident was certainly preventable. Instead of relying on an indication in the control room, a worker appointed to physically check the pressure relief valves in certain intervals could have effectively prevented the accident.

5.3 Fukushima

The Fukushima Daiichi accident occurred following a major earthquake. It received the same rating as Chernobyl on the INES scale, thus making it a major accident. Reportedly, the power plant was hit by a tsunami, consequently, reactors 1–3 suffered a meltdown, because of losing off-site power and on-site backup electricity generation (Lipscy, Kushida & Incerti, 2013). It is clear that the off-site power is vulnerable to natural disasters and terroristic attacks, thus the on-site backup is crucial for the safe shutdown of nuclear power plant operation in case of such an event. Moreover, the tsunami destroyed the main pump cooling system, rendering them useless. All these factors contributed to the meltdown of the aforementioned reactors.

The eventual explosion discharged radioactive material into the environment. Consequently, the land was contaminated and due to the coastal position of the plant, some of the material was discharged directly into the Pacific Ocean. Reportedly, one of the primary isotopes released was Cs-137 (Dong, 2016). It contaminated a large area around Fukushima. Dong (2016) further explains that the isotope has a half-life of 30 years and is absorbed into the top soil layer. The soil is essentially rendered unusable for stock farming and agriculture for many years. Greatly exceeding the limit for caesium in soil, food production was severely impaired. Seawater was used to help cool the reactors after the tsunami. However, Dong (2016) states that “despite the significant increase in caesium isotope levels in the waters off of Japan, their risk is below those generally considered harmful to marine animals and human consumers”. Hence, it can be concluded that the decision to use seawater to cool the reactors was correct and arguably helped to avert an even greater inland calamity.

The cause of the accident was evidently a natural disaster. It can be argued that the disaster was not easily preventable, but assuming that the back-up power generation was better protected, for example by a higher and more robust seawall, the impact of the tsunami could be lessened or entirely eliminated. Additionally, if the plant was moved from its coastal location inland, it would eliminate some of the risks. Nevertheless, moving a nuclear power plant is not financially feasible and an inland location would limit the access to cooling water.

This chapter showed potential scenarios that can happen when the measures fail and an accident actually happens. The effects, while severe, are not as catastrophic as an ordinary person might imagine. The attitude of the general public toward nuclear power plants is discussed in the practical part of the thesis which follows.

6 Practical part

The goal of the practical part of this thesis is to assess the level of awareness of nuclear power plant safety and environmental impact among the general public. The reason for this is the fact that nuclear power used to be thought of (and sometimes still is, even nowadays) as something horrifying. My main motivation was to find out people's perception of nuclear power plants.

6.1 Objective of the research and the research questions

The practical part of the thesis concerns an online questionnaire survey. The survey was meant for the general public due to the relative ease of obtaining a large amount of data. Since the main objective of this research is to find out public awareness and impression of the safety and the environmental impact of nuclear power plants, an online questionnaire is arguably one of the best methods of data collection from a wide sample.

The intermediate objectives of the research were as follows:

a) to identify the extent to which the respondents are familiar with nuclear power plants in general,
b) to identify how the respondents feel about the environmental impact of nuclear power plants,
c) to determine to what extent the respondents believe nuclear power plants actually impact the environment,
d) to determine how the respondents feel about nuclear power plants compared to traditional fossil fuel plants.

The research questions were designed based on the objectives defined above.

RQ1: *To what extent are the respondents familiar with nuclear power plants in general?*

RQ2: *How do the respondents feel about the environmental impact of nuclear power plants?*

RQ3: *To what extent do the respondents believe that nuclear power plants impact the environment?*

RQ4: *How do the respondents feel about nuclear power plants compared to traditional fossil fuel plants?*

6.2 Research design

6.2.1 Research stages

The research design involved the following multiple steps.

1) literary research conducted in the theoretical part of this thesis,
2) definition of the research objectives,
3) formulation of the research questions,
4) selection of the research sample,
5) design and distribution of the questionnaire,
6) analysis and interpretation of the collected data.

6.2.2 Research sample

The type of sampling was random, and the aim was to get about 100 respondents. The respondents were divided based on their age, education level, and gender to show a clearer image of their background. The method chosen for distribution of the questionnaire was sharing it on social media (my personal Facebook page). I contemplated other means of addressing respondents (such as using specialized paid websites for the questionnaire distribution); however, this was not necessary as my goal of one hundred respondents was attained in a relatively short period of time.

6.2.3 Questionnaire design and distribution

A data collection tool had to be designed to conduct the survey. The questionnaire itself consists of ten closed questions. Each question has two to three answers to select from and only one answer can be chosen for each question. The first three questions have the purpose of determining the respondents' background. The rest of the questionnaire is focused on accomplishing the goals that were defined above.

A pilot version of the questionnaire was distributed to a few close acquaintances and colleagues, at first. The reason for this was to get honest feedback which could help me improve the survey questions. However, some suggested that the questions were too technical, others complained that they were not technical enough. Since my aim was to keep the questions as well as the answers concise and simple, I decided that middle ground was the best approach in this case and kept the questionnaire in its original form (see Appendix) with only minor changes.

An online questionnaire survey as a method of gathering large amounts of data was an obvious choice since it increases response rates by reaching the target audience fast. I have decided to use www.survio.com because of the ease of use and its available toolkit which helps with the analyzation of the responses. Since my questionnaire was kept short, just ten questions, I wanted to find a simple and compact designing tool that would enable me to realise the practical part of the thesis and Survio proved to be an adequate tool. The only drawback is the fact that data from more than one hundred responses is a paid feature. However, this had proved not to be a limiting factor as my original goal was at least a hundred responses and I managed to get almost exactly that.

6.3 Data analysis and interpretation

Lastly, an analysis of the respondents' answers was necessary. The questionnaire consists of closed questions, so the analysis was relatively simple and clear. I took a risk by deciding not to include any open-ended questions. The respondents might not agree completely with the presented answers and they would just select the next closest option, thus not answer precisely. However, the compactness and clarity of the questionnaire make it simple to analyse as well as fill out (my reasoning was that a quick, compact survey is likely to attract more respondents than a questionnaire of higher complexity with a plethora of open-ended questions). I strongly believe that the drawbacks are minuscule compared to the advantages.

To analyse the data, I have converted responses from Survio to Microsoft Excel tables. The data is analysed, described and interpreted in this chapter.

6.3.1 The background of the respondents

Question 1. How old are you?

Table 1. *Age of respondents.*

Age	Absolute value	Percentage
Under 18 years old.	0	0 %
18 -24 years old.	83	83 %
25 - 40 years old.	16	16 %
Over 40 years old.	1	1 %
Total	100	100 %

Table 1 clearly indicates that the majority of respondents were between the ages of 18–24. Only 16 % of respondents were between 25–40 years old. None of the respondents were under-age and only 1 % was above the 40-year mark. This leads me to believe that the majority of the respondents are high school/college students. This might have an effect on the quality of responses as many of the respondents might have some sort of technical education.

Question 2. What is your highest completed education level?

Table 2. *Education level of respondents.*

Education level	Absolute value	Percentage
Primary.	0	0 %
Secondary.	64	64 %
Tertiary.	36	36 %
Total	100	100 %

Table 2 confirms that all of the respondents have completed their secondary education level. Tertiary education was completed by 36 % of the respondents and it is probable that most of the respondents are on their way of completing their tertiary education.

Question 3. What is your gender?

Table 3. *Gender of respondents.*

Gender	Absolute value	Percentage
Male.	75	75 %
Female.	25	25 %
Total	100	100 %

The gender of the respondents was predominantly male. The female part comprises only 25 % of the total number of respondents.

6.3.2 Questions concerning the practical part of the thesis

Question 1. In your own opinion, to what extent are you familiar with nuclear power plant safety and environmental impact ?

Table 4. *Level of respondents' familiarity with the topic of NPPs.*

Familiarity	Absolute value	Percentage
Not at all.	15	15 %
Mildly familiar.	76	76 %
Educated on the subject.	9	9 %
Total	100	100 %

The first question was designed to assess the level of familiarity with the concept of environmental impact and safety of nuclear power plants. Of the total number of respondents, 15 % admitted that they were not familiar with the presented topic at all. The vast majority of respondents 76 % consider themselves mildly familiar and the remaining 9 % claim to be educated on the subject. Since 85 % of respondents are at least mildly familiar with the topic it is reasonable to assume that their answers were at least semieducated.

Question 2. Do you believe that nuclear power plants are more harmful to the environment compared to traditional fossil fuel plants?

Table 5. *Perceived harmfulness of NPPs compared to fossil fuel power plants.*

Harmfulness	Absolute value	Percentage
They are more harmful.	6	6 %
They are less harmful.	81	81 %
They are about the same.	13	13 %
Total	100	100 %

Table 5 presents the feelings of respondents towards the harmfulness of NPPs compared to traditional power plants which use fossil fuels for their operation. A vast majority of 81 % believe that NPPs are less harmful to the environment. The belief is correct as NPPs themselves produce considerably less carbon dioxide and other emissions under normal operation. This level of understanding was quite surprising at first. However, Table 4 shows that the majority of respondents are familiar with the topic to a certain extent. Thus, it can be concluded that the self-assessment of the knowledge of respondents holds true.

Question 3. Do you think that spent nuclear fuel storage will cause problems in the future?

Table 6. *Perceived future complications linked with spent nuclear fuel storage*.

Spent fuel storage	Absolute value	Percentage
Yes, the environment will be negatively impacted.	39	39 %
No, it is being disposed of correctly.	61	61 %
Total	100	100 %

Table 6 shows that 61 % of respondents believe that spent nuclear fuel is being stored and disposed of correctly. The rest of the respondents are of the opposite belief. The answers were expected to be about evenly distributed, as the topic of spent nuclear fuel storage is complicated and the efficiency and ecological ramifications of its disposal are debatable.

Question 4. Do you think that nuclear power plants are dangerous to the public?

Table 7. *Perceived danger posed by NPPs to the public.*

Public danger	Absolute value	Percentage
They are safe.	46	46 %
They are relatively safe. I would not mind living near one.	37	37 %
They are very dangerous and I would not want to live near one.	17	17 %
Total	100	100 %

Table 7 indicates that about half of the respondents (46 %) believe that NPPs are safe and do not pose any public danger. Other 37 % believe in the relative safety of nuclear power plants and claim that they would not object to living in the vicinity of such a power plant. The last 17 % believe that NPPs are dangerous and would never live near one. Today, most accidents can be contained on the grounds of the facility, thus sufficiently informed public should have no reason to fear an impact on their lives that is caused by NPPs.

Question 5. If more power plants were to be build what type would you prefer?

Table 8. *Preference of NPPs to fossil power plants.*

Power plant type preference	Absolute value	Percentage
Fossil power plants (coal, oil).	13	13 %
Nuclear power plants.	87	87 %
Total	100	100 %

A vast majority comprising 87 % of respondents would be in favour of building a nuclear power plant rather than a traditional fossil fuel power plant. Given the education level of respondents, this result can be expected.

Question 6. Compared to fossil power plants how efficient do you believe nuclear power plants to be?

Table 9. *Perceived efficiency of NPPs compared to fossil power plants*.

Efficiency	Absolute value	Percentage
NPPs are more efficient.	83	83 %
NPPs are less efficient.	3	3 %
Their efficiency is about the same.	14	14 %
Total	100	100 %

Table 9 shows that most of the respondents (83 %) correctly believe that NPPs are more efficient than fossil fuel power plants. This shows that the other 17 % who believe that NPPs are less efficient or that the efficiency is at the same level are not sufficiently informed about the topic. One of the main benefits of nuclear power is that it is approximately 8000 times more efficient than burning fossil fuels (Parker, n.d.).

Question 7. Would you be in favour of replacing NPPs by other types of power plants?

Table 10. *Replacement of NPPs by other types of power plants.*

Replacement of NPP	Absolute value	Percentage
Yes.	12	12 %
Yes, under the condition of higher efficiency.	70	70 %
No.	18	18 %
Total	100	100 %

Table 10 indicates as expected that the majority of respondents (70 %) would be in favour of replacing NPPs by a more efficient alternative. On the other hand, 18 % are strictly against replacing NPPs altogether which is quite surprising. A minority of respondents (12 %) would be in favour of replacing NPPs regardless. This proves that some of the people are misinformed, as replacing NPPs with, for example, fossil fuel power plants would not be ecologically sound.

6.4 Discussion of research findings

The perception of nuclear power plants among the respondents is quite accurate. Initially, the respondents were asked to evaluate their own knowledge about nuclear power plants, and it is safe to say that they did so quite accurately, based on the results of the research. The majority of the respondents are aware that nuclear power plants do not impact the environment during their operation to the extent that traditional fossil fuel plants do. The disposal of radioactive material linked with the operation of a nuclear power plant is a complicated topic that is discussed in the fourth chapter. The survey participants were divided and not quite certain if the storage of radioactive material might cause complications in the future. Moreover, the perceived danger to the public was relatively low. Only 17 % of participants perceive a nuclear power plant as dangerous and would refuse to live near the facility. When the respondents were asked about the type of power plant they would prefer (nuclear vs. fossil fuel) most of them would be for construction of nuclear power plants. The same holds for the question about the comparison of efficiency between traditional fossil fuel plants and nuclear power plants. The greater number of respondents correctly believe that plants operating on the basis of nuclear energy are more efficient than other presented types of power plants. Unsurprisingly, most people would replace nuclear power plants by a type that has higher efficiency. However, the efficiency concerning fuel consumption is incomparably in favour of nuclear material.

In conclusion, the fact that the majority of respondents are quite aware of the safety and environmental impact of nuclear power plants is quite surprising. Initially, I had expected the general public to be more misinformed about the topic. However, the cause of this might be the sample group. The intended target sample was the general public, but 83 % of the respondents were between the ages of 18–24. The reason for this is most likely one of the methods of sharing the questionnaire. It was shared in a Facebook group containing students from the Brno University of Technology. This leads me to believe that the majority of the respondents are in fact students pursuing their bachelor's or master's degrees in engineering study programmes. Thus, the respondents are probably, at least slightly more informed than the average person.

7 Conclusion

This thesis framed the concept of safety and environmental impact of nuclear power plants. Nuclear power plants were and still might be considered a controversial topic among a considerable number of people. Protests and anti-nuclear power sentiments are not uncommon. However, the right question to be asked in this case seems to be whether these facilities are in fact as harmful and horrifying as those protesters believe them to be or whether the public is just insufficiently informed about the matter.

The thesis formulated the concept of nuclear power plant safety and the actual impact it has on the environment. First, to better understand the underlying processes that take place in these facilities the ways of extracting energy from atoms through nuclear reactions were described. Once the process was explained, the basic principle of nuclear power plant operation was described in order to better illustrate the need for safety and security measures.

Safety, as well as, security is of the utmost importance in any facility that could have a widespread and negative effect on the public and on the environment. Nuclear power plants are certainly not an exception. Thus, the safety measures which are supposed to prevent accidental radiological release from a facility were examined in great detail. The first chapter outlined the importance of eliminating human error, in addition to identifying and eliminating issues with cooling and fuel systems. Another important topic closely linked with the safety of nuclear power plants is their security measures. Security measures are supposed to eradicate the potential intentional misuse of nuclear or other radioactive materials. It may well be argued that nuclear material in possession of someone with ill intentions is bound to have catastrophic consequences. Hence, the security measures and the design philosophy behind those measures were discussed and a potential security breach scenario was explored. Furthermore, to ensure the security of nuclear power plants certain safeguards employed and enforced by the International Atomic Energy Agency were put in place, such as material accountability, physical security, containment and surveillance.

The next chapter dealt with the impact of normally operating nuclear power plants on the environment. The three main ways that nuclear power plants negatively impact the environment are carbon dioxide emissions, radioactive waste, and the decommissioning of the facilities. Carbon dioxide is not directly produced by the operation of nuclear power plants. Nonetheless, the building of the facility, transporting and mining the fuel are all processes that produce carbon dioxide. However, it can be argued that these power plants are more environmentally friendly than, for example, the traditional fossil fuel power plants which produce carbon dioxide directly by their operation. Additionally, the lengthy processes of disposing of radioactive waste and decommissioning of nuclear power plants were discussed.

The final chapter of the theoretical part of the thesis analysed the failure of safety measures and thus consequently abnormally operating nuclear power plants. Probably the most notorious cases of accidents throughout the history of using nuclear energy for generating electric power were examined. These include the accidents that happened in Chernobyl, Fukushima, and the Three Mile Island. The preceding cause and the resulting environmental impacts were discussed in each case. The chapter served to illustrate the importance of correctly functioning safety measures in nuclear power plants and the consequences of their failure.

The practical part of the thesis focused on the research on the level of awareness of nuclear power plant safety and their impact on the environment. The result of the research indicated significantly greater knowledge of the topic than initially expected. Only a small number of the respondents showed a lack of understanding or misinformation about the presented issues. Hopefully, the improvement of awareness of the general public about nuclear power plants will continue in the future.

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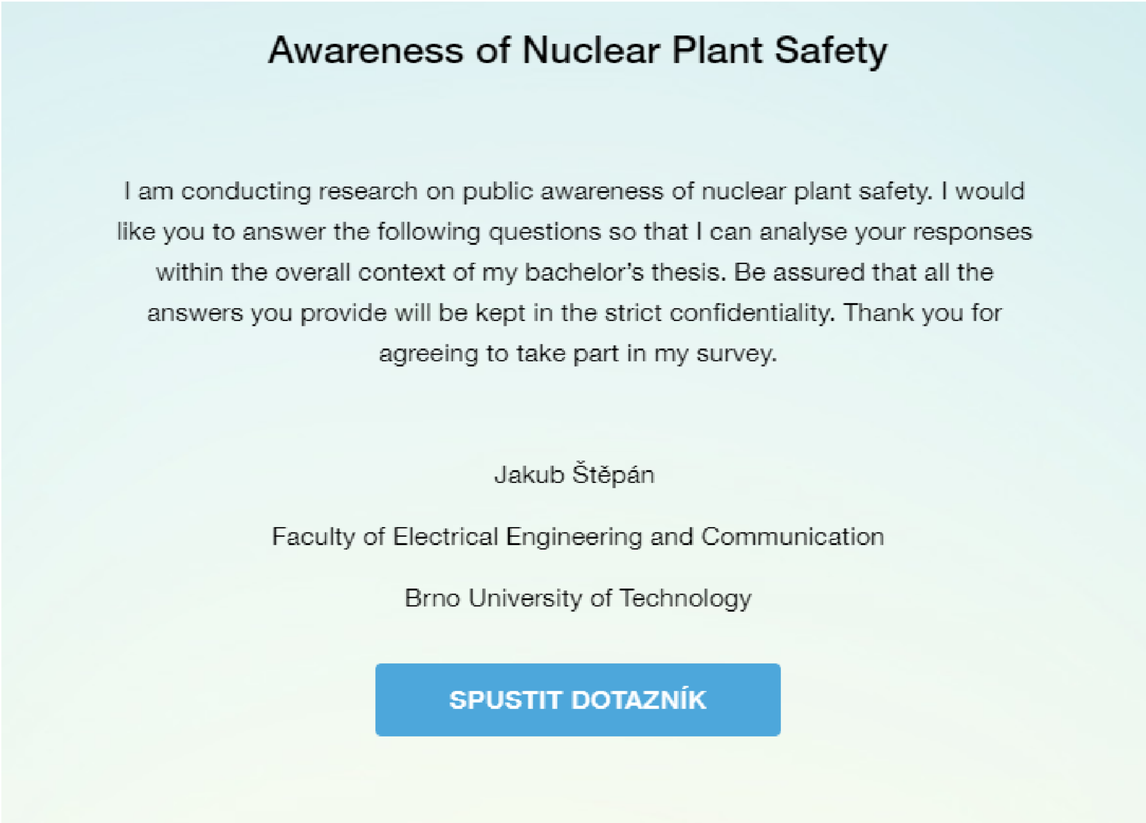
Appendix

Questionnaire "Awareness of Nuclear Plant Safety"



Awareness of Nuclear Plant Safety

I am conducting research on public awareness of nuclear plant safety. I would like you to answer the following questions so that I can analyse your responses within the overall context of my bachelor's thesis. Be assured that all the answers you provide will be kept in the strict confidentiality. Thank you for agreeing to take part in my survey.

Jakub Štěpán

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SPUSTIT DOTAZNÍK

1. Age*

- Under 18.
- 18 - 24 years old.
- 25 - 40 years old.
- Over 40 years old.

2. Finished education level*

- Primary
- Secondary
- Tertiary

3. Gender*

- Male
- Female

4. In your own opinion, to what extent are you familiar with nuclear power plant safety and their environmental impact.*

- Not at all.
- Mildly familiar.
- Educated on the subject.

5. Do you believe that nuclear power plants are more harmful to the environment compared to traditional fossil fuel plants?*

- They are more harmful.
- They are less harmful.
- They are about the same.

6. Do you think that spent nuclear fuel storage will cause problems in the future?*

- Yes, they will negatively impact the environment.
- No, I believe they are being disposed of properly.

7. Do you think that nuclear power plants are dangerous to the public?*

- They are safe.
- They are relatively dangerous, but I would not mind living near one.
- They are very dangerous and I would not like to live near one.

8. If more power plants were to be built what type would you prefer?*

- Fossil power plants (coal, oil).
- Nuclear power plants.

9. Compared to fossil power plants how efficient do you believe nuclear power plants to be?*

- NPPs are more efficient.
- NPPs are less efficient.
- They are about the same.

10. Would you be in favour of replacing NPPs by other types of power plants?*

- Yes.
- Yes, under the condition of higher efficiency.
- No.