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KATONAI
KÖZLÖNY

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Basic Risk Assessment of Nuclear Power Plants

Atomerőművek alapvető kockázatértékelése

Nuclear power plants are classified as highly important and dangerous facilities. Therefore, in addition to the directives for dangerous establishments, they also have to adhere to further special criteria. This article investigates those essential security factors which are designed to ensure nuclear safety. It is very important that the operation of a nuclear power plant is covered from every professional aspect for the sake of nuclear safety. To demonstrate this, various risk factors will be paired with the operational status of the facility. This relates to the fact that the operation of the Hungarian nuclear facility is primarily governed by the Nuclear Safety Manual. Current legislation contains all those important safety precautions which are in accordance with all the highly critical systems of the nuclear facilities that are in operation today. It also includes international recommendations and their relevant points.

Keywords: *nuclear power plant/station, reactor, nuclear facility, operation, safety.*

Az atomerőművek kiemelten fontos és veszélyes üzemeknek minősülnek, ezért a veszélyes üzemekre vonatkozó szabályozókon túl, további speciális kritériumoknak kell megfelelniük. A jelen cikkben azokat az alapvető biztonsági faktorokat veszem vizsgálat alá, amelyek, mint jól lefektetett alapok hivatottak szavatolni a későbbi nukleáris biztonságot. A nukleáris biztonság érdekében lényeges, hogy az atomerőművek üzemeltetése minden szakmai szempontból lefedett legyen, ehhez a kockázati faktorok párosítását vezetem le az egyes létesítményi üzemállapotokhoz. Ehhez kapcsolódik, hogy a magyarországi nukleáris létesítmények működése alapvetően a Nukleáris Biztonsági Szabályzatokban foglaltak alapján valósul meg. A jelenleg hatályos jogszabályok tartalmaznak minden olyan fontos biztonságos üzemeltetésre vonatkozó feltételt, amely alapján ma a nukleáris létesítmények kiemelten fontos rendszerei működnek, hozzávéve a nemzetközi ajánlásokat és azok releváns pontjait.

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Kulcsszavak: *atomerőmű, reaktor, nukleáris létesítmény, üzemeltetés, biztonság*

1. Introduction

Electric power has become integral part of our daily life, however, as it cannot be stored in high quantities, it requires continuous production. Electricity can be easily produced and can be used both in households and by industries in multiple ways. Furthermore, it is essential for both private and business use in today's world of info-communication. In Hungary the biggest proportion of the produced electricity comes from the nuclear power plant (NPP), as it provides more than 50% of the country's total usage of electricity. Every process that can be hazardous for our society and environment requires to be classified by some kind of control directives that are related to a safety protocol. This is because the level of hazard must refer to the safety policies. Therefore, the directives and the convention levels must provide guidance for the safe establishment and operation of technological and industrial systems and processes.[2]

Many research articles have previously given detailed reports that human meeting energy needs fundamentally determines human society. As history has proven, the innovation of energy sources has always come with major technological improvements. Nowadays the exhaustive usage of nuclear energy sources occurs by adhering to serious safety criteria, which were developed following tragic accidents in the past few decades. Moving away from fossil fuels has become the primary objective for humanity and for environmental safety alongside with the exponential rise of our energy needs. This shift in attitude has been necessary because the world's energy production has led to global environmental issues. The usage of nuclear energy regardless of previous accidents is basically clean and sustainable. Therefore, complying with safety criteria is crucial.[3]

The figure below shows the change of the usage of different energy sources with regards to conditional consumption of Million tonnes of oil equivalent (Mtoe).

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[2] *International Basic Safety Standards,* International Atomic Energy Agency, Safety Standards Series No. GSR Part 3, IAEA, Austria, 2014; *Safety of Nuclear Power Plants: Design,* International Atomic Energy Agency, Safety Standards Series No. SSR-2/1, Austria, 2012; László Manga and Lajos Kátai-Urbán, 'Nukleáris balesetekből levonható tanulságok – a tudomány állása. I. rész', *Bolyai Szemle* no 4 (2016), 120–136.

[3] Manga and Kátai-Urbán, 'Nukleáris balesetekből'; Katalin Fekete, 'Cultural Aspects of the Safety of Dangerous Establishments', in *Előadásgyűjtemény: "Veszélyes üzemek biztonsága 2013." Nemzetközi Iparbiztonsági Tudományos Konferencia. Budapest, 2013. április 10.,* ed. by József Dobor (Budapest: Nemzeti Közszolgálati Egyetem, 2013), 158–162

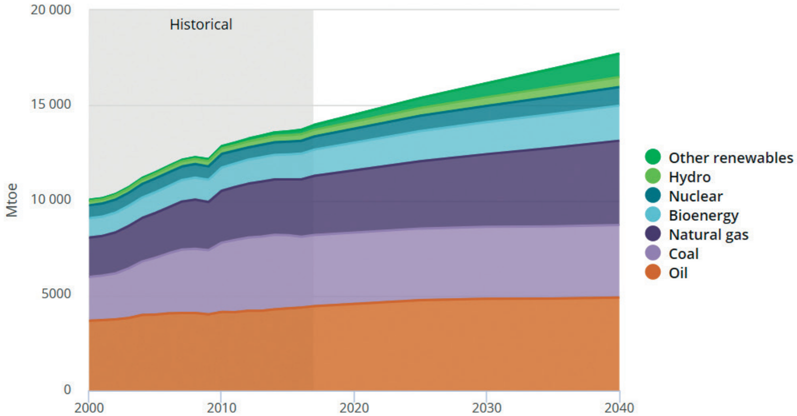

Figure 1. Change in the world primary energy demand according to the International Energy Agency.
Source: 'IEA releases World Energy Outlook 2018'. Dieselnet.

The construction and operation of NPPs are based on such requirements which are implemented through multilevel safety requirements from the planning phases onwards. These ensure the conditions for safe operation during the development and the subsequent conduction of the plant. The primary aspect of the risk assessments determines how the levels of risk measure up to the international safety requirements in each stages of establishing NPPs. During the design and establishment of the new third+ generation NPPs safe operational specifications have occurred as in the case of already existing NPPs. These contain several new technological solutions, which also require regulation of configuration, construction and installation, in the same way as the systems and system components of the earlier NPPs. In the case of new NPPs we can see new technological solutions such as core catcher and hydrogen recombiner. New criteria had to be established for the cooling of the core catcher so that the regulation and the termination of chain reaction can take place in adequate circumstances. The use of hydrogen recombiners is a significant preventative solution in critical events to avoid hydrogen explosion and it is attached to important regulations. The containment now possesses both external and internal cladding which have different protective functions and properties. Therefore, specific safety requirements need to be met. The spent fuel pool is located inside the containment too, whose requirements were already described in the Nuclear Safety Manuals (NSM). However, its current form needs some modifications because it is involved in the necessary intake of the essential safety service water system. Due to the design of the low- and high-pressure pump system of the cooling systems and due to the operational principal of the steam condenser that operates also as the passive nitrogen pressure bag of the reserve service water system, there is a need for new safety rule segments to be defined.[4]

4 *International Basic Safety Standards*; *Government Decree 118/2011. (VII. 11.) of Nuclear safety requirements for nuclear installations and related regulatory activities.*

2. Safety risks of Nuclear Power Plants

It is stated that the NPPs do not have any harmful effects under regular operation and do not cause environmental damage. At the same time, they are a potential source of hazard because in the event of multiple malfunctions they can lead to an emergency. Safe operation is the most important criteria of the NPPs. There is a large quantity of radioactive material in the nuclear reactors from which the employees of the facility need to be protected, and during an incidental event any kind of emission into the environment must be prevented. Large quantity of energy (that is, residual or remnant heat) is released even after the shutdown of a reactor, because the fission of the radioactive materials continues.

The operation of NPPs generates ionising radiation. With regards to other effects (such as vibration, electric current, heat) ionising radiation is not detectable to our senses and does not create direct sensations, but it may present a risk of health damage. With strict adherence to radiation protection and technological standards together with structured practices, the risk of damage to the employees' health is reducible, additionally the deterioration of environment and material properties is preventable. Considering radiation safety, the main aim of the NPPs' operation is to provide organisational, technical and health provisions and their implementation to keep radiation exposure to the employees and to the general public at a reasonably low level. It is important to take into consideration the social and economic circumstances, furthermore the exclusion of every unnecessary radiation exposure and the adherence to dosage limits.[5]

3. General risk aspects

The risk and safety levels of the four units of the NPP in Paks can be considered to be almost the same. The units have a balanced technical design, which means there is no special system or factor that would contribute disproportionately to the risk of the NPP. The safety of a nuclear power plant means that various measures have been taken to prevent radiation from endangering human life, the health of present and future generations, the environment and material goods to go above an acceptable level of risk. To hold to these principles, they must meet the following conditions:

- the heat generated in the reactor must always be removed;
- cooling of the cassettes must also be ensured on the offline unit;
- spent fuel must also be cooled;
- release of radioactive materials into the environment must be prevented (engineering barriers);

[5] *International Basic Safety Standards;* Manga and Kátai-Urbán, 'Nukleáris balesetekből'; *Primary circuit knowledge,* Atomerőmű Tűzoltóság, ATOMIX Kft. Tűzoltási és Kárelhárítási Szakágazat, Szakmai Ismeretek Oktatási anyag, ATOMIX at-me-6.2.2.-1-v2, 01. 07. 2013; *Radiation Protection Regulations, „MSSZ_V20"* (valid from: 01. 04. 2020.), MVM Paksi Atomerőmű Zrt.

- the chain reaction has to be stopped rapidly (control and safety rods);
- cooling must also be provided during every malfunction.[6]

Improving security and reducing risk factors are based on the design and application of the principle of defence in-depth protection. It is a technical safety objective to prevent malfunctions with high safety. When planning, every possible malfunction must be taken into account within the prescribed limits and one must count with the possible consequences. Hence, the probability of a serious accident with a significant aftermath must be sufficiently low. To ensure this, the basic principle that determines the safety philosophy of an NPP is the application of in-depth protection. This is a multilevel set of applied technical solutions and measures, where the risk-reduced safety objective is achieved even if any of them is ineffective. As a result, the design of a nuclear installation takes into account internal faults and possible external influences and is adequately resilient. Internal failures occur as infrequently as possible, and the task is to maintain the operation of safety barriers, to protect the population and the environment even if the defence systems are inefficient. This means that the entire power plant must be designed in such a way that its resistance to internal faults and external influences should be as high as possible, and that internal faults occur as rarely as achievable Appropriate application of technical solutions shall exclude the possibility of human error as much as possible. A high level of construction quality must be ensured during installation, and efforts must be made to prevent deviations from normal operating conditions.[7]

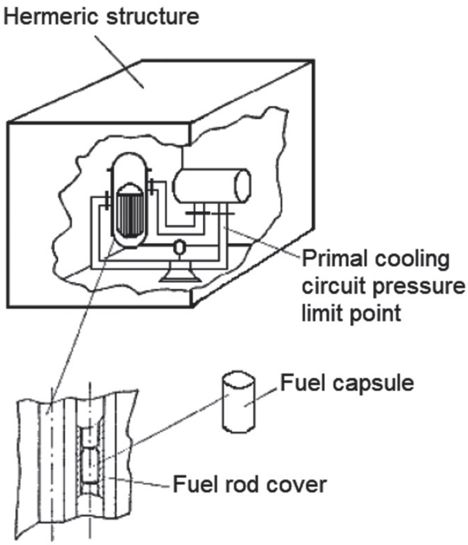

Figure 2. An NPP's basic safety barriers.

Source: Primary circuit knowledge, 8.

6 *Radiation Protection Regulations.*

7 *International Basic Safety Standards*; *Safety of Nuclear Power Plants*; *Nukleáris Biztonsági Szabályzatok*. 3/A. melléklet a 118/2011. (VII. 11.) Korm. rendelethez.

4. Operational states of nuclear establishments

The life of nuclear facilities can be explained in terms of specific operating conditions and operating status. In addition to normal status, we distinguish simulated, safety-relevant expected operational events and foreseeable disturbances. In case of a more complex malfunction or serious accident, the safety functions should offer appropriate procedures depending on the situation. This means that the requirements must be met in such a way that the effect of the safety functions can force the nuclear installation into a controlled or safe shutdown state at the end of the process. To implement the safety functions, special systems and components must be designed. The designed systems must be adjusted to one of the in-depth levels of defence, which are in consistency with the operating conditions. During design, the construction and organisational structures are implemented at multiple, nested levels of protection, providing the opportunity to correct and compensate errors before they lead to serious consequences. These are the design basis to which event factors are assigned depending on the operating status.[8]

Table 1. Operating status of the units of an NPP based on design basis levels.

Operating status	Appellation	Event frequency (f [1/year])
DB1	normal status	–
DB2	expected operational events	f >10-2
DB3	low frequency design failures	10-2 > f >10-4
DB4	very low frequency design failures	10-4 > f >10-5

Source: Government Decree 118/2011. (VII. 11.)

From the perspective of nuclear safety, beyond the above mentioned levels, two extended design basis categories of operating conditions must be defined (DBC), which are assigned to potentially occurring events, depending on their frequency.

- DBC1: the malfunction occurs as a complex fault, that does not trigger meltdown inside the active zone and the spent fuel pool;
- DBC2: major accident involving significant core meltdown.[9]

The implementation of basic safety functions of the nuclear reactors in relation to the operating conditions and in-depth protection has been based on the so-called engineering barriers. According to this, protection of the population and environment against radioactive materials is ensured by a series of leak-proof barriers in case of an accident. The first barrier is the fuel rod cover, which in ideal conditions prevents the release of radioactive isotopes from nuclear fission into the refrigerant. In case of a leakage of the rod, the release of radioactive contamination from the cooling fluid that would enter the refrigerant or would be activated for other reasons is prevented by second barrier, the wall of the primary circuit refrigeration, which is designed

[8] *Government Decree 118/2011. (VII. 11.); Primary circuit knowledge.*
[9] *Government Decree 118/2011. (VII. 11.)*

to withstand high pressure. The third engineering barrier is the wall of the hermetic annulus formed by the rooms containing the primary circuit's main equipment and the localisation tower, whose primary task is to prevent the release of radioactive contaminants into the environment during maximum design failure.

All these barriers must be considered with engineering precision already in the design period of the NPP, as the design and construction of the related systems require the implementation of additional safety aspects, which will make the entire construction a well-functioning, safe unit.[10]

5. Highly critical systems

Important system components for nuclear safety are designed with manageable failure factors, for which relevant research results and accumulated experience are also used. Safety functions are classified into safety classes with respect to fault factors and their consequences, taking into account the in-depth protection and specified operating conditions. In order to separate the protection levels, the classification of safety procedures is associated with the in-depth defence stages. The safety function definitions assigned to the operating levels not only contain prevention and management standards, but also ensure the durability of the protection at the given level. The operation of multiple protection and situation management protocols has performed an effective protective function and operating condition that keeps the situation under control. With the security classification of each protection function there is a deeper level of defence available if any of these systems should have a malfunction. It can prevent danger due to the lost function, but this requires a redundant technological design of security from the very beginning.[11]

If we want to design safety functions and protection systems, all possible events must be identified which could affect the safety of the nuclear establishment. The defined events must then be incorporated into the design on the basis of their generation parameters, consequences and other effects, from which the functional outages, reliability characteristics and operating parameters of the various operating conditions can be derived. The natural effects of the NPP's site and its environment shall be taken into account as well as the intentional or unintentional events. There can be targeted in- or off-site activities and consequences of the nuclear operations like malfunctions or failures of the systems.[12]

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10 *Primary circuit knowledge.*

11 *Safety of Nuclear Power Plant.*

12 *Government Decree 118/2011. (VII. 11.)*; *Primary circuit knowledge*; Balázs Bognár, Lajos Kátai-Urbán, György Kossa, Sándor Kozma, Béla Szakál, and Gyula Vass, *Iparbiztonságtan I. – Kézikönyv az iparbiztonsági üzemeltetői és hatósági feladatok ellátásához* (Budapest: Nemzeti Közszolgálati Egyetem, Nemzeti Közszolgálati és Tankönyv Kiadó Zrt., 2013).

Table 2. Levels of in-depth defence for operational conditions.

Level of in-depth protection	Objectives	Applicable devices	Radiological consequences	Relevant operating status
1.	Prevention of deviations from normal operation and errors	Conservative design, with high quality installation and operation; keeping the main operating parameters within the prescribed limits	No off-site radiological impact beyond official limits	Normal/standard operation (DB1)
2.	Handling of deviations from normal operation and errors	Control and safety systems; other monitoring methods		Expected operational events (DB2)
3. 3.a.	Management of malfunctions to limit radioactive release and prevent fuel melting	Safety systems, operational troubleshooting instructions	None or only minimal off-site radiological impact	Design failures (DB3-4)
3.b.		Safety tools for complex troubleshooting, instructions, on-site accident prevention implementations		Complex operational failures (Suspected multiple failure) (DBC1)
4.	Practical elimination of large or early emissions, management of fuel melting accidents to limit off-site emissions	Additional safety devices to limit fuel melting, accident management instructions, on-site accident prevention measures	Off-site radiological impact that may justify introduction of spatially and temporally limited public precautions	Major accident (DBC2)
5.	Reducing radiological consequences of significant radioactive material releases	On-site and off-site emergency response procedures; intervention levels	Off-site radiological exposure that makes public precautions necessary	Extremely serious accident

Source: Government Decree 118/2011. (VII. 11.), 213.

If a nuclear establishment operates more than one power plant unit or if it is located in the vicinity of another NPP, an analysis shall be performed that clearly shows the potential interactions between the facility and the units, taking all operating conditions into account, including all hazards. This includes analyses of the defence systems that act as security systems shared by multiple NPP units. In light of this, security systems and components must have both active and passive solutions. All operating conditions and in-depth safety levels are designed to provide the necessary accident handling and intervention capabilities. The defence functions must be activated automatically in all cases to prevent the development of more serious consequences.

At the same time, it is not possible to offer the option to deactivate the protection functions and the intervention by an operator can only be available if the time interval between the detection of the occurrence and the implementation of the necessary action proves to be achievable. In addition, the performance of safety functions cannot be hindered by any system failure to operate in normal process.[13]

6. Nuclear safety regulations

Despite the high level of design, construction and operation, continuous inspection and testing, events that could lead to failure or accident (for instance, pipe breakage due to internal material defect, natural disaster, and so on) cannot be ruled out. Therefore, safety systems and troubleshooting instructions are needed to deal with the presumed situation. Safety systems should be designed in such a way that the integrity of the active zone is maintained in the event of any predetermined malfunction. Besides this, they must also be prepared to deal with accidents that are very unlikely but have serious consequences.[14]

In such cases, safety systems no longer provide the adequate protection, and the most dangerous situation for reactors, the core meltdown can occur, which can lead to high level of radioactive release. The risk of these events should be minimised as low as reasonably achievable by installing systems that reduce or at least delay the rate of zone melting, leaving time for other critical measures (for example, eviction of population).

Achieving and maintaining a high level of safety, which also means a low level of risk, is therefore a fundamental aspect in the design and conduct of NPPs. These can be ensured partly by the appropriate design of the physical structure of the technological systems, the application of modern technical solutions, and partly the high-quality implementation of the operation, organisational structure and work coordination. Risk analyses can only be considered complete if the frequency of the zone damage or radioactive release is determined as a consequence of an initial event (technological failures, internal and external hazards such as: fire, flooding or earthquake) that can be assumed in all operating conditions of the plant (different phases of restart/shutdown and rated power output).[15]

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[13] *Government Decree 118/2011. (VII. 11.)*; *Primary circuit knowledge*; Bognár et al., *Iparbiztonságtan I.*

[14] *Safety of Nuclear Power Plants.*

[15] Fekete, 'Cultural Aspects'; Lajos Kátai-Urbán, Katalin Sibalin-Fekete, and GyulaVass, 'Hungarian Regulation on the Protection of Major Accidents Hazards', *Journal of Environmental Protection, safety, Education and Management* 4, no 8 (2016), 83–86.

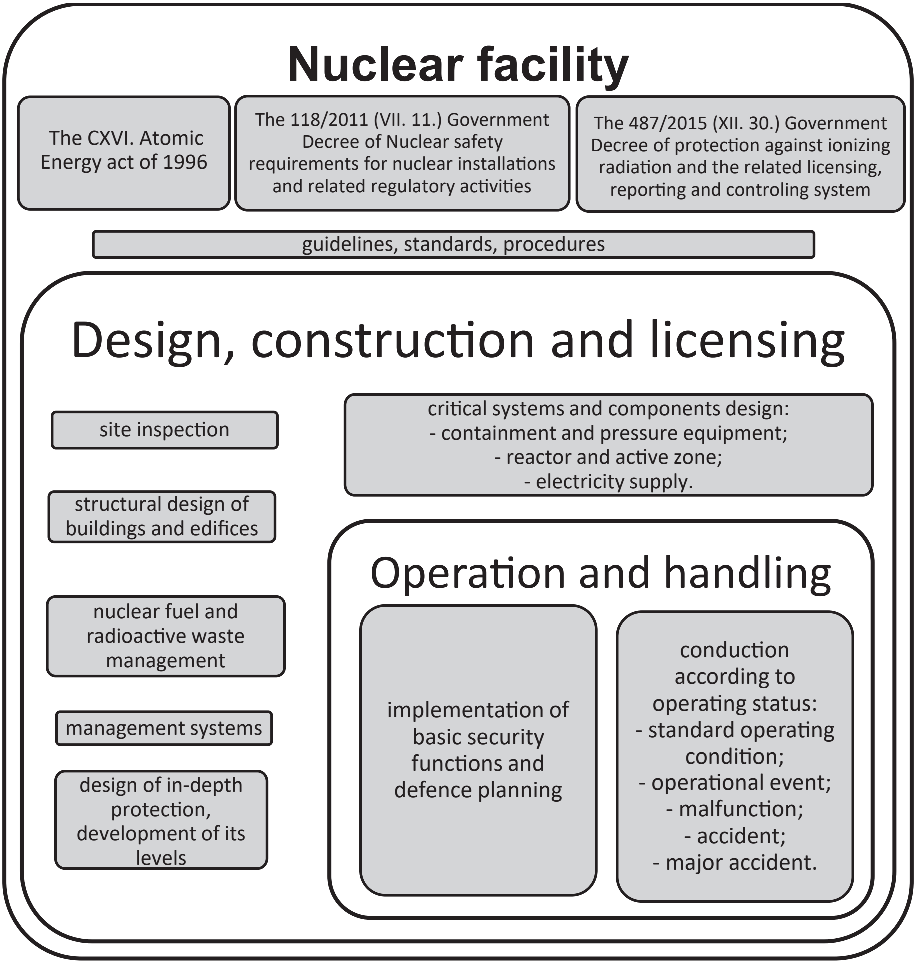

Figure 3. Summary of safety policy design of nuclear facilities.

Source: made by the author.

During the examination of emissions, the completeness includes the impact assessment of all relevant sources of radioactive material (primarily the active zone and spent fuel pool heaters). For the damaging effect assessment event-logical models need to be developed, during which the hazards (initial events) that can lead to zone-damage or radiological release must be analysed first. After any initial event a process simulation shall be used to determine the failure and accident processes that may occur due to a downfall of the safety systems. During the simulation, the necessary and sufficient aspects for the successful intervention of the systems must be identified. System analysis should reveal failures that could hinder successful interventions and the logical conditions which can cause a function loss. By editing these faulty data, the error-specific circumstances of the event-logical model shall be summarised. This should include the expected frequency of initial events, equipment failures, the likelihood of human error, and time intervals for each elementary operation and maintenance activity.

Taking these into consideration, the task of the NPP's environmental protection protocol includes the control of the radioactive discharges of the power plant, determination of their size and composition, and the continuous monitoring of the natural and artificial radiation conditions of the environment, therefore the construction of an NPP must meet a number of criteria even in the planning period. The most fundamental principle is that although it can cause serious damage to human health, wildlife and the environment, but at the same time the safe and peaceful use of nuclear energy has significant advantages in many areas of scientific research and in improving human living conditions, and these advantages can be exploited with adequate safety.[16]

7. Summary and conclusions

The legislation and the relevant Nuclear Safety Regulations have determined the basic safety objectives for the design and construction of new NPPs, the reconstruction and operation of existing NPPs, and the design and constituents of systems that are important for nuclear safety. A long-term, global safety objective of the design and operation of NPPs is to ensure that the risk of potential accidents neither increases nor decreases with the expansion of installed nuclear capacity. To achieve this goal the safety of existing NPPs must be increased by appropriate measures, and technical solutions that meet stricter risk criteria must be applied when setting up and building new systems.

Worldwide, in all industrial sectors where accidents can occur and hazardous substances can harm people and pollute the environment, there is a chance that an unexpected and unforeseen event arises, even with the highest level of safety and strategy. As a result of today's modern technology and innovative thinking, the number of circumstances that can cause industrial accidents have been minimised, although the efforts devoted to damage control and damage elimination have remained procedures to be improved and perfected in the first place.

Beyond these, fire prevention and protection have remained the highest priority in the life of an NPP, as it is not only necessary to prepare for events involving hazardous substances in the plant, but also to ensure nuclear safety. The multiple redundant systems built for fire safety need to operate not only in theory and during test but in real situations too. The point is not only to meet the requirements of the licensing authorities, but to create carefully and properly designed systems that provide protection in all circumstances and help to prevent a disaster. When we exchange views on an NPP, fire protection must be planned from construction to decommissioning. In many cases, events that endanger nuclear safety will be prevented by the fulfilment of fire prevention safety conditions, and if an event requiring intervention does occur, the established fire protection systems will intervene and eliminate the danger. Intervening system components, whether automatic, manual or even human intervention dependent, form

[16] *International Basic Safety Standards.*

an overlapping structure, where each level can handle the threat on its own and the failure of any level does not cause other protection systems to collapse and become unusable. Therefore, by designing and constructing new NPPs and rebuilding existing ones it is very important that the systems and components which provide nuclear safety are outlined and implemented at the highest level.

In terms of safety, the volumes of the NSR contain a list of requirements for all nuclear facilities that guarantee safety from the first stage of design to the final point of decommissioning and discharge. If we look at the development of the currently operating NPP in Paks and take into account that another nuclear facility is being planned in the immediate vicinity of the establishment, it is important that policy upgrades are implemented that guarantee not only the applicability of new technologies, but also consider the effects of the two plants on each other. It is important, for example, that reactor protection measures, which must physically initiate the shutdown of a reactor, include transmission of information that can launch the defence systems in the other power plant, depending on the operating condition of the triggering protection function. To ensure safe operation of the new power plant, the conditions must be guaranteed by methods and procedures that do not affect safety systems of the older power plant and along this no process or failure of the new power plant can induce a domino effect on the old one. Furthermore, the summary of the safety policy of the currently operating NPP in Paks should be used to meet the specific safety requirements of the new NPP which will be built next to the existing plant on the same natural water source in order to meet the international requirements. In the case of operating NPPs, the complex application of safety policies has been proven to be able to intervene effectively in all currently reasonably thought-out and experienced situations. However, a significant number of safety systems get activated by some cooling water process, which have been installed on the same water source, hence the safety design needs to be fundamentally rethought and reorganised so that the current high level of safety/efficiency rate remains at least at the same level or, if possible, even increased.

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