Identification, Analysis and Management of Risks During the Refilling of the Temelín Nuclear Power Plant with Cooling Water

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The critical process of nuclear power plant safety is the reactor cooling. From safety reasons, it is necessary to consider low probable unacceptable risk impacts scenarios. Analysis of data on operation of nuclear power plants showed that one of problems that creates critical situations is a long-term power black-out. The article identifies the risks associated with the existing way of refilling the cooling water for cooling-down of the unit on Temelín nuclear power plant, in the long-term blackout. It analyzes operating conditions and identifies critical points of cooling water supply process, i.e. problems of critical safety function. The paper shows response to extreme accident scenario based on application of feed and bleed method. It compiles a risk management plan for critical items of this process.

Keywords: Nuclear power plant, WWER, risks, blackout, hydropower plant, electric power supply.

1. Introduction

Nuclear power plants (*NPP*) are among the objects of both, the national and the European critical infrastructures. In terms of both, the integral and the nuclear safety, high demands are placed on them. These requirements can be met only by the fact that the technical equipment is designed, manufactured and maintained in accordance with requirements of international standards and national legislation. The operation of a nuclear installation must have inserted and set up a management system that is based on a high safety culture.

The safety of a NPP is technically ensured by: an emergency shutdown system (e.g. at an unexpected increase in the temperature of the primary circuit, the absorption clusters automatically fall, absorbing the neutrons in the reactor core and thereby stopping the further fission reaction); emergency cooling systems; emergency power supply of pumps; and radiation protection systems. Sources of external and internal risks change over time, and from safety reasons, also low probable extreme risk scenarios need to be considered.

To handle with critical situations, it is necessary to have a quick and effective response, i.e. appropriate technical equipment, clear procedures and its management, qualified personnel and clearly distributed responsibilities.

Analysis of data on the operation of NPPs showed that one of the problems that creates critical situations is a long-term power blackout (*SBO*). The paper shows the prepared unit cooling at extreme scenarios based on the application of the feed and bleed (*F&B*) method described in paper (CEZ 2018a,b,c, Jirousek, Prochazkova 2021) and identifies critical points of the entire process in which the cooling process could be disrupted. It has prepared a risk management plan for the critical sites in question.

2. Summary of General Knowledge

Currently, the long-term blackout is usually associated with the functioning of the critical infrastructure that ensures the basic functions of each State ; it is considered as one of the great threats to human society. Evaluation of its impact has been carried out in many States; e.g. in the case of a 14-day power outage in the South Bohemian Region of the Czech Republic (area 10 056 km^2, 625 712 inhabitants, mostly agricultural region) according to (Procházková 2012) means that 0.0001% of the population dies, i.e. 6 citizens, which represents a loss of about 49 914 thousand. CZK; 0.1% of the population, i.e. 626 citizens health will be irreversibly affected, which represents a loss of about 7 743 212 thousand CZK; damage to agriculture (livestock production) will be CZK 3 476 912 000; damage to industry will be CZK 1 815 892 000; damage to the property of citizens will be CZK 251 903 thousand. It is totally CZK 13 337 833 000. To this it must be added the as yet unquantified costs in the field of logistics – supply of drinking water, basic food, maintaining the economic functioning of the territory, etc. The fundamental problem will certainly be to deal with the consequences of mass deaths or culling of cattle and poultry without the use of veterinary facilities. Due to the specifics of the South Bohemian Region, the cost of "bringing out" residents from large cities is not considered.

This example shows huge impacts, but the Fukushima accident (IAEA 2015) showed that impacts of nuclear power station blackout (SBO) are yet worse, due to further long-term impacts on region, human society and set back nuclear technology development. Therefore, SBO, which involves the loss of off-site power concurrent with the failure of the on-site emergency alternative current (AC) electric power system (Baranowsky 1984) is big threat of nuclear power station operators, because long-term one is beyond design accident. The reason is that many safety systems required for reactor core decay heat removal and containment heat removal are dependent on AC power, and therefore, SBO impacts are severe.

2.1. Data on SBO

According to (Zebroski 1984) there have been more than 500 scrams in 77 operating U.S. reactors in the year ending June 1983. In spite of that not all transients lead to a scram, so the total population is somewhat larger. There are also some transients which have only a minor effect on plant dynamics, but which eventually require a plant shutdown. Of this population of transients, about two dozen are associated with events which are classified as "significant events," by US NRC. These are events which have manifest potential for significant damage to plant equipment, or exposure of personnel, and sometimes, reduced margins of core safety. Considering the entire population of U.S. reactors, there have been 59 outages well known excess of normal maintenance and refueling times. These outages total over 50 unit years in the period 1960 to 1982. Perhaps one-third of this outage can be attributed to problems in design or construction, but most can be associated.

The concern about station blackout arose because of the accumulated experience regarding the reliability of AC power supplies. A number of operating plants have experienced a total loss of offsite electrical power, and more occurrences are expected in the future (Baranowski 1984). During these loss-of-offsite-power events, the on-site emergency AC power supplies were available to supply the power needed by vital safety equipment. However, in some instances, one of the redundant emergency power supplies has been unavailable, and in a few cases there has been a complete loss of AC power (Baranowski 1984). During these events, AC power was restored within a few minutes without any serious consequences. In addition, there have been numerous reports where emergency diesel generators failed to start and run in response to tests conducted at operating plants (Baranowski 1984). In consideration of past operating experience and the potential risks associated with a loss of all AC power, the NRC designated "Station Blackout" as an unresolved safety issue (Baranowski 1984). A program was set up to further evaluate the risks of a station blackout, including an assessment of the likelihood of station blackout and the potential for severe accident sequences during a loss of all AC power (Lassahn et al. 1984, Zebroski 1984).The loss of off-site power at NPP is defined as the interruption of the preferred power supply to the essential and non-essential switchgear buses (Baranowski 1984).

Although total loss of off-site power is a relatively infrequent occurrence at NPP, it has happened a number of times in the past, and data base of information has been compiled from past experience (CVUT 2022). From this data base, compiled on the basis of 20 original sources, it follows that sources of SBO are:

- Big unexpected natural disasters (earthquakes, landslides, tsunami, storms, tornados, typhoon, geomagnetic storm, hurricane, snow storm, frost, ball lightning, etc.), that damage both, the external electric power infrastructure and the NPP.
- Technical problems in the NPP as: error in design; insufficient robustness of safety and safety related system; insufficient capacity of diesel generators or batteries; emergency diesel generator started but was unable to supply power; which make impossible the electric power from emergency or external sources to critical NPP components.

- External electric power infrastructure failure (natural disaster, insufficient robustness, overloading etc.).
- Human error, which make impossible the electric power from sources to critical NPP components.
- Terrorist attack, which can disturb the electric power from external sources to critical NPP components.
- Cyberattack to NPP safety management system.
- War or corruption, which can disturb the electric power from external sources to critical NPP components.

Database show that usually, the SBO is caused by combination of several events, as it is typical for all complex technical installations failure (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019). From these data and a review of relevant design and operational characteristics, the frequency and duration relationships for loss of off-site power events at NPP have been developed. Historically, according to (Baranowski 1984): a loss of off-site power occurs with a frequency of about once per five reactor-years to once per ten reactor-years; typical duration of these events is on the order of one-half to one hour. However, there has been experience at some power plants in which the frequency of off-site power loss has been substantially in excess of the average, and in other instances the duration of off-site power outages has greatly exceeded the norm; data show that plant-centered events account for the majority of the loss of off-site power occurrences. The principal factors which have been identified as affecting the frequency and duration of off-site power losses are: design of preferred power distribution system, particularly the degree of independence of each off-site power circuit, and the availability of alternate, nearby power sources; operations which can com-promise redundancy or independence of multiple off-site power sources, including human error; grid stability and security, and the ability to restore power to a nuclear plant site with a grid blackout; and geographic susceptibility to external hazards (weather) which can cause loss of offsite power for extended periods; reliability characteristics of emergency AC power systems were evaluated considering design, operational factors, and past operating experience.

Substantial operating data were investigated to determine the failure rate and the most likely modes of failure for both independent and common causes. Diesel generator reliability performance information was collected from 36 US NPPs with conclusion that long-term SBO at NPP is possible, and therefore, further protection is necessary.

2.2. Lessons Learned from SBO

Data summarized in (CVUT 2022) show that SBO caused losses and damages on public assets. In every case it requires costs for renovation of technical fittings. The long-term SBO also means big economic losses for the region due to loss of energy source. Therefore, the IAEA, OECD/NEA and US NRC and NPP operators do all for preventing the SBO and for fast effective response if blackout origin. To be capable of fast response to accident, the technical equipment, response personnel, response procedure and other important items must be prepared in advance (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019). Based on concerns about SBO risk and associated reliability of emergency diesel generators, the U.S. Nuclear Regulatory Commissions issued the SBO rule (USNRC 1988a) and the associated Regulatory Guide (USNRC 1988b). The first one cited document requires that NPP must have the capability to withstand an SBO and maintain core cooling for a specific duration known as station blackout coping capability. The second cited document provides procedure for assessment of the station blackout coping capability considering factors identified in the SBO rule. Further US NRC documents are (USNRC 2005, 2007). The manage the SBO, the IAEA has documents (IAEA 1983, USNRC 2007). From all documents it follows that the managing the SBO in the design and the operation is main task of safety culture the State and both, the NPP operators and the NPP supervision body.

2.3 Short Description on Feed & Bleed Method

One of tried-and-true response procedure is “Feed & Bleed” method (IAEA 2019). The F&B method was developed by Westinghouse as a countermeasure following the Three Mile Island-2 accident in 1979 and was subsequently implemented in the IAEA Recommendations (IAEA 2019, INSAG 1999). In harmony with the international practice (CEZ 2018a, SUJB 2019), this method might be used in cases when active cooling systems are not available. It is necessary to give that this method goes beyond the original design of emergency systems in NPPs (IAEA 2020).

The principle of F&B consists in cooling the reactor core into an open circuit. The coolant is pumped into secondary side of steam generator (SG) using the emergency equipment. Here it heats up and so it takes heat from the primary circuit. The resulting steam progresses from the SG by steam pipe outside the containment is released through by-pass valve to the atmosphere. It is clear from the description that this method of cooling is accompanied by a complete loss of the coolant used (IAEA 2020).

3. Risks and Safety of Technical Facilities

Risk is the degree of probable losses and damages to the monitored assets in the event of a harmful phenomenon, which in terms of comparability, is normed per unit of time and unit of space (Procházková 2018). It represents the degree of safety disruption of the monitored element in the event of a possible harmful phenomenon. Since the research of technical installations (Procházková 2017, 2018) showed that incidents, accidents, as well as failures of technical installations occur in about 80% when combining the harmful phenomena, it is necessary to monitor not only partial risks but also the integral risk. Therefore, the integral safety is associated with the management not only of large partial risks posed by beyond design natural disasters, but above all with the management of integral risk.

Safety is understood as a system-level property that is shaped by a human's measures and actions and can only be ensured by high-quality anthropogenic management (Procházková 2017, 2018).Integral safety respects the systemic understanding the monitored element and changes in time and space (Procházková, Procházka, Lukavský, Beran, Šindlerová 2019). It is based on a systemic, proactive and strategically targeted approach. It is understood as an emergent property of an element, on which the existence of an element depends; i.e. it is the most hierarchically determining property of an element. It is a set of measures and activities that, considering the nature of the critical element understood as a system of systems and all possible risks and threats, aim to ensure the functioning the elements, links and flows of critical infrastructure, so that under no circumstances do they fail to endanger themselves or their surroundings. Risk and safety are not complementary quantities, since the safety of each entity can be increased through organizational measures, e.g. by introducing the warning systems and backup solutions, without reducing the risk size; an additional concept to safety is criticality (Procházková 2017, 2018).

4. Data and Methods

NPP Temelín is a power plant with two WWER-1000 pressure water units, model 320 located not far from the Vltava River (CEZ 2010). Scheme of NPP Temelín and its surrounding is in Figure 1.

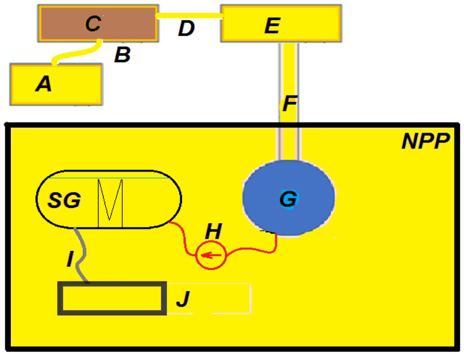

Fig. 1. Situation scheme of SBO solving. NPP- nuclear pover plant; ***A*** - external blackout diversional and mobile (DAM) power supply consumption hydro-power plant Hněvkovice; ***B*** - The DAM power network of–DAM means for pumping to SG; ***C***- hydro-power plant Hněvkovice; ***D***- power network between hydro-plant and pumping station Hněvkovice; ***E***- NPP pumping station of raw water Hněvkovice; ***F***- underground double pipelines of raw water; ***G***- reservoir of raw water; ***SG*** - steam generator; ***I*** - Lines of blow-down; ***J*** - Collector of SBO blow-down water from ***SG***.

1. Heat Sink Systems

At normal shutdown and in design emergency conditions, the SG is used only at the initial stage when the residual power of the active zone is high (CEZ 2008). After reducing the temperature and pressure in the primary circuit according to the prescribed trend, the use of SG during normal shutdown is no longer considered, heat sink continues with active emergency systems (CEZ 2010). Emergency systems of water-moderated and water-cooled reactors WWER have been designed as closed circuits with forced circulation of heat transfer media (CEZ 2010). Their purpose is to move residual power from the primary circuit to ultimate heat sink (recipient with sufficient thermal capacity e.g. sea, river, atmosphere). They consist of passive and active subsystems: passive ones serve to maintain pressure in the primary circuit - their main representatives are: hydro-accumulators, stable pressure vessels that maintain coolant pressure by overpressure of the nitrogen cushion; active ones have a divisional layout, which means that that they are functionally completely separated from each other, including the power supply from divisional diesel generators Totally, they are 3 divisions and each includes the sub-systems for: a high-pressure injection; high-pressure refilling; low-pressure circulation and shower. On the secondary circuit, the active emergency system represents an electrically powered pump of water supply from emergency tanks to SG.

4.2. Ultimate Heat Sink System

In order to preserve NPP safety, it is necessary to ensure ultimate heat sink, and for this it is necessary so the SG might perform its functions also at beyond critical conditions. The solution of this emergency situation depends on situation criticality (Jiroušek 2022). After Fukushima accident and the IAEA recommendation (IAEA 2019), responses to many emergency situations were prepared (CEZ 2010). The application F&B method is described in (Jirousek, Prochazkova 2021**).**

4.3. Methods Used at Risk-Based Cooling

Process of cooling the reactor at SBO needs to be safe at all type of conditions. Therefore, in harmony with knowledge given above, they must be managed both, the partial risks and the integral risk. The integral risk is determined by help of decision support system (Jiroušek 2022), which is adaptation of this one for complex facilities (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019).

For ensuring the safe cooling by the F&B method it is constructed process model according to (Krogstie, Sindre, Jorgensen 2006). Then are determined risks connected with this process according to way in (Procházková 2018). For all important risks it is constructed risk management plan based on TQM management method (Zairi 1991) and recommended by ISO 31 000 and ISO 31 010. The aim of risk management plan is to ensure the NPP coexistence with surroundings at ultimate heat sink. Two actors are considered - public administration, which supervises activities in the territory with aim to ensure the safety of territory and citizens, and operator, who is responsible for the safety of managed technical facility, which also includes the protection of the surroundings and inhabitants.

5. Sources of Risks at Response to SBO

On the beginning, it is important to give that the management of NPP (Atomic Act No. 263/2016 Coll.) respects ISO 9000, i.e. management documents correspond to the strategic management codified by the TQM (Zairi 1991). In this paragraph, we follow emergency (cooling-down) process when source of raw water in Temelín NPP must be used. It is the worst scenario in which the crisis legislation must be used. Therefore, in this case, according to legislation (Acts: No 110/1998 Coll. and No. 240/2000 Coll.), the management of whole response process has several levels.

The first management level is government chairman or governor (Act No 240/ 2000 Coll.); this person is also crisis staff chairman. The second management level for NPP as subject of critical infrastructure (Governmental Order No. 432/ 2010 Coll.) according to (Government Order No. 462/2000 Coll.) creates: commander IZS (Integrated Rescue System) according to act No 239/2000 Coll.; NPP director, who also represents ***A***, ***B***, ***D*** and ***F*** (Figure 1); director ***C*** (Figure 1); and SUJB chairman (Atomic Act No. 263/2016 Coll.). The third level is NPP Temelín level; according to Government Order No. 462 /2000 Coll. it consists of: plant shift supervisor; Temelín NPP crisis staff chairman; manager ***SG***; and managers of components ***G***, ***H***, ***I*** and ***J*** (Figure 1). The complete description is in (Jiroušek 2022). Each of mentioned subjects has proper internal operating procedures (*IOP*)and emergency operating procedures (*EOP)*. In frame of crisis preparedness, the mutual cooperation of all participants is regularly trained in agreement with (Government Order No. 462 /2000 Coll.). NPP emergency personnel has moreover regular exercises on full-scope simulator on individual and collective levels and in whole system. Responsibilities on individual levels are in harmony with standard common in Europe (Delongu 2016).

The main targets of all measures and activities is to avoid core melting. Measures for risk mitigation are in all above cited documents. In all participating subjects shown in Figure 1, they are processed and tested for response to the worst emergency situation in question special emergency operating procedures - *EOPs* (CEZ 2018 a,b,c) and internal operating procedures - *IOPs* (CEZ 2022). On NPP Temelín, the main roles at executing the measures for risk mitigation according to nature of risk source have: unit shift supervisor and NPP emergency manager, who have to disposal qualified personnel according to CEZ managing documents (CEZ 2022). With regard to generic risk management plan in (Procházková, Procházka, Lukavský, Dostál, Procházka, Ouhrabka 2019), risk management plan for cooling process at the worst SBO scenario by F&B method is given in Table 1.

Table 1. Risk management plan for the worst SBO scenario.

Risk source	Description of risk	Occurrence probability Size of impacts	Measures for risk mitigation
Coordination problems (managing, communication and cyber) on the second management level	Disruption of response process	Probability: low Impacts: great	*Measures:* Region crisis plan *Execute:* manager of part in which problem happened *Responsibility:* Governor
Coordination problems (managing, communication and cyber) on the third management level (i.e. Temelín level)	Disruption of response process	Probability: low Impacts: great	*Measures:* NPP Temelín crisis preparedness plan *Execute:* in dependence on point at which problem happened either NPP crisis staff chairman or ***SG*** manager or component ***G*** manager or component ***H*** manager or component ***I*** manager or component ***J*** *Responsibility*: NPP director
Cyber infrastructure NPP Temelín failure	Disruption of process cooling	Probability: low Impacts: great	*Measures:* NPP IOP and EOP *Execute:* NPP crisis staff chairman *Responsibility:* NPP director
Human errors in ***A***, ***B***, ***C***, ***D*** and ***F***	Disruption of process cooling	Probability: low Impacts: great	*Measures:* IOP of subjects in which error happened *Execute:* manager of section in which error happened *Responsibility:* director of section in which error happened
Human errors in NPP Temelín	Consequences depend on point at which error happened	Probability: medium Impacts: low to great	*Measures:* NPP Temelín IOP *Execute:* manager of section in which error happened (***SG***; ***G***, ***H***, ***I*** and ***J***) *Responsibility:* NPP director
Technical problems - ***A***	Disruption of response process	Probability: low Impacts: great	*Measures:* NPP EOP for ***A*** *Execute:* plant shift supervisor *Responsibility:* NPP Director
Technical problems -***B***	Disruption of response process	Probability: low Impacts: great	*Measures:* NPP EOP for ***B*** *Execute:* plant shift supervisor *Responsibility:* NPP director
Technical problems ***C***	Disruption of response process	Probability: low Impacts: great	*Measures:* EOP ***C*** *Execute:* shift supervisor ***C*** *Responsibility:* director ***C***
Technical problems - ***D***	Disruption of response process	Probability: low Impacts: great	*Measures:* NPP EOP for ***D*** *Execute:* plant shift supervisor *Responsibility:* NPP director

Technical problems - ***E***	Disruption of response process	Probability: low Impacts: great	*Measures:* NPP EOP for ***E*** *Execute:* plant shift supervisor *Responsibility:* NPP director
Technical problems - ***F***	Disruption of response process	Probability: low Impacts: great	*Measures:* NPP EOP ***F*** Execute: plant shift supervisor Responsibility: NPP director
Technical problems - ***G***	Disruption of response process	Probability: low Impacts: great	Measures: NPP EOP Execute: plant shift supervisor Responsibility: director
Technical problems - ***H***	Disruption of response process	Probability: low Impacts: great	Measures: NPP EOP Execute: plant shift supervisor Responsibility: NPP director
Technical problems -***SG***	Disruption of response process	Probability: low Impacts: great	Measures: NPP EOP Execute: plant shift supervisor Responsibility: NPP director
Technical problems - ***I***	Disruption of response process	Probability: low Impacts: medium	Measures: NPP EOP Execute: plant shift supervisor Responsibility: director ***NPP***
Technical problems - ***J***	Disruption of response process	Probability: low Impacts: low	Measures: NPP EOP Execute: plant shift supervisor Responsibility: NPP director
External / Internal disaster	Disruption of process cooling	Probability: low Impacts: great	Measures: NPP EOP Execute: NPP crisis staff chairman Responsibility: NPP director
Insider	Disruption of process cooling	Probability: low Impacts: great	Measures: NPP IOP and EOP Execute: NPP crisis staff chairman Responsibility: NPP director
Terrorist attack	Disruption of process cooling	Probability: low Impacts: great	Measures: region crisis plan Execute: NPP crisis staff chairman Responsibility: Governor Co-operation: IZS and SUJB

Based on the results given in Table 1, the obligation to pay attention to the conditions of all entities that are important during the response to the worst SBO scenario within the framework of crisis management of region has been put into practice. Exercises of entities included in the second level of management of the monitored crisis situation management take place every two years.

7. Conclusion

It can be concluded that to response to the worst SBO scenario in the NPP Temelín meet all new recommendations (IAEA 2019), the national action plan (SUJB 2019). The existing supply of raw water for feed and bleed is well sufficient for the first 29 days of SBO cooling (CEZ 2008). However, the analysis of the results of the blackouts database (CVUT 2022) shows the importance of periodic replenishment of the water reservoir after 29th day of event. In combination with measures to limit the concentration of chlorides in boiler water due to the influence of SG chlorides (Jiroušek Procházková 2021), it allows to prolong SBO cooling in the medium and long term. The re-filling of raw water and the reduction of the risks of stress corrosion crack, crevice corrosion to the lowest reasonably achievable level, in accordance with the ALARP principle (Procházková 2015, 2017), prolongs the cooling of the reactor core. It also reduces the risk of containment bypass (IAEA 2020).

Analysis of all available coolant reserves (CEZ 2008, 2010) of different quality shows that there is enough time to decide and prepare the necessary DAM means for the resumption of replenishment of raw water. In addition, the "SBO blow-down” (Jirousek Prochazkova 2021) of SG is able to maintain the concentration of chlorides in SG even after 29th day if the raw water supply cannot be restored and water from the circulation circuit of the towers must be used. The blow-down water from the SG with the potential content of radioactive particles remains inside the NPP-in the pools of the essential service water system (CEZ 2010, Jirousek Prochazkova 2021). The entire described complex allows the application of spontaneous radioactive decay reducing the amount of iodine 131, which, in the event of premature breaking of barriers, could leak into the vicinity of the NPP. As it can be seen in Table 1, for all important risks, which can threaten the cooling process in case of the worst SBO scenario are prepared mitigating procedures and management rules.

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