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Discussion on Practical Elimination of Early or Large Releases for WWER-1000/V320

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Abstract

The paper presents a brief summary of the introduction of the term "practical elimination" as prevention of the conditions that could lead to early or large radioactive releases. The concept of "practical elimination" is defined as part of the Defence in Depth (DiD) of Nuclear Power Plant (NPP) in the International Atomic Energy Agency (IAEA) document INSAG-12 in 1999. But, the special attention to it was paid after the accident in Fukushima NPP in 2011. The mechanisms of the containment failure of reactor WWER-1000/V320 are presented. As an example, the summarized design features and preventing and mitigation measures already implemented at Kozloduy NPP to extend the design basis and beyond design basis envelop are presented. Issues related to external steam explosion are underlined for further study.

Keywords

Practical Elimination, Early Radioactive Release, Large Radioactive Release, WWER-1000/V320, Kozloduy NPP

1. Introduction

Based on the IAEA INSAG-12 [1], the Defence in Depth (DiD) concept [2] [3] provides an overall strategy for safety measures and features of Nuclear Power Plants (NPPs) (para 47). Two corollary principles follow the general statement of DiD—accident prevention and accident mitigation. Although a continuous effort to increase the scope of the severe accidents that have been taken into consideration and to reduce their off-site consequences, a further reduction the potential radiological consequences is an important goal for future NPPs (para 124). An important advantage of future plants is their ability to incorporate corrections to deficiencies identified in the past (para 125). In that context, the concept of "practical elimination" of early or large releases [4] is also defined, but the attention to it extremely increases after the accident in Fukushima NPP in 2011.

2. The Term "Practical Elimination"

2.1. Requirements

The concept of "practical elimination" of early or large releases is an issue, defined in details in the IAEA "Safety of NPPs: Design", SSR2/1 [5], and in the WENRA Safety of new NPP design [6]. According to the updated in 2016 IAEA SSR-2/1, Rev.1, paragraph 2.11 [7]:

"*The design for safety of a nuclear power plant applies the safety principle that practical measures must be taken to mitigate the consequences for human life and health and for the environment of nuclear or radiation accidents* (*Principle* 8 *of the Fundamental Safety Principles*). *Plant event sequences that could result in high radiation doses or in a large radioactive release have to be* "*practically eliminated*" *and plant event sequences with a significant frequency of occurrence have to have no*, *or only minor*, *potential radiological consequences. An essential objective is that the necessity for off-site protective actions to mitigate radiological consequences be limited or even eliminated in technical terms*, *although such measures might still be required by the responsible authorities.*"

Requirements concerning "practical elimination" can be found in the revised Regulation on Ensuring the Safety of Nuclear Power Plants [8]. This regulation was issued in 2016 by the Bulgarian Regulatory Agency (BNRA). It is developed based on the WENRA safety goals for new NPP designs [6] and the updated after the Fukushima NPP accident reference levels for safety harmonisation of NPPs in operation [9], as well as the latest IAEA safety standards regarding: site selection for nuclear facilities, design, construction, commissioning and operation. Furthermore, this regulation introduces the provisions of the Council Directive 2014/87/EURATOM, of 8 July 2014, establishing a Community framework for the nuclear safety of nuclear installations.

The regulation [8] states that:

*Art.*4 (4) "1) *accidents with the melting of nuclear fuel that lead to early or large radioactive releases into the environment should practically eliminated;*

2) *for the accidents with the melting of nuclear fuel that cannot practically eliminated*, *design provisions have to be taken so that only limited protective measures in area and time are needed for the public* (*no permanent relocation*, *no need for emergency evacuation outside the immediate vicinity of the plant*, *limited sheltering*, *no long term restrictions in food consumption*) *and that sufficient time is available to implement these measures.*"

*Art.*72 (6) "*With the safety analysis demonstrated that accidents with the melting of nuclear fuel*, *leading to large or early releases of radioactive substances into the environment are practically eliminated.*"

In respect to the practical elimination, another BNRA document, the safety guide "Deterministic Safety Assessment" [10] defines in the section 4.18, p.12 that;

"*For new plant designs the first priority is to prevent by a robust design* ("*practically eliminate*") *the severe accidents that could lead to large or early releases to the environment, including high pressure core melt scenarios, if they cannot be excluded as physically impossible. Each representative or limiting accident sequence should be assessed for the purpose of practical elimination. The prevention of a particular sequence should be demonstrated primarily by deterministic arguments complemented with probabilistic, where appropriate, taking into account the uncertainties resulting from the limited knowledge about particular physical phenomena. Important fact is that the practical elimination of accident sequences should not be demonstrated solely by very low frequency of occurrence, below an established threshold value.*"

2.2. Achievement of "Practical Elimination"

The "practical elimination" is achieved by prevention of the conditions that could lead to an early radioactive release or a large radioactive release [11].

2.3. Demonstration of "Practical Elimination"

Accident sequences with early or large releases could be considered to have been practically eliminated [6]:

- 1) if it is physically impossible for the accident sequence to occur or
- 2) if the accident sequence can be considered with a high degree of confidence to be extremely unlikely to arise (IAEA SSR-2/1).

The demonstration should show sufficient knowledge of the accident condition analyzed and of the phenomena involved, substantiated by relevant evidence.

Demonstration of practical elimination should be mainly based on the criterion of physical impossibility. The criterion for extreme unlikelihood with high confidence should be used with lower priority. Such approach should minimize uncertainties and increase the robustness of the NPP safety case.

The demonstration of "practical elimination" has to be achieved by deterministic considerations supported by probabilistic considerations, taking into account the uncertainties due to the limited knowledge of some physical phenomena [10] [11].

The IAEA TECDOC-1791 [11] recommends to pay attention of practical eliminating of the following severe accident conditions which could:

- damage the containment in an early phase as a result of direct containment heating, some steam explosions or large hydrogen detonation;
- damage the containment in a late phase as a result of basemat melt-through or containment excessive pressure;
- occur during an open containment—notably in shutdown states;
- bypass the containment (e.g. Steam Generator (SG) tube rupture or an Interfacing System Loss of Coolant Accident (ISLOCA).

Moreover, the aforementioned document [11] proposes the following categories of accident conditions that should be addressed for "practical elimination":

• Events that could lead to prompt reactor core damage and consequent early containment failure:

- Failure of a large component in the reactor coolant system (RCS);
- Uncontrolled reactivity accidents.

• Severe accident phenomena which could lead to early containment failure:

- Direct containment heating;
- Large steam explosion;
- Hydrogen detonation.

• Severe accident phenomena which could lead to late containment failure:

- Molten core concrete interaction (MCCI);
- Loss of containment heat removal.

• Severe accident with containment bypass;

• Significant fuel degradation in a storage pool.

3. Design Features and Prevention and Mitigation Measures for Severe Accidents Management

The Kozloduy NPP is used as an example for providing a discussion on "practical elimination" of early or large releases for NPP with a WWER-1000/V320 reactor types. A number of significant modifications have been made to the existing design of the units 5 and 6 of Kozloduy NPP (WWER-1000/V320). Some new equipment has been put in place to prevent the occurrence of severe accidents or mitigate their consequences. The more significant modernization includes: containment hydrogen reducing system; after accident containment pressure reducing system; alternative steam generators feed water system; detectors for steam under reactor vessel cap; wide range thermo-couples; Post-Accident Monitoring System (PAMS); Safety Parameter Display System (SPDS); electrical power supply; high temperatures safety devices; water supply for the spent fuel pools; new center for accident management.

Recently issued publication [12] "Status of Severe Accident Management Guidelines (SAMGs) at KNPP" contains an overview of the above mentioned technical provisions and its implementations. Furthermore, the results from researches dedicated on some issues concerning the management of severe accidents are discussed in [13] [14] [15]. References [16] [17] [18] explain the status of Level 2 Probabilistic safety Assessment (PSA) and current studies in this area.

In the following table, the summarized design features of WWER-1000/V320 and prevention and mitigation measures to eliminate main phenomena during severe accident are presented (**Table 1**).

Distribution of the main mechanism of containment failures are presented in **Figure 1** and **Figure 2**.

Some results of sensitivity analyses of Large Early Release Frequency (LERF) based on Level 2 PSA, are presented below.

Table 1. Measures for severe accident management.

Phenomena	WWER-1000/V320 Design features and prevention and mitigation measures	
	Design features	Additional prevention and mitigation measures
Core melt	• Active medium and low-pressure safety injection (TQn3 and TQn2); • Passive Hydro Accumulators; • Emergency boron injection (TQn4).	• Additional diesel generators; • Qualification of some systems to operate as safety systems (TK system); • Water injection in reactor core or SG by mobile fire protection equipment in extreme conditions.
Core melt under high pressure	• Primary depressurization system; • Safety valves; • Spray system.	• Qualification of some systems operates as safety systems (YR and TK).
Pressure vessel failure	• In-vessel retention (by in-vessel injection of water).	• By external vessel cooling with water
External steam explosion	• None. The cavity is dry.	• Need additional investigation in case of flooding of cavity for In-Vessel Melt Retention(IVMR).
Basemat melt-through	• In-vessel melt retention by water injection.	• Plugging all ionization chamber channels located in the walls of the reactor vessel cavity; • Ex-vessel measures (see below).
Containment overpressure	• Containment spray (earlier phase); • Larger containment free volume.	• Containment venting system (scrubber).
Hydrogen detonation	• Larger containment free volume.	• Hydrogen recombiners; • Long term containment management (risk for late phase release).
Containment bypass	• Accident management (for Primary to Secondary (PRISE) events using appropriate procedures).	• Ex-vessel measures (corium spreading, corium cooling by water supplying); • Long term cooldown of corium.
Accident in spent fuel pool (SFP)	• Water level and temperature monitoring; • Emergency water supply system.	• Even SFP heat distribution; • Water injection in SFP by mobile fire protection equipment in extreme conditions.

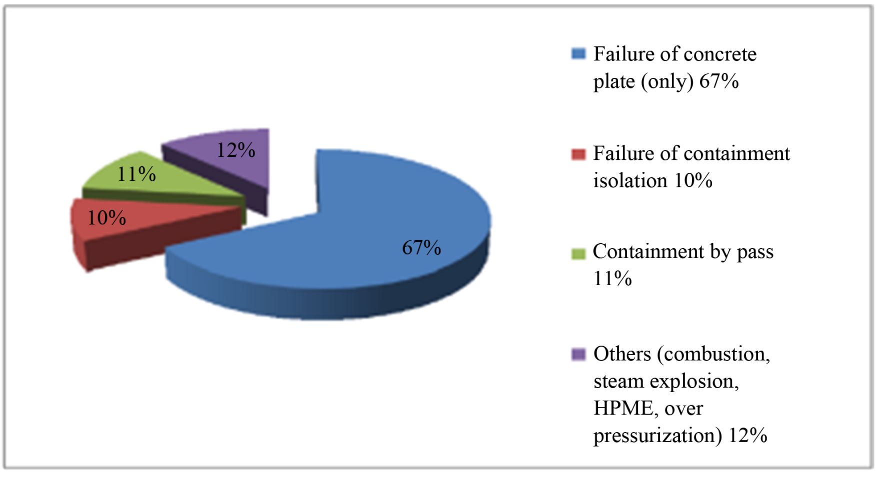

Figure 1. Base case.

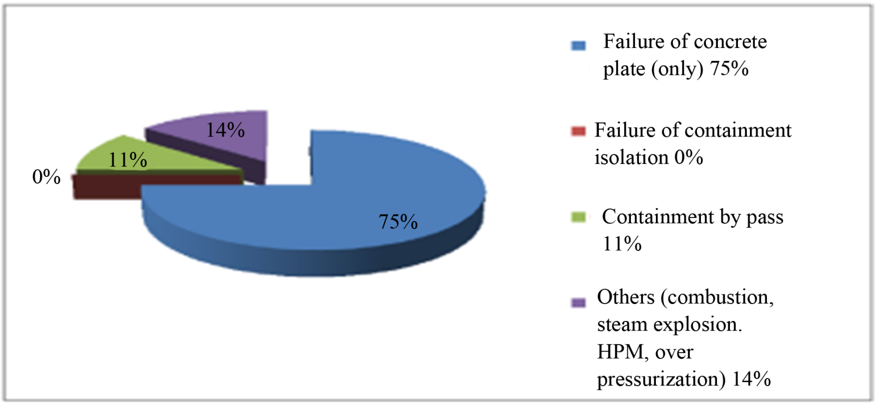

Figure 2. Sensitivity analyses.

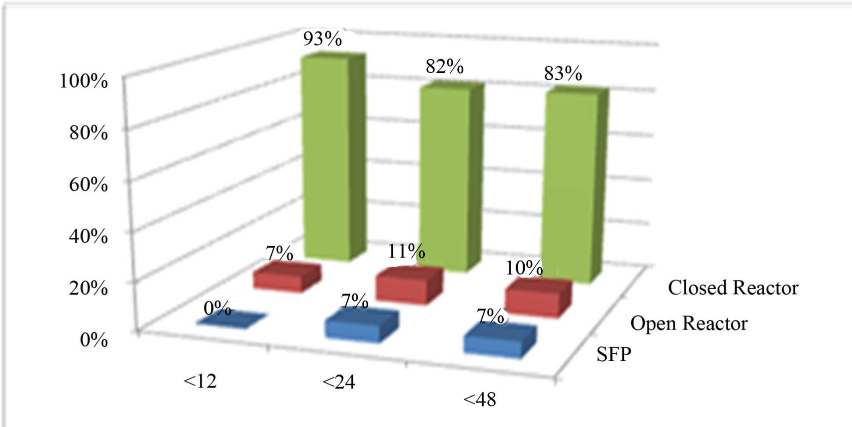

Figure 3. Distribution of LERF by Reactor states and SFP (Source: [18]).

Figure 3 [18] shows LERF distribution for different reactor states (open and closed reactor) and for the spent fuel pool (SFP). The closed reactor is a main contributor to the risk of radioactive releases into the environment.

For the interpretation of the results presented in **Table 2**, the values defined in the safety guide "Probabilistic Safety Analysis of Nuclear Power Plants" [19] was taken into consideration. This safety guide contains quantitative criteria for severe accidents—limits of a large release requiring immediate protective measures. Furthermore, these criteria are specified for new and for existing NPPs.

According to Section 1.3 from the current guide, regarding the existing NPPs:

"*b*) *the frequency of large radioactive releases into the environment that require implementation of urgent protective measures for the public shall be lower than* 10-5 *events per NPP per year.*"

According to the same guide, Section 1.4, for new NPPs:

"*b*) *the frequency of large radioactive releases into the environment that requires undertaking of immediate protective measures for the population shall not exceed* 1.10-6 *events per NPP per year.*"

It should be stressed that threshold values for a large radioactive release frequency were used in the frame of the interpretation of Level 2 PSA results.

Table 2. Isolation of Containment (some results of sensitivity analyses).

Description	LERF (basic)	LERF (Sensitivity analysis)	Relative variation [%]	LRF (basic)	LRF (Sensitivity analysis)	Relative Variation [%]
LERF < 12 hours	4.41E−06	2.59E−06	70.3	1.98E−05	2.15E−05	7.9
LERF < 24 hours	4.91E−06	2.89E−06	70.0	1.93E−05	2.12E−05	9.0
LERF < 48 hours	5.12E−06	3.10E−06	65.1	1.91E−05	2.10E−05	9.1

Results in the Table 2 demonstrated that LERF values are significantly less that threshold value (LERF < 10 - 5 1/y) defined in the normative document.

4. Summary

The concept of "practical elimination" is defined as part of the Defence in Depth (DiD) of NPP in the IAEA document INSAG-12 in 1999. But, the special attention to it was paid after the accident in Fukushima NPP in 2011. The "practical elimination" is achieved by prevention of the conditions that could lead to early or large radioactive releases [7]. From this point of view, the mechanisms for the containment failure of reactor WWER-1000/V320 are presented. The summarized design features and preventing and mitigation measures already implemented at Kozloduy NPP to extend the design basis and beyond design basis envelop are presented. Issues related to external steam explosion are underlined for further study.

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