Protective Alternatives of SMR against Extreme Threat Scenario – A Preliminary Risk Analysis

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INTRODUCTION

The article presents a preliminary risk analysis of the main features in NPP (Nuclear Power Plant) that includes SMR - Small and Modular Reactors, given an extreme threat scenario. A review of the structure and systems of the SMR is followed by systematic definitions and analysis of the threat scenario to which a preliminary risk analysis was carried out. The article outlines the basic events caused by the referred threat scenario, which had led to (1) possible failure mechanisms according to FTA (Fault-Tree-Analysis), (2) critical protective circuits, and to (3) detecting critical topics for the protection and safety of the reactor.

RESULTS

The Threat Scenario

SMR may face many hazards which can potentially lead to failure in the reactor core. The main hazards are aircraft crash, missile hit, and car bomb explosion. One of this research main objectives is to examine the survivability (resilience) of the SMR to the effects of explosion, shock and ground movements that may lead to LOCA (Loss of Coolant Accident) resulting in a core melting. These scenarios have direct consequences on the destruction of the structure and the systems of the SMR, as well as indirect consequences, which could be caused as a result of indirect damage to vital cooling systems of the reactor, due to fractures and cracks in sensitive systems such as critical pipelines connecting coolant resources to the RV (Reactor Vessel). It is assumed that due to the RV remarkable toughness (geometry, thickness, and structure) it will remain intact under the extreme event hazards. It is also assumed that due to the spatial locations of the various protection systems, and their autonomous operation, not all of them will be hit due to single hit.

Definition of Basic Events and Consequences

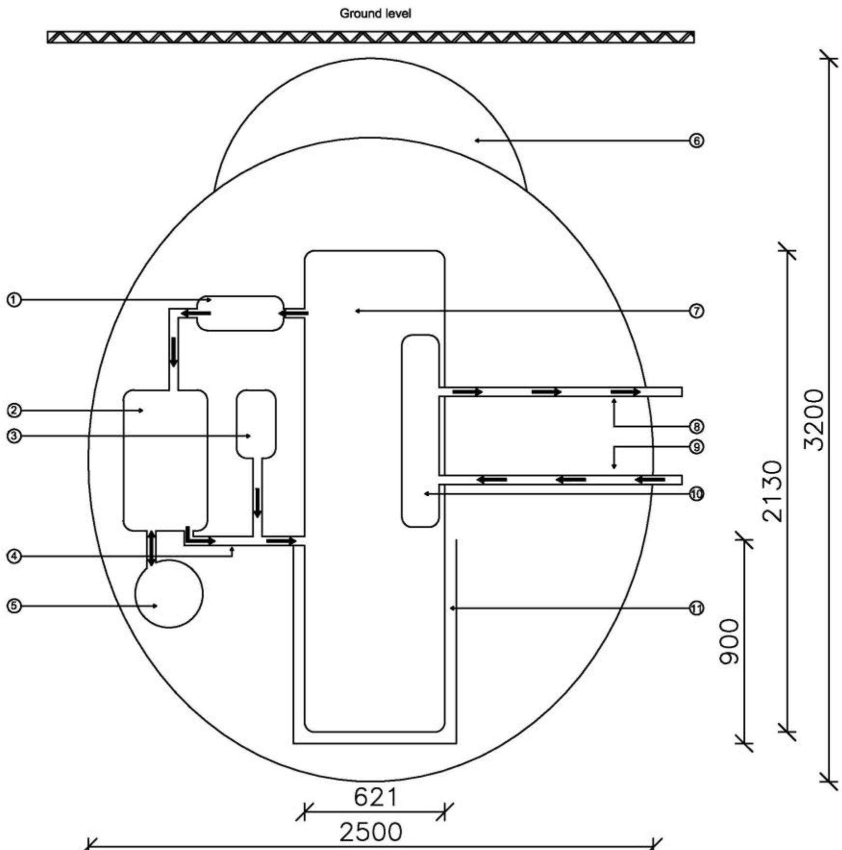
Given the referred threat scenario, two "state of nature" were defined:

A. Warning systems did not identify the extreme event, and/or automatic shutdown systems did not shut down the reactor core successfully.

B. According to Smith and wright[3] and Bajs et al.[1], once the reactor protection system detects extreme event, it will perform automatic shutdown. Core shutdown will be accomplished thanks to gravity by the falling of the CRDM (Control Rod Drive Mechanism) into the reactor core. Alternatively, core shutdown may be accomplished by the injection of borated water into the RV. Following shutdown, the reactor's thermal power decreases quickly and drastically. According to El-Wakil[2], the reactor's capacity declines to between 7% and 0.1% of the thermal output before shutdown, and later decreases to even lower values within a duration of an hour to several days, depending on the operation of the reactor before the break. In fact, within a few hours, the reactor's thermal power drops below 1% from its original capacity. Consequently, only one proper cooling system, with ongoing external power supply, is required to prevent core melting caused by LOCA. SMR has only five passive safety systems:

1. Emergency Heat Removal System (EHRS): is designed to transfer heat from the coolant to the environment during an accident.
2. Emergency Boration Tanks (EBT): two systems, providing way of alternative reactor shutdown by supplying borated water through the DVI (Direct Vessel Injection) lines into the RV. In addition, these containers provide a water source to the primary system during an emergency.
3. Pressure Suppression System (PSS): consists of six water tanks and a mutual gas storage tank. This system controls the CV pressure below 1.0 MPa.

4. Automatic Depressurization System (ADS): its role is ensuring equal pressure between the CV and RV. It consists of two 4-inch parallel pipes, each with two closed valves. The single line discharges into the Pressure Suppression System water tank through a sparger.
5. Long-Term Cooling System (LTCS): Implemented by a cavity at the bottom of the RV. This cavity accumulates the coolant and condensed liquid as well. In case of LOCA, it fills up above the level of the core allowing the core to be saturated in water.



Legend:

1	Automatic Depressurization System	7	RV-Reactor Vessel
2	Pressure Suppression pool	8	Steam line
3	Emergency Boration Tanks	9	Water line
4	DVI-Direct vessel Injection	10	SG- Steam Generator
5	Pressure Suppression pool gas space	11	RV cavity
6	Bolted and flanged closure head		

Figure 1. Scheme of SMR Containment Vessel

Qualitative FTA

Failure mechanisms in the SMR for the given threat scenario are modeled using a qualitative FTA, indicating the critical components in the failure mechanism. The primary failure event (Top Event) is Loss Of Coolant Accident (LOCA) event, which can lead to core melting. SMR has three protective circuits:
1. RV cooling.
2. Containment Vessel cooling.
3. External mechanisms of emergency cooling.

Assuming successful shutdown, the three protective circuits mentioned above are linked with an "OR" gate to the LOCA top event. Each of them has its own fault tree according to its own failure mechanisms:
CV loss of coolant failure occurs if one of the two following systems fails (Figure 2):
A. *DVI lines*: pipes failure due to a direct or indirect hit (shock or thrust).
B. *Simultaneous failure of the two safety systems located within the CV:*
1. *Pressure Suppression System (PSS):* fails only if all the six pools fails simultaneously.

2. *Automatic Depressurization System (ADS):* fails only if the two water lines fail simultaneously.

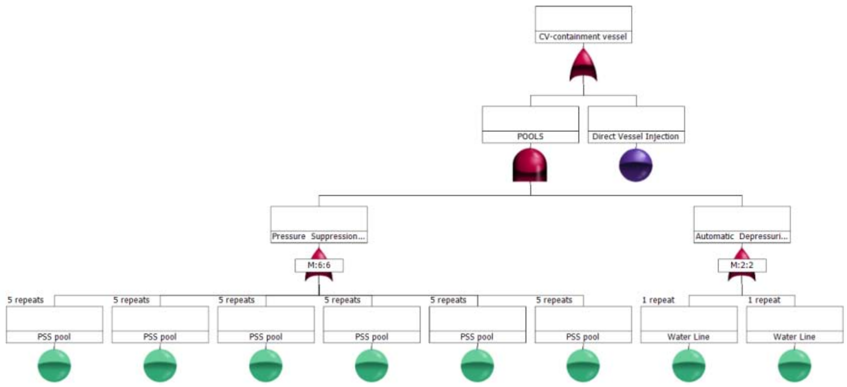


Figure 2. CV loss of coolant failure fault tree diagram.

Similarly, RV loss of coolant failure occurs if one of the main cooling systems, which are integrated in the RV, fails:

A. *RCP-Reactor Coolant Pumps:* failure occurs when all eight pumps fail simultaneously.
B: *SG-Steam Generators:* failure occurs when all eight SGs fail simultaneously.
C. *Pressurizer:* fails due to a direct or indirect hit at the pressurizer containment.

External above-grade systems failure will occur only if the two following systems fail:
A. *Emergency Heat Removal System (EHRS):* consists of Refueling Water Storage Tank (RWST) and four heat exchangers connected to four SGs. This system fails when failure occurs in the RWST or in the four heat exchangers simultaneously. The successful operation of these components is depended on the reliable operation of the exterior pipeline systems.
B. *Makeup Tanks:* consists of eight SG makeup water tanks connected to all of SGs. Each container is connected to the steam and water lines of its SG. This system fails if failure occurs in the containers or in the steam and water lines respectively.

As mentioned above, these analyses are based on the hypothesis that the reactor shutdown performed successfully. Nevertheless, it is important to interpret the reactor shutdown failure:
A reactor shutdown failure will occur if the following systems fail simultaneously:

A. *CRDM:* failure occurs if the rods do not fall into the reactor, and/or they do fall but do not perform shutdown.
B. *EBT- Emergency Boration Tanks:* failure occurs when the two tanks fail simultaneously.

SUMMARY AND CONCLUSION

A preliminary risk analysis was carried out to explore the risks associated with operating an SMR given an extreme threat scenario that is a single extreme event that may cause failure of some protective systems. The risk analysis refers to the following "State of nature" situations:
1. Automatic shutdown systems did not identify the extreme event, and / or did not have time to perform shutdown as required.
2. Automatic shutdown systems identified the extreme event, and were able to perform shutdown of the reactor core successfully.

Initial qualitative analysis depicts that the safety systems of the SMR are of high reliability since they are based on three circuits, two of which are essentially passive (RV and CV)
The analysis, referred to the successful shutdown of the reactor, shows that the internal safety circuits have a high degree of redundancy. Both the interior cooling systems of the RV and CV are characterized by a high degree of redundancy. Consequently, focus on protecting the RV or CV, which according to the hypothesis

of this study will be underground, could ensure a safe shutdown of the reactor given a reference extreme event and assuming the shutdown of the reactor was reached.

REFERENCES

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