Chapter

Importance Analysis of Containment Spray System in Pressurized Water Reactor (PWR)

Muhammad Zubair and Priyonta Rahman

Abstract

The basic purpose of the containment spray system (CSS) is to cool the containment atmosphere when the internal pressure of the containment exceeds a certain limit. Water is transferred by a pump from the storage tank via heat exchangers to the overhead spray nozzles in the roof of the containment. This water cools the atmosphere of the containment. In this research, the reliability analysis of CSS has been investigated using fault tree analysis (FTA). The results of the top event probabilities, minimal cut sets (MCS), risk decrease factor (RDF), risk increase factor (RIF), and sensitivity analysis were obtained for the WASH-1400 data base.

Keywords: importance analysis, pressurized water reactor, containment spray system, fault tree analysis, RiskSpectrum

1. Introduction

Nuclear power is a source of sustainable energy, making a significant contribution in the generation of electricity worldwide. Nuclear reactors provide clean energy and is ensured to be safe through the thorough study of nuclear power plants (NPPs) called the probabilistic safety assessment (PSA). PSA is used as an evaluation tool which recognizes the potential risks and accident scenarios resulting in an accident due to the liability of failure of certain components or systems as a whole [1–3]. In an attempt at the aversion of catastrophes, several safety systems are put in place where containment spray system is one among the various redundant safety features in pressurized water reactors (PWRs). The system is aimed at heat removal within the containment when appropriate along with the reduction of radionuclide concentration discharged into the atmosphere. This safety-related system is situated in the auxiliary building and containment of the reactor [4].

A nuclear reactor is provided to take strict safety measures against radioactive contamination of the environment using a diverse arrangement of multiple redundant safety systems [5]. The containment spray system is an engineered safety feature to preserve the integrity of the containment in case of over pressurization. It is designed to bring down the internal peak pressure of the containment by half in a span of 24 hours in case of a loss of coolant accident (LOCA), along with removal of fission products [6].

2. Working of containment spray system

The CSS consists of two identical but independent trains where each train consists of a containment spray pump (CSP), a containment spray heat exchanger (CSHX), a containment spray mini-flow heat exchanger, associated pipes and valves, and containment spray headers located in the upper dome of the containment. A simplified diagram of the CSS is shown in **Figure 1**. The two trains are redundant systems which has the capability of providing 100 percent flow individually during accident conditions and also provides reliability in case one of the trains stop working and makes them testable. In case of maintenance, one of the trains can be shut down and worked on while the other is free to operate.

The CSS in APR-1400 is designed as such that when the internal pressure of the containment surpasses the design limit, a containment spray actuation signal (CSAS) is sent to the pumps to start operation [7]. Once the actuation signal is received, the in-containment refueling water storage tank (IRWST) is used as the suction source for the containment spray system. The CSS pumps discharge water from the IRWST through the set of heat exchangers before sending it to the overhead spray. Once the containment pressure is detected to reach a certain value, the valves open automatically to allow the flow of spray water to the nozzles. The water travels to the spray headers and are divided into small droplets to fall throughout the containment.

Two isolating valves in the system are located in the pipe between the tank and the spray nozzles. The valves are in a closed position under normal operation to isolate the CSS from the rest of the plant. Additional valves are present to ensure the isolation of the overhead spray. The spray nozzles are arranged in concentric circles, at several angles, to ensure adequate coverage of the containment volume resulting in continuous cooling of the reactor system. The droplets from the spray headers cools the atmosphere and the remnants fall into the holdup volume tank (HVT), which is transported back to the IRWST. This certain design of the CSS is maintained in the APR-1400 plant design in countries like Korea, USA, and UAE [8, 9].

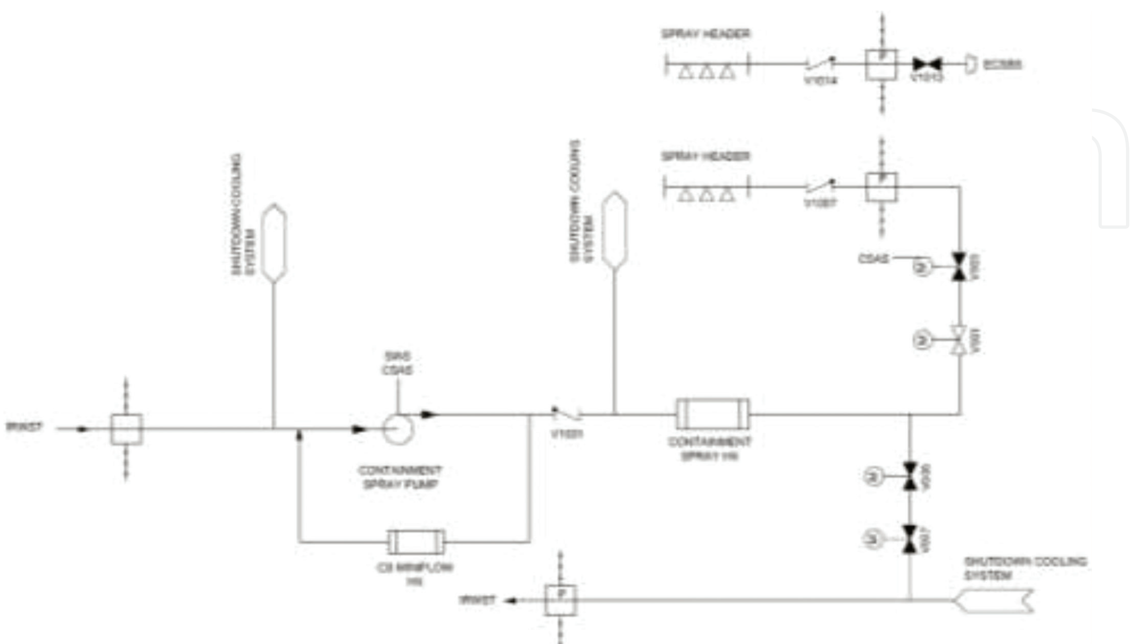

Figure 1.
Containment spray system in APR-1400.

3. Design features of the containment spray system

The containment spray pumps are centrifugal pumps responsible for transporting water from the IRWST to the spray nozzles at the top of the dome. The pumps discharge into the heat exchangers to cool the water. The CSS pumps are identical to the shutdown cooling pumps (SCP) and thus are interchangeable. In case the CSS pumps are inoperative, the SCPs can be used to carry out the operation.

The containment spray heat exchangers are used to remove heat from the containment spray water in the event of an accident. The heat exchangers have a U-tube design with a tube and shell side. The hot water is passed through the tube transferring heat to the cold water in the shell side.

The containment spray headers are located at the top of the containment dome in concentric circles which ensures adequate coverage of the containment building volume and homogeneous distribution of the spray water. The isolation valves in the spray headers control the flow of water into the nozzles and open on the receipt of a CSAS. This reduces the chances of accidental spraying when it is not intended to. The design of the spray nozzles is required to be as such to minimize clogging. They are required to avoid any internal moving parts or restrictions which could possibly interfere with the passage of the flow or restrict it [10].

4. Analysis of CSS fault tree

RiskSpectrum Analysis Tools (RSAT) is a software that enables study of PSA utilizing fault trees. It conducts several analyses such as MCS analysis, uncertainty analysis, importance/sensitivity analysis, and time-dependent analysis. A fault tree was modeled in the RiskSpectrum software according to the fault tree presented in the WASH-1400 report. The report is a 1975 reactor safety study report conducted to assess the accident risks in U.S. commercial nuclear power plants. The unavailability's of the events involved in the fault tree are given in **Table 1** [11].

The fault trees constructed for containment spray system are shown in **Figures 2–4**.

Event		**Unavailability (q)**
Subsystem A	**Subsystem B**	
CXVA004X	CXVB004X	1.00E-03
CST100AC	CST100BC	ε
CMV100AC	CMV100BC	1.00E-04
CXVA002X	CXVB002X	1.00E-02
CFLA01AP	CFLB01BP	1.10E-04
CCL1A01G	CCL1B01G	3.00E-04
CM0A01AF	CM0B01BF	ε
CST1A01F	CST1B01F	1.00E-03
CPMA01AA	CPMB01BA	1.00E-03
CPMA01AF	CPMB01BF	1.50E-05
CCVA001C	CCVB001C	1.00E-04
CNZA001P	CNZB001P	1.30E-04

Event		Unavailability (q)
Subsystem A	**Subsystem B**	
GCL01	GCL02	4.60E-03
JD00	JC00	4.10E-05
JK00	JJ00	1.10E-06
CTK0001R		ε
CTK0001L		ε
CVT0001P		4.40E-07
JH00		4.10E-05
JG00		4.10E-05

Note: The symbol "ε" denotes that the unavailability is assumed to be negligible.

Table 1.
Basic event unavailability.

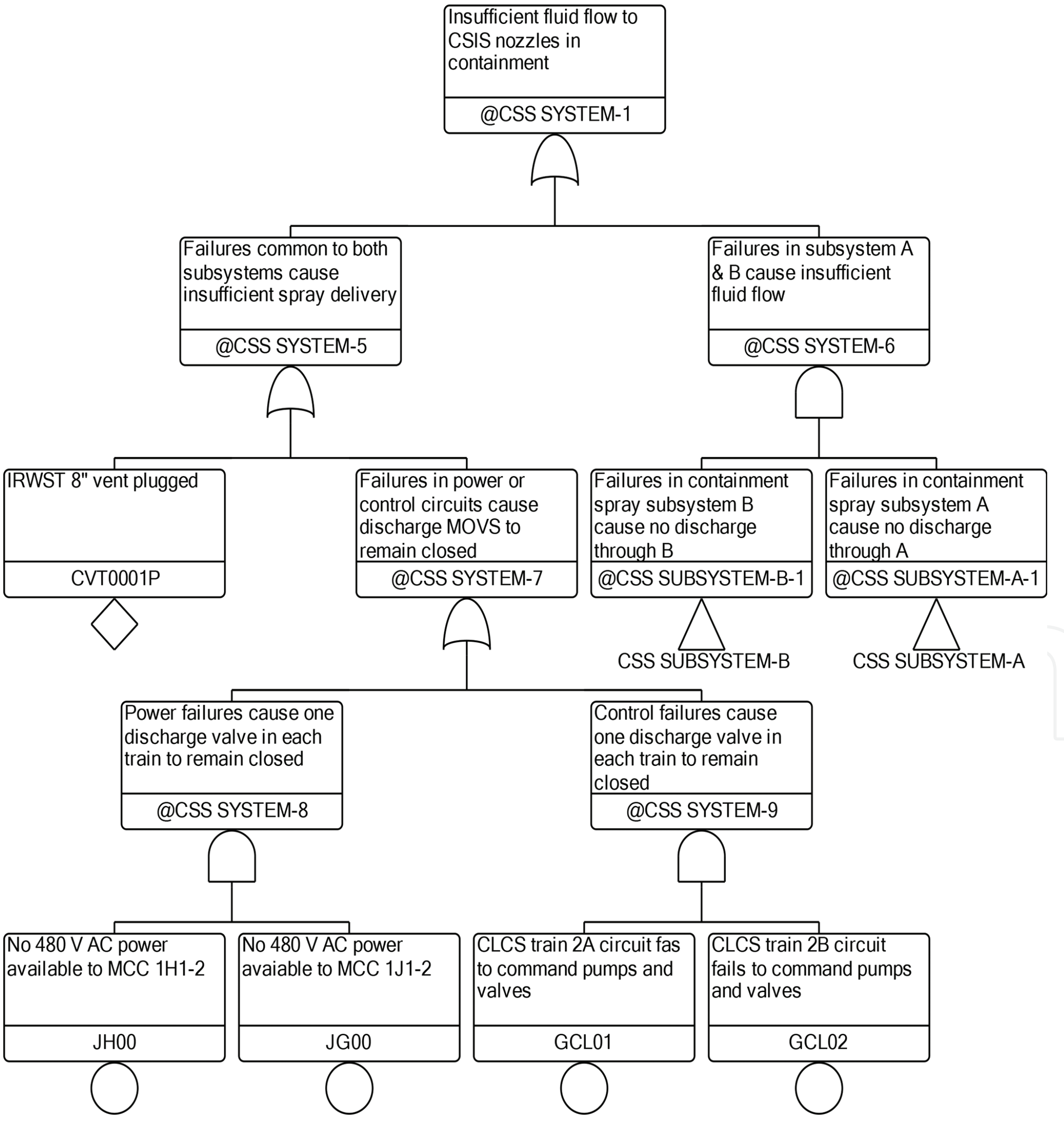

Figure 2.
Containment spray system fault tree (Part 1 of 3).

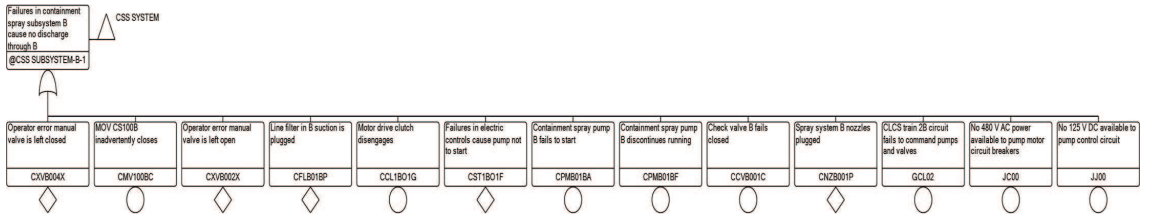

Figure 3.
Containment spray system fault tree (Part 2 of 3).

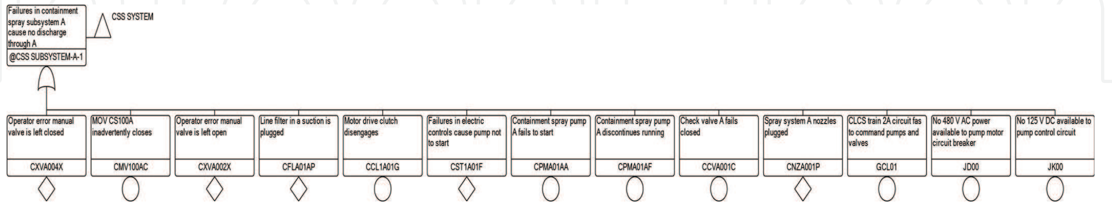

Figure 4.
Containment spray system fault tree (Part 3 of 3).

The MCS analysis conducted on the containment spray system showed that the top event probability (Insufficient fluid flow to CSIS nozzles in containment) is 3.47E-04 with 171 minimal cut sets. The first 10 minimal cut sets against the probability are represented in **Figure 5**. It shows that the minimal cut set with the highest probability of 1.00E-04 is a combination of operator error leaving the manual valve open in both subsystems A and B.

Importance analysis was also conducted on the fault trees which showed the risk decrease factor, risk increase factor, and the sensitivity for each event in **Figures 6–8**, respectively. Risk decrease factor is the reduction in risk if the feature was assumed to be optimized or made perfectly reliable whereas, risk increase factor is the increase in risk if the feature was assumed to be absent or to fail. The graphs below show that manual valves left open in subsystem A due to operator error has the highest RDF, RIF, and sensitivity in the CSS system, followed by the identical event in subsystem B.

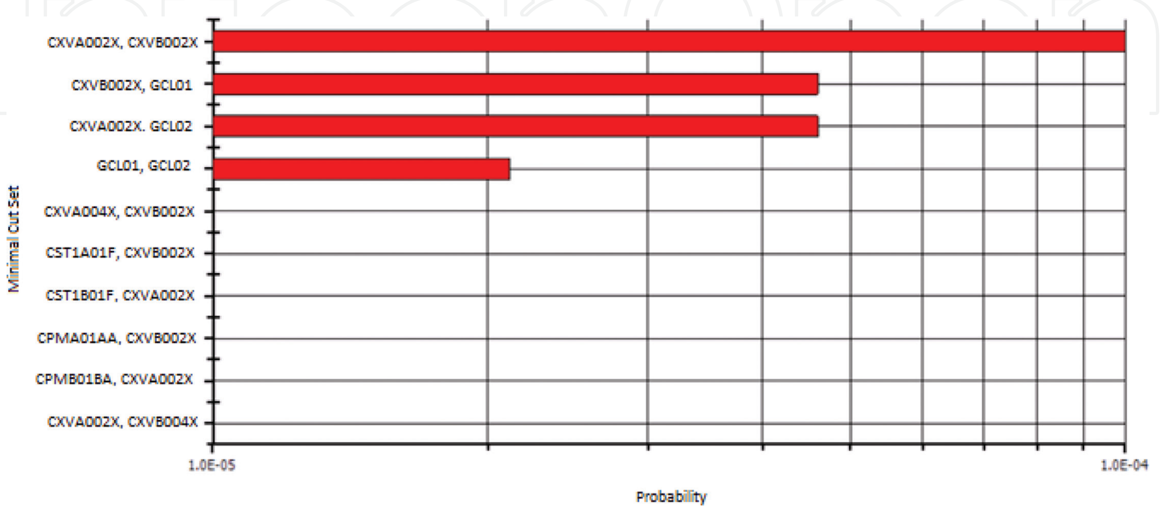

Figure 5.
Top 10 minimal cut sets in a CSS system.

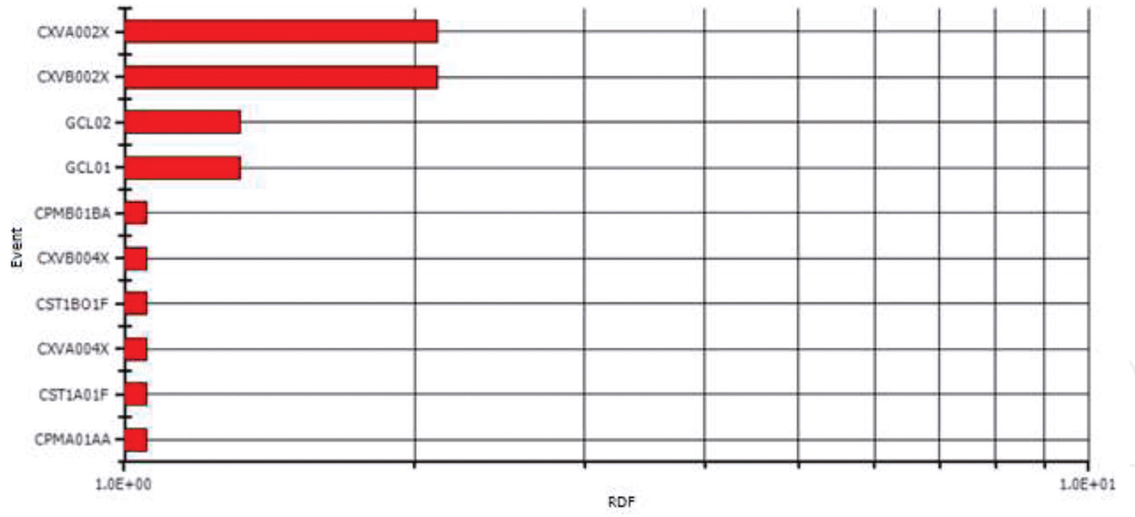

Figure 6.
Basic event RDF.

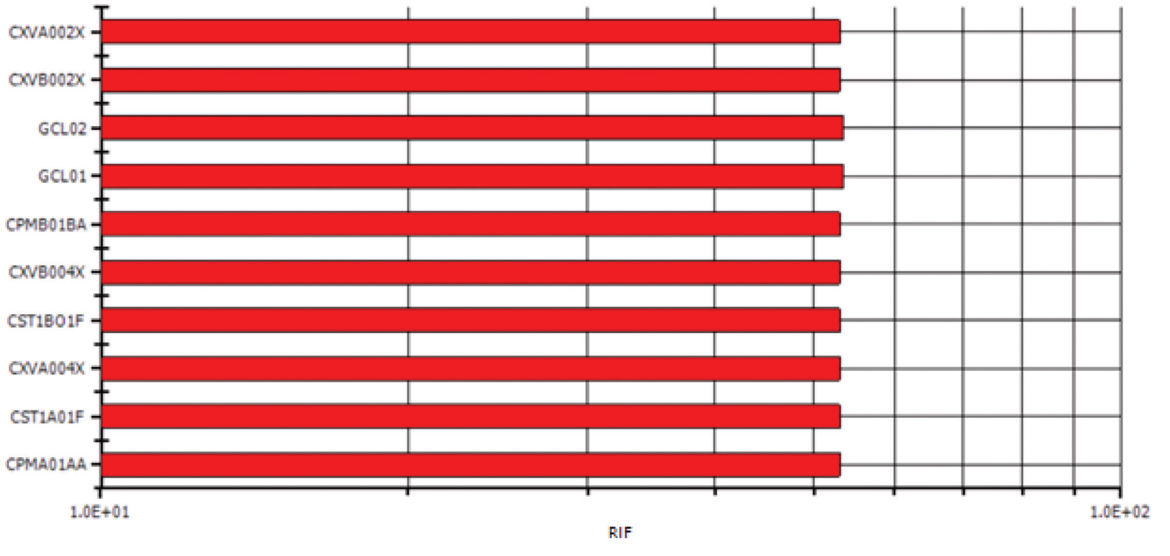

Figure 7.
Basic event RIF.

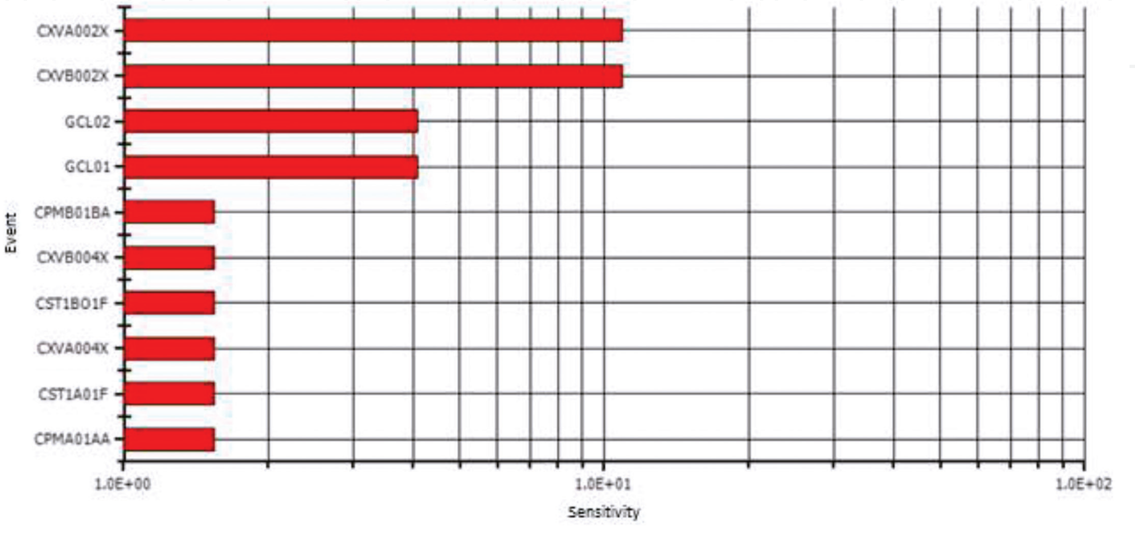

Figure 8.
Basic event sensitivity.

5. Conclusions

Containment spray systems are a crucial part of nuclear power plants as a safety feature. The system is aimed at heat removal within the containment. The CSS consists of two identical, independent trains and is designed as such that when the internal pressure of the containment surpasses the design limit, a containment spray actuation signal starts operation of the CSS. Water from the storage tank is transported to the overhead sprays at the top of the dome from where water is sprayed to ensure adequate coverage of the containment volume resulting in continuous cooling of the reactor system. Analysis of the constructed fault tree in RiskSpectrum from the WASH-1400 report gave in return the top event probability and the list of minimal cut sets. It also showed that the highest RDF, RIF, and sensitivity belonged to the event of operator error where the manual valve is left open in train A.

Acknowledgements

The authors are thankful to university of Sharjah for providing research facilities.

Author details

Muhammad Zubair[1,2]* and Priyonta Rahman[1]

1 Department of Mechanical and Nuclear Engineering, University of Sharjah, Sharjah, UAE

2 Nuclear Energy System Simulation and Safety (NE3S) Research Group, Research Institute of Sciences and Engineering, University of Sharjah, Sharjah, UAE

*Address all correspondence to: mzubair@sharjah.ac.ae

References

[1] Zubair M, Ababneh A, Ishag A. Station black out concurrent with PORV failure using a generic pressurized water reactor simulator. Annals of Nuclear Energy. 2017;**110**:1081-1090

[2] Zubair M, Ishag A. Sensitivity analysis of APR-1400's reactor protection system by using RiskSpectrum PSA. Nuclear Engineering and Design. 2018;**339**:225-234

[3] Ajit V, Srividya A, Durga K. Reliability and Safety Engineering. London: Springer; 2010. pp. 323-369. DOI: 10.1007/978-1-84996-232-2

[4] US Nuclear Regulatory Commission. APR1400 Design Control Document Tier 1. 2018. Retrieved from https://www.nrc.gov/docs/ML1822/ML18228A647.pdf

[5] Gianni P. Nuclear Safety. 1st ed. Amsterdam: Butterworth-Heinemann; 2006. DOI: https://doi.org/10.1016/B978-0-7506-6723-4.X5000-1

[6] US Nuclear Regulatory Commission. Emergency Core Cooling Systems. 2016. Retrieved from https://www.nrc.gov/docs/ML2005/ML20057E160.pdf

[7] US Nuclear Regulatory Commission. Chapter 11.4 Containment Spray. 2011. Retrieved form https://www.nrc.gov/docs/ML1125/ML11251A006.html

[8] Nuclear Energy Agency. Design description and comparison of design differences between APR1400. Plants. 2018:10 Retrieved from https://ww6w.oecd-nea.org/mdep/documents/TR-APR1400-01%20Design%20Description%20and%20Comparison%20of%20Design%20Differences.pdf

[9] US Nuclear Regulatory Commission. Chapter 6 Engineered Safety Features. 2018. Retrieved from https://www.nrc.gov/docs/ML1822/ML18228A653.pdf

[10] US Nuclear Regulatory Commission. Advanced Power Reactor 1400 (APR1400) Final Safety Evaluation Report. 2018. p. 77-85. Retrieved from https://www.nrc.gov/docs/ML1821/ML18212A092.pdf

[11] U.S. Nuclear Regulatory Commission. Reactor safety study: An assessment of accident risks in U.S. commercial nuclear power plants. In: Appendix. Vol. II. Washington: D.C; 1975