

Development of Open Prototype PSA Model using IAEA iPWR Simulator

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1. Introduction

In recent years, a variety of strategies have been pursued worldwide to achieve carbon neutrality and facilitate the transition of energy systems. Among these, Small Modular Reactors (SMRs) have attracted significant attention due to their advantages, including reliable electricity supply, shortened construction periods, and enhanced safety. Of the SMR designs under development, Light Water Reactor (LWR)-based SMRs are most prevalent, owing to their higher technological maturity.

The Probabilistic Safety Assessment (PSA) methodology for LWR-based SMRs is similar to that used for conventional Pressurized Water Reactors (PWRs). However, unique design features of LWR-based SMRs, such as multi-module configurations, passive safety systems, and integrated designs, present challenges for the direct application of existing PSA models. Addressing these challenges requires international research collaboration, which can be facilitated by sharing open-source, standardized PSA models.

In this context, this study aims to develop a prototype PSA model using iPWR, a nuclear reactor simulation program provided by the International Atomic Energy Agency (IAEA). The proposed model is expected to serve as a basis for future international research collaboration on the PSA of LWR-based SMRs and an educational resource for training.

2. Overview of iPWR

2.1. Overall System Description [1]

The IAEA provides a suite of nuclear reactor simulation programs to support the education and training in its Member States, among which iPWR is a representative example. This simulator represents not only the reactor behavior under normal operating conditions but also its responses to transients and accident scenarios.

To represent the overall operation, the simulator incorporates the following systems:

Table I. List of Systems in iPWR

System	Abbreviation
Reactor Coolant System	RCS
Main Steam System	MSS

Feedwater System	FWS
Turbine System	TUR
Generator System	GEN
Condenser System	CNR
Circulating Water System	CWS
Containment Building System	CBS
Automatic Depressurization System	ADS
Containment Cooling System	CCS
Gravity Injection System	GIS
Pressure Injection System	PIS
Passive Decay Heat Removal System	PDHR
Protection and Control System	PCS

iPWR is a compact and advanced light water reactor designed to simplify reactor operation and enhance safety. Its key features include modularity, passive safety systems for core and containment cooling, and an integrated design in which primary system components are located within the Reactor Pressure Vessel (RPV).

Locating the primary system components within the RPV eliminates the need for conventional primary circuit piping, thereby reducing the risk of a Loss-of-Coolant Accident (LOCA). Furthermore, passive safety systems such as the ADS and PIS are directly connected to the RPV, enabling temperature and pressure control independent of external power sources or operator action. Figure 1 illustrates the overall system configuration of iPWR.

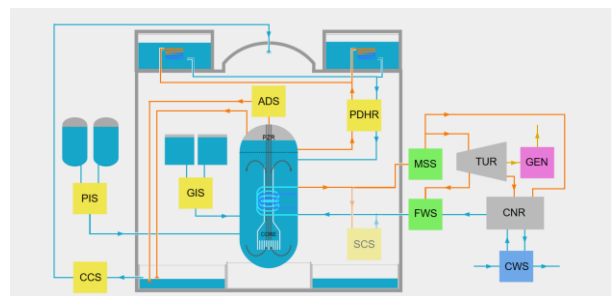


Fig 1. Schematic overview of iPWR

The variables at stable state are as follows:

- Generator load: 45 MW(e)
- FW flow: 78 kg/s
- T_{avg} : 287.5°C
- Pressurizer pressure: 15.5 MPa

2.2. Safety Systems Description

The PSA model considers the following safety systems:

- **ADS:** The ADS is actuated by opening three valves installed in the primary system, allowing steam to be released into the suppression pool within the containment, where it condenses. Through this mechanism, the ADS depressurizes the reactor, thereby preventing void formation in the core and subsequent core damage.

- **CCS:** The CCS is an active system that is automatically actuated when the containment pressure exceeds 0.019 MPa. It pumps borated water from the suppression pool and sprays it into the containment via spray nozzles. This process depressurizes the containment to below its design pressure limit in the event of a LOCA, steam line break, or feedwater line break.

- **GIS:** The GIS is a passive system that is actuated by gravity when the RPV pressure falls below 0.5 MPa. Its function is to depressurize the primary system and ensure an adequate shutdown margin by injecting water into the RPV. Once actuated, the check valves open automatically, allowing borated water in the tank to flow into the primary system by gravity. The volume of the tanks, in conjunction with the PIS, is designed to maintain core coverage in the event of a LOCA.

- **PIS:** The PIS is a passive system that is actuated to inject borated water into the RPV once the ADS has depressurized the RCS to 5.0 MPa. The tanks are pressurized to ensure that the RPV is flooded only when the system pressure falls below the design setpoint. This injection is designed to maintain core coverage in the event of a LOCA.

- **PDHR:** The PDHR operates by condensing primary system steam in emergency condensers located in pools inside the containment. Upon activation, the inlet and outlet valves open while the FWS and MSS are isolated, allowing water in the condenser tubes to drain into the RPV and draw steam into the condensers. The steam transfers its heat to the pool water, thereby forming a natural circulation loop.

3. Methods and Results

3.1. Basic Approaches

This study develops a prototype PSA model to evaluate the safety of LWR-based SMRs, using iPWR as a reference. From literature survey, it turned out no PSA model has yet been developed for iPWR. It introduces additional considerations for PSA compared to conventional LWRs due to its unique design features. For instance, because the primary system components are located within the RPV, large and medium break

LOCAs, which are typically considered in LWR PSA, can be excluded from the analysis. Furthermore, the presence of passive safety systems reduces the risk significance of the electric power system.

The implementation of the model is based on iPWR simulation program provided by the IAEA. The simulator offers open-source resources including system descriptions, operating procedures, representations of reactor physical behavior under both normal and abnormal conditions, as well as Piping and Instrumentation Diagrams (P&IDs).

3.2. Event Tree and Fault Tree Construction [2]

Event trees are developed to model initiating events, including a LOCA and a Loss-of-Feedwater event (LOFW). The associated fault trees are subsequently constructed for the safety systems represented at the headings of the event trees. In addition, initiating events are simulated with reference to the simulator manual published by the IAEA. A LOCA is initiated by activating the 'RCSV01 Leakage' option in the generic malfunctions, while a LOFW is initiated by loading the 'Loss of normal feedwater flow' in the specific malfunctions.

- **LOCA:** A LOCA is defined as an accident involving a breach in the RCS that reduces coolant inventory and may impair the removal of heat from the reactor core. It constitutes one of the most important initiating events in safety assessments, as it directly challenges the reactor core cooling function.

- **LOFW:** A LOFW is defined as an initiating event involving the loss of feedwater supply to the steam generators, thereby limiting heat removal from the reactor core through the secondary side. Since the steam generators function as the primary heat sink in LWRs, the loss of feedwater constitutes a critical initiating event in safety assessments, as it directly challenges the reactor core cooling function.

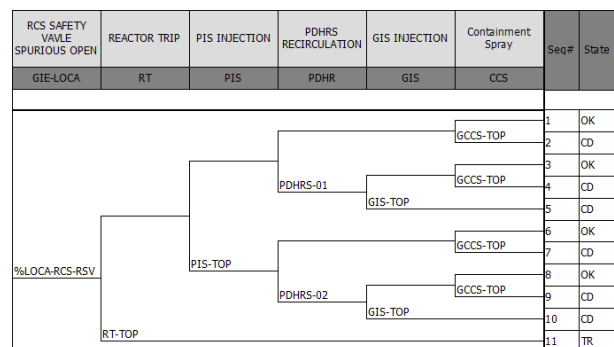


Fig 2. Event Tree of LOCA

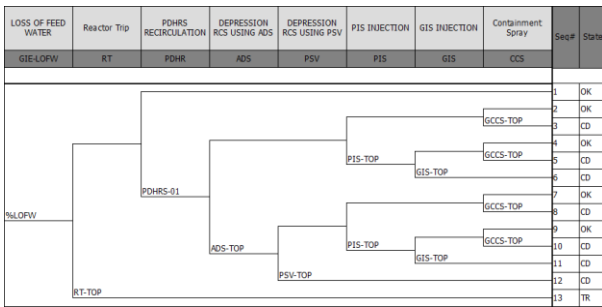


Fig 3. Event Tree of LOFW

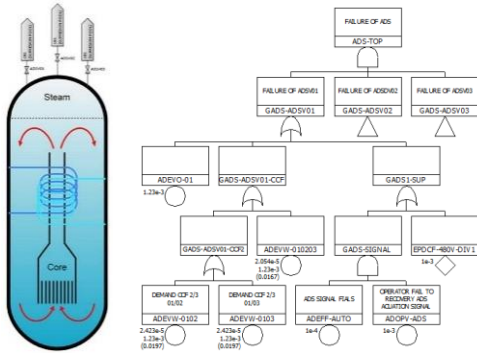


Fig 4. P&ID and Fault Tree of ADS

The headings of the event trees are determined by simulating each initiating event and sequentially shutting down the associated safety systems using malfunctions. Success criteria are defined from the observed trends of key variables, such as the temperature and pressure of the RCS.

The fault trees are constructed using the P&IDs provided in the simulator manual published by the IAEA. The reliability data used in the fault trees are derived from NUREG/CR-6928 [3] and expert judgment assumptions, and the initiating event frequencies are also derived from NUREG/CR-6928. As a result of the quantification, when the cut-off value is set to $1.0E-14$, the Core Damage Frequency (CDF) is calculated to be $8.687E-9$ for LOCA, while that for LOFW is $9.812E-11$.

Cut Set									
%LOCA-RCS-RSV									
No	Value	F/V	Acc	BE#1	BE#2	BE#3	BE#4	BE#5	BE#7
1	2.058e-9	0.232802	%LOCA-RCS-RSV	CCEVW-0104	#GIE-LOCA-02				
2	1.576e-9	0.179286	%LOCA-RCS-RSV	CCSPF-CBS2	#GIE-LOCA-02				
3	6.250e-10	0.071147	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
4	6.217e-10	0.070768	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
5	3.075e-10	0.035004	%LOCA-RCS-RSV	CCEVO-04	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
6	3.075e-10	0.035004	%LOCA-RCS-RSV	CCEVO-04	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
7	2.500e-10	0.028459	%LOCA-RCS-RSV	CCSPF-CBS5	CCSPF-CBS6	EPDIF-480V-DIV1	#GIE-LOCA-02		
8	2.500e-10	0.028459	%LOCA-RCS-RSV	CCSPF-CBS5	CCSPF-CBS6	EPDIF-480V-DIV1	#GIE-LOCA-02		
9	2.500e-10	0.028459	%LOCA-RCS-RSV	CCSPF-CBS5	CCSPF-CBS6	EPDIF-480V-DIV1	#GIE-LOCA-02		
10	2.500e-10	0.028459	%LOCA-RCS-RSV	CCSPF-CBS5	CCSPF-CBS6	EPDIF-480V-DIV1	#GIE-LOCA-02		
11	1.513e-10	0.017222	%LOCA-RCS-RSV	CCEVO-01	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
12	1.470e-10	0.016734	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
13	1.470e-10	0.016734	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
14	1.230e-10	0.014002	%LOCA-RCS-RSV	CCEVO-04	EPENF-6.9KV-DIV	#GIE-LOCA-02			
15	1.230e-10	0.014002	%LOCA-RCS-RSV	CCEVO-04	EPENF-6.9KV-DIV	#GIE-LOCA-02			
16	1.230e-10	0.014002	%LOCA-RCS-RSV	CCEVO-04	EPENF-6.9KV-DIV	#GIE-LOCA-02			
17	1.230e-10	0.014002	%LOCA-RCS-RSV	CCEVO-04	EPENF-6.9KV-DIV	#GIE-LOCA-02			
18	1.000e-10	0.011384	%LOCA-RCS-RSV	EPDIF-480V-DIV1	EPENF-6.9KV-DIV	#GIE-LOCA-02			
19	1.000e-10	0.011384	%LOCA-RCS-RSV	EPDIF-480V-DIV1	EPENF-6.9KV-DIV	#GIE-LOCA-02			
20	1.000e-10	0.011384	%LOCA-RCS-RSV	EPDIF-480V-DIV1	EPENF-6.9KV-DIV	#GIE-LOCA-02			
21	1.000e-10	0.011384	%LOCA-RCS-RSV	EPDIF-480V-DIV1	EPENF-6.9KV-DIV	#GIE-LOCA-02			
22	7.232e-11	0.008233	%LOCA-RCS-RSV	CCEVO-01	CCSPF-CBS2	CCSPF-CBS5	#GIE-LOCA-02		
23	7.232e-11	0.008233	%LOCA-RCS-RSV	CCEVO-01	CCSPF-CBS2	CCSPF-CBS5	#GIE-LOCA-02		
24	5.880e-11	0.006694	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
25	5.880e-11	0.006694	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
26	5.880e-11	0.006694	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
27	5.880e-11	0.006694	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
28	4.872e-11	0.005546	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
29	4.872e-11	0.005546	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		
30	3.457e-11	0.003936	%LOCA-RCS-RSV	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	#GIE-LOCA-02		

Fig 5. Cut Set Lists for LOCA

Cut Set									
%LOFW									
No	Value	F/V	Acc	BE#1	BE#2	BE#3	BE#4	BE#5	BE#7
1	2.144e-11	0.002441	%LOFW	CCEVW-0104	RHVVO-SV2	#GIE-LOFW-03			
2	1.645e-11	0.001873	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
3	6.525e-12	0.000743	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
4	6.490e-12	0.000739	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
5	3.210e-12	0.000365	%LOFW	CCEVO-04	CCSPF-CBS2	CCSPF-CBS5	RHVVO-SV2	#GIE-LOFW-03	
6	3.210e-12	0.000365	%LOFW	CCEVO-04	CCSPF-CBS2	CCSPF-CBS5	RHVVO-SV2	#GIE-LOFW-03	
7	2.610e-12	0.000297	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
8	2.610e-12	0.000297	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
9	2.610e-12	0.000297	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
10	2.610e-12	0.000297	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
11	1.579e-12	0.000180	%LOFW	CCEVO-01	CCEVO-04	RHVVO-SV2	#GIE-LOFW-03		
12	1.535e-12	0.000175	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
13	1.535e-12	0.000175	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
14	1.284e-12	0.000146	%LOFW	CCEVO-01	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
15	1.284e-12	0.000146	%LOFW	CCEVO-01	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
16	1.284e-12	0.000146	%LOFW	CCEVO-01	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
17	1.284e-12	0.000146	%LOFW	CCEVO-01	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
18	1.044e-12	0.000119	%LOFW	EPDIF-480V-DIV1	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
19	1.044e-12	0.000119	%LOFW	EPDIF-480V-DIV1	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
20	1.044e-12	0.000119	%LOFW	EPDIF-480V-DIV1	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
21	1.044e-12	0.000119	%LOFW	EPDIF-480V-DIV1	EPDIF-480V-DIV1	RHVVO-SV2	#GIE-LOFW-03		
22	8.243e-13	0.000105	%LOFW	CCEVW-0104	RHVVO-SV2/4	#GIE-LOFW-03			
23	8.243e-13	0.000105	%LOFW	CCEVW-0104	RHVVO-SV2/4	#GIE-LOFW-03			
24	7.551e-13	0.000086	%LOFW	CCEVO-04	RHVVO-SV2	#GIE-LOFW-03			
25	7.551e-13	0.000086	%LOFW	CCEVO-04	RHVVO-SV2	#GIE-LOFW-03			
26	7.091e-13	0.000081	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
27	7.091e-13	0.000081	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
28	6.139e-13	0.000070	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
29	6.139e-13	0.000070	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	
30	6.139e-13	0.000070	%LOFW	CCSPF-CBS2	CCSPF-CBS5	CCSPF-CBS6	RHVVO-SV2	#GIE-LOFW-03	

Fig 6. Cut Set List for LOFW

The cut set of LOCA with the highest CDF can be briefly described as follows.

- %LOCA-RCS-RSV&CCEVW-0104&#GIE-LOCA-02: The LOCA is initiated by the malfunction of the RCS safety valve (%LOCA-RCS-RSV). Despite the successful completion of subsequent safety actions, including Reactor Trip (RT), actuation of PIS and operation of PDHR, core damage eventually occurs due to a Common Cause Failure (CCF) of the CCS valve, which serves as the final heat removal path (LOCA sequence 02).

The cut set of LOFW with the highest CDF can be briefly described as follows.

- %LOFW&CCEVW-0104&RHVVO-SV2&#GIE-LOFW-03: The LOFW is initiated by the trip of the feedwater pumps (%LOFW), followed by a CCF of the PDHR manual valve. Despite the successful completion of subsequent safety actions, including actuation of ADS, PIS, and GIS, core damage eventually occurs due to a CCF of the CCS valve, which serves as the final heat removal path (LOFW sequence 03).

4. Conclusions

In this study, a PSA model for LWR-based SMRs is developed and quantified using iPWR. Major initiating events, a LOCA and a LOFW, are defined based on the simulator. Event trees and corresponding fault trees are constructed, and the resulting CDF is derived. These analyses are conducted on the basis of the simulator manual published by the IAEA and publicly available reliability data.

Given that existing PSA models have limitations in their direct application to LWR-based SMRs, this study expands the safety assessment methodology for LWR-based SMRs by incorporating the unique design features of iPWR, such as its modularity, passive safety systems, and integrated design. Furthermore, the PSA model developed in this study is based on open-source resources, enabling it to serve not only as an educational

tool for students but also as a foundation for future international collaborative research on the PSA of LWR-based SMRs.

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