Comparison of Reliability Analysis of the Reactor Protection System between Jordan Research Reactors and Nuclear Power Plants

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1. Introduction

Recently, Jordan has established its first nuclear research reactor named Jordan Research and Training reactor (JRTR) to become the first Nuclear Center in Jordan. This research reactor was built by the cooperation of Korean Atomic Energy Research Institute (KAERI) and Daewoo Engineering and Construction (E&C) company.

The 5 MW_{th} multipurpose open-tank-in-pool reactor is designed for research, training, and education purposes to enhance the knowledge of nuclear sciences and engineering in Jordan. And producing medical and industrial radioisotopes.

Jordan Research and Training Reactor as all other research reactors around the world consists of a set of Instrumentation and control systems which are used to safely operate the reactor and make it under control. The Reactor Regulating System (RRS) which is used to regulate the reactor power, the Reactor Protection System (RPS) which is provide safety shutdown of the reactor and engineering safety features are some of the control systems which keep the reactor under control (safe operation).(1)

The main objective of this research is comparing the Reactor Protection System (RPS) reliability for the JRTR with a typical Nuclear Power Plant model.

2. Instrumentation and control Systems

2.1. Jordan Research and Training Reactor (JRTR) consists of the following Instrumentation and Control (I&C) Systems:

A) Safety Systems:

1- Reactor Protection System (RPS).
2-Post Accident Monitoring System (PAMS).

B) Non-Safety Systems:

1- Reactor Regulating System (RRS).
2-Alternate Protection System (APS).
3- Information and Process System (IPS).
4- Automatic Seismic Trip System (ASTS).

Most of the instrumentation and control systems of JRTR are based on digital technology. All nuclear instruments designed and maintained in such a way that inspection and validation of the system quality are consistent with their classifications.

The RPS system is responsible for initiating a reactor trip to protect the core by generating a trip signal to activate the safety control rod axe man, SCRAM, by inserting all the control rods (four control absorber rods, CARs, and two second shutdown rods, SSRs) inside the core when some operation trip parameters exceed the trip pre-specified criteria. Also the RPS prevents the release of radioactive materials to the environment through the engineered safety features actuation to mitigate the consequences of accidents. Three independent measurement channels, electrically isolated and physically separated, are provided for each parameter.

The RPS for JRTR is designed based on 2-out-of-3 voting logic received from three redundant channels as shown in Figure (1). Each channel consists of the following components:

1- Sensors
2- Bi-stable processor (BP)
3- Coincidence circuit (CC)
4- Initiation circuit (IC)
5- Actuation circuit (AC)
6- Interface and test processor (ITP)
7- Maintenance and test processor (MTP)

8- Other equipment necessary to monitor selected reactor conditions and to provide reliable and rapid reactor protective action. (2)

2.2 Reactor Protection System of Nuclear Power Plant:

Generally, the main difference between the Nuclear Power Plant Protection System (PPS) and Research Reactor Protection System (RPS) is the existence of four redundant channels in PPS comparing to three channels in RPS. Accordingly, the applied voting logic in PPS is 2-out-of-4 instead of 2-out-of-3 in the RPS.

It is worth mentioning that both systems ,PPS & RPS, share the same components mentioned above except that the IC in PPS includes initiation relays, an under-voltage trip circuit, and shunt trip circuit. AC includes actuation circuit breakers. The architecture of PPS is simplified in this work for the purpose of comparison with the RPS.

Research reactors can be shutdown every 45 days so that the maintenance and testing are performed during that time(4). However, the case is different for the NPPs since it is supposed to be operated up to 12 - 18 months continuously without shutdown. Sometimes, the maintenance is needed to be conducted during the operation.(3)

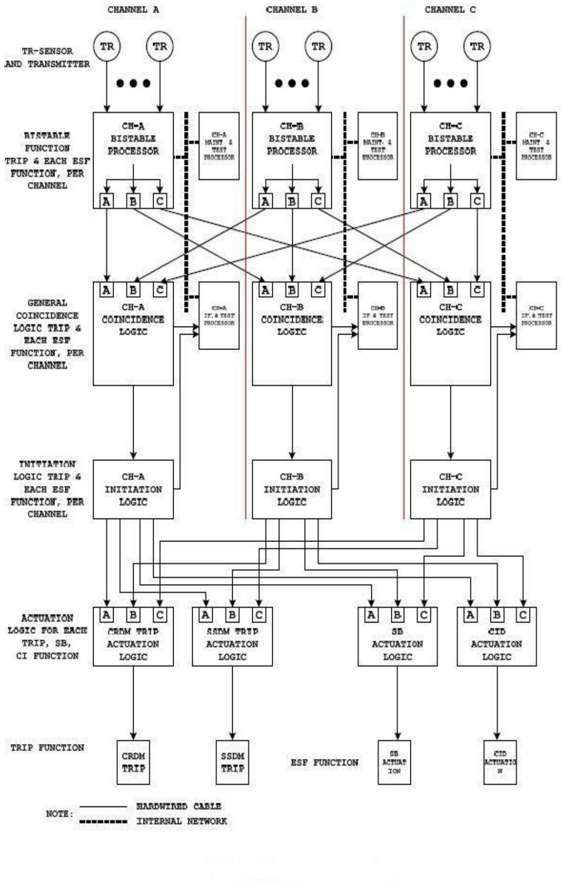

Figure 1: Channels of JRTR reactor protection system

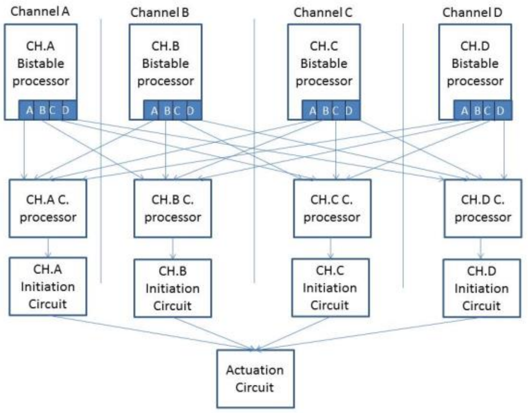

Figure 2.: groups of NPP RPS components

Table 1Example of trip parameters of voting logic

	NPP status	**JRTR status**
Ch.A (neutron Power Hi trip signal)+Ch.B (PCS flow trip signal)	Not trip	trip
Ch.A(neutron power hi trip signal)+Ch.B(neutron power hi trip signal)	Trip	Trip

3. Theory & Methodology:

In this paper, the Probabilistic Safety Assessment (PSA) technique is used to find a numerical method to determine the hazard quantity of nuclear facilities. It is also used to determine the undesired scenarios may happen with probability estimations. In addition, it is show how the results could be, and can provide indirect knowledge such as the importance of hazard contributors individually.

In PSA, the first task to do is to establish a top event and mark out the different risks that could result in this event. System malfunctions are associated and determined by a system model such as the fault tree, which is used to figure out the logical combinations arrangements of easier events. At the least level, the primary event (basic event) of the fault trees are allocated likelihood distributions. (5)

4. Problem Description

According to the above explanation of the two systems, the following differences can be noted; the RPS consists of three channels but PPS consists of four channels. However, the PPS is superior to withstand the failure of channels. If the system failure is considered more conservatively, the PPS can perform the protective actions when two channels are failed to operate.

The second issue is about the organization of the components. In the PPS, it uses digital system for the bi-stable and coincidence logic, but the RPS uses relays for designing the coincidence logic. For that reason, the PPS is called a fully digital system. The fully digital system gives advantages about the usability and maintenance, but the implementation of fully digital system should be faced with the hardware cost issue. Even though the RPS is not a fully digital protection system, it complies with the safety requirements. Moreover, the RPS reduces the implementation cost that is designed to combine digital processor and analog relays.

5. Results Discussion & Reliability Evaluation:

The AIMS-PSA was used for the comparison of the reliability of the RPS of research reactor and power plant based on minimal cut-sets of fault tree. In addition, a comparison between the costs of implementation of the Hardware was estimated. Table (1) shows a comparison between research reactor and power plant RPS components.(6)

Table 2 Comparison between RPS of Research Reactor and NPP

RPS Components	**Research Reactor**	**Nuclear Power Plant**
Bistable	Digital (PLC)	Digital (PLC)
Coincidence	Analog (Relays)	Digital (PLC)
Initiation	Analog (Relays)	Analog (Relays)
Actuation	Analog (Relays)	Analog (Circuit Breakers)

The PPS consists of four channels and is a fully digital system, while the RPS consists of three channels and the digital system is only used for bi-stable logic. Intuitionally, the RPS is cheaper than PPS in the respect of cost evaluation. However, the cost evaluation cannot be a criterion of a safety system because the reliability is more important for the protection system. Therefore, the reliabilities for both systems were studied in this paper.

For evaluating the reliability of the RPS, both systems were modeled separately using AIMS-PSA. Firstly, the model is started with studying and recognizing the fault tree parameters, which is concerned on fault tree technique, and then analyzing each system based on their architecture. Each system was separated to groups, actuation, initiation, coincidence, and bi-stable. Finally, the fault trees that are related to the failing of trip the reactor for the two systems were drawn and analyzed. Figures (4) and (5) show the simplified fault trees for RPS and PPS using the AIMS-PSA mode. (5)

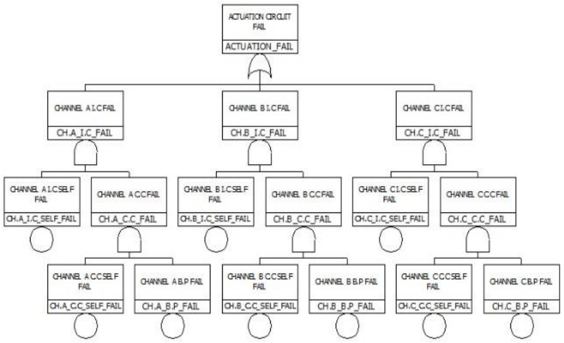

Figure (3) Simplified RPS fault tree

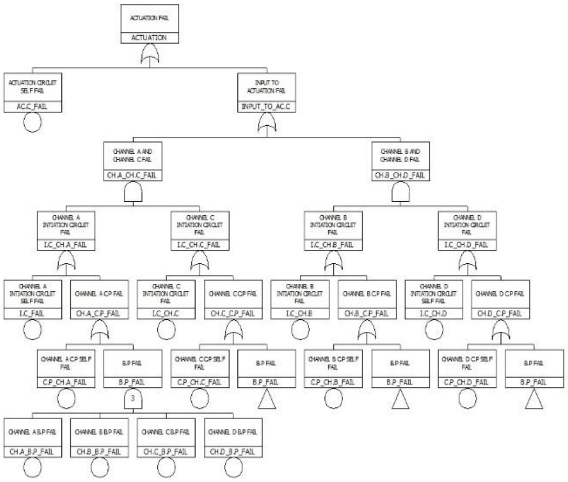

Figure (4) Simplified PPS fault tree

To get the reliability result from those systems, the following assumptions had been made:

1. The scope of the analysis only covers from the input of the protection system to actuation.
2. The RPS and the PPS use the same type of digital systems.
3. Common Cause Failures & human errors.

Human errors in this study, are the basic events, that operators fail to generate a trip signal were considered in the fault tree analysis. And its failure probability is assumed to be 1.0E-03. In addition, the Common Cause Failures (CCFs) are events consisting of component failures that meet four criteria:

1. A demand signal had been received in the case of two or more separated components are degenerated, that includes a failure during demand, deficiencies, or in service testing.
2. A failure of a component during a predefined period of time such as success of the PSA mission would be uncertain.
3. A single common cause and coupling mechanism that results of a component failures.
4. A failure of a component during an established component boundary.

In this study, the (β) factor method is used for the quantitative evaluation of CCFs. The likelihood of CCF is evaluated in relation to the random failure rate of the component. A (β) factor is estimated such that β% of the failure rate is attributed to the CC and (1-β) % to the random failure rate of the component. That assumed to be 5% in this study.

Tables (3) and (4) explain the minimal cutsets of the fault tree for the RPS and the PPS. Table (5) explains the event codes of common cause failures and human error. According to Table (3), the RPS unavailability for research reactors is 4.38E-06. This reliability result is mainly caused by the CCF of the relays (RPRYW). The coincidence, initiation, and actuation logics of the RPS are designed by using relays. For that reason, a CCF of relays can be a critical factor. In case of PPS in nuclear power plant, the unavailability is 7.60E-06. This result is caused by the CCF of TCBs (RPRBW). The Trip Circuit Breakers (TCBs) is used for the actuation circuit. Generally, the failure rate of the circuit breaker is higher than in other components such as relay, digital processor, etc**.** According to the below tables, it can be noticed that the reliability of RPS for JRTR that is used three channels are almost similar to PPS in the nuclear power plant that used four channels.

Table 3Minimal cutsets of fault tree for the RPS

Table 4Minimal cutsets of the fault tree for the PPS

No.	Value	F-V	Acc.	BE#1	BE#2
1	7.60E-06	0.991417	091417	RPRBW	
2	2.31E-08	0.003014	0.994431	Circuit_B_fail	Ciecuit_D_fail
3	2.31E-08	0.003014	0.997444	Circuit_B_fail	Circuit_D_fail
4	8.98E-09	0.001171	0.998615	RPUVW	RPSHW
5	5.35E-09	0.000698	0.999313	RPOMW	RPOOH-Trip

Table 5 Description of event codes

Event Code	Description
RPMWW	CCF of Manual Trip switches
RPRYW	CCF of Relays
RPIMW	CCF of Input Modules
RPPMW	CCF of Process Modules
RPOMW	CCF of Output Modules
RPUVW	CCF of UVs
RPSHW	CCF of Shunts
RPRBW	CCF of TCBs
RPPMWCP	CCF of Process Modules (CP)
RPOPH-TRIP	Operator fails to trip manually

6. Conclusion:

A moderately detailed fault tree of research reactors and power plants was developed and quantified using AIMS-PSA. The fault trees were developed for the research reactor protection system with three channels and for the power plant protection system with four channels. The top of the fault tree was for estimating and calculating the probability of failure of each system to safely shutdown the reactor by inserting the control rods and providing the engineered safety features.

Evaluating the reliability started with studying and recognizing the fault tree parameters, this evaluating was concerned on the fault tree technique, and then analyzing each system based on the architecture. Each system was separated to groups, actuation, initiation, coincidence, and bi-stable.

No.	Value	F-V	Acc.	BE#1	BE#2
1	4.36E-06	0.994527	0.994527	RPRYW	
2	1.07E-08	0.002441	0.996968	RPOMW	RPOPH_TRIP
3	1.04E-08	0.002372	0.99934	RPIMW	RPOPH_TRIP
4	2.72E-09	0.00062	0.999961	RPPMW	RPOPH_TRIP
5	1.98E-11	0.000005	0.999965	RPOMW	RPMWW

Finally, the fault trees for failing to trip the reactor for the two systems were drawn and analyzed. After that, the probability failure of each component, the CCF and HE are involved in, then the minimal cutsets are obtained for the RPS and PPS.

The probability of failure of each system were close to each other that indicate that reliability is close to each other and hence the RPS for research reactor with three channel and analog C.C similar to PPS with four channels and digital C.C.

7. References:

1. Jordan Research and Training Reactor (JTRT) FSAR, Ch.5 (Reactor) Section 5.1 (Summary Description).
2. JRTR, System Description for Reactor Protection System, JR-681-KJ-414-001, Rev. 0
3. APR1400 Design Control Document Tier 2, Chapter 7 Instrumentation and Control, APR1400-K-XFS-NP, Rev.0, December 2014.
4. JRTR, Design Specification for Reactor Protection System, JR-681-KJ-416-001, Rev. No. : 0.
5. O. Nusbaumer, Introduction to Probabilistic Safety Assessments (PSA), Leibstadt NPP. http://nusbaumer.tripod.com/resources/publications/nusbaumer_introduction_to_probabilistic_safety_assessments.pdf
6. AIMS-PSA Release 2.0 Reference Manual, Rev.1.0, KAERI-ISA-MEMO-AIMS-03-ENG.