Establishment of Postulated Initiating Events for the High-Performance Research Reactor

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1. Introduction

KAERI is developing the multi-purposed, High-Performance Research Reactors (HPRR), which incorporates plate type fuels of high density U_3Si_2-Al. The HPRR has thermal power more than 20 MW and upward direction in the reactor core. The unsecured core technologies of fuel element locking device and control element drive mechanism in upward flow core have been developed and the basic system design of the reactor is under development.

This paper outlines the methodology used to set up the Initiating Events (IEs) and provides the complete set of IEs for the HPRR. The IEs are ultimately established by screening, comparing, and reconciling the IEs developed through Master Logic Diagram (MLD) analysis with those gathered from regulatory documents and other research reactors.

2. Descriptions of Design Features

The Reactor Structure Assembly (RSA) is positioned at the bottom of the reactor pool, comprising the inlet plenum, grid plate, fuel element locking bar, control absorber element guide tubes, upper guide structure, reactor cover, reactor outlet, and heavy water vessel, as depicted in Figure 1 [1].

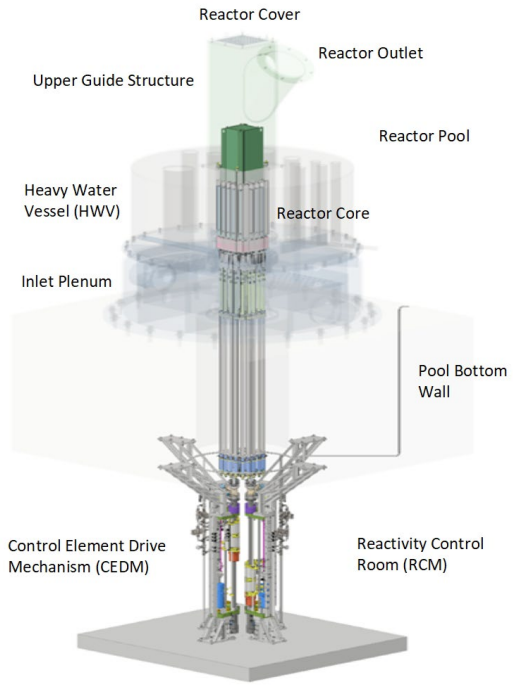


Fig. 1. Configuration of RSA and CEDMs for the HPRR

The Control Element Drive Mechanisms (CEDMs) responsible for reactivity control are situated in the Reactivity Control Room (RCM) with the control devices for the fuel element locking bars.

The Heavy Water System (HWS) is designed to transfer heat from the Heavy Water Vessel (HWV) to the Secondary Cooling System (SCS) and to control reactivity by draining the heavy water from the HWV to the Heavy Water Dump Tank (HWDT).

The reactor cooling system comprises the Primary Coolant System (PCS), Pool Water Management System (PWMS), Hot Water Layer System (HWLS), and Irradiation Holes Cooling System (IHCS) as shown in Figure 2 [2].

The instruments and control system consists of the Reactor Protection System (RPS), Accident Monitoring System (AMS), Reactor Regulating System (RRS), Alternate Protection System (APS), Information Processing System (IPS), Process Instrumentation and Control System (PICS), Automatic Seismic Trip System (ASTS), and Radiation Monitoring System (RMS).

The Secondary Coolant System (SCS) including Cooling Tower (CT), Emergency Water Make-up System (EWMS), Heating, Ventilation, and Air Conditioning System (HVACS), and Compressed Air Supply System (CASS) are included in the reactor facility.

The HPRR provides the utilization facilities: Neutron Beam Facility (NBF), Cold Neutron Source Facility (CNSF), Neutron Transmutation Doping Facility (NTDF), Irradiation Facility (IF), Hydraulic Transfer System (HTS), and Pneumatic Transfer System (PTS).

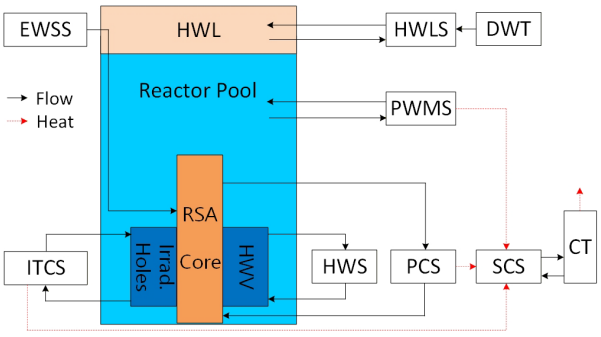


Fig. 2. Block Diagram of Fluid Systems for the HPRR

3. Methodology of Setting Up Initiating Events

3.1 General Approaches to Setting up IEs

Set-up of IEs is an important step in the safety analysis and design of research reactors and their utilization facilities. IEs are scenarios that initiate anticipated transients and postulated accidents and that are assumed to potentially lead to safety challenges or require mitigation actions.

To ensure that no potential initiating events (IEs) are missed during the design and safety analysis of new research reactors, a systematic, structured, and multi-layered identification process is needed.

In general, the following approaches to identifying initiating events are used not to miss any critical scenarios, such as Compiling and Screening Method (CSM), Review of Operational Experience (ROE), Master Logic Diagram (MLD), and Failure Modes and Effects Analysis (FMEA) [3~5].

3.2 Approaches to Setting up IEs for the HPRR

For the systematic establishment of IEs for the High-Performance Research Reactor (HPRR) while ensuring no potential events are overlooked, a structured and multi-layered identification process is applied as follows:

(1) Compiling Lists of Initiating Events: Gather initiating events from authoritative sources like NUREG-1537, IAEA Specific Safety Requirements (SSR-3), IAEA Specific Safety Guide (SSG-20), and Safety Analysis Reports of similar research reactors.
(2) Screening Out Inapplicable Events: Evaluate the compiled list to remove events that are incredible or irrelevant to the HPRR, based on an examination of the reactor and its utilization facilities.
(3) Analyzing MLD for the HPRR: Utilize the Master Logic Diagram (MLD) to analyze the design characteristics of the HPRR and deduce the initiating events.
(4) Cross-Checking Events: Compare the initiating events derived from steps (2) and (3) to identify any potential omissions from step (3) and incorporate them.
(5) Grouping Events by Reactor Responses: Categorize the initiating events by grouping those that result in similar reactor responses.
(6) Including Design Extension Conditions (DECs): Add DECs that involve multiple failures, such as single initiating event coupled with a failure of safety-related systems necessary for mitigation.

FMEA requires detailed design information on structures, systems, and components, which may not be available during the conceptual design phase, making it less suitable for identifying initiating events at this stage.

Given the extensive operational history of multi-purpose open-pool and open-tank type research reactors worldwide, historical incident data and operational experience are likely to be encompassed within the initiating events identified in steps (1) and (2).

4. Set up of Initiating Events for the HPRR

4.1 Compiling and Screening out of IEs

The initiating events assumed in IAEA safety requirements and guides [6, 7] and in NUREG-1537 Part I [8] have been gathered and reviewed. In addition, the initiating events in the HANARO and RRR [9, 10] have been also investigated. The initiating events incredible or irrelevant to the HPRR are screened out based on an examination of design and operation characteristics of the HPRR and its utilization facilities.

4.2 Analysis of MLD for the HPRR

In this Master Logic Diagram (MLD) analysis, radioactive release is identified as the top event undesired to protect against for the HPRR. As illustrated in Figure 3, the top event can be broken down into several categories based on the source of radioactive release:

(1) Failure of Reactor System: This involves failures in the three main safety functions such as reactivity control, residual heat removal, and radioactive confinement and shielding.
(2) Mishandling or Malfunction of Fuel, Equipment, and Utilization Facilities: This category concerns failures in components and systems that could lead to radioactive release, including:
- Fuel: Issues related to fuel handling and storage.
- Equipment: Mechanical or technical failures in reactor support systems.
- Utilization Facilities: Failures in reactor utilization facilities.

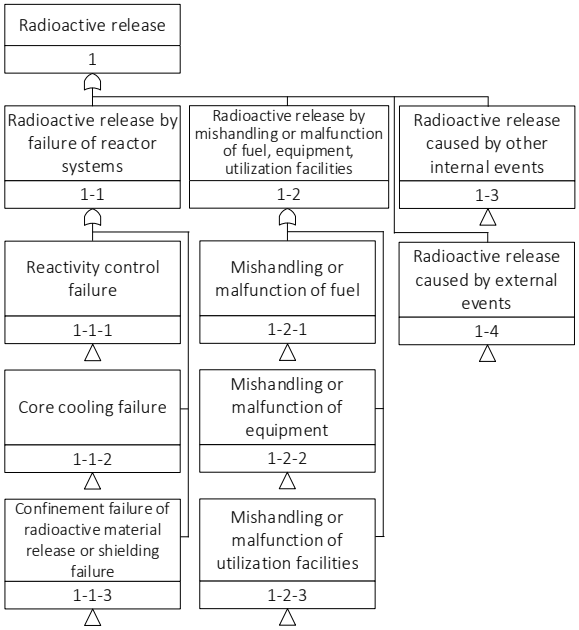


Fig. 3. Block Diagram of Fluid Systems for the HPRR

The symbols used in the MLD are detailed in Table 1, providing clarity on the various elements and their interactions within the system.

Table 1 Descriptions of Symbols in the MLD

Symbols	Name	Description
○	Basic event	Events that do not require further development
⌓	OR gate	Event OR operation where the output event occurs if any of the events occur
△	Transfer symbol	Receiving input from other diagrams or output to other diagrams

The top event is broken down into detailed sub-events, each of which is a possible cause of the considered top event. This process continues until a sufficient level of detail is achieved by identifying events that directly challenge safety functions. Considering all physically possible phenomena is crucial to ensure the completeness of this approach. The IEs of 84 for the HPRR are identified from the basic events that cannot be further divided into sub-events. Of them 8 IEs are screened out because they are covered by other events.

Table 2 Initiating Events Deduced from the MLD

ID No.	Initiating Events from the MLD
1-1-1-1-1	Inadvertent withdrawal of a CAE
1-1-1-1-2	Structural failure of a CAE
1-1-1-2-1	Inadvertent loading or unloading of an irradiation target
1-1-1-3-1	Cold coolant supply
1-1-1-4-1	Leakage of light or heavy water into a beam tube
1-1-1-4-2	Leakage of heavy water into the core
1-1-2-1-1	Flow blockage in a fuel element
1-1-2-2-1	Loss of normal electric power
1-1-2-2-2	Loss of forced flow by malfunction of a PCP
1-1-2-2-3	Shaft break or seizure of a PCP
1-1-2-2-4	Inadvertent closure of an isolation valve of PCS
1-1-2-2-5	Core flow reduction due to core bypass
1-1-2-2-6-1	Loss of normal forced flow by malfunction of a SCP
1-1-2-2-6-2	Pipe rupture of the SCS
1-1-2-2-6-3	Failure of cooling tower
1-1-3-1-1	Fuel cladding failure due to a manufacturing defect
1-1-3-2-1	Rupture of the primary coolant boundary
1-1-3-2-2	Rupture of a guide tube of the CAEs
1-1-3-2-3	Rupture of other pool-connected water boundary
1-1-3-2-4	Damaged pool liner
1-1-3-2-5	Pump-down of the pool
1-1-3-3-1	Loss of hot water layer
1-1-3-3-2	Loss or reduction of shielding structures
1-2-1-1	Misloading of a fuel
1-2-1-2	Dropping of a fuel element in transfer
1-2-1-3	Criticality in fuel storage
1-2-1-4	Criticality in fuel loading in the core
1-2-2-1-1	Loss of heavy water flow
1-2-2-1-2	Rupture of heavy water boundary
1-2-2-1-4	Inadvertent dumping of heavy water
1-2-2-2-1	Loss of pool cooling flow of the PWMS
1-2-2-2-4	Pump-down of the pool by the PWMS
1-2-2-3-1	Spurious initiation of the emergency water supply
1-2-2-5-1	Malfunction of supply or exhaust fans
1-2-2-5-2	Malfunction of filtering of radioactive materials
1-2-2-5-3	Inadvertent closure of the reactor building isolation damper
1-2-2-6-1	Malfunction or spurious signals of I&C systems
1-2-2-6-2	Malfunction or faults of the electrical systems
1-2-2-6-3	Malfunction of the CASS
1-2-3-1-1	Loss of coolant flow of the IHCS
1-2-3-1-2	Rupture of coolant boundary of the IHCS
1-2-3-2-1	Loss of cooling capability by failures of refrigerator
1-2-3-2-2	Increase of cooling load due to loss of vacuum or reactor power transient
1-2-3-2-3	Leakage of light water to the vacuum vessel
1-2-3-2-4	Leakage of H_2 to the room
1-2-3-2-5	Deflagration or detonation of H_2/O_2
1-2-3-2-6	Reactivity insertion due to liquefaction of the Moderator Cell
1-2-3-4-2	Rupture of a capsule or a cladding of FM target
1-2-3-4-3	Loading of a target to unplanned location
1-2-3-4-4	Dropping of a rig
1-2-3-5-1	Dropping of an NTD ingot
1-2-3-5-2	Loss of cooling of an NTD ingot
1-2-3-6-1	Loss of cooling of the HTS
1-2-3-6-2	Rupture of coolant boundary of the HTS
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1-3-1	Internal fire
1-3-2	Internal explosion
1-3-3	Missile effects
1-3-4	Internal flooding
1-3-5	Dropping of heavy loads
1-3-6	Exothermic chemical reaction
1-4-1	Earthquake
1-4-2	Wind (typhoon, cyclones, hurricanes, tornadoes, storm)
1-4-3	Flooding
1-4-4	Lightning strike
1-4-5	Fire or explosion
1-4-6	Aircraft crash
1-4-7	Accidents on transport routes
1-4-8	Effects from adjacent facilities

4.3 Comparison between the IEs Resulted from the MLD and the CSM

The IEs are compared with those resulted from the compiling and screening out approach. The comparative analysis demonstrates that the initiating events derived from MLD analysis address all scenarios with the exception of extreme meteorological phenomena. These extreme meteorological events are contingent upon the specific licensing requirements of the host country. As external events are site-specific, they can be finalized following the determination of the reactor site.

4.4 Grouping IEs by Reactor Response

The initiating events are classified based on the reactor's response patterns following each event. This categorization groups events that trigger similar reactor behaviors and safety system activations. The classification enables efficient identification of potential risk pathways and facilitates targeted safety analysis. The initiating events are categorized according to IAEA safety requirements and guides of SSR-3 and SSG-20, and NUREG-1537 Part I.

NUREG-1537 does not require consideration of special internal events, which should instead be addressed in the design of structures, systems, and components rather than in the accident analysis section of Safety Analysis Reports. On the other hand, it requires the identification of a Maximum Hypothetical Accident (MHA), which represents the limiting accident with the highest postulated fission product release at the facility. The MHA should bound all credible potential accidents at that facility, yet should be an event that is not likely to occur during the life of the facility.

4.5 Design Extension Conditions for the HPRR

The IAEA safety standard SSR-3 [6] stipulates that research reactors shall develop a set of Design Extension Conditions (DECs) to enhance safety by enabling the facility to withstand accidents more severe than design basis accidents or those involving additional failures, without unacceptable radiological consequences.

The DECs encompass scenarios beyond design basis accidents, where radioactive releases are maintained within acceptable limits using best estimate methodologies. These conditions include events without significant fuel degradation and with core melting.

The development of DECs shall be based on engineering judgment and a graded approach, as appropriate. Through this process, events with significantly lower probability than design basis accidents and those resulting from multiple independent failures may be classified as DECs.

In the United States, NUREG-1537 [8] does not explicitly mandate the classification of initiating events by occurrence frequency and the establishment of DECs.

As presented in Table 3, the Design Extension Conditions (DECs) identified for the HPRR are accompanied by rationales explaining their selection. These DECs represent scenarios that have been evaluated for their potential impact and likelihood, ensuring comprehensive safety analysis for the research reactor.

A loss of pool water due to beam tube ruptures is considered plausible when multiple failures occur simultaneously in both the pool water boundary and beam port flange. Such multiple failures are statistically very unlikely. The beam port flange is also designed to withstand hydraulic loads of the reactor pool height independently. To prevent this risk, the beam tubes are equipped with leak detection systems for both water and helium gas, enabling operators to identify and address single failure before they escalate.

The Anticipated Transient Without Scram (ATWS) is designated as a DEC. The without scram in anticipated transients encompasses either a failure of the RPS or a failure of dropping of two CAEs. The RPS is digital-based architecture so that common-cause or common-mode failure is considered in the scenario. The failure scenario of two CAEs comprises single failure criterion of a CAE and additional failure of a CAE.

The design basis accidents involving either a failure of the RPS or a failure of dropping of CAEs are not classified as DECs because these multiple failures are considered extremely unlikely events based on engineering judgment. That is, each of a design basis accident, a failure of the RPS, or a failure of dropping of CAEs is unlikely to occur during the facility's operational lifespan.

Extreme meteorological phenomena are designated as DECs, with their specific limits determined by owner requirements based on the reactor's geographical location and site-specific conditions.

Table 3 Design Extension Conditions for the HPRR

Category	ID No.	DECs	Rationales
Independent Multiple Failures	1	Loss of pool water due to ruptures of a beam tube	Multiple failures of a beam tube in the pool water boundary and the beam port flange
	2	Anticipated Transients without Scram	Anticipated transients plus either a failure of the RPS or a failure of dropping of two CAEs
Very Unlikely Events	3	Extreme meteorological phenomena	The limits of extreme meteorological phenomena shall be defined by owner requirements considering the reactor site

4. Conclusions

A systematic, structured, and multi-layered identification process has been performed to ensure that no potential Initiating Events (IEs) are missed during the design and safety analysis of the High-Performance Research Reactor (HPRR).

This work provides descriptions of the design characteristics and features of the HPRR, an outline of the methodology for identifying IEs, an investigation of the IEs proposed in the regulatory documents and considered in other multi-purpose research reactors, and the IEs developed for the HPRR through Master Logic Diagram (MLD) analysis.

The IEs for the HPRR are ultimately established by screening, comparing, and reconciling the IEs developed through MLD analysis with those investigated from regulatory documents and other research reactors.

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