Master Logic Diagram: An Approach to Identify Initiating Events of HTGRs

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Abstract. Initiating events of a nuclear power plant being evaluated need to be firstly identified prior to applying probabilistic safety assessment on that plant. Various types of master logic diagrams (MLDs) have been proposed for searching initiating events of the next generation of nuclear power plants, which have limited data and operating experiences. Those MLDs are different in the number of steps or levels and different in the basis for developing them. This study proposed another type of MLD approach to find high temperature gas cooled reactor (HTGR) initiating events. It consists of five functional steps starting from the top event representing the final objective of the safety functions to the basic event representing the goal of the MLD development, which is an initiating event. The application of the proposed approach to search for two HTGR initiating events, i.e. power turbine generator trip and loss of offsite power, is provided. The results confirmed that the proposed MLD is feasible for finding HTGR initiating events.

Keywords: Master logic diagram, initiating events, high temperature gas cooled reactor, probabilistic safety assessment.

Introduction

Probabilistic safety assessment (PSA) has been considered as an important tool to evaluate safety systems of nuclear power plants (NPPs). It can ensure the safety of NPPs in relation to potential initiating events [1, 2]. To deal with the limitation of the conventional PSA due to lack of historical failure data for evaluating the reliability of a safety system, fuzzy numbers have also been introduced into NPP PSA [3, 4]. When PSA results suggest that changes should be made to the design to improve safety, the changes should be applied where reasonably applicable.

To perform PSA, all initiating events need to be firstly identified and evaluated. An initiating event is an event, which can affect the normal operation of a plant and potentially lead to an accident when plant-mitigating systems do not properly work as expected. Initiating events include component failures, human errors, internal hazards and external hazards. Because core damage is unlikely to happen, the goals of the PSA for high temperature gas cooled reactors (HTGRs) should not be the estimation of a core damage frequency (CDF) and a large early release frequency (LERF) as in light water reactors (LWRs) [5]. The objective of HTGR PSA is to calculate frequencies of HTGR-specific
plant state corresponding to all licensing basis events (LBEs).

Due to the unique concept of HTGR technologies whose designs are very different from LWR technologies, lists of existing initiating events of LWRs are not relevant. Therefore, initiating events, which are specific to HTGR technology design, needs to be identified. International Atomic Energy Agency (IAEA) recommends applying a systematic approach to search for initiating events of a nuclear power plant[6].

We encounter from literatures that master logic diagram (MLD) approaches have been applied to identify nuclear power plant initiating events in the past [7] and have been proposed for searching initiating events of the next generation of nuclear plants (NGNPs) [8]. MLD is a logic diagram, which is similar to a fault tree but without formal mathematical properties[9]. It can represent the effects of a failure in a complex system [10] and provides a great degree of certainty for identifying initiating events [7]. Furthermore, Ahn, et al. [11] found that this approach can logically identify additional initiating events and group initiating events. Each MLD approach proposed in those previous studies has different steps and basis in finding initiating events. The purpose of this study is to propose and discuss another type of MLD approach to search for HTGR initiating events. The proposed MLD approach consists of five steps to finally find an initiating event. To show the process of the proposed MLD, searching processes of two HTGR initiating events, i.e. power turbine generator trip and loss of offsite power, are provided and discussed.

**HTGR Safety Philosophy**

Currently, there are two designs of HTGRs, namely, pebble bed reactors (PBRs) and prismatic block reactors (PMRs) [12, 13]. PBRs consist of fuel in the form of pebbles, which are stacked together in a cylindrical pressure vessel. Meanwhile, PMRs refer to a prismatic block core configuration in which hexagonal graphite blocks with fuel elements are stacked to fit in a cylindrical pressure vessel. Both designs are shown in Figure 1[14].

![Figure 1. Two types of HTGR designs [14].](image-url)
HTGRs have been designed to be inherently safe reactors in which active safety systems and operator intervention are not needed when unexpected events happen [15]. This safety enhancement is achieved through the implementation of inherent safety features and engineered passive safety features [16, 17]. Inherent safety features are realized through Tri Iso-Structural (TRISO) – coated fuel particles, graphite moderator, and helium coolant. The TRISO-coated fuel particles in which three ceramic coating layers, i.e. inner pyrocarbon (IPyC), silicon carbide (SiC), and outer pyrocarbon (OPyC), surround fissionable fuel kernel as shown in Figure 2 [18]. TRISO-coated fuel particles can withstand extremely high temperature up to 2000 °C [19].

![TRISO-coated fuel particle](image)

**Figure 2.** TRISO-coated fuel particle [18].

Meanwhile, the engineered passive safety features are characterized by passive heat removal capability and inherent shutdown capability. The passive heat removal feature is achieved through the low-power-density core with a relatively large height-to-diameter ratio within an un-insulated steel reactor vessel. The inherent shutdown capability is achieved by large negative temperature coefficient and large thermal margin to enable reactor to deal with scram failure.

**Methodology**

MLD approach proposed in this study consists of five functional steps as graphically shown in Fig. 3. In the sequel, the detail of each functional step is elaborated.

![MLD master logic diagram approach](image)

**Figure 3.** Proposed master logic diagram approach.
Step 1:
This functional step generates the final objective of the safety functions of a plant, which is being investigated. The output of this step is, then, set as the top event of the proposed master logic diagram.

Step 2:
This functional step identifies sources, which can cause the top event identified in Step 1. The output of this step is a list of sources to the top event when transients occur to the system or failures happen to systems, structures and components (SSCs).

Step 3:
This functional step identifies transients, which could occur to the system or failures, which could happen to SSCs of the plant being investigated. The output of this step is a list of system transients or SSC failures.

Step 4:
This functional step identifies safety functions, which are required to perform, to avoid system transients or SSC failures. The output of this step is a list of required and supportive safety functions.

Step 5:
This functional step identifies challenges to safety functions defined in Step 4, which could cause system transients or SSC failures defined in Step 3. The output of this step is a list of initiating events.

Results and Discussion
To obtain an operating license, possible initiating events and all sequential events following those initiating events of the nuclear power plant being proposed to be constructed need to be provided. HTGRs as the next generation of nuclear power plants, which have limited operating data and experiences, also need to provide a list of initiating events, which could cause the release of radioactive materials into environment. This section discusses the process of finding two HTGR initiating events, i.e. power turbine generator trip and loss of offsite power, to illustrate the implementation of the proposed MLD approach described in Section 3.

Step 1:
The final objective of HTGR safety functions is to prevent or mitigate radioactive material releases into environment. This study, then, justifies that material radioactive releases into environment is the top event of the proposed MLD as graphically shown in Fig. 4.

Step 2:
Sources of radioactive materials in HTGRs can be classified into two categories, i.e. from inside of the helium pressure boundary (HPB) and from outside of the HPB. Both sources are shown in Table 1[8].
Table 1. Sources of radioactive materials in HTGRs[8].

| Categories            | Material radioactive sources                                                                                                                                 |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| From Inside of HPB    | • Fuel elements in the core                                                                                                                                    |
|                       | • Intact coated particles                                                                                                                                        |
|                       | • Failed or defected coated particles                                                                                                                             |
|                       | • Uranium contamination outside coated particles                                                                                                               |
|                       | • Materials attached to graphite components                                                                                                                     |
|                       | • Dust and plate-out on the surface of the HPB                                                                                                                  |
|                       | • Circulating primary coolant activity                                                                                                                           |
| From Outside of HPB   | • Fuel elements in the storage systems                                                                                                                           |
|                       | • Gas-borne activities in the helium purification system (HPS)                                                                                                   |
|                       | • Solid and liquid rad-waste systems                                                                                                                              |

Those two source categories in Table 1 are, then, presented as the sources of the top event in the proposed MLD in Fig. 4.

Step 3:
Radioactive materials could be released from the inside of the helium pressure boundary (HPB) if the possible conditions defined below happen to HTGRs[8]:

a. Plant transients with intact primary system HPB;
b. Energy conversion system transients with intact HPB and reactivity addition;
c. Primary system HPB leaks and breaks;
d. HPB heat exchanger failures.

In condition a, fission products could be vented from HPB through the vessel relief valve in response to the possibility of the primary circuit to be over pressured if helium is not released. This condition could be triggered by a water ingress event [20]. Helium in the reactor building is, then, released to environment through reactor building vent. For illustration purposes only, the plant transients with intact primary system HPB is the only system transient shown in the proposed MLD in Fig. 4.

Step 4:
The conditions of the required and supportive safety functions, which could cause plant transients with intact primary system HPB, are[8]:

a. Main loop and shutdown cooling system (SCS) are still capable of forced cooling operation
b. Main loop system fails but SCS is still capable of operation
c. SCS fails but main loop system is still capable of operation
d. Main loop and SCS are not capable of operation.

To simplify the proposed MLD, only the first two conditions are presented in Fig. 4, which relate to initiating events illustrated in this study.

Step 5:
The cause of the plant transients with intact HPB in Step 3 in which the main loop and shutdown cooling system are still operated by forced cooling in Step 4 is power turbine generator trip[8]. Therefore, power turbine generator trip is an initiating event for HTGRs. Meanwhile, the cause of the plant transients with intact HPB in Step 3in which main loop system fails but shutdown cooling system is still in operation in Step 4 is loss of offsite power[8]. Therefore, loss of offsite power is another initiating event for HTGR.

All these processes and their corresponding results are graphically shown in the proposed MLD in Fig. 4. Following the same procedures, other HTGR initiating events should be able to be identified.
Figure 4. Master logic diagram for power turbine generator trip and loss of offsite power.

It can be seen from Fig. 4 that power turbine generator trip and loss of offsite power are two of many initiating events, which should be developed for HTGRs. Generally, these results have demonstrated that the proposed MLD can be implemented to search for HTGR initiating events.

Conclusion
The proposed master logic diagram approach has been applied to search for HTGR initiating events. It consists of five main steps. To illustrate the applicability of the proposed MLD approach, searching for two initiating events that could initiate the release of the radioactive materials into environment, i.e. power turbine generator trip and loss of offsite power, have been discussed. The results of the case study confirmed that the proposed MLD is feasible for finding HTGR initiating events. Nevertheless, the proposed MLD still needs to be further investigated to see how effective it will search for HTGR initiating events.

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