Discussion of Developing HTGR Emergency Action Levels Applying Probabilistic Risk Assessment

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Abstract: Emergency action level (EAL) is a pre-determined, site specific, observable threshold for a plant initiating condition that places the plant in a given emergency classification level. The original EAL scheme was developed in the post-Three Mile Island accident era and documented in NUREG-0654/FEMA-REP-1, “Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants”. After that a series of technical documents named as “Methodology for Development of Emergency Action Levels,” (NEI 99-01) give a detail description on developing EAL scheme for Power Water Reactor (PWR) and Boiling Water Reactor (BWR). The most recent outcome NEI 07-01 focus on the advanced passive light water reactors. However, neither of these documents are focus on the high temperature gas-cooled reactor (HTGR).

High Temperature Gas-cooled Reactor (HTGR) has specific safety characteristics which are different from water-cooled reactor to some extent. Because of inherent design features of the HTGR, a significant reduction is achieved in the potential for an offsite radiological release. The tri-structural isotropic (TRISO)-coated fuel is particularly critical to the prevention of radiological releases besides other fission-product barriers. The accident transients occur over hours and days, not seconds. No fast-acting active safety systems are required to maintain the fuel within design limits and so on. These characteristics are significant to emergency planning and will affect the HTGR EAL development. It is not suitable for applying water-cooled reactors’ EAL to HTGR.

The paper discusses the EAL differences between HTGR and water-cooled reactor. Probabilistic risk assessment technology is suggested to develop appropriate HTGR EALs.

Keywords: EAL, HTGR, PRA

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1. INTRODUCTION

Emergency response Planning and Preparedness is the final layer of defense-in-depth strategy in the Nuclear Power Plant (NPP). And Emergency Action Level (EAL) should be developed in NPP Emergency Planning (EP) to provide the defined thresholds for implementing a range of pre-planned emergency response measures. As defined in reference [1], EAL is a pre-determined, site specific, observable threshold for a plant Initiating Condition(IC) that places the plant in a given emergency classification level.

The original EAL scheme was developed in the post-Three Mile Island accident era and documented in NUREG-0654/FEMA-REP-1, “Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants” on October 1980 [2]. After that a persistent research work has been spread by EAL Task force in USA and a series of technical documents have published which developed the methodology for Light Water Reactor (LWR) EAL [3-4]. NEI 97-03 and NEI 99-01 are classical documents, among which NEI 99-01 Revision 6 “Development of Emergency Action Levels for Non-Passive Reactors” is the most recent EAL scheme [5]. As a supplement, a methodology for developing advanced passive light water reactor EAL has also been issued numbering NEI 07-01 on July 2009[6].

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The investigation shows similar framework even if several differences exist in local field. The following table can describe the framework for developing EAL. Key terms include Emergency Classification Level (ECL), Recognition Category（RC）and initiating condition (IC).

ECL is a set of names or titles established by the US Nuclear Regulatory Commission (NRC) for grouping off-normal events or conditions according to (1) relative likelihood and seriousness of the potential or actual events, and (2) the time-sensitive onsite and offsite radiological protective actions necessary to respond to such events. The emergency classification levels, in ascending order of severity, are:

1. Notification of Unusual Event (NOUE)
2. Alert
3. Site Area Emergency (SAE)
4. General Emergency (GE)

ECL can be triggered by different degraded conditions and hazards, which are collected into the Recognition Category (RC). RC represents a certain classification rule for IC/EALs, and it became clear and convenient for ICs and EALs identification and application according to the RCs. At early time in NUREG-0654/FEMA-REP-1, ICs and EALs are listed individually, and then four basic categories are built in NEI 97-03 and NEI 99-01 Rev.4 continuously enhances NEI 97-03 Revision 3 by consolidating the system malfunction ICs and example EALs which address conditions that may be postulated to occur at NPPs during plant shutdown conditions (Recognition Category C). Also included are ICs and example EALs that fully address conditions that may be postulated to occur at permanently Defueled Stations (Recognition Category D) and Independent Spent Fuel Storage Installations (Recognition Category E). Seven general RCs are structured at present as shown in Table 1.

IC and EAL for each recognition category were arranged as matrices. They are Symptom-based, Fission product barrier-based or Event-Based. Symptom-based ICs and EALs are parameters or conditions that are measurable over some range using plant instrumentation (e.g., core temperature, reactor coolant level, radiological effluent, etc.). When one or more of these parameters or conditions are off-normal, reactor operators will implement procedures to identify the probable cause(s) and take corrective action. Fission product barrier-based ICs and EALs are the subset of symptom-based EALs that refer specifically to the level of challenge to the principal barriers against the release of radioactive material from the reactor core to the environment. These barriers are the fuel cladding, the reactor coolant system pressure boundary, and the containment. The barrier-based ICs and EALs consider the level of challenge to each individual barrier - potentially lost and actual lost - and the total number of barriers under challenge. Event-based ICs and EALs define a variety of specific occurrences that have potential or actual safety significance. These include the failure of an automatic reactor scram/trip to shut down the reactor, natural phenomena (e.g., an earthquake), or man-made hazards such as a toxic gas release.

Table 1 the EAL Framework in NEI Series

Emergency Classification Level(ECL)			
Notification of Unusual Event	Alert	Site Area Emergency	General Emergency

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IC/EAL Recognition Category (RC)	A: Abnormal Rad Levels / Radiological Effluent		Initiating condition
	C: Cold Shutdown/Refuelling System Malfunction		⇩
	D: Defueled Station Malfunction	⇨	Emergency action level
	E: Events Related to ISFSI		● Operating mode applicability
	F: Fission Product Barrier Degradation		
	H: Hazard and Other Conditions Affecting Plant Safety		● Notes
	S: System Malfunction		● Basis

China nuclear industry and regulatory agency keep tracking the development of EAL methodology in recent years. A plant-specific EAL for NPP licensing is required by nuclear safety regulations. A nuclear safety guideline named “development of Emergency Action Level for pressurized water reactor” is drafting out and will be issued soon. The technical basis of this nuclear safety guideline derived from NEI documents described as above. The pressurized water reactor (PWR) NPP will follow it developing their plant-specific EAL and feedbacks will be collected in turn to improve the guideline.

2. EAL FOR HIGH TEMPERATURE GAS-COOLED REACTOR

High Temperature Gas-cooled Reactor (HTGR) has been selected in Next Generation Nuclear Plant (NGNP) project by USA Energy Policy Act in 2005. HTGR attracted much more attention of the nuclear industry than before. Helium-cooled graphite moderated reactor is the dominating type in present HTGR technology, which is also our concern in the paper. Based on the helium-cooled reactor operational experiments world-wide such as Peach Bottom, AVR and so on, the technology of HTGR is maturing from the research and pilot project to the business applications. Besides USA NGNP project, other countries are also trying HTGR commercial popularizing, among which China go ahead in the present period.

Research reactor HTR-10 has operated in the campus of Institute of nuclear and new energy technology Tsinghua University since 2003. High Temperature Gas Cooled Reactor – Pebble Bed Module (HTR-PM) involving the INET design technology already entered into the construction design phase in China. The unique safety design philosophy and advanced concepts to improve the safety and the economic competitive power such as inherent safety and passive safety characteristics have been successfully incorporated in the design of HTR-PM. It possibly may become the first commercial service HTGR NPP in the world.

HTR-PM licensing is pushing according to nuclear regulatory procedures. In order to provide the sufficient protection for the public and environment, HTR-PM NNP consider the emergency preparation and planning even so HTR-PM has been demonstrated a relatively low risk level by safety analysis. How to determine the HTR-PM EAL is a touch problem.

The NEI 99-01 emergency classification scheme accounts for the design differences between PWRs and BWRs by specifying EALs unique to each type of Nuclear Steam Supply System (NSSS). Guidance is provided to aid in the development of EALs appropriate to different PWR NSSS types. Where necessary, development guidance also addresses unique considerations for advanced non-passive reactor designs such as the Advanced Boiling Water Reactor (ABWR), the Advanced Pressurized Water Reactor (APWR) and the Evolutionary Power Reactor (EPR). While seldom research work is correlative to HTGR. So it is urgently necessary to study the HTGR EAL. The paper think the following general steps are better for HTGR EAL study:

STEP1: Research and share the outcome of existing EAL methodology.
STEP2: Modify the EAL methodology according to the HTGR technical characteristics.
STEP3: Use of the PSA insight to assess the EAL fitness.

The safety basis difference between the LWR and HTGR brought the necessary to modify the present LWR EAL framework. A specific difference between the LWR safety basis and the HTGR one is the principal barrier to release radionuclides to the environment. In the current LWR designs, the principal barrier to release for severe accidents is the high-pressure, low-leakage containment building. The limiting Licensing Basic Event (LBE) for the LWR is the loss-of-coolant accident resulting from a breach of the primary coolant system. This postulated accident results in fuel damage and a rapid transient of seconds to minutes in duration characterized by high energy release of the high temperature pressurized water primary coolant. These characteristics require the low-leakage high-pressure containment to absorb the stored energy of the coolant system and contain radionuclides released from the fuel. The pre-determined emergency planning and preparation are also required to provide a rapid response according to these characteristics [7].

In contrast, the principal barrier to radionuclide release for postulated LBEs in the HTGR, including Beyond Design Basis Accidents (BDBAs), is the reactor’s TRISO-coated fuel including the fuel particle kernel, which contains the nuclear fuel material, and the multi-layered fuel particle coatings that together constitute the TRISO coating system. Based on previous modular HTGR safety analyses, it is expected that there will be no postulated condition of the plant that results in significant fuel particle degradation or any other significant core damage. This is because of the robust nature of the fuel particle, in conjunction with passive and inherent design characteristics of the reactor that limit excursions in power and fuel temperatures. These characteristics, combined with specifications and quality control on the production of the fuel, assure that most of the fission products will be contained within the fuel under all LBEs. This limits the amount of radionuclides that are transported into the coolant system, therefore, the amount that could be released in a postulated breach of the coolant pressure boundary. At the same time, this also delays the release start time and provide relative longer prepare time for emergency response [7].

3. DISCUSSION OF HTGR EAL

3.1. General Review

The objective of nuclear safety is protection of the health and safety of the public and protection of the environment. HTGR commercial spread should fulfil this objective and defense-in-depth strategy including the emergency planning are practice in the HTGR design. Current emergency classification framework is universal and should be used in HTGR NPP emergency plan. While the perfect safety characteristics of HTGR also bring the flexibility on the EP design. Because they mitigate the severity of postulated licensing basis events and reduce the potential release of the associated radiological source terms and dose consequences. Specifically, the analysis indicated that Environmental Protection Agency(EPA) Protective action Guides (PAGs) for the early phase of an atmospheric release are not exceeded at the plant site's exclusion area boundary (EAB), which will support the associated licensing objective of establishing the plume exposure emergency planning zone (EPZ) at the EAB and further simplify the offsite emergency. Four emergency classification levels including general emergency will keep in the HTGR NPP EP, while the top level, i.e., general emergency may only be triggered by external events or internal hazards other than the HTGR internal events.

A review of NEI ICs and EALs indicated that most do not apply to the HTGR. Symptom-based IC/EALs fit for LWR will encounter reformation according to HTGR unique design features. Gas instead of water becomes the reactor coolant, which makes the coolant level identifier do not exist again. The gas coolant temperature and pressure will act as important indicators serving for HTGR IC/EALs. Fission product barrier-based IC/EALs will change due to HTRG specific TRISO fuel and venting confinement, which are significantly different from those of traditional LWRs. Event-based IC/EALs, especially "Hazards and other conditions affecting plant safety" would apply to HTGR, while the seriousness of the event still need reevaluate when depending on them to clarify the emergency level.

3.2. Fission Product Barrier Degradation IC/EAL

ECL can be triggered by different conditions including the loss of one or more Fission Product Barriers (FPBs). As described earlier, A RC named Fission Product Barrier Degradation (F) has developed by the LWR based EAL methodology. Three fission product barriers considering in the RC "F" are Fuel Clad, Reactor Coolant System boundary and Containment. The trigger logic is shown in figure 1, and the trigger conditions are as below:

1. Any loss or any potential loss of either the fuel clad or RCS barrier will trigger the ALERT,
2. Loss or potential loss of any two barriers will trigger SITE AREA EMERGENCY, and
3. Loss of any two barriers and loss or potential loss of the third barrier.

The trigger conditions can be used in the mode of Power Operation, Hot Standby, Startup and Hot shutdown [5].

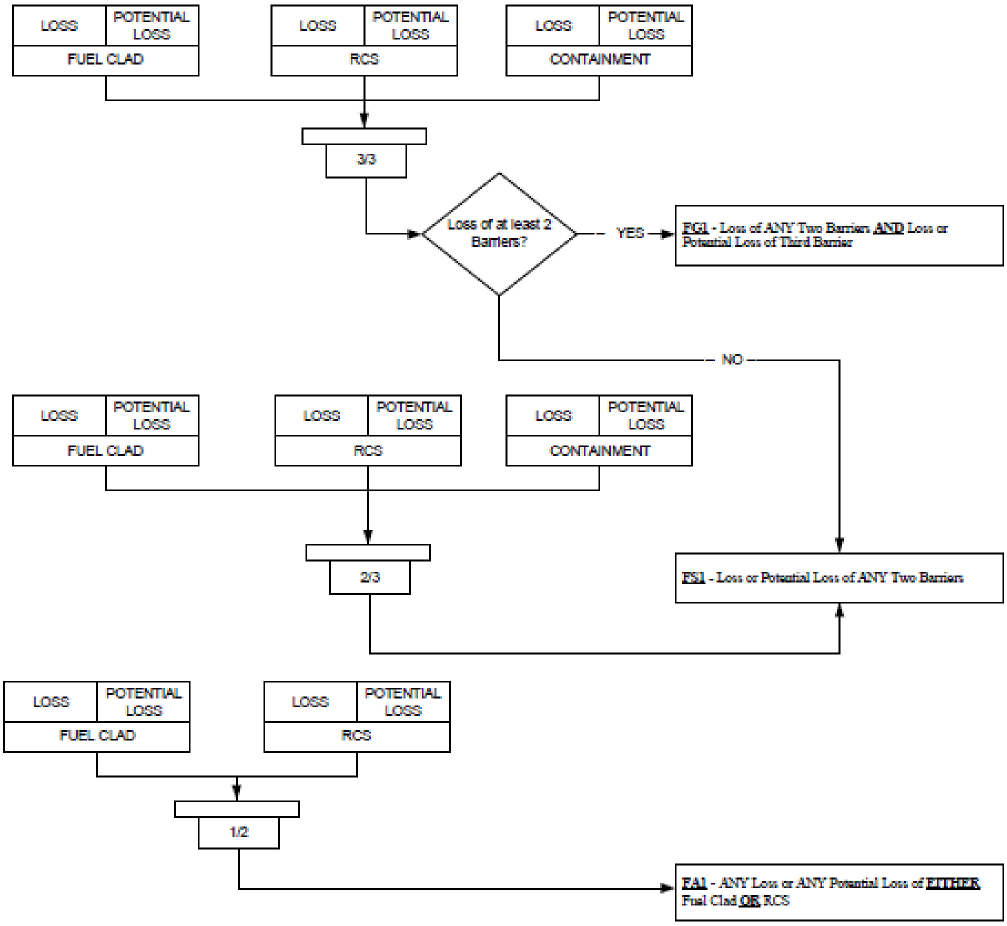

Figure 1. The Fission Product Barrier Degradation (F) logic flow diagram [5]

Condition 1 gives the fuel clad and RCS barrier the same importance in ECs. It is worthy discussing in HTGR EAL. As we mentioned in section 2, TRISO fuel is used in HTGR and the multi-layered coating acts similar function as the fuel clad in the LWR. The Silicon Carbide (SiC) barrier coating is the most important coating in multi-layered coating because it provides most of the structural strength and dimensional stability and serves as the primary barrier to the release of fission products. The high-density Outer Pyrocarbon coating, which shrinks under irradiation, also generates a compressive stress in the dimensionally stable SiC, partially compensating for the tensile stress component induced by the internal gas pressure. The Pyrocarbon coatings also effectively retain fission gases in fuel particles with defective (as manufactured) or failed (in service) SiC layers up to about 1800 ℃, which is much higher than that of LWR fuel element cladding. The structure of TRISO fuel is show in figure 2.

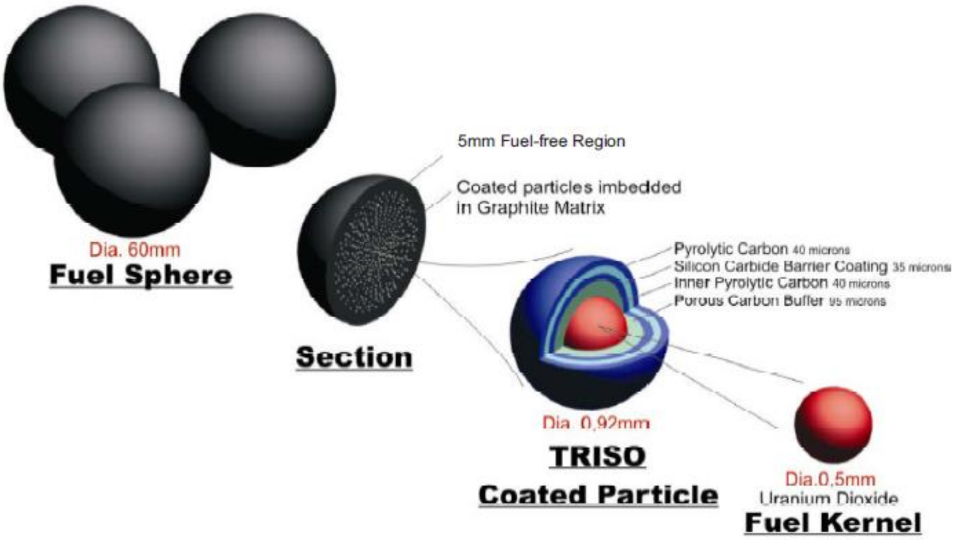

Figure 2. Structure of Pebble Bed Fuel Element

The properties of the TRISO particles are among the most important factors determining the radiological safety of the HTGR. At the same time, the accident analysis and a large body of accident simulation heating test data for TRISO fuel demonstrates the excellent accident condition performance. This limits the amount of radionuclides that are transported into the RCS and, therefore, the amount that could be released in a postulated RCS leakage or breach accident.

It is the fact that the fuel clad in LWR is not exist in HTGR and replaced TRISO particle' multi-layered coating plays a much more important and robust function in preventing the fission product release. For this reason we think it is not suitable to take it the same rank as the RCS in the IC/EALs framework. That is, "any loss or potential loss of either the fuel clad (replaced by multi-layered coating in HTGR) or RCS barrier" in CONDITON 1 should be described separately. Whether loss or potential loss of multi-layered coating in HTGR will lead to ALERT or which RC level should be trigger is still open to discuss. We cannot give the further suggestion on the trigger logic condition1 in HTGR yet. On the other hand, the observable threshold for the TRISO multi-layered coating loss or potential loss is also a Gordian knot, which may difficult to indicate due to the high failure temperature, which may bring much difference from the existing LWR IC/EALs.

3.3. HTGR PRA Application

The study has been done to explore the feasibility of using PRA to provide risk insights about EAL schemes. The U.S. Nuclear Regulatory Commission (NRC) and its contractors from Information System Laboratories, Inc. (ISL), and Innovative Engineering & Safety Solutions, LLC has select Peach Bottom, Surry and Sequoyah as the pilot plants to evaluate their EALs by applying PRA. Reference [8] gives the first effort outcome. This study focused on the use of one of the PRA generated risk metrics (CCDP). It was limited to Level-1 PRA for internal event initiators, and it was applied to one BWR and two PWR plants. Using level-2 PRA supporting the risk-informed evaluation of EALs has also been pilot by M.Z.Azarm Randy Sullivan and so on. The results of these study are plant-specific, based on the consistency of the results, the insights in many cases can be applied generically for other plants including HTGR NPP [9].

Using PRA approach to evaluate consistency of EALs in a given EC require a pre-existing EALs scheme. While no HTGR specific EALs are provided for this work currently. So the primary work is to develop a set of IC/EALs scheme for HTGR NPP. PRA can provide risk insights to this work.

Actually, PSA technology has been encouraged to use in more possible fields in HTR-PM design. So far the internal initiating event PSA under the power operation mode has been finished and be reviewed together with the regulatory review processes of preliminary safety analysis [10]. PSA is continue to the low power and shutdown operation mode and the radioactive source outside the core.

HTR-PM safety analysis reveals that the core heat-up process is slow and the maximum fuel temperature never exceeds the 1620℃ limit so that most of the fission products can be effectively retained in the coated fuel particles. HTR-PM cannot find the similar pinch points for the core damage or large early release phenomena. So there’s no need for separate Level 1/2 PSA models in HTR-PM and HTR-PM PSA is performed in an integrated format to combine level 1 and 2 PSA. Release Category (RC) are defined for the event trees end state. The characteristic terms of RC contains the release frequency, release radionuclides’ quantity and release duration which are closely related to the Emergency Classification. Table 2 gives the way to obtain risk insights from the HTR-PM PRA RC.

Table 2. Using the RC Characteristics term to Determine Emergency Classification

The characteristic terms of RC	RC frequency	Relative likelihood of potential radiological event
	RC release radionuclides’ quantity	Relative seriousness of the potential radiological event
	Release time	The time-sensitive onsite and offsite radiological protective actions necessary to respond to such events
	Release duration	

The other key point is to determine the limits of the characteristic terms of RC corresponding to each emergency classification. As a quantitative method, PRA can gain the value of each RC characteristic terms. HTR-PM RC quantification has finished from which a mapping relation to the ECLs is trying to build.

4. INSIGHT AND FURTHER WORK

Although this study was intended as an exploratory study and many work are under way, it is identified that a number of insight and observations that could help with future HTR-PM IC/EALs development.

1. Existing emergency classification level is fit for all Nuclear Power Plant including HTGR NPP.
2. The IC and EALs developed based on BWR and LWR NPP need to be refreshed based on HTGR NPP characteristics.
3. Risk information can help to improve HTGR emergency classification scheme and develop IC and EALs. PRA approach can not only evaluate consistency of EALs in a given EC but also scan and build the appropriate IC and EALs for a new reactor type NPP.
4. The feasibility of applying PRA in other types of IC/EALs besides FPB IC/EALs is optimistic. The level 1/level 2 integrated PRA model and the release category quantification will extend its range of application.

In the near future, the following areas are identified for further evaluation:

1. Build the mapping relation between HTGR PRA quantification results and the emergency classification level.
2. Review and select suitable conditions as the emergency initiating conditions and develop the site specific, observable thresholds for the initiating conditions. PRA initiating event analysis and failure mode and effect analysis can help this process.
3. Integrate proposed EALs into the HTGR relative regulation code to further improve the HTGR NPP design.

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