A Comparative Study on Safety Design Requirements between HTGR and LWR

Julwan Hendry PURBA, Damianus Toersiwi SONY TJAHYANI
Center for Nuclear Reactor Technology and Safety
National Nuclear Energy Agency of Indonesia (BATAN)
Gd. 80 Kawasan Puspiptek Serpong, Tangerang Selatan 15310, Banten – Indonesia

Email: purba-jh@batan.go.id

Abstract. SSR–2/1 defines safety objectives, safety principles, and safety concepts, which shall be met by designs of nuclear power plants (NPPs). It provides NPP designs with an up to date level of safety to help organizations involved in design, manufacture, construction, modification, maintenance, operation and decommissioning. General safety design requirements in the SSR–2/1 are defined based on the designs and technologies of light water reactors (LWRs). From the design and technology points of view, high temperature gas-cooled reactors (HTGRs) are very different from LWRs. In HTGR, the coated particle fuel is the strongest, ultimate and primary fission product barrier as opposed to the containment building in LWRs. Hence, maintaining the integrity of the coated particle fuel should be the focus of the HTGR safety design aspect. Consequently, the existing known and stable safety design requirements in SSR–2/1 are not well suited for HTGRs. The purpose of this paper is to comparatively study safety design requirements between HTGR and LWR. To achieve this objective, four important safety design requirements in the SSR–2/1, i.e. design extension condition, emergency core cooling system, functional containment, and accident management, are selected to be discussed. The study concluded that a tailored set of safety design requirements derived from those defined in SSR–2/1 should be developed by considering HTGR specific characteristics.

Keywords: SSR–2/1, safety design requirement, HTGR, LWR.

1. Introduction
The primary objective of a safety design of a nuclear power plant (NPP) is to protect people and environment against radiation risks in any possible state and condition of the plant. Safety design requirements of NPPs are generally defined in SSR–2/1 [1]. Following the accident in the Fukushima Daiichi NPPs in Japan, which attracts more and more attention on nuclear safety and affects much on the nuclear energy policies in many countries [2, 3], SSR–2/1 has been superseded by SSR–2/1 (Rev. 1) [4] by proposing a concept of Design Extension Condition (DEC) and made it as a part of the Beyond Design Basis Accident (BDBA) conditions [5]. SSR–2/1 elaborates safety objectives, safety principles, and safety concepts, which shall be met by designs of NPPs. It provides NPP designs with an up to date level of safety. It can help organizations, which are involved in design, manufacture, construction, modification, maintenance, operation, and decommissioning of NPPs, to improve safety.

General safety design requirements defined in the SSR–2/1 are developed based on the designs and technologies of light water reactors (LWRs), which are largely driven by the possibility of core
meltdown. When one fuel element fails, this failure can cause neighbouring fuel elements to fail and, hence, can generate significant additional failures. This failure mechanism will, therefore, change the heat removal path. If cooling systems to remove residual heat from the core are not available, the integrity of the core can get challenged.

On the other hand, designs and technologies of high temperature gas-cooled reactors (HTGRs) are very different from LWRs. HTGRs are designed as such to extensively utilizing inherent safety features to prevent plant conditions that could lead to fuel failure and fission product releases. HTGR inherent safety features include TRISO-coated fuel particles, graphite moderator, and helium coolant [6]. These design features are able to regulate nuclear power without relying on active systems or operator intervention when unexpected events happen. TRISO-coated fuel particles consist of fissionable fuel kernel, which is surrounded by porous pyrolytic carbon (PyC), inner pyrocarbon (IPyC), silicon carbide (SiC), and outer pyrocarbon (OPyC) as shown in Fig. 1.

![Fig. 1. TRISO-coated fuel particle [7].](image)

In HTGR, the coated particle fuel is the strongest, ultimate and primary barrier for fission product retention as opposed to the containment building in LWRs. Pressure vessel failure and kernel migration can affect the integrity of the coated fuel particles [8]. In the event of coated fuel particle failure, the failure of one particle will not cause neighbouring coated fuel particles to fail. Their failure mechanisms are totally independent and driven only by maximum fuel temperatures. Even though there are coated fuel particle failures, the heat removal path will not change as in LWR. Hence, the fuel cool-ability will not get affected and the integrity of those coated fuel particles are still maintained. HTGR has been selected by the United State Department of Energy (US DOE) as the reference design for the next generation of nuclear plant due to its safety and reliability [9].

From the design and technology points of view, it can be seen that the safety of HTGRs is notably defined by high quality ceramic-coated fuel particles. Inherent nuclear and heat transfer properties can maintain fuel temperatures within acceptable limits to ensure that core damage is very unlikely to happen under all conditions. Therefore, the existing known and stable safety design requirements established for LWRs in SSR–2/1 are not well suited for HTGRs. Different approaches to develop safety design requirements for HTGRs are necessary. The purpose of this paper is to comparatively study safety design requirements between HTGR and LWR. To achieve this objective, four important safety design requirements in the SSR-2/1 (Rev. 1), i.e. design extension condition, emergency core cooling system, functional containment, and accident management, are selected to be reviewed and discussed. A wide range of available literatures, such as scientific publications and IAEA publications as well as lectures, is investigated.

2. HTGR Fundamental Safety Functions
Two common designs of HTGRs are pebble bed reactors (PBRs) in which pebble fuels are stacked together in a cylindrical pressure vessel and prismatic block reactors (PMRs) in which fuel elements are stacked to fit in a cylindrical pressure vessel [10]. Both designs are shown in Fig. 2. [11].
The major characteristics, which differentiate HTGR from LWR, are the introduction of ceramic-coated particle fuel, the use of helium as the coolant, and the use of graphite as the moderating material [12]. Ceramic coated and carbon-based fuels can withstand extremely higher temperatures. Helium coolant can minimize stored energy due to its low heat capacity property. Graphite does not experience chemical reaction that can produce explosive gases.

HTGR fundamental safety functions to maintain the integrity of the coated fuel particles are through controlling heat generation, removing residual heat, controlling chemical attacks [13]. Design provisions to control heat generation in HTGR are an intrinsic shutdown system and a reliable control material insertion system. The intrinsic shutdown system includes a very large core negative temperature coefficient and large thermal margin. Meanwhile, the reliable control material insertion system consists of a control rod drop system and a backup or reserve shutdown system. These two passive systems can fall down by gravity.

HTGR design provisions to remove residual heat are the large thermal capacity, the high thermal conductivity and low power density of the core. The low core power density can limit the amount of decay heat. The geometry of the core is designed to be long, slender and annular cylindrical geometry and is surrounded by an un-insulated reactor vessel to effectively remove heat through natural process, i.e. conduction, convection, and radiation. This passive heat removal capability is graphically shown in Fig. 3 [14].
Reactor cavity cooling system (RCCS) is to maintain the temperatures of the structures and reactor building concrete within allowable limit. This system can be cooled by natural convection of air or water [15]. If RCCS were not available, heat from reactor vessel walls would be transferred to the ground to maintain the maximum core temperature to be well below its design limit. In this cooling mode, vessel creep deformation is likely to occur at the core mid plane after several days [16].

The integrity of the fuel particles and graphite core structure can be challenged by two types of chemical attacks, i.e. air ingress and water ingress [17, 18]. Large amounts of air ingress or water ingress accident is one of HTGR design extension conditions [19]. HTGR design provisions to control chemical attacks are by slowing down oxidation rate and limiting source of water. Slowing down oxidation rate can be achieved through the utilization of high integrity nuclear grade pressure vessels, core flow area and friction loss restriction, ceramic-coated particles, and reactor building ventilation. Meanwhile, limiting source of water can be achieved through steam generator isolation and steam generator dump system, reacting water-graphite through endothermic reaction, and coating fuel particle with graphite to protect fuel [15].

3. Methodology
SSR–2/1 (Rev. 1) is published by the International Atomic Energy Agency (IAEA) to provide NPPs with an up to date level of safety. This publication consists of general safety design requirements, which are defined based on LWR designs and technologies. Clarification of this publication to reactor types other than LWR, such as HTGRs, need to be consistently identified. Safety design requirements of HTGR and LWR to be compared in this study are design extension condition, emergency core cooling, functional containment, and accident management as graphically shown in Fig. 4.

Fig.4. HTGR and LWR safety design comparison.

Those four safety design requirements are reviewed and discussed based on a wide range of available literatures, such as scientific publications and IAEA publications as well as lectures.

4. Results and Discussion
Due to the unique concept of HTGR designs and technologies, which are very different from those of LWR defined in SSR–2/1, the realization of the concept of design extension condition, emergency core cooling, functional containment, and accident management in HTGR is, off course, different from those in LWR. In the sequel, those four safety design requirements are compared and discussed.

4.1 Design extension condition
A design extension condition (DEC) is a postulated accident condition, which is not considered for design basis accidents but it is still considered in the design process to keep radioactive material releases within acceptable limits [20]. DEC comprise of events without significant fuel degradation and with melting of the reactor core as shown in Fig. 5 [4]. DEC shall be addressed in the design to prevent those events or to mitigate their consequences.
Safety features for DECs depend on the reactor technology and design. In LWRs, design extension conditions are provided to maintain the integrity of the containment building and bring the plant into a controlled state to practically eliminate an early radioactive release or a large radioactive release [2]. Due to the high thermal resistance of coated fuel particle and graphite core internal, the reactor core of HTGRs cannot be physically melt. There is no possibility of reaching a severe accident as in LWR in which large release of radioactive materials could occur caused by reactor core severe degradation or melting. Even if DBA occurs together with the failure of the reactor cavity cooling system (RCCS), the temperature of the fuel cannot exceed its safety limit according to a number of existing analysis results. Since there is no possibility to reach a severe accident, the old definition of DEC cannot directly be applied to HTGRs. To comply with the principle of the DEC requirement defined in SSR–2/1, it is necessary for HTGR designers to perform an analysis of a plausible DEC. They need to consider other mechanisms that may lead to large releases as opposed to core melt in LWRs. Postulated accident conditions, which could be categorised as plausible DECs, are massive air ingress or massive water ingress. From these plausible DECs, additional safety features or extension of the safety system capabilities might be required to maintain the integrity of the fuel. The main technical objective of considering DECs in HTGRs is to provide assurance that HTGR has been designed as such to prevent accident conditions that could significantly challenge the integrity of the fuel.

4.2 Emergency cooling of the core
Among the accidents to be importantly considered in the design of NPPs for licensing purpose is the complete loss of coolant accident. Generally, a cooling system is designed to remove heat from the reactor core to an ultimate heat sink. In LWRs, an emergency core cooling system is required under accident conditions to ensure necessary and adequate cooling process through the reactor core to finally transfer heat from the core into an ultimate heat sink. LWR design provisions for this requirement are redundant and diverse systems and components.

In HTGRs, any cooling process through the reactor core is not required under accident conditions. Mechanisms to transfer heat from the reactor core to the outside of the reactor pressure vessel are through conduction, natural convection and radiation. These mechanisms are sufficient for removing residual heat and have inherently function in the reactor core structures. HTGR design uses simple and reliable passive means to ensure that fuel temperatures are still within allowable limits even without the presence of the primary system coolant. RCCS is only necessary for preventing the reactor cavity concrete to be overheating during normal operation and under accident condition.

4.3 Functional containment
A functional containment can be defined as a barrier or a set of barriers to effectively limit radionuclide releases into the environment under normal operating conditions, anticipated operational occurrences, and accident conditions. LWRs employ a functional containment, which consists of an
integrated set of five radionuclide retention barriers, i.e. the fuel matrix, the fuel cladding, the primary coolant boundary, the containment building, and the reactor building. Meanwhile, HTGRs employ the coated fuel particle kernel, the fuel particle coatings surrounding the particle kernel, the carbonaceous matrix and graphite surrounding the fuel particles, the reactor helium pressure boundary, and the reactor building as their functional containments.

The most important barrier for radionuclide retention for HTGRs is the closest barrier to the source of radionuclides, which is the ceramic coating layers surrounding the fuel kernel [21, 22]. This coating system has been engineered as a miniature pressure vessel to provide containment function to retain radionuclides and gases generated in the fuel kernel. Hence, the coated particle fuel is the strongest, ultimate and primary fission product barrier in HTGR designs. This barrier is analogue with the containment building in LWRs.

As the primary containment for HTGRs, maintaining the integrity of the coated particle fuel should be the focus of the HTGR safety design. These fuel types can maintain their integrity at extremely high temperature to retain radionuclides under all accident conditions. This property becomes the key element in the HTGR design and licensing. Factors that can affect the capability of the TRISO to retain fission product are coating layer microstructure, chemical impurities, irradiation flux, temperature history, and chemical attack [18].

4.4 Accident management
Accident management can be defined as a set of actions to prevent the escalation of an event into a severe accident, to mitigate the consequences of a severe accident, and to achieve a long-term safe stable state [23]. A severe accident is any accident, which is more severe than design basis accidents (DBAs) and can lead to core degradation. Three Mile Island (TMI), Chernobyl, and Fukushima accidents are three nuclear power plant accidents, which belong to the severe accidents category [24].

Accident management in LWRs relies on automatic safety actions and prescribed operator actions to maintain related safety functions for a long time. In HTGRs, accident management relies more on design features. Under accident condition, decay heat is removed from the core through reactor internals and the reactor pressure vessel (RPV) by natural heat transport mechanism [25]. This mechanism includes thermal conduction, convection and radiation. These mechanisms can ensure that the maximum fuel temperature will always below its safety limit. This is the most important safety-related parameter in HTGR design technologies.

In case of a DBA and RCCS failure occur at the same time, which is considered as a DEC in HTGRs, the maximum fuel temperature is still well below the safety limit. In this condition, engineered safety features, such as the cooling system of the RPV structures, and operator actions, such as manual pressure relief of the primary circuit, are required to maintain the RPV temperature and the primary pressure are well below their safety limits.

HTGR inherent phenomena, such as integrity of the core graphite structures at high temperatures and natural heat transfer mechanism, make accident management much more easier. Those lead to a large grace period to allow operators to implement corrective actions as needed.

From the discussion elaborated above, it can be concluded that HTGR fuel structures forms the principal barrier to the radioactive material releases. HTGR inherent safety features make events leading to severe damage highly unlikely, even though all active cooling systems fail and complete loss of coolant occur. Residual heat can be removed solely through physical processes, which are conduction, radiation, and convection, to maintain the integrity of the fuel element. This constitutes the main differentiating aspects from LWRs. Therefore, safety design requirements in SSR–2/1 needs to be thought in different ways to develop a more appropriate licensing process for HTGRs.

5. Conclusion
Design extension conditions are provided to maintain the integrity of the confinement functions and bring the plant into a controlled state to practically eliminate an early radioactive release or a large radioactive release. To comply with the principle of DEC requirement, HTGR designers need to
perform an analysis of plausible DEC that may lead to large releases as opposed to core melt in LWR. An emergency core cooling system is required under accident conditions to ensure necessary and adequate cooling process through the reactor core to finally transfer heat from the core into an ultimate heat sink. Different from LWR whose design provisions for removing residual heat are redundancy, and diverse systems and components; conduction, natural convection and radiation are sufficient for HTGR and have inherently function in the reactor core structures. A functional containment is a barrier or a set of barriers to effectively limit radionuclide releases into the environment under normal operating conditions, anticipated operational occurrences, and accident conditions. HTGR relies on the ceramic coating layers surrounding the fuel kernel as the primary functional containment for radionuclide retention as opposed to containment building in LWR. Accident management is a set of actions to prevent the escalation of an event into a severe accident, to mitigate the consequences of a severe accident, and to achieve a long-term safe stable state. Automatic safety actions and prescribed operator actions are part of accident management in LWR to maintain related safety functions for a long time. Different from LWR, accident management in HTGR relies more on design features to provide a large grace period of time to allow operators to implement corrective actions as needed. From the design and technology points of views, a tailored set of safety requirements derived from those general safety design requirements defined in SSR–2/1 should be developed by considering specific safety characteristics of HTGRs.

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