ABSTRACT

In Korea, the development of very high temperature gas cooled reactor (VHTR) for hydrogen production was launched with target dates of 2022 for the completion of construction and 2026 for prototypical demonstrations according to the “Action Plan for Developing Future Nuclear Systems” approved by the Atomic Energy Commission in 2008. Korean Institute of Nuclear Safety (KINS) also started to develop regulatory requirements for the VHTR for the preparation of the licensing application of the VHTR. The VHTR design is characterized by 1) the refractory triple isotropic layers coated fuel particles (TRISO CFP) which can retain the fission products and then provides a unique robustness of the first barrier for the fission products, 2) the inert, single phase helium gas as coolant and graphite with high temperature stability and long response times as moderator, 3) negative temperature coefficient of reactivity and 4) passive core cooling and decay heat removal by natural process, etc. The designs of VHTR are different from those of conventional light water reactors (LWRs), so the existing regulatory environment may not be suited for the VHTR design and, therefore, proper safety requirements should be developed incorporating the unique characteristics of VHTR design. In this paper, as a part of activities to develop the complete general design requirements (GDRs) for VHTR, the applicability of the current GDRs for the LWR to the design of the VHTR was evaluated and then the GDRs were classified in the following categories: (1) the GDR to be applicable to the VHTR, (2) the GDR to be modified due to the design differences, and (3) the requirement not applicable to the VHTR.

1 INTRODUCTION

High Temperature Gas-cooled Reactors (HTGR) are helium-cooled, graphite-moderated thermal reactors with refractory TRISO fuel which can produce high temperature heat. The very high temperature gas-cooled reactor (VHTR) designed for operation up to 1,000°C is currently under development as a Generation-IV reactor, which can be used not only to contribute high-efficiency electricity generation but also to supply industrial process heat or the massive amounts of hydrogen necessary for the hydrogen economy [1]. In this context, Korea Atomic Energy Research Institute (KAERI) has launched the NHDD (nuclear
hydrogen development and demonstration) project with target dates of 2022 for the construction of VHTR demonstration reactor [2]. Since 2010, Korea Institute of Nuclear Safety (KINS) has also started regulatory research to prepare the licensing of the VHTR demonstration reactor, which is focused on the establishment of regulatory framework for VHTR and the development of regulatory audit technology including audit-calculation code systems for VHTR [3].

Given the VHTR’s unique design approaches with passive and inherent safety features, the regulatory requirements and guides, which provide appropriate guidance in licensing and safety assessments of VHTR, may require specific consideration incorporating the unique design characteristics of VHTR with the generally accepted principles of nuclear safety. As a part of activities to develop the complete GDRs for VHTR, the evaluation of the applicability of the current LWR GDRs to the design of the VHTR is given. The GDRs for VHTR are identified through (1) the GDR to be applicable to the VHTR, (2) the GDR to be modified due to the design differences, and (3) the requirement not applicable to the VHTR.

2 DESIGN CHARACTERISTICS OF VHTR

The VHTR is defined as a helium-cooled, graphite moderated reactor with a core outlet temperature in excess of 900°C and a long-term goal of achieving an outlet temperature of 1000°C. By virtue of the very high temperature in core outlet, the VHTR is suited for the production of huge amounts of hydrogen in addition to electricity. From these characteristics, the VHTR is chosen as one of the Generation IV systems. In this context, the Korea Atomic Energy Research Institute (KAERI) is pursuing the Nuclear Hydrogen Development and Demonstration (NHDD) Project; the NHDD reactor is to be limited to 200 MW-thermal with no decision yet made as to fuel/core type, and the construction of demonstration reactor is planned to be completed in 2020s after ongoing research and development activities [4-6].

From the preliminary NHDD system design of KAERI, the system consists of a reactor, intermediate heat transport loop and coupled hydrogen systems as shown in Figure 1. The primary coolant system is cooled by helium and consists of a reactor pressure vessel, a concentric hot gas duct, a circulator and a compact intermediate heat exchanger (IHX). As in Figure 1, an underground reactor installation concept is employed, which allows for heat transfer to the ground even in the loss of passive cooling and can protect reactor system from a possible explosion in a hydrogen storage area. This preliminary NHDD design is used as a reference in evaluating the applicability of the existing general design requirements to VHTR of hydrogen production.

Figure 1: Layout of NHDD System
The VHTR design is characterized by 1) the refractory triple isotropic layers coated fuel particles (TRISO CFP) which can retain the fission products and then provides a unique robustness of the first barrier for the fission products, 2) the inert, single phase helium gas as coolant and graphite with high temperature stability and long response times as moderator, 3) large negative temperature coefficient of reactivity and 4) passive core cooling and decay heat removal by natural process, etc.

Unlike LWR fuel cladding, the use of refractory TRISO fuel embedded in a graphite matrix retains primarily the fission products because it can withstand higher temperatures than the fuel itself without incurring structural damage. Furthermore, the massive graphite structures in the reactor core provide an extremely large heat capacity that, when coupled with the low power density of the core, results in very low and predictable temperature transients. The mean free path of neutrons in graphite also provides a neutronically stable core that contributes to a very large negative temperature coefficient. Helium, a coolant of the HTGR primary loop, will not change phase in the reactor, thus eliminating two-phased flow within the LWR reactor circuit. The large negative temperature coefficient of reactivity of VHTR, along with the large thermal margin, provide for an inherent shutdown capability to deal with their anticipated transient without scram (ATWS) condition. Further confidence of the ability to shutdown the reactor is provided by the diverse reactivity control systems.

The annular core of VHTR configured to have a large core surface-to-volume ratio, combining with high heat capacity and low power density, makes possible passive remove residual and decay heat from the core even under the worst accident condition regardless of whether helium coolant is present. The reactor cavity cooling system (RCCS) surrounding the reactor vessel removes heat radiating from the reactor vessel outer surface.

For the VHTR, the TRISO fuel provides the primary radionuclides release barrier and vented low pressure containment (VLPC) building is considered instead of the high pressure leak tight containment building which is the primary barrier of LWR.

Relying on these inherent safety characteristics of TRISO fuel, graphite moderator, helium coolant, and passive hear removal capability, VHTR can be designed to prevent core meltdown and then to eliminate the need for public evacuation regardless of the severity of any accident. These characteristics support one of the objectives of the HTGR safety basis, which is to limit calculated dose from releases so that regulatory requirements for protection of the public health and safety of the public and protection of the environment are met at an exclusion area boundary. This also supports the associated licensing objective of establishing the plant emergency planning zone at the EAB (emergency area boundary) and supports flexibility in siting the VHTR plant with the objective of locating the VHTR in close proximity to industrial processes to improve the efficiency of energy transport to the processes.

3 APPLICABILITY OF THE CURRENT GDR TO VHTR

The general design requirements, which correspond to the Section 2 (Structure, Installations, and Performance of Reactor Facilities) of “Regulations on Technical Standards for Nuclear Reactor Facilities, Etc” of the Nuclear Safety & Security Commission (NSSC) [7], are intended to provide guidance in establishing the principal design criteria. The current requirements were developed for LWRs and a stable regulatory environment for LWRs has been established for many years. Furthermore, the intent of the GDR was preserved, if applicable, to a VHTR even though the LWR prescriptive features contained in the current GDR wording (e.g. DNB, ECCS) may need to change because of the reactor characteristics [8,9]. By starting with the existing LWR GDR as a base, and keeping the one-to-one
correspondence and intent, the process allows the current GDRs to be applied to a VHTR with very little revision. Because of the significant design differences between VHTR and LWR as described in the previous section, the first task in establishing a VHTR regulatory framework is to identify (1) the GDR to be applicable to the VHTR, (2) the GDR to be modified due to the design differences, and (3) the requirement not applicable to the VHTR.

In conducting the evaluation of the current GDRs for applicability to a VHTR, 27 GDR required no changes, 3 GDR required only minor wording changes, 8 required technically changes, and 1 were found not to be applicable. In addition, 3 new GDR was determined to be needed. The general intents of the LWR DGRs were found to be applicable to VHTR design and, therefore, most GDRs were retained or required relatively minor modifications. In several instances (art. 2, 15, 22), LWR-specific terminologies, such as DNB, water boiling, and LOCA, etc., were replaced with VHTR-specific one to improve applicability. In Table 1, the current GDRs are listed with remarks on applicability results of each GDR.

Table 1: Summary of Applicability of General Design Requirements to VHTR

<table>
<thead>
<tr>
<th>General Design Requirements (Articles of Technical Standards)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Definition</td>
<td>Applicable with change of LWR-specific terminology (e.g. DNB)</td>
</tr>
<tr>
<td>12 Safety Classes and Standards</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>13 External Events Design Bases</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>14 Fire Protection, etc</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>15 Environmental Effects Design Bases, etc</td>
<td>Applicable with change of LWR specific terminology (LOCA)</td>
</tr>
<tr>
<td>16 Sharing of Facility</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>17 Reactor Design</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>18 Inherent Reactor Protection</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>19 Suppression of Reactor Power Oscillations</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>20 I&amp;C System</td>
<td>Applicable with changes of items to be monitored</td>
</tr>
<tr>
<td>21 Reactor Coolant Pressure Boundary</td>
<td>Applicable with modification of the definition of “reactor coolant pressure boundary”</td>
</tr>
<tr>
<td>22 Reactor Cooling Systems, etc</td>
<td>Applicable with change of LWR specific terminology(water coolant)</td>
</tr>
<tr>
<td>23 Reactor Containment, etc</td>
<td>Applicable with considering the vented containment building</td>
</tr>
<tr>
<td>24 Electric Power System</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>25 Control Room, etc</td>
<td>Applicable but remove the ECCS</td>
</tr>
<tr>
<td>26 Protection System</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>27 Diverse Protection System</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>28 Reactivity Control System</td>
<td>Applicable but remove liquid reactivity control</td>
</tr>
<tr>
<td>29 Residual Heat Removal System</td>
<td>Applicable with considering PCCS</td>
</tr>
<tr>
<td>30 Emergency Core Cooling System</td>
<td>Applicable with being merged into Art. 29</td>
</tr>
<tr>
<td>31 Ultimate Heat Sink</td>
<td>Applicable without change</td>
</tr>
<tr>
<td>32 Radioactive Processing &amp; Storage Systems</td>
<td>Applicable without change</td>
</tr>
</tbody>
</table>
33 Fuel Handling & Storage Facilities  Applicable without change
34 Radiation Protection Provisions  Applicable without change
35 Reactor Core, etc  Applicable without change
36 Reactivity Core Material Drive Mechanism  Applicable without change
37 Overpressure Protection  Applicable without change
38 Alarm Devices, etc  Applicable without change
39 Prevention of Steep Slope Collapse  Not applicable
40 Use of Qualified Equipment  Applicable without change
41 Test/Inspect/Maintenance, etc  Applicable without change
42 Design Bases Accidents  Applicable with replacing LOCA with DBA of HTGR
43 Protection during Startup, Shutdown, and Low Power Operations  Applicable without change
44 Reliability  Applicable without change
45 Human Factors  Applicable without change
46 Optimization of Radiation Protection  Applicable without change
47 Emergency Response Facilities and Equipment  Applicable without change
48 Limiting Conditions for Operation  Applicable without change
49 Initial Tests  Applicable without change

The requirements (art. 28) related to liquid reactivity control system shall be replaced by those for the substitute reactivity control system since VHTR does not use liquid reactivity control materials. The requirements for core cooling of LWR (art. 29 and 30) consist of two requirements: emergency core cooling and residual heat removal. However, since VHTR are designed to passively remove residual and decay heat by RCCS during operation and accident conditions, these two requirements shall be modified to be merged into one. The requirement (art. 20) related to I&C system, which enumerates variables and systems to be monitored and controlled, including the items related to water coolant, shall be modified according to the VHTR design.

Some requirements (art. 21, 23, 25, 42) which refer to a loss of coolant accident (LOCA) as design basis accident (DBA), shall be modified to design basis depressurization accident of VHTR. In particular, the requirement (art. 23) related to the reactor containment, which states that LWR containment is expected to be an “essentially leak-tightness barrier for radionuclide release, shall be modified to address the vented reactor building concept of VHTR.

New requirements that need to be added to the GDRs are as follows: reactor cavity cooling system, helium supply and purification system, and power conversion system for hydrogen production, which are not adopted in current LWR GDRs.

4 REFLECTION OF IAEA SAFETY REQUIREMENTS

To evolve the design, safety assessment and licensing of future reactors IAEA has proposed to develop technology-neutral safety requirements [10]. After the Fukushima accident, the IAEA is also strongly focused on international safety standards and improving safety review. IAEA Safety Standards No.SSR-2/1 [11], which was revised to ensure the highest level of safety reflecting the present consensus in 2012, defines the safety objectives, safety functions and what should be the safety in design. It also contains technical changes in safety regulations to strengthen the safety of the nuclear power plants (NPPs). The VHTR is one of the Gen IV reactors and its level of safety shall be enhanced than that of the existing
NPPs. Therefore, it is necessary to reflect the safety enhancement by the IAEA in the domestic safety requirements. The following requirements were identified to be reflected in the GDRs for VHTR in Korea: defense-in-depth (DID), design extension conditions (DEC), decommissioning, interface of safety with security and safeguards, operating experience and safety research results, prevention of harmful effects between systems, etc.

A requirement for the defense-in-depth needs to be added in the GDRs to provide several levels of defense to prevent accidents and to mitigate their consequences. All levels of defense shall be kept available at all times and any relaxations justified. Most prominent change comes in dealing the severe accident. Requirement 20 of SSR-2/1 defines the design extension conditions (DEC) as accidents that are either more severe than design basis accidents or that involve additional failures. For DEC, a new requirement needs to be added to take the measures to maintain releases of radioactive materials within acceptable limits on the basis of the best estimated approach. It also needs to consider establishment of measures to prevent and to mitigate DEC as far as reasonably practicable. Special consideration shall be given at the design stage to incorporate features to facilitate the decommissioning, so that a requirement needs to be added to take account of the choice of materials to minimize radioactive wastes and of the access capabilities. For assurance of safety, security, and safeguards, a requirement needs to be added to establish safety measures, nuclear security measures, and safeguards arrangements and to implement them in an integrated manner so that they do not compromise one another.

5 CONCLUSIONS

For the preparation of the licensing of the VHTR demonstration reactor, a study has been performed for the development of the general design requirements for the VHTR. The current GDRs were evaluated for their applicability to the VHTR by reflecting the design characteristics of HTGR. Based on this study, complete GDRs for VHTR will be developed reflecting lessons learned from Fukushima accidents and requirements related to risk-informed regulations in the future.

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REFERENCES


