Phenomena Identification and Ranking Tables Related to the HTR-PM Accident Analysis

Fubing CHEN, Yanhua ZHENG, Lei SHI, Fu LI, Yujie DONG, Zuoyi ZHANG
Institute of Nuclear and New Energy Technology, Tsinghua University, the key laboratory of advanced reactor engineering and safety, Ministry of Education
Energy Science Building, Tsinghua University, Beijing 100084, China
phone: +86-010-62782953, chenfubing@tsinghua.edu.cn

Abstract – The High Temperature Gas-cooled Reactor-Pebble Bed Module (HTR-PM), which is designed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University, is now under its civil engineering construction. In conformance with the Chinese safety requirements related to the development, assessment, application and quality assurance of computer software used in the safety analysis of nuclear power plants (NPPs), a phenomena identification and ranking table (PIRT) process was conducted on the subject of the HTR-PM accident analysis by an expert panel sponsored by INET, on the basis of the latest HTR-PM design scheme. The PIRT objective is to identify safety-relevant phenomena that may occur during normal operation and accident conditions, and to assess research activities pertaining to code development and assessment, such as the code validation work in INET.

In the PIRT process, safety-related phenomena were identified by the expert panel for the following HTR-PM scenarios: normal operation (NO), pressurized loss of forced cooling (PLOFC), depressurized loss of forced cooling (DLOFC), air ingress following DLOFC, anticipated transients without scram (ATWS) and steam/water ingress. Subsequently, relative importance of each phenomenon was evaluated according to its effect or influence on the primary evaluation criteria established by the expert panel, such as the fuel failure fraction and the maximum fuel center temperature. In addition, each identified phenomenon was assigned a knowledge level rank by the expert panel, indicating the prediction capability for this phenomenon based on existing analytical tools. What is more, all of the PIRT elements were well documented by a special report, including PIRT issues, objectives, descriptions of the HTR-PM plant and accident scenarios, evaluation criteria, current knowledge base, ranking scales of relative importance and knowledge level, a set of PIRTs, and expert discussions.

I. INTRODUCTION

The concept of modular High Temperature Gas-cooled Reactor (HTGR) was originally proposed and developed in Germany and USA during the 1980s. Utilizing the technical basis of HTGRs, this concept is further characterized by its inherent safety features that are guaranteed completely through passive means. Considered as a safe, efficient, economic and environment-friendly high temperature energy source for the industrial cogeneration of electricity and process heat, the modular HTGR experienced substantial development in several countries over the past two decades [1]. In China, this advanced reactor type now has two most representative cases, i.e., the 10 MWt test module (HTR-10) under operation and the 250 MWt pebble bed module (HTR-PM) under construction, both of which are designed by the institute of nuclear and new energy technology (INET) of Tsinghua University [2, 3].

In the design process of a modular HTGR, it is of paramount importance to predict the operation
performance and the safety aspects with a high degree of reliability. Principal tools utilized in such predictions include various computer programs, covering the field of reactor physics, thermal hydraulics, accident analysis, and so on. In light of the Chinese nuclear safety requirements, computer programs, analytical methods and plant models used in the safety analysis shall be verified and validated; in addition, adequate consideration shall be given to uncertainties. Accordingly, the National Nuclear Safety Administration (NNSA) of China drafted a specific nuclear safety guide in 2013, which is related to the development, assessment, application and quality assurance of computer software used in the safety analysis of nuclear power plants (NPPs). Previously, a regulatory guide focusing on the similar issues was also officially published by the U.S. Nuclear Regulatory Commission (NRC) in 2005 [4]. This regulatory guide provides principles to the developers of an NPP evaluation model that may include one or more computer programs, special models and all other information necessary for the calculation of a specific event sequence. Meanwhile, guidance provided to the NRC reviewers was further issued in 2007 as Section 15.0.2 of the Standard Review Plan (SRP) [5]. In the above-mentioned nuclear safety regulations, one cornerstone is the phenomena identification and ranking table (PIRT) process that defines the important phenomena existing in postulated accident sequences to be analyzed. PIRT was originally formulated as part of the code scaling, applicability and uncertainty (CSAU) evaluation methodology, which was developed by NRC in 1989 with the purpose of supporting the application of best estimate plus uncertainty (BEPU) approach in accident analysis [6]. This process is a systematic and effective way of providing expert assessment for safety-relevant phenomena that may occur in hypothetical accidents of NPPs [7]. Through the application of PIRT, relative importance as well as knowledge level of each phenomenon can be judged by experts. Thus, research aspects with high priority can be determined.

In conformance with the preceding safety requirements and safety guides, a PIRT process was conducted by an INET expert panel on the subject of the HTR-PM accident analysis. The PIRT panel was comprised of nine members involving different subtopics of modular HTGRs: PIRT methodology, neutronics, thermal hydraulics, accident analysis, code development, fission product transport and TRISO coated particle. In 2008, the preliminary safety analysis report (PSAR) of the HTR-PM was submitted to the Chinese regulatory body for applying the construction permit (CP). Subsequently, review results were fed back by NNSA with the main product of preliminary safety evaluation report (PSER). At present, the HTR-PM is under the stage of construction design and its final safety analysis report (FSAR) is under preparation. Consequently, the latest design information and safety assessment including great details are completely available to the expert panel. As the prototype of the HTR-PM, the HTR-10 has been successfully run for several years with different power levels since 2003. During the relatively long period of commissioning and operation, various kinds of tests were carried out on this reactor [8, 9]. Hence, the PIRT work of the HTR-PM accident analysis can be strongly supported by the design output, operation experience and test data of the HTR-10. In addition, technical advances and historical lessons from the AVR, the THTR-300 and the HTR-MODULE concept are learned by INET at all times. Considering the design progress of the HTR-PM and the current knowledge base, the experts are of the opinion that it is appropriate, feasible and beneficial to perform the PIRT exercises relating to the HTR-PM accident analysis at this stage.

The PIRT experts have completed an evaluation for the safety-related phenomena that will dominate the HTR-PM behavior during normal operation and accident conditions. Issues addressed by this PIRT are the importance of different phenomena in representative accident scenarios and the prediction capability for these phenomena based on existing analysis techniques and test data. The preliminary PIRTs will initially provide the basis for evaluating: 1) the applicability of computer codes employed in the HTR-PM thermal hydraulics calculation and accident analysis; 2) the adequacy of test data used in the validation process of these codes; 3) the requirements for the development of new codes and models needed by further analysis. Additionally, the resulting information will be submitted to NNSA to provide insights for the review of the HTR-PM safety analysis reports.

II. DESIGN FEATURES OF THE HTR-PM

The HTR-PM demonstration plant consists of two nuclear steam supply system (NSSS), which are called modules. These two NSSS modules feed one steam turbine, generating an electric power of 210 MW. Each module is comprised of a 250 MWth modular reactor with a single zone pebble bed core, a once through steam generator containing 19 helical tube assemblies and a vertical helium circulator located on the top of the steam generator. The reactor and the steam generator are installed in two separate pressure vessels, which are arranged side by side and connected by a horizontal hot gas duct pressure vessel. These three vessels constitute the primary pressure boundary of one NSSS module, as shown in Fig. 1, where the coolant flow direction under normal operation is also illustrated. Detailed
information and key parameters of the HTR-PM are referred to elsewhere [3].

Fig. 1: Primary system of an HTR-PM NSSS module

As mentioned before, the HTR-PM reactor, based on the modular HTGR concept, incorporates inherent safety features in its design, thus meeting the fundamental safety goals of Generation IV nuclear energy systems. At present, the HTR-PM is under the civil engineering construction. According to the main technical scheme, typical design features of the HTR-PM can be summarized by the following aspects.

- The reactor core is composed of spherical fuel elements containing high-performance coated fuel particles (CFPs). Under any operation conditions or postulated accident scenarios, all radioactive fission products can be effectively retained in CFPs with a very low fuel failure fraction.
- The graphite-moderated, helium-cooled pebble bed core is mainly characterized by its low power density, large heat capacity, high effective thermal conductivity and large temperature margins to fuel failure.
- Since the active core zone is entirely surrounded by ceramic materials, i.e., graphite reflectors and carbon bricks, the reactor internals can withstand and endure very high temperatures.
- In the case of an accident, the helium circulator will be switched off by the reactor protection system, resulting in the loss of forced cooling in the primary circuit. The subsequent core heat-up will immediately lead to a consequential temperature rise. Due to the negative reactivity temperature coefficients of the fuel and the moderator, the reactor can be automatically shut down.
- Two independent shutdown systems are arranged in the side reflector of the HTR-PM reactor, including a control rod system and a small absorber ball system. Despite the automatic shutdown capability, the reactor can also be scrammed by these two systems without any doubt.
- A passive reactor cavity cooling system (RCCS) is designed to remove the residual heat from the core completely through natural mechanisms, such as heat radiation and natural circulation.
- Each NSSS module is housed in the ventilated low pressure containment (VLPC). This structure can accommodate the reactor depressurization dynamically and may be used instead of the leak-tight sealed containment.

III. PIRT PROCEDURE AND REPRESENTATIVE RESULTS

III.A. PIRT Procedure for the HTR-PM Accident Analysis

Originating from the CSAU methodology, the PIRT process was widely applied to various accidents of light water reactors (LWRs), e.g., loss of coolant accident, main steam line break and rod ejection accident. Through the further development, PIRT has become a powerful tool to establish phenomena-based modeling requirements for safety analysis computer codes and to define test data needs for the validation of such analytical tools. All PIRTs have a common goal: understanding the plant behavior in the context of identifying significant phenomena, processes, parameters and so on. A generic PIRT procedure was conceptually illustrated by Wilson and Boyack, and its typical application was detailedly described [10]. However, the details of each PIRT study may vary depending on the specific problem to be resolved, bringing some modifications to the basic PIRT approach. For example, a nine-step PIRT process was developed by NRC to conduct the PIRT work for the next generation nuclear plant (NGNP) [11], which is a very high temperature reactor (VHTR) under concept design. Containing the main elements recommended by the generic PIRT procedure, this process has been successfully applied in different research fields of the NGNP. Because of this, the nine-step PIRT process was utilized by the INET experts as a standard procedure to perform the HTR-PM PIRT. Since the PIRT issues, objectives, knowledge base and the HTR-PM plant hardware are described above, these parts of the PIRT procedure will not be introduced any more here. The
application of other PIRT steps is illustrated in Fig. 2 and briefly described in subsequent sections.

![PIRT procedure for the HTR-PM accident analysis](image)

Fig. 2: PIRT procedure for the HTR-PM accident analysis

(1) Define accident scenarios

Taking into account the latest design option of the HTR-PM, the FSAR is now under preparation based on the PSAR approved by NNSA. Such work provides the basis for the consideration of the HTR-PM accident scenarios in the current PIRT study. In the accident analysis, a comprehensive list of postulated initiating events, mainly focusing on the internal events, has been developed based on operation experience and engineering judgement of the HTGR plant, probabilistic and deterministic safety analysis of the HTR-PM. In the PIRT study, initiating events were grouped by the expert panel according to dominant phenomena in the event sequences for the purpose of considering all the important phenomena and processes with minimum repetition. This categorization of initiating events led to the selection of accident scenarios in the PIRT process. Scenarios considered by the PIRT experts are listed as follows.

- Pressurized loss of forced cooling (PLOFC);
- Depressurized loss of forced cooling (DLOFC);
- Air ingress following the DLOFC;
- Anticipated transients without scram (ATWS);
- Steam/water ingress.

The above accident scenarios, which can be derived from combinations of initiating events and plant operation states, have already been detailedly described and quantitatively analyzed in the PSAR and will be further analyzed in the FSAR. Moreover, analysis results of the HTR-PM postulated accidents can be partly found in the references [12-15].

As the starting point of different postulated accidents, normal operation (NO) is very important since it provides initial and boundary conditions for the development of event sequences. Therefore, NO was fully covered in the PIRT process.

(2) Define evaluation criteria

In this PIRT step, primary evaluation criteria need to be established to judge the relative importance of phenomena and processes influencing the plant response to postulated event sequences. In the context of PIRT application, these evaluation criteria are usually derived from the regulatory requirements, such as fission product release from the fuel or a more specific term. Consequently the evaluation criteria are used to ensure that the plant keeps within the design envelope during normal operation and the radioactivity release is within limitation under accident conditions.

Taking the NGNP PIRT work as a reference, the INET experts established evaluation criteria with different levels for the HTR-PM PIRT, which are described as follows.

1. First level: dose at the plant site boundary (or radioactivity release from the VLPC);
2. Second level: worker dose;
3. Third level: fuel failure fraction during normal operation or accident scenarios;
4. Lower level criteria:
   - maximum fuel center temperature and fuel element corrosion extent, each of which is a precursor to the criterion of fuel failure fraction;
   - service conditions of reactor pressure vessel (RPV), vessel supporting structures, core barrel and other important metal internals, e.g., temperature, pressure, oxidation extent and integrity;
   - temperature, pressure and integrity of the reactor cavity;
   - coolant activity in the primary circuit (including graphite dust).

(3) Identify plausible phenomena

In the previous steps, the HTR-PM plant hardware was defined and the accident scenarios were selected. Following that, the PIRT experts identified all the plausible phenomena for each scenario. Before the identification, the term “phenomena” was expanded by the expert panel. In this way, the HTR-PM PIRT process focused on not only phenomena but also processes, parameters, factors and characteristics that may influence the plant response to the postulated initiating events and their subsequent event sequences.

Through the key phenomena listed by the experts, a comparison can be made between the phenomenological requirements imposed on analytical tools used to simulate accident scenarios and existing analysis capabilities in INET. These two aspects point out the direction of code development and assessment, and also determine the data needs which support the validation activities including both code-to-code and code-to-test benchmarks.

(4) Develop importance ranking

This step is the heart of the PIRT process and is dependent on the phenomena lists identified in the last step. Each phenomenon, process, parameter, factor or characteristic was assessed according to its relative importance to one or more evaluation criteria. In the importance ranking process, a scale of low, medium and high was adopted due to its
easiness for application, as qualitatively defined in Table 1. Each phenomenon was assigned an importance rank by the expert panel with a discussion about the reasons of the assignment.

Table 1 Importance scale

<table>
<thead>
<tr>
<th>Importance</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (L)</td>
<td>Small effect on evaluation criteria</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>Moderate influence on evaluation criteria</td>
</tr>
<tr>
<td>High (H)</td>
<td>Dominant impact on evaluation criteria</td>
</tr>
</tbody>
</table>

(5) Assess knowledge level

Another important part of the PIRT process is scoring the knowledge level for each phenomenon to reflect the adequacy of analytical tools and test data. A qualitative scale of knowledge level, which was supplied by NRC during the NGNP PIRT process, was directly used by the INET experts. Definitions of the knowledge level ranks are given in Table 2. Each phenomenon was ranked as H, M or L, accompanied by the rationale for such assignment.

Table 2 Knowledge level scale

<table>
<thead>
<tr>
<th>Knowledge level</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (L)</td>
<td>0–30% of complete knowledge and understanding</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>30–70% of complete knowledge and understanding</td>
</tr>
<tr>
<td>High (H)</td>
<td>70–100% of complete knowledge and understanding</td>
</tr>
</tbody>
</table>

(6) Document PIRT results

The final product of the PIRT process is a set of tables, i.e., PIRTs, listing the plausible phenomena which may dominate the HTR-PM behavior during different conditions, and giving importance ranks as well as knowledge level ranks of these phenomena along with the ranking rationales. Nevertheless, these tables are not enough to convey all the information that will be needed by users and reviewers of the PIRTs. As a result, a special report providing excellent documentation of the whole PIRT process and the final results was prepared by INET and has been submitted to NNSA for peer review. The documentation includes PIRT issues, objectives, descriptions of the HTR-PM plant and accident scenarios, evaluation criteria, current knowledge base, ranking scales of relative importance and knowledge level, a set of PIRTs, and expert discussions and analyses of the PIRT process, results and its future application.

III.B. Typical PIRT results

Using the nine-step process, the PIRT expert panel established tables for the following HTR-PM scenarios: NO, PLOFC, DLOFC, air ingress, ATWS and steam/water ingress. A total of 73 phenomena were identified, assessed and ranked by the experts.

In the resulting tables, only the collective importance and knowledge level are averaged ones, representing a consensus from the participating experts. Some highlights of the discussions are given in the rationale columns of the PIRTs. In the PIRT process the expert panel noticed the following facts: the HTR-PM has entered the stage of construction design; major design features of the systems, structures and components have been fixed; analysis models have been established for detailed multi-circuits simulation; computer codes employed in the HTR-PM design and analysis have been benchmarked through various ways especially using the HTR-10 data; to resolve the safety-relevant issues, a large number of engineering verification experiments have been performed. As a result, knowledge levels of most phenomena were ranked as H or M.

A complete list of the identified phenomena and detailed descriptions of their ranks constitute a large body of information that is beyond the scope of a single paper. Accordingly, only some typical PIRT results are presented here by Table 3 as examples, including key phenomena in different scenarios, importance ranks and knowledge level ranks with the accompanying rationales.

IV. CONCLUSIONS

Based on the latest HTR-PM design scheme, a PIRT process was conducted on the subject of the HTR-PM accident analysis by an expert panel sponsored by INET. In the PIRT process, phenomena having significance to the plant behavior during different scenarios were identified. Additionally, each phenomenon was assessed and ranked with respect to its relative importance and current knowledge level. Finally, a special report was prepared to document all of the PIRT elements. The PIRTs will be used to evaluate the adequacy of existing computer codes and test data supporting the HTR-PM accident analysis, and to define the further requirements of code improvement and data supplement.

PIRT is an iterative process since it depends on the following aspects to a great extent: the HTR-PM design scheme; progress of the theoretical analysis,
out-of-pile experiments and plant operation experience. Therefore, the preliminary PIRTs will need revisions in the future, taking account of the latest achievements in code simulations and tests.

ACKNOWLEDGMENTS

This work has been supported by the Chinese National S&T Major Project (Grant No. ZX069).

REFERENCES

Table 3 Typical PIRT results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Phenomenon</th>
<th>Importance</th>
<th>Knowledge level</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>Coolant bypass flow</td>
<td>M</td>
<td>&gt;The coolant bypass flow determines the active core cooling and has great impact on the fuel temperature, but the maximum fuel center temperature will be far below its limit value during normal operation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO</td>
<td>Pebble flow</td>
<td>H</td>
<td>&gt;The pebble flow pattern affects the maximum fuel center temperature and the fuel burnup. &gt;Fuel pebbles may be entrained resulting in recirculation zones where pebble flow will be stagnant. &gt;Uncertainties of pebble flow are not so great in the HTR-PM due to its very tall single zone core.</td>
</tr>
<tr>
<td>PLOFC</td>
<td>RPV emissivity</td>
<td>M</td>
<td>&gt;This parameter dominates the heat transfer process from the RPV to the RCCS under accident conditions. &gt;Emissivity of the RPV inner surface may change due to the environment degradation.</td>
</tr>
<tr>
<td></td>
<td>Radiation heat transfer from the core top surface to the RPV upper head</td>
<td>M</td>
<td>&gt;This heat transport mechanism affects temperatures of the upper internals and the RPV upper head, thus having influence on the integrity of these components.</td>
</tr>
<tr>
<td>DLOFC</td>
<td>Core effective thermal conductivity</td>
<td>H</td>
<td>&gt;It is the major parameter affecting the maximum fuel center temperature under the DLOFC condition.</td>
</tr>
<tr>
<td>Scenario</td>
<td>Phenomenon</td>
<td>Importance</td>
<td>Knowledge level</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Residual heat distribution vs. time and space</td>
<td>graphite thermal conductivity which is determined by the crystal structures, neutron irradiations and temperature variations.</td>
<td>&gt;It is another major parameter affecting the maximum fuel center temperature under the DLOFC condition.</td>
<td>H &gt;There are many models and formulations describing the core effective thermal conductivity and the ZSB-R model is considered as the best one.</td>
</tr>
<tr>
<td>Air ingress</td>
<td>Molecular diffusion</td>
<td>&gt;Before the onset of natural circulation, air in the reactor cavity will enter the RPV through molecular diffusion. However, it is not so important to the fuel temperature due to the low transport rate of the oxygen. &gt;The diffusion process is very slow, so chemical reaction between the graphite and the oxygen is very slow. &gt;A number of factors can override the diffusion, including the operator actions, initial conditions and break locations.</td>
<td>M &gt;Under idealized conditions, the phenomenon can be well calculated. M &gt;Basic research on the topic of molecular dynamics has been carried out in INET.</td>
</tr>
<tr>
<td>Air flow from the VLPC to the reactor cavity</td>
<td>H &gt;If the air ingress accident is not mitigated, then this phenomenon will determine the long-term oxidation of the core.</td>
<td>H &gt;It depends on the VLPC performance and the pressure difference between the reactor cavity and other VLPC cavities. &gt;Design of the HTR-PM VLPC has been completed.</td>
<td></td>
</tr>
<tr>
<td>ATWS</td>
<td>Temperature coefficients of reactivity (including fuel, moderator and reflector)</td>
<td>H &gt;They provide the basis for the HTR-PM inherent safety features. &gt;The reactor self-shutdown under the ATWS condition is guaranteed by these parameters.</td>
<td>H &gt; Temperature coefficients of reactivity were measured on the HTR-10 and similar tests will be specially conducted on the HTR-TM. &gt;Negative temperature feedback effect was fully verified by the AVR dynamic tests and the HTR-10 safety demonstration tests.</td>
</tr>
<tr>
<td>Reactivity worth of the small absorber ball system</td>
<td>M &gt;Without the control rods insertion, the reactor may achieve recriticality under</td>
<td>H &gt;The reactivity worth was measured for the HTR-10 small absorber ball system</td>
<td></td>
</tr>
<tr>
<td>Scenario</td>
<td>Phenomenon</td>
<td>Importance</td>
<td>Knowledge level</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Steam/water ingress</td>
<td>Reactivity insertion due to steam/water ingress</td>
<td>The small absorber ball system is the standby means of reactivity control. &gt; The positive reactivity insertion decreases the control rod effectiveness. &gt; It depends on the amount of steam/water entering the primary system. &gt; Water will probably be converted to steam in the high temperature environment of the reactor, resulting in less reactivity impacts.</td>
<td>H &gt; Reactivity can be calculated if distribution of the steam/water is known. &gt; Bounding calculation is sufficient for the reactivity insertion.</td>
</tr>
<tr>
<td>Amount of steam/water ingress</td>
<td></td>
<td>The steam/water mass determines the following aspects: positive reactivity, pressure transition and remaining steam/water for the subsequent oxidation with graphite.</td>
<td>H &gt; Steam/water ingress is limited by the steam generator evacuation system. &gt; Bounding analysis is sufficient from the viewpoint of conservatism.</td>
</tr>
</tbody>
</table>