HTR-PM Safety requirement and Licensing experience

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Abstract – HTR-PM is a 200MWe modular pebble bed high temperature reactor demonstration plant which is being built in Shidao Bay, Weihai, Shandong, China. The main design parameters of HTR-PM were fixed in 2006, the basic design was completed in 2008. The review of Preliminary Safety Analysis Report (PSAR) of HTR-PM was started in April 2008, completed in September 2009. In general, HTR-PM design complies with the current safety requirement for nuclear power plant in China, no special standards are developed for modular HTR. Anyway, Chinese Nuclear Safety Authority, together with the designers, developed some dedicated design criteria for key systems and components and published the guideline for the review of safety analysis report of HTR-PM, based on the experiences from licensing of HTR-10 and new development of nuclear safety. The probabilistic safety goal for HTR-PM was also defined by the safety authority. The review of HTR-PM PSAR lasted for one and a half years, with 3 dialogues meetings and 8 topics meetings, with more than 2000 worksheets and answer sheets. The heavily discussed topics during the PSAR review process included: the requirement for the sub-atmospheric ventilation system, the utilization of PSA in design process, the scope of beyond design basis accidents, the requirement for the qualification of TRISO coating particle fuel, and etc. Because of the characteristics of first of a kind for the demonstration plant, the safety authority emphasized the requirement for the experiment and validation, the PSAR was licensed with certain licensing conditions. The whole licensing process was under control, and was re-evaluated again after Fukushima accident to be shown that the design of HTR-PM complies with current safety requirement. This is a good example for how to license a new reactor.

Keywords: HTR-PM, safety requirement, licensing experience, safety goal

I. INTRODUCTION

Chinese High Temperature gas cooled Reactor—Pebble-bed Module (HTR-PM) demonstration plant is started the construction in Dec. 2012, plans to put into operation in the end of 2017. This project is included in one of the sixteen Chinese National Key Science and Technology Projects. The main technical developer of this plant is Institute of Nuclear and New Energy Technology (INET), Tsinghua University. The EPC contractor is Chinergy Co. Ltd, the Utility company is Huaneng Shandong Shidao Bay Nuclear Power Company (HSNPC).

The main technical parameters of HTR-PM can be found in Table 1. More information can be found in reference 1.

HTR-PM adopts the pebble bed design, maintains modular concept which eliminate the possibility of large release of radioactive material into environment in case of accident, adopts the single zone core to simplify the structure design, adopts the steam turbine to reduce the market risk, adopts the configuration of 2 reactor modules coupling with 1 larger turbine to demonstrate the flexibility of unit power size.

The feasibility study of this project was started in 2001 after the successful operation of 10MW high
temperature test reactor (HTR-10), the standard design was launched in 2004, and main parameters were fixed in 2006, the basic design was finished in 2008, then the PSAR was submitted to National Nuclear Safety Authority (NNSA) for review, and the review of Preliminary Safety Analysis Report (PSAR) \(^2\) was completed in Sep. 2009. In 2006, the HTR-PM project was listed in the national medium-long-term Science and technology development program, the implementation plan was approved by the State Council in Feb. 2008. The first pour of concrete for HTR-PM was taken place in Dec. 9 2012, it is schedule to operate in the end of 2017.

II. LICENSING PROCESS

The PSAR was submitted to NNSA in April 2008, the review finished in September 2009 after the national nuclear safety expert committee approved the Preliminary Safety Evaluation Report (PSER). After Fukushima accident, the NNSA re-evaluated the HTR-PM again, the main change to the design is to increase the site seismic design level from 0.15g to 0.20g according to new geologic data.

During the PSAR review, more than 2000 questions were aroused by the reviewers, and 8 additional topics reports were requested. It was a hard work, but the whole review process progresses smoothly.

II.A. Regulatory framework in China

Although HTR has some special features like different coolant and different safety approach, there are no different licensing requirement for HTR plant in the world, and it is same in China. This means the licensing of HTR is based on current regulatory framework which is developed mostly from LWR experiences.

In China, the regulatory framework for NPP licensing is based on 3 layers structure. First layer is the national laws, the second layer is the safety requirement (namely HAF series), the third layer is the safety guideline (namely HAD series). Of course, below the safety requirement, there are additional layer of standards and norms for the design of component and systems, such as the national standards (GB series), industry standards (EJ series, NB series), and international standards such as ASME, IEEE, IEC are also adopted.

Of course, all these general requirement must be met in general, but according to the specialty of HTR, some of the articles in the requirement or standard are not applicable, or must be with some modifications, especially for the safety guide and industrial standard which are mostly developed for LWR. The difference or special consideration on the HTR licensing are considered by the licensing authority, as announced in the guideline for HTR-PM safety review \(^3\), before the start of the PSAR review.

Before the announce the review guideline, the detailed design criteria for HTR-PM key systems and components are developed by the designer, and were reviewed by the licensing authority, reached primary agreement. The design criteria covers the detailed design consideration and requirement of the systems and designs for HTR-PM, contains 40 chapters covering 40 different aspects or systems in HTR-PM, based on the design and licensing experience in HTR-10 project, and the preliminary technical specification of HTR-PM. This design criteria are based on old version that were developed for HTR-10 and verified in HTR-10 project, and reflect the newly development and progress of the nuclear safety requirement and industrial standards.

II.B. Licensing process

In China, the licensing of nuclear power plant are divided into 2 steps. First step is the application of Construct Permit (CP), by review of the PSAR. The second step is the application of the fuel loading permit, or operation permit, by review of the PSAR. In each step, the assessment of the environment impact report is also included, plus the assessment of some other special topic reports such as “Occupational health topic report”, “Occupational safety topic report”, “Fire control topic report”, and etc., by other government departments.

II.C. HTR-PM PSAR review

The review of HTR-PM PSAR lasted from April 2008 to September 2009. More than 100 reviewers are involved.

The main activities of review includes the question sheets from reviewers and the answers from the designers, combined with the dialogues meeting between reviewers and designers. More than 2000 working sheets and answers sheets are produced during PSAR review. And 8 additional topics reports for more detailed analysis on some selected topics are requested to be submitted to licensing authorities and reviewed, one example is the analysis of beyond design basis accident, another report is for scheme of the first core and running-in phase.

Finally the review result and main findings during the review process are evaluated and proved by the national nuclear safety expert commission, which are held in September 25-26, 2009, and then National Nuclear Safety Authority issued the Construct Permit for HTR-PM in 2012. The delay is partly because of national safety re-evaluation plan after the Fukushima accident.
III. MAIN ACCIDENT AND SAFETY FEATURES OF HTR-PM

The inherent safety features for modular HTR is well accepted for HTR community, because under all accident condition, the fuel will retain almost all the fission production, no need of active engineering safety features, and the consequence to the environment is limited. As a result, the off-site emergency plan is not necessary from the technical viewpoint.

However, the safety of HTR-PM must be verified by the safety analysis. According to current Chinese Safety requirement, the safety analysis must be done with deterministic procedure plus the probabilistic safety analysis.

The philosophy for deterministic safety analysis for HTR-PM is same as in for the LWR, such as the classification of accidents is based on the frequency of initial events, combined with the pre-determined acceptance criteria for each category of accidents, by assuming the availability of safety class of engineering safety features, with conservative assumption on the input and the model.

In the other side, the PSA are requested to be done to get the overview of the safety performance of the HTR-PM, and also help the selection of the initiating events.

III.A. Accident overview

Following the same philosophy in LWR, the operation conditions of HTR-PM is classified as the normal operation (NO), anticipated operation occurrence (AOO), design basis accident (DBA). Other operation conditions are classified as beyond design basis accidents (BDBA). NO, AOO and DBA are classified and analyzed according to the occurrence frequency of the initiating events, and their radioactive consequence must meet the acceptance criteria of each type of accident according to the deterministic approach philosophy, with the help of accident mitigation of engineering safety features.

The engineering safety features are designed to mitigate the consequence of the AOO and DBA, and requested to be qualified as safety class.

In HTR-PM, the type of accident can be classified by other criteria, and can be classified into categories of the general reactivity accident, increase of heat removal from primary circuit, decrease of heat removal from primary circuit, loss of forced cooling accident (LOFC), water ingress accident, air ingress accident, ATWS, and the accident in auxiliary system. For HTR, the reactor is not sensible for the loss of coolant, also the fuel temperature will reach the maximum value in the case of depressurized LOFC (DLOFC) accident, and no safety class emergency core cooling system is required. Therefore the DLOFC is a remarkable accident which is used to evaluate the maximum fuel temperature and is used to evaluate capability of the cavity cooling system which is used to transfer the decay heat from the core to the environment after the reactor is shutdown. Although the maximum fuel temperature will not exceed the design limit even though the cavity cooling system is failed even in the case of DLOFC, in the case of HTR-PM, the cavity cooling system is design as the safety class system.

Besides the trip of reactor and helium circulator, the following safety engineered safety features are designed for HTR-PM, such as the isolation of the secondary circuit, isolation of pipes connected primary circuit, dump of steam generator in case of steam generator tube rupture accident.

The consequence of BDBA is evaluated by PSA, and all systems with safety class or non-safety class can be used to mitigate the consequence for BDBA. The acceptance criteria for BDBA is the probabilistic safety goal defined by the safety authority, as discussed later.

III.B. LOFC accident

LOFC is the typical accident for modular HTR. Normally the depressurized LOFC (DLOFC) accident will cause the maximum fuel temperature, because all the coolant are lost and the decay heat is removed only via conduction and radiation through the pebble bed, then through the graphite reflector and core internal and pressure vessel. While the pressurized LOFC (PLOFC) will cause the highest pressure vessel temperature because the decay heat will transferred to the pressure vessel more rapidly with the help of natural circulation of helium besides the conduction and radiation in the pebble bed.

In HTR-PM, the DLOFC is evaluated as the enveloping accident for the maximum fuel temperature, and the PLOFC accident is evaluated to determine the temperature margins for the reactor pressure vessel and the capacity of the decay heat removal system (sometimes also referred as the cavity cooling system). As one of design basis accidents, the consequence of DLOFC and PLOFC in HTR-PM is acceptable.

PLOFC accident indicates no loss of coolant. And DLOFC accident indicated the break of pipe connected with pressure vessel and the total loss of all coolant. But DLOFC does not mean that environment air will come to reactor core, or air ingress accident, because the air is difficult to come into the reactor core through one break in pipe.

III.C. Water ingress accident
Another category of interested accident in HTR is water ingress accident, which is caused by the break of steam generator tubes, and water from secondary circuit will flow into the reactor core, and cause the change the reactivity, and cause the corrosion of graphite in fuel element and reflector, and maybe cause the opening of the safety valve in primary circuit, and release some radioactive material into the environment.

Water ingress accident is mitigated with the dumping of steam generator to reduce the amount of the water entering the primary circuit, after the shutdown of the reactor and isolation of the secondary circuit. And water ingress accident be further mitigated by the water removal capability of the helium purification system to reduce the corrosion, and by the pressure adjustment capability of the helium supporting system to avoid the opening of safety valve. These late two measures are classified as non-safety class in the safety analysis, but it can reduce the accident consequence, and are be analyzed in PSA, can be treated as measure of as low as reasonable achievable (ALARA) principle.

### III.D. Air ingress

Air ingress accident is another important accident for HTR. Although it is not classified as design basis accident (DBA) according to its occurrence probability, it is analyzed during PSA as the BDBA, and the frequency and consequence are summed to total risk and probabilistic safety goal. The hypothetic initiating event for air ingress accident is the break of the one pipe connected to the bottom of RPV and another pipe connected to the top of RPV, therefore the chimney effect in core can take place. Another hypothetic initiating event for air ingress accident is the break of hot gas duct, therefore the natural circulation of air through the core can take place after the helium in the core are diffused out long time later. The probability of these two events are very low, the consequence of this type of accident are analyzed just to determine whether the emergency plan is necessary or not.

As one of BDBAs, the consequence of air ingress accident can be tolerated within 72 hours to avoid the offsite emergency plan actions. Therefore there are enough time to take countermeasure to mitigate the consequence, such as to prevent the air ingress, and to filter the release.

### III.E. Source term

The source term are analyzed for each accident sequence.

Acceptance criteria are defined for AOO as 0.25mSv/plant-year, and 5mSv for each rare event and 10mSv for each limiting event, all of them are defined at the plant site boundary. The rare events and limiting events are two sub-categories of DBA.

More detailed analysis of source term are included in the PSA and environment impact report.

In HTR-PM, the radioactive release will be very small, as the direct consequence of the break of the primary circuit. After the break of primary circuit, the radioactive material in the released helium and graphite dust is also limited because of the high quality of the modern TRISO coated particle fuel during normal operation and accident conditions. The additional failure of TRISO particles and following enhanced release of fission production is also limited according to the heating up experiment of TRISO fuel. And the filtration function of cavity ventilation system can reduce the Iodine release efficiently because of the long tolerance time of several days. In the case of water ingress accident, steam will increase the release of the fission product from the failed particles, and the source term are analyzed for the consequence of the opening of safety valve of primary circuit, if the pressure control function of the helium purification and supporting system doesn’t work after long time. The biggest source term are expected for the air ingress accident which will corrode the fuel matrix, and may increase the failure rate of the fuel particle, then increase the release of the fission product. Although air ingress accident is classified as the BDBA with very low probability, the dose at plant site boundary is also lower than 50mSv, which is the limit for evacuation.

Actually the source term are analyzed for each accident according to its power, temperature, release profile of each accident, one simple criteria are also used to briefly assess the release. That criteria is the maximum fuel temperature. In the case of HTR-PM, the limit of 1620°C are used, and this limit are not exceeded for all accidents with enough margin. And the uncertainty for this maximum fuel temperature are also an interested topic during PSAR review, and are deeply investigated by the designer, and be treated as one topic for IAEA CRP on HTGR modeling uncertainty.

### III.F. Safety features

In the safety analysis for HTR-PM demonstration plant, both deterministic and probabilistic approaches are required and implemented.

Deterministic approach means the traditional safety analysis with some pre-defined conservative assumption and deterministic acceptance criteria. For example, the classification of the accidents according to occurrence frequency, the acceptance criteria for each class of accident, and the safety class.
engineering safety features for each accident to mitigate the consequence in order to meet the requirement of the acceptance criteria.

The probabilistic approach means the probabilistic safety analysis (PSA), with the defined probabilistic safety goal, and the thorough evaluation of the accident spectrum and release of each accident consequence. For PSA, the best estimation model can be used, and all systems including non-safety operating systems can be used to mitigate the consequence according to its availability and functions. Finally the answer whether the probabilistic safety goal is reached or not must be given by PSA. Of course the PSA can do more in the project as discussed in section IV.D.

According to HTR-PM PSAR report, both the deterministic and probabilistic safety criteria are met, and the result are accepted by NNSA.

IV. MAIN TOPICS AND CONCLUSION IN LICENSING

During PSAR review, there are many topics are discussed, evaluated, assessed, and many additional analysis and explanation are requested. Some topics are listed in following.

IV.A. Safety goal

The most important topic is to show what kind of safety level HTR-PM can reach to.

The simple requirement is that no offsite emergency plan is needed.

The detailed requirement is defined by the safety authority and verified by PSA. That is, the total frequency for accident sequences whose consequence is larger than 50mSv at the plant site boundary must be lower than $10^{-5}$/reactor-year. The 50mSv is chosen because it is the limit for the action for evacuation. The index of $10^{-5}$/reactor-year is chosen because it is used in URD and EUR, although it corresponds to a different dose limit. And the index of $10^{-5}$/reactor-year is a reasonable value which is achievable and is within the knowledge of the probabilistic expert. Of course, according to the final PSA result, the achieved frequency referring to larger dose release is much lower than $10^{-5}$/reactor-year.

Therefore the goad to technically eliminate the off-site emergency plan is achieved.

IV.B. Containment

To describe the structure to contain the reactor, in the community of LWR, the containment is usually used. But in the community of HTR, the terminology of confinement is usually used. How to choose the terminology is one issue, how to define the requirement is the real issue. Finally the safety authority named it as the Vented Low Pressure Containment (VLPC) for HTR-PM project.

Actually the safety authority and the designer reached to agreement to the function requirement to this structure first, such as to support the RPV, to physically protect the reactor, to shield the neutron and gamma ray from the reactor, to maintain the sub-atmosphere condition during normal operation to limit the air activation, to discharge the quick release of helium in case of large break of primary pipe to protect the cavity itself, and to provide the possibility to filter the release during the later-on core heating up phase. According to the function requirement and source term results for the primary circuit break accidents, the safety classification for the accident cavity ventilation system is changed from safety class to non-safety class during the licensing phase, this change reflected the rationality of the safety authority, and the confidence to the safety features of HTR-PM both from the viewpoint of designer and safety authority.

IV.C. Standards

The norms and standards used in the HTR-PM design are another important topic. Based on the generic safety requirement defined by the national laws and safety requirement and safety guide, which is developed from the experience of LWR, but is generally applicable for both the LWR and HTR. In another side, the design norms and standards for the systems and components for HTR may have particularities, because HTR have special TRISO coated particle fuel, special ceramic core internal, special coolant helium, special pebble bed core, special structure for control rod and small absorber sphere system, special reactor shutdown philosophy, special structure and temperature range for steam generator, special design for the reactor cavity, and etc., besides the similar or same requirement for the pressure boundary, for the instrumentation and control system, for the electric system, and for civil structure, etc.

Therefore, for the norms and standards, the ASME is generally applicable, the IEEE and IEC standards are applicable also, and equivalent Chinese national standards and nuclear industry standards are applicable for HTR-PM project, and some KTA standards concerning graphite structure in pebble bed reactor, concerning property of helium and pebble bed core are also adopted in HTR-PM project. This arrangement were discussed with the safety authority, and were endorsed by the safety authority before the start of the licensing process. And most important experience for HTR-PM is that the design criteria for HTR-PM were drafted out early by the
IV. PSA

It is new experience for the HTR-PM designer to carry out PSA. The safety authority required the PSA, and encouraged to extend the PSA to whole design process, in order to achieve the balanced design, and to show what kind of safety level can reached, by verification of probabilistic safety goal.

Because of the safety features of HTR-PM, no core melt and large release of fission product are expected, normal process of PSA level 1, PSA level 2 and PSA level 3 are not applicable for HTR-PM. The PSA experts in HTR-PM project developed integrated PSA procedure to directly identify the frequency of each accident sequence and the dose release to the environment, directly the risk of each accident. This result can directly verify whether the probabilistic safety goal is achieved or not.

Another example of integration of PSA with design is to help to select the initiating events, both for PSA evaluation, and for the classification of design basis accidents.

Another difficulty for PSA in HTR-PM is how to evaluate the failure rate or availability of the passive system, such as the cavity cooling system with pure natural circulation without any passive components. The main idea is to identify the failure probability according to the probability for out ranging of physical parameter which will cause the failure of system, for example much higher environment temperature may cause the boiling of the water in the cavity cooling system which may stop the natural circulation.

IV.D. Verification and Validation

Verification and validation (V&V) on safety analysis software is a long term work. It is required by the safety authority. Although many of safety analysis software are widely used by many institutes, have long experience of validation and benchmarking activities based on experimental facilities and reactor worldwide, some V&V work are being done in INET, including the analysis the code and theoretical manual itself, improvement on the models, additional benchmarking calculation on new data from experimental facilities and HTR-10 operation history, and etc. The result are reported to the safety authority continually.

The international cooperation also contributes to the V&V activities, for example exchanging of experimental data, benchmarking calculation, comparison between different software from different sources.

VI. CONSTRUCT PERMIT CONDITIONS

After finishing the review of PSAR, and issuing the construct permit, safety authority requires the licensee to continuously report the progress concerning the HTR-PM safety analysis, including the new progress on V&V activities, detailed analysis on first core and running-in phase, revision on the technical specification, more detailed seismic analysis, the progress on the fuel element radiation experiment, and etc. Early involvement and regulation along design process is the good experience and practice of NNSA. This follows the good practice in the joint development of the HTR-PM design criteria between designer and safety authority before the licensing process.

As the world first modular HTR power plant which want to eliminate the necessity of off-site emergency plan and has little operation experience, the licensing process has many challenges, both from the viewpoint of the designer and of the safety authority.

Based on the experience of HTR-10, and the development of new licensing philosophy and requirement worldwide, NNSA successfully reviewed the PSAR within one and a half years. The good practices can be summarized as: early involvement, early development of the design criteria, early definition of the review guideline, early definition of the probabilistic safety goal, regulation and surveillance on whole design and construction phase.

Some topics aroused in the PSAR review process also are good experiences for licensing of a new power plant, such as the requirement for VLPC, the deterministic plus probabilistic approach, the definition of the probabilistic safety goal, the continuous requirement for verification and validation, the integration of PSA into design, and etc.

In a summary, through the licensing of HTR-PM, high level of safety are achieved, from both the deterministic and probabilistic viewpoint. Regardless
of the inherent safety, the real challenges from the viewpoint of designers are the availability of the active components, and the availability of the plant, which will be demonstrated by the operation of HTR-PM, and can be further improved through the operation experience feedback.

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REFERENCES


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