Proceedings of the HTR 2014
Weihai, China, October 27-31, 2014
Paper HTR2014-71314

Control room conceptual design of nuclear power plant with multiple modular high temperature gas-cooled reactors

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Abstract-A conceptual design of the control room layout for the nuclear power plant with multiple modular high temperature gas-cooled reactors has been developed. The modular high temperature gas-cooled reactors may need to be grouped to produce as much energy as a utility demands to realize the economic efficiency. There are many differences between the multi-modular plant and the current NPPs in the control room. These differences may include the staffing level, the human-machine interface design, the operation mode, etc. The potential challenges of the human factor engineering (HFE) in the control room of the multi-modular plant are analyzed, including the operation workload of the multi-modular tasks, how to help the crew to keep situation awareness of all modules, and how to support team work, the control of shared system between modules, etc. A concept design of control room for the multi-modular plant is presented based on the design aspect of HTR-PM (High temperature gas-cooled reactor pebble bed module). HFE issues are considered in the conceptual design of control room for the multi-modular plant and some design strategies are presented. As a novel conceptual design, verifications and validations are needed, and focus of further work is sketch out.
Keyword-High temperature gas cooled reactor; Multiple modules; Control room design.

I INTRODUCTION

Modular High temperature gas cooled reactor (MHTGR) [1-2] is a promising solution to meet future energy needs. Due to the design aspects of the MHTGR, the electrical output of an individual reactor module is relatively small compared to that of a typical commercial nuclear power plant. However, reactors can be grouped to produce as much energy as a utility demands due to the economic benefits, which form a nuclear energy system with multiple modules [3-4].

The configuration of a multi-modular plant is different from current NPPs, the differences include the layout of the infrastructure, integral placement of primary coolant system component and shared systems or resources among modules, the instrument and controls [5-6], etc. Due to the differences of the multi-modular plant and current NPPs, the U.S. Nuclear Regulatory Commission (NRC) conducted research to examine the human factors engineering (HFE) and the operational aspects [7] of small modular reactors (SMR). The research identified some potential human-performance issues that should be considered in NRC's reviews of small modular reactor designs and in future research activities. These issues include: multi-unit operations and teamwork [8-9], staffing mode and staffing level, control room configuration and workstation design, human-machine interface (HMI) design [10] for multi-unit monitoring and control, operational impact of control systems for shared aspects [11] of SMRs, etc.

The demonstration construction [12] of the Chinese design of MHTGR, named as high-temperature gas-cooled reactor-pebble bed module (HTR-PM) in Shandong province has resumed in December, 2012. The HTR-PM plant consists of two nuclear steam supply systems (NSSS), which are the modules. Each module includes a single zone 250MW$_{th}$ pebble-bed modular reactor and a steam generator. The steam generated by the two NSSSs respectively feeds one steam turbine generating an electric power of 210MW.

Based on the current design aspect of HTR-PM, this paper analyzed the challenges of human factor engineering in the control room of the plant with multiple HTR-PMs, and presents a conceptual design of control room layout. As there is no operating experience from predecessor plants for the multi-modular plant, all the design concept need to be further verified.

II HFE ISSUES IN THE CONTROL ROOM FOR A PLANT WITH MULTIPLE HTR-PMS

The two-modular HTR-PM employ a single control room as the control center of the plant, and the multi-modular HTR-PM may use only one control room to avoid the communication difficulty between operators in different control rooms.

In the control room, multiple modules may be operated by one operator (crew). The challenge to the operator lies in monitoring such a control system to confirm that individual modules and shared system are performing properly, and that there are no degradations of the I&C system.

The main differences between the multi-modular plant and current NPPs are shown in Table 1. The HFE challenges of the multi-modular HTR-PM may include the staffing level, situation awareness and workload of the operator, and the HMI designs, etc.

Table 1 Operation differences of multi-modular HTR-PM and current NPPs

Items	Multi-modular HTR-PM	Current NPPs
Number of modules operated via one control room	multiple	single
Number of modules operated by one operator (crew)	multiple	single
Staffing level	unknown	4-5
Shared system	some	none

II.A Staffing level

Staffing level [13] here refers to the number of operators in the control room and the roles and responsibilities of each operator.

In a regular NPP, 4 or 5 operators are needed in one control room, including the reactor operator, turbine operator, etc. All the operators are focus on one reactor or one unit. In the multi-modular plant, may be the number of operators is roughly equal with current NPPs, but the operators may have to focus on different modules or units, which is the most different.

The current regulation for staffing level may be not proper for the multi-modular plant. However, the policies at present are not clearly shown that one operator is allowed to operate more than one module. Therefore, the staffing level in the control room of the multi-modular plant need to be further verified.

II.B Situation awareness and workload

Situation awareness is so important for the operators in the control room. In regular NPPs, the operator should maintain situation awareness of a single unit to ensure that they would not neglect the important changes of the plant; in the multi-modular plant, the operator should maintain sufficient situation awareness of each unit, which is a challenge to tax crews and individual operators and increase the mental workload of the operator.

II.C HMI design

For the regular NPPs, the HMIs supply the operator with parameters and controls of the whole plant. In the multi-modular plant, the function of HMIs is the same. The challenge lies in that how the detailed HMI design, including the alarms, displays and controls enable a single operator or a crew to manage more than one module.

There are two considerations of the HMI design. The first arrangement is that HMIs for each module are separated from others; the second arrangement is the HMIs for all modules are integrated. Each arrangement has its own advantages and disadvantages. For example, if the HMIs for each module are separated, the operator may neglect other modules when focus on one module; if the HMIs are integrated, the risk of confusion between modules is increased.

The challenges of the HMI design is that how to help operator keep situation awareness of each module and the whole plant.

II.D Other HFE issues

There are other HFE issues associated with the multi-modular plant, such as the team work, control of shared systems, different status of each unit, etc., which also have potential to impact human performance.

For the multi-modular system, the concept of operations is in the preliminary stages, control room and HSI designs are all in conceptual phase. However, the further studies should be focused on the issues above.

III CONCEPTUAL DESIGN OF THE CONTROL ROOM

III.A Function analysis

According to the standards and guidelines [14], the design of control room of a nuclear power plant is a systematic process, which starts with the function analysis and assignment (FA&A).

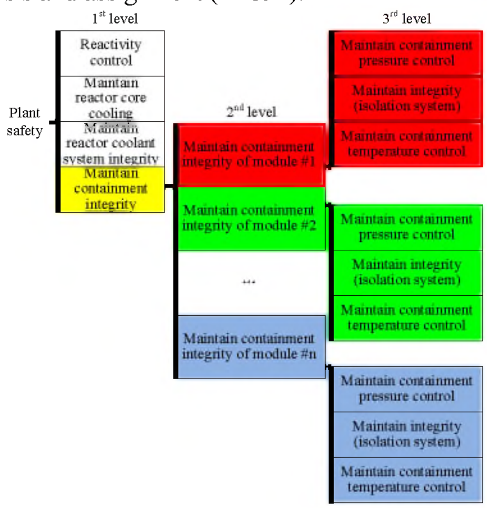

Fig. 1 Function analysis of the multi-modular plant

The top goals of the plant include the safety goal and the availability goal. However, the multi-modular design has its own characteristics. An example of sub-goal decomposition on the first level of maintaining containment integrity is shown in Fig. 1. On the second level, the goal can be decomposed into two sub-goals: maintaining containment integrity of the two modules, respectively. On the third level, the sub-goals of the modules are the same, and the follow-up function decomposition of the plant safety can be done only to one module, because other reactor modules are exactly the same, and some applicative experiences can be adopted from the research project of HTR-10 [15] as a single unit.

III.B Function assignment consideration

Based on the design characteristic of HTR-PM, including the inherent safety, the passive residual heat removal, etc., the function allocation between automation and human being is as follows:

1. Benefited from the digital I&C system, the operation of the plant are highly automated, while some functions of low action frequency are controlled manually, such as the operations of reactor start-up and power control under low level.
2. The initiation of reactor protection and engineering safety features are automatically, with the manual controls as backup.
3. The non-safety automation functions are all started and directed by the operators in the control room, under close monitoring and supervision. The operators can intervene the automation if necessary.

The automation will be used extensively in the multi-modular HTR-PM and no rapid actions are needed.

The function analysis shows that the plant goal can be decomposed into several set of the same sub-goals of the reactor modules respectively. Thus, the functions of HMIs for the reactor modules should be the same.

III.C Modular design of HMIs

The independent HMIs for a single module are “modular” designs of the control console. The HMIs for one module are independent with others.

For an individual module, the minimized HMIs are considered to involve functions as follows:

1. Safety manual initiations for reactor trip and engineering safety features as the backup of the automatic protection action.
2. Safety monitoring for protection parameters.
3. Safety monitoring for post-accident parameters.
4. The normal monitoring and operation of the reactor module.

As a conceptual design, the basic monitoring and control of one HTR module can be realized through a console in Fig. 2.

Monitoring and control of an individual module can be done here by one operator. The non-safety visual display units are driven by the computer of the distributed control system (DCS), and the operator can get any information he need through the displays. The safety visual display units are used to monitor the protection parameters and to do post-accident monitoring.

The indicators for important signals are set on the console too, such as reactor trip, the initiation of the engineering safety features, etc.

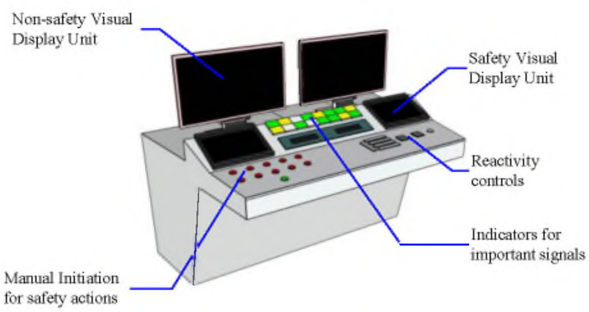

Fig. 2 A control console for one reactor module

Besides the small control consoles, the large display panels in the front of the control room should be employed to give the operators an overview of the whole plant. The large display panel can be designed modularly, and the large display for one module can be designed identical with other modules, and the display in front of the control console is dedicated for one module.

According to the experience of the two-modular HTR-PM, the large display may be composed of the mimic displays and alarm tile displays. Compared with flexible large screen displays [16], the mimic displays supply the personnel spatially dedicated continually visible (SDCV) displays [17], which support rapid detection and enhanced pattern recognition. The position of the mimic displays is fixed, and cannot be switchover. The operator can easily get information without interface management. The position of each device on the mimics is fixed, and can be easily found by a glance, not like the devices displayed in the computer screens, the position of a device is different in one page from that in other pages.

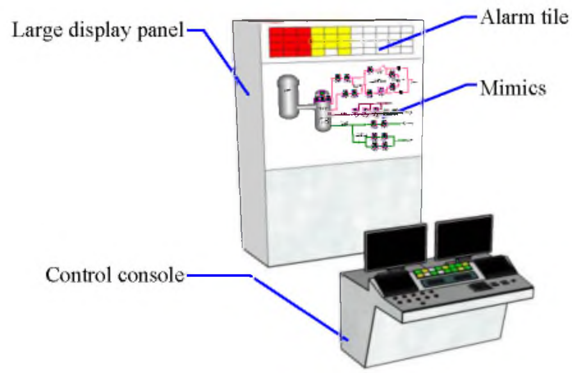

Fig. 3 Control console and display panel for one reactor module

The control room can be composed of some reactor control consoles and large display panels in Fig. 3 and a console and panel of the turbine and other common system control. The number of the reactor control consoles and large displays is depending on the number of the module in the plant.

The arrangement in the control room can be realized in the form of Fig. 4. In Fig. 4, different colors refer to HMIs for different modules. HMIs for each module are identical with each other, including the control console and display panel in the front. The HMIs of one module are independent with others.

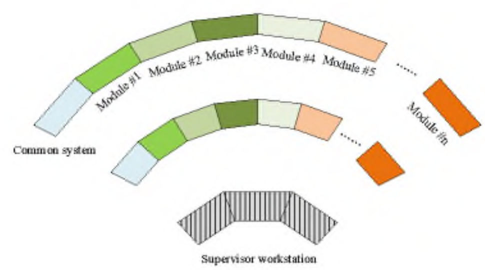

Fig. 4 Conceptual layout of the control room

III.D Advantages of the modular design of HMIs

This modular arrangement of HMIs has many advantages:

1. The number of module in the plant can be scaled due to the utility need, and the number of control consoles also can be scaled under this modular design of HMIs.
2. Enable the flexibility of staffing level change. At present, the staffing level of the SMRs have not been finally determined, compared

with that integrated design, this style enables one operator operate one module or more.

3. Avoiding the confusion between modules operated by one operator.
4. The mimic displays in front of the console help the operator keep an overview of the whole plant, not only focus on the current modules, but also other modules.

IV DISCUSSION AND FURTHER WORK

IV.A Current work

The two-modular HTR-PM is under construction at present. As the first plant with two module-reactor coupled to one steam turbine, there is little operating experience, and the verification and validation are very important. A verification platform is designed and realized, as shown in Fig.5.

The room area of platform is exactly the same as the real control room of the project, and the HMIs are the same too. The V&V of the HMIs can be done here, and the improvement of the design will be developed according to the result of V&V.

The static validation is finished, such as the validation of the font size of the tile, the view angle of the symbol, the color contrast of the displays, etc. The dynamic validation associated with the operation procedures and models of plant and process is under development.

Fig.5 A picture of the V&V platform of the two-modular HTR-PM

IV.B Discussion and Further work

The plant with multiple modular reactors is under development, the staffing level, the work load of operators, situation awareness and teamwork will be the focus in the HFE review.

This modular design of HMIs presented in this paper needs to be further verified, such as the number of displays, and the team work of the crew under this design of HMIs.

V CONCLUSION

Based on the design characteristics of HTR-PM, a conceptual design of control room for the nuclear plant with multiple HTR-PMs is presented. A modular design concept of control console and large display panel are presented. The control room of a plant with multiple reactor modules can be realized by assembling some identical control consoles and panels. The number of the consoles and panels can be scaled according with the number of the reactor modules. It is a promising solution for control room design of the multi-modular plant.

ACKNOWLEDGMENTS

This work has been supported by the National S&T Major Project (Grant No.ZX06901), and Tsinghua University Initiative Scientific Research Program.

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