nature portfolio

Peer Review File

Testing the Feasibility of Multi-Modular Design in an HTR-PM Nuclear Plant

Corresponding Author: Dr Zhe Dong

Parts of this Peer Review File have been redacted as indicated to remove third-party material.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This is an excellent paper on an important subject for development and deployment of multi-modular SMR worldwide that want to rely on shared equipment (e.g. control room or BOP).

Please increase the size of Fig. 1c)

Please have the English and the use of specific technical terms checked by an I&C expert. (e.g. correct “inertial” by “inertia”)

p.2: you mention that a steam temperature of 520°C was achieved, which is a deviation from the originally targeted 540°C, and you say that with an equilibrium core you expect an improvement. It would be positive if you could provide the temperature profile of helium and steam along the heat exchange surface in the steam generator to understand whether the reason is possibly the steam generator design.

p.2: you mention that the loss of cooling tests have been performed with initially full power. Was the core already at equilibrium for these tests and if not, what would be the effect (e.g. on afterheat directly after scram)? Maybe explain that similar tests had been conducted in other HTGR in the past, but not from full power (please check if this is correct, e.g. AVR, HTTR...).

Fig. 3: Are the sensors of Reactor Module #2 connected to a separate CCS or to the same as for #1? If they are separate, how do the two CCS talk to each other? Is there a redundancy of sensors and if so, do you use e.g. a 2 out of 3 logic in the CCS to avoid unnecessary reactor scrams? What is the physical shape of the CCS? Is it a Programmable Logic Controller (PLC)? Please explain more about its capabilities and whether it is redundant (e.g. like on airplanes).
The CCS seems to be an active component ensuring the operability and to some extent the safety of the multi-module plant. Have you analyzed what will happen if the CCS itself malfunctions? Have you analyzed the reaction of the CCS in case of component failure (e.g. assuming a pump seizure)? What are the requirements on the CCS imposed by the nuclear regulator?

Section 2: It is not completely clear what are “controllers” and what are sensors. It is also not clear what input data is measured (e.g. temperature, flow-rate) and which parameter is changed (output) to control them. For instance, do you control the reactor power by modifying the helium pressure or by modifying the helium flow-rate or both? Is the power control of both modules connected or separate?

Section 2.1: why are the steam outlet temperatures the most sensitive process variables?

Fig. 6: In the beginning of the transient, the hot He and SG outlet steam temperatures are 553/520°C whereas the cold He/SG feedwater inlet temperatures are 245/161°C. Isn’t the resulting pinch point temperature difference in the Steam Generator then a bit small? Could this explain the lower than expected SG outlet steam temperature?
Wasn’t the initial idea to achieve a hot He temperature of about 750°C? Wouldn’t this then also affect the passive coolability of the reactor core?

Section 2.3: Not clear which “transducer” you mean. Did you simulate a failure of the primary helium flowrate sensor in the #1 reactor (assuming no redundancy of sensors)? Note that for this test, the reactor power is not 100%.

Section 3: You explain the benign behavior of the multi-module HTR-PM. From the data presented in the paper, one may conclude that much of this positive outcome depends on the high thermal inertia of the reactor cores due to the graphite mass. You seem to conclude, however, that a “well-designed coordination mechanism can guarantee the stable operation for multi-modular SMR” in general. Wouldn’t it be advisable to limit this conclusion to reactors with a similar power density/thermal inertia ratio? E.g. would fast reactor SMRs with higher power density and less thermal inertia in a multi-module configuration react in a similarly benign manner? Please make a statement on this matter.

Section 4: Your study looks essentially at power plants with shared BOP equipment. However, what is equally important for multi-module plants is the capability to use a single control room with limited staff for several modules. Can you possibly make a statement on this as well based on your experience?

Section 5.1: you mention a hot helium temperature of around 700°C, which is much higher than what we see in the figures in Section 2. Please explain.
In the set of equations, it is not clear how the time dependence is incorporated. E.g. how do you consider the inertia of the helium blowers in the helium flow-rate control?

Reviewer #2

(Remarks to the Author)
The manuscript explores the practical verification of a multi-modular nuclear power plant scheme using the HTR-PM. Comprising two reactor modules driving a single turbine, the HTR-PM demonstrates the feasibility of coordinated control during power ramping, turbine trips, and reactor trips. The study highlights the significance of multi-modular coordination in achieving economic and safe operation for large-scale deployment of SMRs, setting a precedent for future advancements in nuclear power plant designs.

Overall, the manuscript is scientifically sound, novel, and highly relevant to the field. With a few enhancements, it can make a more compelling case for the practical adoption of multi-modular SMR schemes.

My comments:

1. While the novelty is evident, it would benefit from clearer articulation of how the findings advance or challenge existing knowledge in SMR development.
2. Highlighting specific innovations in the CCS design or its adaptability to other reactor types could strengthen the manuscript's impact.
3. Broaden the discussion to include how this approach can inform future SMR designs.
4. Expand on the potential implications for policy, regulatory frameworks, and commercialization in the nuclear energy sector.
5. Add quantitative comparisons to strengthen claims of economic and operational benefits.
6. Provide a clearer articulation of the manuscript’s novelty and contributions.
7. Address broader implications for the nuclear power industry, including potential adoption challenges.
8. Discuss the adaptability of the findings to different reactor types and global energy strategies.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I have looked at the authors’ responses to Reviewer 1 and I would like to acknowledge their effort in improving the paper accordingly.
The comments by Reviewer 2 are more high-level trying to increase the overall reach and impact of the paper, but I understand, also there the authors have made a significant effort.

I am fine with the revisions.
Thank you again for the opportunity to review this interesting paper.

Reviewer #2

(Remarks to the Author)

Responses to the Comments

The authors would like to thank deeply to the reviewers for the positive evaluation and constructive comments. The authors have revised the manuscript carefully according to these valuable comments, and the detailed responses to the comments are given as follows.

Responses to the Comments from Reviewer 1

Comment 1: This is an excellent paper on an important subject for development and deployment of multi-modular SMR worldwide that want to rely on shared equipment (e.g. control room or BOP).

Response: The author would like to thank deeply for the positive evaluation on the result of this paper, giving a great encouragement to the authors. To guarantee the economy of small modular reactor (SMR) plants, it is recommended to apply the multi-modular scheme, where the steam flows from multiple SMR-based nuclear steam supply (NSSS) modules are combined together before driving the common load equipment for power generation or cogeneration. The coordinated control is key in providing safe and stable operation for the multi-modular SMR plants. The test results presented in this paper confirm the feasibility of multi-modular scheme for the first time, showing the promising future in building large-scale nuclear power plants (NPPs) with a system of SMRs. This manuscript has been revised according the constructive and insightful comments provided by Reviewer 1.

Comment 2: Please increase the size of Fig. 1c)

Response: Thanks for the comment. The size of Fig. 1(c) has been enlarged in the revised manuscript for showing the layout of the nuclear island clearly.

Comment 3: Please have the English and the use of specific technical terms checked by an I&C expert. (e.g. correct "inertial" by "inertia")

Response: Thanks deeply for this advice in enhancing the language and the use of technical terms. In the revised manuscript, the authors have corrected "inertial" by "inertia", and have consulted I&C experts to improve the English and the use of specific technical terms.

Comment 4: p.2: you mention that a steam temperature of 520°C was achieved, which is a deviation from the originally targeted 540°C, and you say that with an equilibrium core you expect an improvement. It would be positive if you could provide the temperature profile of helium and steam along the heat exchange surface in the steam generator to understand whether the reason is possibly the steam generator design.

Response: Thanks for the valuable comment on the operation point of steam temperature. Actually, the deviation of steam temperature is not caused by the temperature distribution along the heat exchanging surface of the steam generators, but is caused by the hot helium temperature. Currently, the two HTR-PM reactor cores are in the transition phase to their equilibrium stage with a large amount of graphite spheres to be replaced by fuel elements, giving that the current hot helium temperature at the reactor outlet is lower than that of an equilibrium reactor core. Thereby, the operation point of steam temperature is set to be 520℃ currently. When the reactor cores reach their equilibrium state, the hot helium temperature can be further improved observably, and steam temperature can reach the expected value of 540℃. As there is no temperature sensor such as thermal couple arranged along the heat exchanging surfaces of the steam generators, it is not possible to give the measurements of helium and steam temperature profile along the heat exchanging surfaces, but the temperatures of hot helium flow, cold helium flow, feedwater flow and motive steam flow at the primary and secondary inlets and outlets of the steam generators are provided in the test results.

In the revised manuscript, the above discussion about the steam temperature has been briefly added to the end of second paragraph in Section 1. Thanks again for the valuable comment.

Comment 5: p.2: you mention that the loss of cooling tests have been performed with initially full power. Was the core already at equilibrium for these tests and if not, what would be the effect (e.g. on afterheat directly after scram)? Maybe explain that similar tests had been conducted in other HTGR in the past, but not from full power (please check if this is correct, e.g. AVR, HTTR...).

Response: Thanks for this important comment and the interest on the loss of cooling tests performed on the two reactors of HTR-PM power plant. The details about the loss of cooling tests have been given in the published paper "Loss-of-cooling tests to verify inherent safety feature in the world's first HTR-PM nuclear power plant", which is listed as reference [18] of this manuscript. During the loss-of-cooling tests of two HTR-PM reactors, the reactor cores are not at equilibrium states, but in the transition period to the equilibrium. For a reactor core in the transition period, there are still graphite balls in the bottom space, limiting the hot helium temperature at the reactor core outlet. However, after the reactor shut down, the highest core temperature occurs in the upper section of the reactor core. Since the upper sections of both the equilibrium core and the core in transition period are constituted by fuel elements, the core state does not influence the result of loss-of-cooling tests. More importantly, the main factor determining whether or not the decay heat can be removed naturally is the reactor power-level, which is the key bottleneck of decay heat removal. Although similar tests were performed on the German AVR, Chinese HTR-10 and Japanese HTTRs, the power-levels are all lower than 50 MWt. The loss-of-cooling tests on the HTR-PM reactors which operate at the power-level of 200MWt being the same with that of the rated thermal power of German HTR-Module reactors, manifesting the existence of commercial inherent safety for the first time. Therefore, the main difference between the loss-of-cooling tests on the HTR-PM reactors and those on AVR, HTTR and HTR-10 is that the latter tests verify that the inherent safety can be reached, while the former tests on HTR-PM verify the existence of commercial-scale inherent safety.

In the revised manuscript, the above discussion has also been briefly added to the end of the 2nd paragraph in Section 1 just below Fig. 2.

Comment 6: Fig. 3: Are the sensors of Reactor Module #2 connected to a separate CCS or to the same as for #1? If they are separate, how do the two CCS talk to each other? Is there a redundancy of sensors and if so, do you use e.g. a 2 out of 3 logic in the CCS to avoid unnecessary reactor scrams? What is the physical shape of the CCS? Is it a Programmable Logic Controller (PLC)? Please explain more about its capabilities and whether it is redundant (e.g. like on airplanes).

Response: Thanks deeply for the insightful comment about the CCS. Focusing on the test results, the introduction to the CCS design and its implementation is given briefly in the original manuscript. According to this comment, to emphasize the individual control between two reactor modules, Fig.3 is modified and shown as the following Fig. I. From Fig. I, the sensors of reactor module

#2 are connected an individual coordinated control subsystem composed by (1) neutron flux controller, (2) helium controller, (3) feedwater flowrate controller, (4) helium temperature controller, (5) steam temperature controller and (6) thermal power controller like that of #1 module. Actually, each reactor module is equipped with these six controllers individually, giving the coordination amongst multiple process variables belonging a single reactor module. From Fig. I, it can be seen that the two reactor modules provide superheated steam of the same parameter to a common turbine-generator system, and the coordination between two reactor modules is given by the main steam pressure control stabilizing the common steam pressure at the inlet of the steam turbine. For the coordination between modules, it is also necessary to stabilize the steam temperatures at the secondary outlets of steam generators by the individually equipped steam temperature controllers.

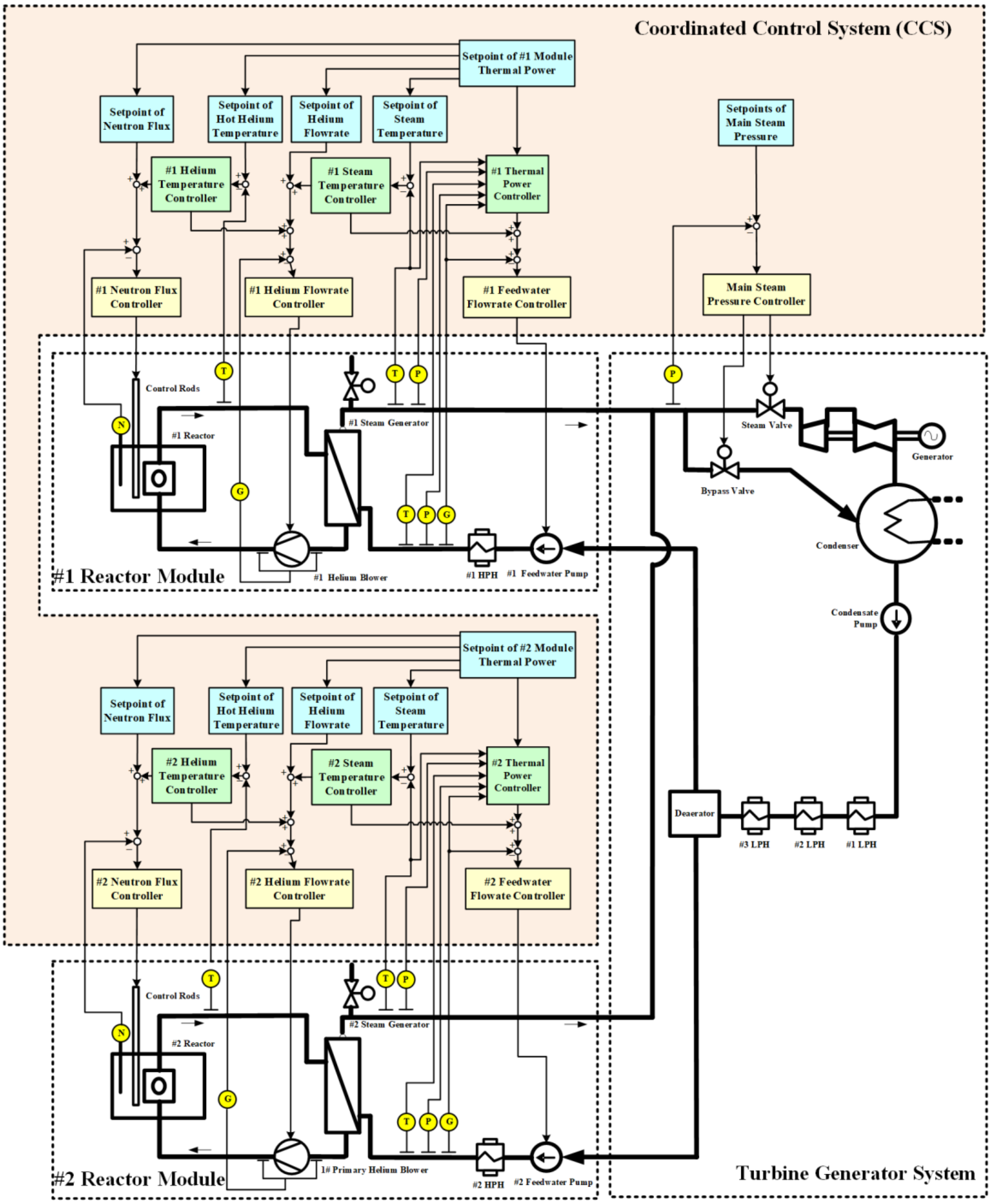

Fig. I. Composition of the coordinated control system of HTR-PM plant

In addition, there are redundance of sensors for measuring process variables. From Fig. 3, it can be seen that the measurements of process variables, including the reactor neutron flux, helium flowrate, feedwater flowrate, steam temperature as well as steam pressure at the OTSG secondary outlet, feedwater temperature as well as feedwater pressure at the OTSG secondary inlet, and main steam pressure at the turbine inlet are all input signals of the CCS. For each process variable inputted to the CCS, three or even four redundant sensors are equipped for the measurement of the process variable. For the process variables with 3 redundant sensors, 2 out of 3 logic is adopted to avoid unnecessary reactor scrams. For the process variables with 4 redundant sensors, 3 out of 4 logic is adopted.

For the physical shape of the CCS, a distributed control system (DCS) platform is adopted for implementing the controllers of the CCS. The DCS is divided to two layers called Level 1 and Level 2. A large amount of control stations and several redundant real-time servers are interconnected by the Level 1 ethernet, while several operator stations, the engineer station and the redundant historical servers, real-time servers as well as computing servers are interconnected by the Level 2 ethernet. The real-time servers are connected to both Level 1 and 2 networks, performing the bridge between Levels 1 and 2. The measurement signals are sent from the field instruments to the Level 1 control stations by the hard-wired connections, and then the control stations give the hardwired driving signals of the actuators such as the control rods, primary helium blowers, feed-water pumps and main steam regulating valve according to the commands from operators and the errors between the measurements and the setpoints of the controlled variables. In addition, each control station is composed of several input-output (IO) modules, a local control computer and a hot standby redundant local control computer. The schematically hierarchy architecture of the DCS platform is shown in the following Fig. II.

In the revised manuscript, Fig. 3 is modified as Fig. I to illustrate that those six controllers are equipped to each reactor module individually. The discussion on sensor redundance and the physical shape of CCS are all added to the newly given section 2.1 in the revised manuscript, and the following Fig. II has also been added to the revised manuscript as Fig. 4.

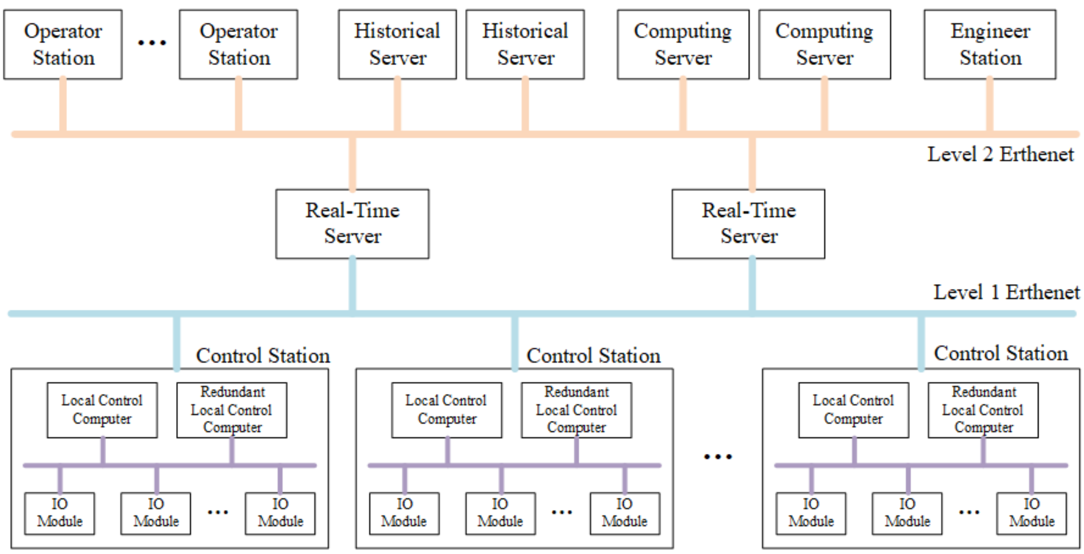

Fig. II. Schematical architecture of the distributed control system (DCS) platform

Comment 7: The CCS seems to be an active component ensuring the operability and to some extent the safety of the multi-module plant. Have you analyzed what will happen if the CCS itself malfunctions? Have you analyzed the reaction of the CCS in case of component failure (e.g. assuming a pump seizure)? What are the requirements on the CCS imposed by the nuclear regulator?

Response: Thanks deeply for the comment about the fail-safe characteristics of the CCS. As the reactor modules have independent safety systems, a pump seizure leads to a fast decrease of feedwater flowrate. Since the ratio of the primary flowrate to the secondary flowrate is a protection variable, when the ratio increases to a certain threshold, the reactor protection system will shut down the reactor module with the pump seizure, and the other reactor module continues to drive the turbine for power generation. Actually, the responses in the scenario of one pump seizure is similar to the responses to the reactor trip induced by the failure of the transducer (i.e. frequency converter) of a helium blower. From test results in the scenario of reactor trip, it can be seen that the plant can keep operating stably even if there is a trip of one reactor module. For the component failure leading to the emergency shutdown of steam turbine, from the tests results in the scenario of turbine trip, it can be also seen that one reactor module can keep a stable operation with the steam bypassed to the condenser.

Besides the component failure triggering the protection system, the authors know that the fault tolerant control (FTC) under some minor failure is very important to guarantee the operation performance. In the revised manuscript, the authors have added the development of FTC as one of the future works in the end of Section 4.

Comment 8: Section 2: It is not completely clear what are "controllers" and what are sensors. It is also not clear what input data is measured (e.g. temperature, flow-rate) and which parameter is changed (output) to control them. For instance, do you control the reactor power by modifying the helium pressure or by modifying the helium flow-rate or both? Is the power control of both modules connected or separate?

Response: Thanks deeply for this constructive comment on giving the input signal and output variable of each controller. Usually, we call the input and output as the controlled variable and manipulated variable of the controller respectively, and the pairing of the controlled variable and manipulated variable for the seven controllers are given in the following Table I. From Table I and the above Fig. I, it can be seen that the input and output of each controller are given specifically.

In the revise manuscript, Table I has been added to Section 2.1 as Table 1 to show the input and output of each controller belonging the CCS.

Table I. Pairing of controlled variables and manipulated variables for coordinated control

	Controller	Controlled Variable	Manipulated Variable
1	Neutron flux controller	Neutron flux of reactor core	Control rod speed
2	Hot helium controller	Hot helium at the primary inlet of steam generator	Revision to the setpoint of neutron flux
3	Helium flowrate controller	Primary helium flowrate	Rotational rate of the primary helium blower
4	Steam temperature controller	Steam temperature at the secondary outlet of steam generator	Revision to the setpoint of primary helium flowrate
5	Feedwater flowrate controller	Feedwater flowrate of the steam generator	Rotational rate of the feedwater pump

	Controller	Controlled Variable	Manipulated Variable
6	Thermal power controller	Output thermal power of the reactor module	Revision to the setpoint of feedwater flowrate
7	Main steam pressure controller	Steam pressure at the inlet of steam turbine	Openings of main steam regulating valve and bypass regulating valve

Comment 9: Section 2.1: why are the steam outlet temperatures the most sensitive process variables?

Response: Thanks for the comment on saying the outlet steam temperatures are the most sensitive process variables. The reason is that the thermal inertia of the once-through steam generator (OTSG) is very small with respect the modular high temperature gas-cooled reactor (mHTGR) and the other types of steam generators such as the U-tube steam generator (UTSG). Hence, the outlet steam temperature of (OTSG) is very sensitive to the variations of both the primary flowrate and the secondary feedwater flowrate.

In the revised manuscript, to avoid the misunderstanding, the statement “which are the most sensitive process variables” are deleted from the paragraph corresponding to the test result of power ramping.

Comment 10: Fig. 6: In the beginning of the transient, the hot He and SG outlet steam temperatures are 553/520°C whereas the cold He/SG feedwater inlet temperatures are 245/161°C. Isn’t the resulting pinch point temperature difference in the Steam Generator then a bit small? Could this explain the lower than expected SG outlet steam temperature?

Response: Thanks deeply for the important comment on the reason of the lower SG outlet steam temperature. Actually, the authors agree with the reviewer on the small pinch point temperature difference of the steam generators. As we have discussed in the response to Comment 4, the key reason causing the smaller pinch point temperature difference is given by the lower hot helium temperature. Currently, the two reactor cores are in the transition stage to the equilibrium state, and there are still many graphite balls in the bottom space of the reactor cores, giving that the hot helium temperature at the reactor core outlet is still lower than the expected value. When the reactor cores reach their equilibrium state, the hot helium temperature will be higher, and the outlet steam temperatures of SG are expected to be 540°C.

In the revised manuscript, the statement “When the reactor cores reach their equilibrium stage, the hot helium temperatures at the core outlet can be further improved, and the steam temperature is expected to operate at 540□” has been added to the paragraph just below Fig. 1.

Comment 11: Wasn’t the initial idea to achieve a hot He temperature of about 750°C? Wouldn’t this then also affect the passive coolability of the reactor core? Section 2.3: Not clear which “transducer” you mean. Did you simulate a failure of the primary helium flowrate sensor in the #1 reactor (assuming no redundancy of sensors)? Note that for this test, the reactor power is not 100%.

Response: Thanks for the valuable comment on the hot helium temperature, the meaning of “transducer”, the simulation of a failure of the primary helium flowrate sensor in #1 reactor and the reactor power-level for the tests.

Firstly, the designed hot helium temperature at reactor core outlet is 750°C. However, due to the reactor cores are in the transition stage, the current hot helium at the reactor outlet is about

685°C which has been presented in reference [18] of the revised manuscript. In addition, due to the existence of bypass flow inside the reactors, the current hot helium temperature at the primary inlet of steam generator is 553°C or so. Since the decay heat power is given by the reactor power-level, and the decay heat power directly affect the passive coolability, the hot helium temperature cannot affect the passive coolability of the reactor core. This manuscript focuses on verifying the multi-modular scheme and the related coordinated control strategy. The test results on the passive cooling have been presented in reference [18].

Secondly, the transducer refer to the frequency-converter being utilized to adjust the rotational rate of the primary helium blower. The failure of the frequency-converter induces that the primary helium flowrate decreases to zero quickly, causing the protection system to shut down the reactor module.

Thirdly, there are four redundant sensors for measuring the primary helium flowrate, giving the fail-safe under the malfunction of one helium flowrate sensor. Moreover, it worthy to be noted that the test results presented in this manuscript are not given by simulation, but are given by the real tests on the HTR-PM plant.

Fourthly, as the HTR-PM reactors adopt the MEDUL (MEhrfach DUrchLauf = several passes through the core) cycle of fuel burnup, and the recycling rate is seen as 15 times for the specified burnup. As stated in the original manuscript, achieving continuous operation of the fuel handling systems has been a challenging endeavor. Considering the two HTR-PM reactor cores are in the transition phase to their equilibrium stage with a large amount of graphite spheres to be replaced, it is decided to operate the two reactors of the HTR-PM plant with a highest power of 200 MWt in the running-in stage of reactor cores. The tests are all performed at the reactor power being larger than 190 MWt which is reasonable for normal operation. The little difference in reactor power and its maximal value cannot influence the verification of multi-modular scheme and the related coordinated control strategy.

In the revised manuscript, the word “transducer” has been changed to be frequency-converter, the discussion on the power-level of the test has been added to Section 2.1, and the explanation on why the outlet steam temperature of SG is lower than 540°C has been added to the paragraph below Fig. 1. The actual initial operation power-level has been also added to the paragraph giving the tests results under the scenarios of power ramping, turbine trip and reactor trip.

Comment 12: Section 3: You explain the benign behavior of the multi-module HTR-PM. From the data presented in the paper, one may conclude that much of this positive outcome depends on the high thermal inertia of the reactor cores due to the graphite mass. You seem to conclude, however, that a “well-designed coordination mechanism can guarantee the stable operation for multi-modular SMR” in general. Wouldn’t it be advisable to limit this conclusion to reactors with a similar power density/thermal inertia ratio? E.g. would fast reactor SMRs with higher power density and less thermal inertia in a multi-module configuration react in a similarly benign manner? Please make a statement on this matter.

Response: Thanks for the comment on the relationship between the thermal inertia and coordinated control performance. Actually, to guarantee the inherent safety or passive coolability, the thermal inertia of the reactor cores is designed to be quite high so as to limite the temperature overshoot during fully passive decay heat removing. To provide high temperature steam, the once-through steam generators (OTSG) with low thermal inertia are adopted. In addition, the OTSG is arranged side-by-side to the reactor in the same module. It can be seen that the reactor with high thermal inertia is tightly coupled with the OTSG with low thermal inertia. Though the high thermal inertia of reactor core may give the stability of hot helium temperature, it cannot guarantee the stability of steam temperature which can be quickly varied by the changes in primary helium flow and secondary feedwater flow, giving that the neutron flux, helium flowrate and feedwater flowrate of a reactor module should be carefully regulated to guarantee the stable operation of a reactor module. Moreover, as the two reactor modules provide superheated steam to a common turbine, the modules are coupled together by the common BOP equipment. As the steam pressure reflects the generation and consumption of steam, it is also crucial to be stabilized for providing a necessary condition for the stable operation of the entire power plant. Hence, the coordinated control mechanism is very important for the multi-modular HTR-PM plant. The test results presented in Section 3 show the feasibility of multi-modular scheme and coordinated control strategy.

For the other type of SMRs designed with passive safety, the multi-modular can be used to apply the passive safety to the entire nuclear plant with any desired power ratings, and the coordinated control strategy proposed in this paper is applicable to guarantee the stable operation of these multi-modular SMR plants. For those SMRs having higher power density and lower thermal inertia, although there may be some difference in the single reactor module control, the coordinated control of multiple modules proposed in this paper is worthy to be referenced since the multiple modules in the same multi-modular unit are coupled together by the common secondary fluid flow network (FFN).

In the revised manuscript, the statement "a well-designed coordination mechanism can guarantee the stable operation for multi-modular SMR power plants" has been revised to be "a well-designed coordination mechanism can guarantee the stable operation for multi-modular SMR power plants, at least for those SMRs with low power density and high thermal inertia".

Comment 13: Section 4: Your study looks essentially at power plants with shared BOP equipment. However, what is equally important for multi-module plants is the capability to use a single control room with limited staff for several modules. Can you possibly make a statement on this as well based on your experience?

Response: Thanks for the insightful comment on influence of automatic multi-modular coordinated control to the staff limitation. The authors agree with the reviewer on the importance of the capability of multi-modular plants in using a single control room with limited staff. Actually, the modules and BOP equipment of the HTR-PM plants share a single control room shown by the following Fig.III, where each reactor module is assigned with one reactor operator individually. There is also an operator assigned for the BOP equipment, and a chief operator leading the operation team. The coordinated control system gives the automatic control function that can lower down the working load of the operators, and provides a necessary condition in limiting the number of staffs. Based on the verification of the automatic coordinated control in this paper, the staff of the under-designed HTR-PM600 nuclear power plant has been limited, where one reactor operator is assigned to monitor and control two reactor modules.

In the revised manuscript, Fig. III is added to Fig. 1 as Fig. 1(d) to show the main control room of the HTR-PM plant, and the statement of "the automatic coordinated control mechanism is able to lower down the working load of operators, giving the founded basis to limit the staff for multi-modular nuclear plants" has been added at the end of section 3.

[REDACTED]

Fig. III Control room of the HTR-PM plant

Comment 14: Section 5.1: you mention a hot helium temperature of around 700°C, which is much higher than what we see in the figures in Section 2. Please explain.

Response: Thanks for pointing out the improper statement on the hot helium temperature in section 5.1. From the statement in Section 2.2 of the revised manuscript, the hot helium temperature showed in Figs. 6, 7, 9, 10, 12 and 13 refers to the temperature of the hot helium at the primary inlet of the steam generator. While in section 5.1, the hot helium temperature refers to the temperature of the hot helium at the outlet of the reactor core.

In the revised manuscript, to avoid misunderstanding, the statement of "it is heated up to a high temperature around 700°C" has been revised to be "it is heated up to a high temperature around 700°C at the outlet of the pebble bed" in the revised manuscript.

Comment 15: In the set of equations, it is not clear how the time dependence is incorporated. E.g. how do you consider the inertia of the helium blowers in the helium flow-rate control?

Response: Thanks for pointing the unclearness in addressing the influence of the inertia of the helium blowers to the helium flowrate control. Due to the adoption of active magnetic bearing, the inertia of the helium blowers is so small that it cannot the leads to the degradation of helium flowrate control under the same control law. For the designed control (11), the inertia of helium blower can be compensated by enlarging gain k_{P3} in equation (11), which has been added to Remark 1 in the revised manuscript.

Responses to the Comments from Reviewer 2

Comment 1: The manuscript explores the practical verification of a multi-modular nuclear power plant scheme using the HTR-PM. Comprising two reactor modules driving a single turbine, the HTR-PM demonstrates the feasibility of coordinated control during power ramping, turbine trips, and reactor trips. The study highlights the significance of multi-modular coordination in achieving economic and safe operation for large-scale deployment of SMRs, setting a precedent for future advancements in nuclear power plant designs. Overall, the manuscript is scientifically sound, novel, and highly relevant to the field. With a few enhancements, it can make a more compelling case for the practical adoption of multi-modular SMR schemes.

Response: The authors would like to thank deeply for the positive evaluation and insightful comments given by Reviewer 2, giving a great encouragement to the authors. According to these comments, the manuscript has been carefully revised and enhanced for being a more compelling case for the practical adoption of multi-modular SMR schemes.

Comment 2: While the novelty is evident, it would benefit from clearer articulation of how the findings advance or challenge existing knowledge in SMR development.

Response: Thanks for the important comment in clearing the main novelty of this manuscript. As the rated power of typical small modular reactors (SMRs) is restricted for realizing the passive safety or even inherent safety, how to build large-scale nuclear power plants (NPPs) with SMRs is a challenging problem of science and technology. A possible solution is the multi-modular scheme of using multiple nuclear reactor modules to drive a common steam turbine. Although the multi-modular scheme was adopted by the NPP designs such as the German HTR-Module and the U.S. MHTGR, it is not verified practically until the tests of power ramping, turbine trip and reactor trip performed on the HTR-PM plant, where the HTR-PM plant is the world's first multi-modular nuclear power plant (NPP) in the commercial operation stage. The test results presented in this manuscript verify not only the feasibility of the multi-modular scheme but also the related multi-modular coordinated control strategy for the first time in the world. The multi-modular scheme can be applied to all the SMRs generating superheated steam, and the multi-modular coordinated control strategy proposed in this paper is referenceable to those multi-modular NPPs based on some other types of SMRs.

The above discussion about the clearance of novelty has been added to the last paragraph of Section 1 to show how the findings in this paper advance the existing knowledge in SMR development.

Comment 3: Highlighting specific innovations in the CCS design or its adaptability to other reactor types could strengthen the manuscript's impact.

Response: Thanks deeply for the insightful comment on highlighting the innovations of CCS design so as to strengthen the manuscript's impact. The current CCS of nuclear power plants (NPPs) can only handle the coupling of process variables inside a single reactor module. While, the multi-modular CCS newly built in this paper can handle not only the coupling of process variables inside a single reactor module but also the coupling amongst multiple reactor modules. As the coupling amongst multiple reactor modules is generally given by the common secondary loop fluid flow network (FFN), the coordinated method of modules in addressing the coupling of multiple modules can be applied to the multi-modular nuclear plant based on the other types of SMRs.

In the revised manuscript, the above discussion has been added to the last paragraph of Section 1.

Comment 4: Broaden the discussion to include how this approach can inform future SMR designs.

Response: Thanks for the valuable comment on discussing the influence of this study on the future SMR designs. With comparison to the widely deployed commercial pressurized water reactors (PWRs) with rated thermal power over 3000MWt, the key virtue of SMRs is their passive or even inherent safety features. The tradeoff of realizing passive or inherent safety is the restriction on the power density and the rated power of SMRs. Thereby, how to build large-scale NPPs based on multiple SMRs is a key problem to be solved for the development of SMRs. A possible solution to this problem is the multi-modular scheme, where multiple SMR-based reactor modules provide superheated steam to a common steam turbine. Since the multiple reactor modules are coupled by the common steam turbine, one of the central issues in deploying the multi-modular scheme is proposing a proper multi-modular coordinated control method to handle the coupling of process variables inside a single reactor module and the coupling of multiple reactor modules.

The results in this manuscript verify the feasibility of the multi-modular scheme as well as the related newly-built multi-modular coordinated control, paving the way of going multi-modular, i.e., the way of building large-scale NPPs based on a system of small modular reactors, for the first time. This work on multi-modular scheme and related coordinated control gives a prominent influence on the future SMR designs. Actually, by deploying multi-modular scheme, the passive or inherent safety feature can be applied to the NPPs with any desired power rating. In the future, the objective single SMR design is realizing passive or inherent safety and giving the ability of generating superheated steam. While, the objective of the multi-modular SMR plant design is to use a proper number of SMR-based reactor modules to match a steam turbine with expected ratings and designing the coordinated control system for guaranteeing stable and efficient operation.

The above discussion on the influence to future SMR designs has been added as the last paragraph of Section 3 in the revised manuscript.

Comment 5: Expand on the potential implications for policy, regulatory frameworks, and commercialization in the nuclear energy sector.

Response: Thanks deeply for the helpful comment on expanding the potential implication for policy and commercialization as well as regulatory frameworks in the nuclear energy sector.

Considering the policy, China takes an active and positive policy on the research, development and commercialization of multi-modular high temperature gas-cooled reactor plant (HTGR) technology. China begun the research and development of HTGR technology since the end of 1970s. After the Chinese high temperature gas-cooled test reactor HTR-10 attained its first criticality in 2001, the HTR-PM project was launched with a high priority under the Chinese Science and Technology Plan for the period 2006-2020. The objective of HTR-PM project is to develop, construct and operate a multi-modular HTGR demonstration power plant, founding a solid step for the commercialization of mHTGR technology. The implementation plan and the budget of HTR-PM project was approved by the State Council of China in February 2008, and the HTR-PM project received final approval from the China's cabinet about two weeks before the Fukushima accident in 2011. After the construction permit license was issued by the National Nuclear Safety Administration

(NNSA) of China, the first concrete of the HTR-PM was poured on December 9, 2012, and the commissioning of HTR-PM plant started early in 2020. The HTR-PM plant was connected to the grid on December 20, 2021, and entered to its commercial operation at December 6, 2023, not only verifying the multi-modular HTGR plant technology solidly but also promoting the commercialization greatly. Right after HTR-PM plant connecting to the grid, the 600MWe multi-modular HTGR commercial plant HTR-PM600 for electricity generation and cogeneration is now under research and development. The authors believe that the commercial operation of the HTR-PM demonstration plant and the development of the HTR-PM600 commercial plants can stimulate the governments and authorities of other countries to give more active and positive policy on the development of SMR plants.

Considering the regulation frameworks, the HTR-PM plant adopts the modular HTGR (mHTGR) with the rated thermal power is around 200MWt, and thus the licensing of HTR-PM belongs to the scope of licensing SMR designs. Before the licensing of HTR-PM reactors, the safety tests performed on the test reactor HTR-10 had verified the feasibility of realizing inherent safety. With the HTR-10 as their prototype, the mHTGRs of the HTR-PM plant are designed to be inherently safe. The multiple reactor modules of the HTR-PM plant have their own independent safety system, and are not dependent on the other parts of the plant. Although NNSA had acquired large experience and knowledge of modular HTGR by licensing the HTR-10, a series of detailed reports including those on PSA and accidents analysis were carefully prepared and reviewed by the NNSA during the licensing procedure of HTR-PM. The construction permit of the HTR-PM was issued, and the first concreted was poured on December 9, 2012. The operation permit was granted on August 20, 2021, and the plant was connected to the grid on December 20, 2021. In 2023, all licensing tests (nearly 400) were accomplished, a series of regulation check was performed by NNSA, and the HTR-PM entered its commercial operation following a successful 168-hour demonstration run. Specifically, the loss-of-cooling tests performed on the two HTR-PM reactors manifest the existence of commercial scale inherent safety, while verifying the correctness of reactor design and safety analysis. The commercial operation of HTR-PM plant speeds up the licensing of 600MWe multi-modular HTR-PM600 plant, and one HTR-PM600 plant is now under construction.

Considering the commercialization, it can be seen from the discussion on the policy that the commercialization of the modular HTGR is being carried out by China. Currently, both the pressurized water reactor plant HPR1000 and the multi-modular HTGR plant HTR-PM600 are two types of nuclear plants under batch commercial construction. Compared to the commercial PWR HPR1000 with main steam temperature lower than 300^{o}C, the multi-modular HTGR plants HTR-PM and HTR-PM600 has a much higher the steam temperature over 520^{o}C. Therefore, the commercialization of the multi-modular HTGR plant HTR-PM and HTR-PM600 and that of the HPR1000 are highly complementary with each other. Actually, the PWR plants such as HPR1000 are suitable to be used as the baseload power sources of the grid, while the HTR-PM and HTR-PM600 are more proper to be adopted as the heat sources for those hard-to-decarbonize industrial processes and for cogeneration. Therefore, the global decarbonization needs the support from the commercialization of HTR-PM and HTR-PM600, which has no zero-sum game with the development of PWR plants.

In a summary, the roadmap of developing multi-modular HTGR plant technology in China can be divided into three steps, including the 10MWt test reactor HTR-10, the 2x200MWt demonstration plant HTR-PM and the six-modular 600MWe commercial plant HTR-PM600. There is a strong policy support from the government, and a licensing framework of multi-modular HTGR plants have been established. The commercialization of multi-modular HTGR plant technology has been carried out, the six-modular HTGR plant HTR-PM600 plants are now under design or construction, and will play an important role in providing clean heat and power to those hard-to-decarbonize industrial sectors.

In the revised manuscript, the key part of those expanded discussion on the policy, regulation framework and commercialization of multi-modular HTGR plant technology has been added as the sixth paragraph in Section 3.

Comment 6: Add quantitative comparisons to strengthen claims of economic and operational benefits.

Response: Thanks for the meaningful comment on the economic competitiveness as well as the operation benefits of multi-modular nuclear power plants.

According to our practice, the economics of NPPs adopting passive or inherently safe SMRs is mainly achieved by the multi-modular scheme, where the superheated steam provided by multiple reactor modules are combined together for driving a common turbine, while the high pressure and temperature of motive steam gives not only a high Rankine cycle efficiency but also the feasibility of using the plant as an industrial heat source. However, the current power generation cost of HTR-PM plant is still about 20% higher than that of commercial PWR plants, and this could be managed by cogeneration and further by the mass production of reactor modules.

In addition, the operation of SMR-based multi-modular NPPs benefits from the flexibility provided by the multi-modular coordinated control mechanism. As we can see from the test results in the scenario of power-ramping, it is feasible to select a part of the reactor modules to perform the power ramping, while the other modules can keep operating stably at constant power-levels. With more reactor modules engaged in power ramping, the changing rate of the plant output electrical power is higher, leading to a better load-following performance. The multi-modular SMR plant operating with satisfactory load-following capability can provide flexibility to balance the intermittent renewables, which in turn enhances the economy of SMRs.

The above discussion on the economic and operational benefits of multi-modular SMR plant has been combined into the 5th paragraph of Section 3 in the revised manuscript.

Comment 7: Provide a clearer articulation of the manuscript’s novelty and contributions.

Response: Thanks deeply for this important comment on clearing the novelty and contributions. To achieve passive or even inherent safety, the rated power of typical SMRs is strictly restricted, how to build large-scale nuclear power plants (NPPs) with SMRs is a challenging problem in the field of nuclear science and technology. A possible solution is the multi-modular scheme of multiple SMR-based reactor modules providing superheated steam for driving a common turbine. Although the multi-modular scheme was adopted by the NPP designs such as the German HTR-Module and the U.S. MHTGR, it is not verified practically until the tests performed on the HTR-PM plant presented in this paper. The test results verify not only the feasibility of the multi-modular scheme but also the effectiveness of newly-built multi-modular coordinated control for the first time in the world.

In a summary, the key contribution of the work in this paper is that the safety and the economy of SMRs can be balanced by the multi-modular scheme, where several passively or even inherently safe SMRs provide superheated to a common steam turbine. By adopting the multi-modular scheme, the passive or inherent safety of a single SMR can be applied to the large-scale nuclear plant with any desired power ratings. Moreover, the key innovation of this work is the newly-built multi-modular coordinated control method and system, being able to handle the coupling of process variables inside a single reactor module and that of multiple modules while providing asymptotically stable operation.

The above clearance on the novelty and contribution of this manuscript has been embedded into the last paragraph of Section 1.

Comment 8: Address broader implications for the nuclear power industry, including potential adoption challenges.

Response: Thanks deeply for this constructive comment on the implication to nuclear power industry. Actually, the multi-modular NPP scheme has begun to influence the nuclear power industry, at least the Chinese nuclear industry. Based on the experience in the design, construction and operation of HTR-PM plant, the 600MWe multi-modular high temperature gas-cooled reactor nuclear plants are under design and development for electricity generation and cogeneration. Since the outlet steam temperature of mHTGR module is about 520°C, the multi-modular high temperature gas-cooled reactor plants is promising and competitive to be adopted as the industrial heat sources for those difficult-to-decarbonize sectors such as petrochemical processes and metallurgical works. One of a crucial challenge in deploying multi-modular nuclear plants is to enhance the flexibility for better following the variable electrical and thermal demand.

The above discussion on the implications and potential challenges has been added at the end of the paragraph in Section 4.

Comment 9: Discuss the adaptability of the findings to different reactor types and global energy strategies.

Response: Thanks for the valuable comment on the adaptability of the findings to different reactor types and global energy strategies. As the multi-modular scheme refers to the adoption of using several nuclear reactor modules providing superheated steam for a common steam turbine, it is applicable to not only the modular high temperature gas-cooled reactor (mHTGR) but also all the types of nuclear reactor modules being able to generate superheated steam. Since the multiple reactor modules in a multi-modular NPP are coupled together by the common secondary fluid flow network (FFN), the proposed coordinated control between reactor modules can be also applicable to different reactor module types. Moreover, as the difference between the dynamics of mHTGR module and that of other type reactor modules is limited, the coordinated control for a single reactor module is referenceable to the control other types of reactor modules.

In the revised manuscript, the general adaptability of multi-modular scheme has been added to the last paragraph of the Section 3, the adaptability of the coordinated control between reactor modules has been added to Remark 2 in Section 5, and the analysis on the reference value of the coordinated control for a single reactor module has been added to Remark 1 in Section 5.

Response to the Comment from Reviewer 1

Comment: I have looked at the authors' responses to Reviewer 1 and I would like to acknowledge their effort in improving the paper accordingly. The comments by Reviewer 2 are more high-level trying to increase the overall reach and impact of the paper, but I understand, also there the authors have made a significant effort. I am fine with the revisions. Thank you again for the opportunity to review this interesting paper.

Response: The authors would like to thank deeply for the positive evaluation on the revised manuscript, giving a great encouragement to the authors for the future research on the control of nuclear power plants. Actually, the authors have also learned much from the comments given by the anonymous reviewers. Thanks deeply again for the opportunity to revise the manuscript according to the insightful and valuable comments.