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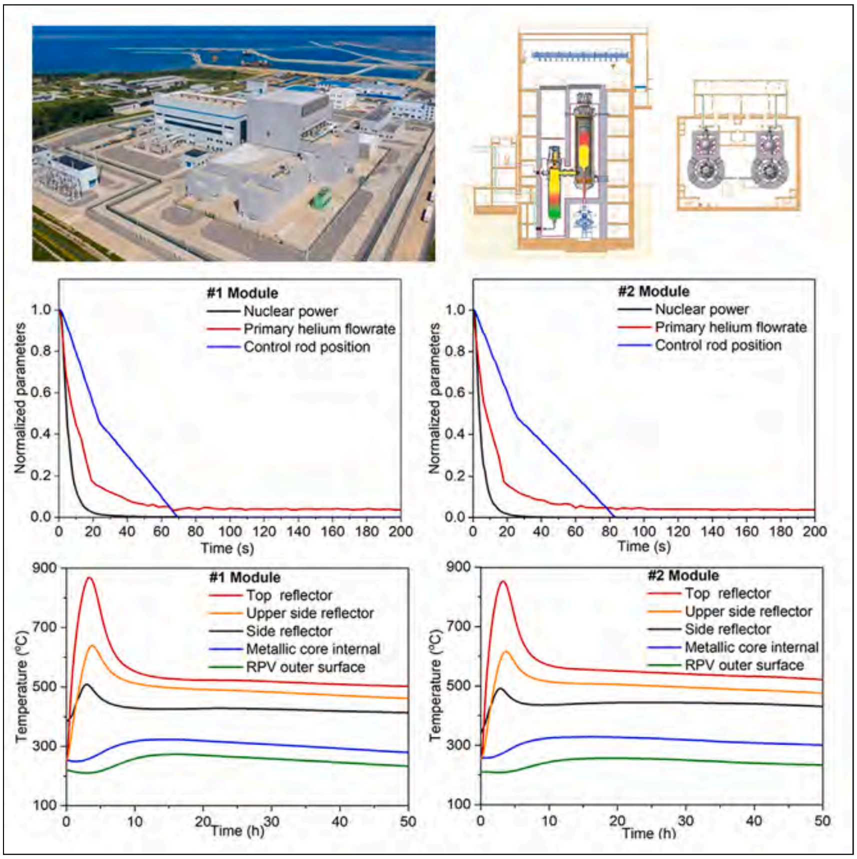

The loss-of-cooling tests performed on the two reactors of high-temperature reactor with pebble-bed module (HTR-PM) nuclear power plant show for the first time that commercial-scale nuclear fission reactors can be cooled down naturally without emergency core cooling systems.

Zuoyi Zhang, Yujie Dong, Fu Li, ..., Han Zhang, Zhipeng Chen, Xiaowei Li

dongzhe@mail.tsinghua.edu.cn

Highlights

The loss-of-cooling tests were performed on HTR-PM reactors at 200-MWt power level

The test results show that the reactors can be naturally cooled down

The existence of commercial-scale inherent safety is manifested for the first time

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Loss-of-cooling tests to verify inherent safety feature in the world's first HTR-PM nuclear power plant

Zuoyi Zhang,[1] Yujie Dong,[1] Fu Li,[1] Xiaojin Huang,[1] Yanhua Zheng,[1] Zhe Dong,[1,2,*] Han Zhang,[1] Zhipeng Chen,[1] and Xiaowei Li[1]

SUMMARY

Nuclear fission energy is the low-carbon resource that helps manage the cost of deep decarbonization. Safety is the basis of deploying nuclear power plants near load centers on a large scale. The inherent safety of nuclear reactors depends solely on the laws of nature. The world's first demonstration plant of a high-temperature reactor with a pebble-bed module (HTR-PM) entered its commercial operation on December 6, 2023. Two safety tests were conducted on the two reactor modules of the HTR-PM plant, each at a power of 200 MWt. During the tests, the active power supply was totally switched off to see if the decay heat can be removed passively. The responses of nuclear power and temperatures within different reactor structures show that the reactors can be cooled down naturally without active intervention. The results of the tests manifest the existence of commercial-scale inherent safety for the first time.

INTRODUCTION

After the Three Mile Island accident, Alvin M. Weinberg, one of the founders of the US nuclear industry, pointed out that it is necessary to develop inherently safe nuclear reactors to lift the curtain on the second era of nuclear energy.[1] The inherently safe reactors, as defined, refer to those nuclear fission reactors whose safety relies not on intervention of humans or electromechanical devices but instead depends only on the natural principles of physics and chemistry. It was also recommended that the Swedish PIUS reactor and the German modular high-temperature reactor (HTR)-module are two promising candidates.[1] The severe Chernobyl accident in 1986 and the Fukushima Daiichi accident in 2011 manifest once again that strictly guaranteeing safety is the basis for the large-scale deployment of nuclear energy as a means to address climate change.[2]

The HTR is a helium-cooled reactor with graphite as both moderator and structural material, where the fuel element is made by embedding several thousand TRISO-coated particles into a spherical or prismatic matrix. Each TRISO particle is fabricated by coating a kernel of UO_2 with layers of pyrocarbon (PyC) and silicon carbide (SiC), which are able to prevent the leakage of fission products without exceeding a proven fuel temperature limit, for example, 1,620°C. The modular HTR evolves from the classic HTR based on principles that restrict module power, power density, and core diameter. The decay heat, which is the primary cause of core melting in a nuclear fission reactor, can be dissipated to the environment naturally by heat conduction, radiation, and natural convection, without adopting emergency core cooling systems.[3]

CONTEXT & SCALE

Strictly guaranteeing safety is the basis for the large-scale deployment of nuclear energy as a means to address climate change. It was pointed out by Alvin M. Weinberg, one of the founders of the US nuclear industry, in 1984 that inherently safe commercial reactors will open the second nuclear era. Since then, realizing inherent nuclear safety on a commercial scale has been a dream of all scientists and engineers in the field of nuclear energy, where the key issue is removing the decay heat without active intervention. Although the feasibility of realizing inherent safety has been verified on the small test reactors, such as the German high-temperature test reactor AVR and the Chinese high-temperature test reactor HTR-10, the existence of commercial-scale inherent safety had not been manifested until the loss-of-cooling tests were performed on the two reactors of world's first high-temperature reactor with pebble-bed module (HTR-PM) nuclear plant, each at the power level of 200 MWt.

The HTR with pebble-bed module (HTR-PM) was invented by Prof. R. Schulten in Germany. The basic physical principles and safety features of the pebble-bed reactor were intensively researched at the Research Center Juelich under the leadership of Prof. R. Schulten and Prof. K. Kugeler. The 15-MWe pebble-bed experimental reactor AVR and the 300-MWe THTR demonstration plant were developed and operated in Germany from the 1960s to the 1980s. Dr. H. Reutler and Prof. G. Lohnert of SIEMENS/Interatom proposed the module concept.[4,5] Throughout the 1980s and the 1990s, significant progress was made in the research and design of modular HTR demonstration plants, such as the 200-MWt pebble-bed reactor HTR-module in Germany by SIEMENS/Interatom[6] and the 350-MWt prismatic reactor MHTGR in the US by General Atomics.[7] Japan constructed a test reactor of 30-MWt HTTR in the 1990s.[8] South Africa worked on the PBMR[9,10] concept during the 1990s and 2000s. More recently, in the US, X-energy has developed the Xe-100 concept,[11] featuring a pebble-bed reactor module with a power output of 200 MWt.

In China, the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University has worked on the modular HTR technologies for almost 4 decades, since 1984. During the first 2 decades from 1984 to 2003, a 10-MWt pebble-bed high-temperature test reactor (HTR-10) was built at the INET site in the suburb of Beijing.[12] Over the subsequent 2 decades, from 2004 to 2023, a significant milestone was achieved with the construction of a 200-MWe demonstration plant of a HTR-PM demo at the China Shandong Shidao Bay site.[13] This project was a collaborative effort of Tsinghua University as the technical leader, China HUANENG as the owner of the plant, and China National Nuclear Corporation (CNNC) as the engineering, procurement, and construction (EPC) contractor. The plant consists of two HTR-PM reactor modules and a common steam turbine. The construction permit was issued and the first concrete 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. Following a successful 168-h demonstration run, the HTR-PM plant entered commercial operation on December 6, 2023.[14] The HTR-PM represents a significant achievement as the world's first modular HTR plant that has been built and operated. Immediately after its connection to the grid, comments were made that China had taken a pioneering role in the development of small modular reactors (SMRs) with this groundbreaking project.[15]

The bird's-eye view picture of the plant building, the layout of the nuclear island, as well as simplified diagrams of the reactor module, and the power generation process of HTR-PM plant are all shown in Figure 1. The HTR-PM plant mainly consists of two reactor modules driving a shared steam turbine. Each module primarily comprises a pebble-bed reactor core, a helical-coil once-through steam generator, and a primary helium circulator. The reactor core and steam generator of each module are arranged side-by-side, connected to each other by a horizontal gas duct, and the primary helium circulator is mounted on the top of the steam generator. The cold helium is guided into the reactor by the outer annular pipe of the gas duct driven by the primary helium circulator. Within the reactor, the cold helium flows through the boreholes inside the side reflector from the bottom to the top of the reactor, where it is collected in a designated area known as the cold helium plenum in the top reflector before entering the pebble-bed core at the top. Then, the helium passes through the pebble-bed core downward, absorbing heat and reaching a high temperature. After being collected in the hot gas plenum inside the bottom reflector, the hot helium is guided through the gas duct's inner pipe to the steam generator's primary side, where it heats the secondary feed-water of the steam generator into superheated steam. The cold helium flow is redirected at the bottom

[1]Institute of Nuclear and New Energy Technology (INET), Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China

[2]Lead contact

*Correspondence:
dongzhe@mail.tsinghua.edu.cn

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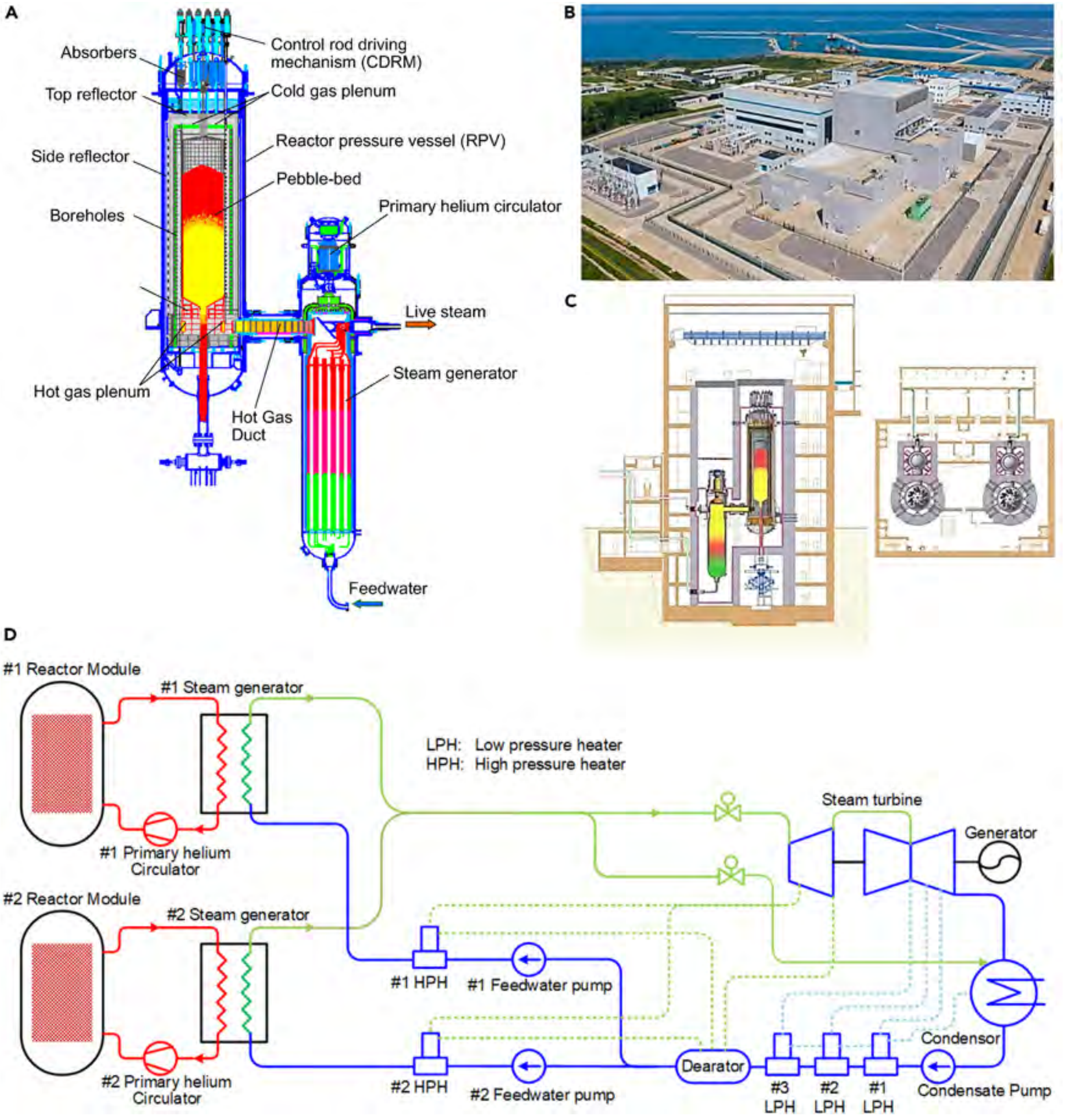

Figure 1. Schematic view of HTR-PM demo plant
(A) Composition of NSSS module.
(B) Bird's-eye view of the plant building.
(C) Layout of the nuclear island.
(D) Simplified process diagram of the power generation process.

of the steam generator and flows upward in the annular space between the steam generator shroud and the inner wall of the steam generator pressure vessel. Finally, the primary circulator returns the helium to the reactor for the next cycle. The superheated steam generated by the two modules is combined before entering the steam turbine for power generation. The main operation parameters of the reactor modules at the 200-MWt power level are given in Table 1.

The HTR-PM reactors adopt the MEhrfach DUrchLauf (MEDUL = 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

Table 1. Main operation parameters of HTR-PM at 200-MW$_t$ power level

Parameter	Unit	#1 Module operation	#2 Module operation	Design
Reactor nuclear power	MW	200	200	250
Primary helium pressure	MPa	6.8	6.8	7
Inlet/outlet helium temperature of the reactor core	°C	243/685	246/688	250/750
Number of fuel and graphite spheres transported into the core/number of spheres in a core	–	2.2	1.9	–
Steam pressure at turbine inlet	MPa	11.0	11.0	13.25
Steam temperature at turbine inlet	°C	523	523	535
Feed-water temperature	°C	160	161	205
Cooling gas radioactivity inventory in the primary circuit	GBq	54	30	700
Active core diameter/height	m	3/11		
Number of control rods	–	24		
Number of small absorber shutdown systems	–	6		
Fuel element type	–	TRISO (UO_2)		
Heavy metal loading per fuel element in the equilibrium core	g	7		
Enrichment of fresh fuel elements in the equilibrium core	%	8.5		
Enrichment of fuel elements in the initial core	%	4.2		
Fuel element diameter	mm	60		
Fuel cycle	–	MEDUL		
Maximum fuel temperature at normal operation	°C	1,200		
Maximum fuel temperature at accident	°C	1,620		

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 needing to be replaced, the two reactors operate at 200 MWt in the running-in stage of reactor cores.

Each fuel element has a diameter of 6 cm and contains approximately 12,000 TRISO-coated particles within its inner graphite matrix. The TRISO particles are able to prevent fission product release from fuel elements under a maximum temperature of 1620°C, thereby determining the mean power density to be about 3.2 MW/m^3. This power density is about 1/30 of that of a commercial pressurized water reactor (PWR), guaranteeing that the decay heat can be efficiently removed by heat transport mechanisms, such as the conduction, radiation, and natural circulation, to the reactor cavity cooling system (RCCS), which is located outside the reactor pressure vessel (RPV). The RCCS consists of three redundant water natural circulation channels and air coolers driven by the air natural circulation, operating under both normal and accident conditions without the need for valve actions. There are no emergency core cooling systems besides the normal power transportation through the steam generator and heat transfer from the RPV surface to the RCCS located within the reactor plant building. Additionally, each reactor module is equipped with 24 reflector rods for reactor shutdown and power regulation. Six small absorber sphere systems play the role of reserved shutdown systems.

The fuel elements of HTR-PM are continuously fed to the pebble-bed cores and discharged through the fuel handling systems. This operational approach maintains an almost zero excess reactivity requirement for burnup compensation to avoid the high excess reactivity because of fueling in the conventional nuclear power plants. Due to the online fuel handling manner of HTR-PM, different types of fuel elements can be used, and the total fuel cycle can be adjusted if necessary, allowing a very high flexibility of operation. Actually, the composition of the reactor core varies across the initial, running-in, and equilibrium stages. The initial core consists of 4.2% enrichment fuel elements and graphite spheres, whereas the equilibrium core consists of 8.5% enrichment fuel elements. In addition, a series of fuel qualification tests including PIE were performed on the specimen of HTR-PM fuel elements at the Nuclear Research and Consultancy Group (NRG) of the Netherlands and the Institute for Transuranium Elements at the Joint Research Centre (JRC-ITU) of the European Commission in Karlsruhe in the licensing stage.[16]

Since December 9, 2022, the HTR-PM plant can steadily operate with two reactor modules driving a common steam turbine. Over a period of approximately 100 days, from January 3 to April 9, 2023, the plant consistently generated electrical power at the level of 38 MWe, while maintaining a thermal power output of around 70 MWt from both modules. The steady operation of the HTR-PM demo validates not only the feasibility of system and equipment design, fabrication, and installation but also underscores the effectiveness of the multi-module scheme. Currently, the reactor cores of the HTR-PM demo are in the running-in stage, and the pebble-beds are composed of fuel elements and graphite spheres. Achieving continuous operation of the fuel handling systems for this pioneering equipment has been a challenging endeavor. Until now, nearly 2 million fuel and graphite spheres have been loaded into and discharged from the cores of the two modules.

In 2023, nearly 400 tests were accomplished, and a series of regulation checks was performed by the national nuclear safety agency during some important tests. Starting from June 9, 2023, the plant coordinated control system can be switched on to provide automatic regulation for the key process variables, including thermal power, neutron flux, helium temperature at the steam generator primary inlet, steam temperature at the secondary outlet, primary helium flowrate, feed-water flowrate, and main steam pressure. The two reactor modules are able to operate at 200 MWt, the same level as the SIEMENS/Interatom HTR-module's designed module power. We are very careful to verify the parameters and the working conditions of all components, systems, and structures to ensure they are in proper status. The reactor module power is maintained at 200 MWt, and the main steam temperature is currently kept at 520°C. In the future, when the equilibrium cores are achieved, the reactor module power will be further improved, and it is expected that main steam temperature will increase to 540°C. Figure 2 shows the steady operation status of the #1 reactor module during the period from 0:00 a.m. August 11 to 9:00 a.m. August 13, 2023, from which it can be seen that the key process variables are well controlled to operate near their setpoints.

To confirm the presence of inherent safe reactors on a commercial scale, two natural cooling tests were performed on the #1 reactor module on August 13, 2023 and the #2 reactor module on September 1, 2023. During the entirety of the tests, the reactor modules were naturally cooled down without emergency core cooling systems or any cooling system driven by power. Although the feasibility of realizing inherent safety has been shown by the safety tests carried out on the test reactors of 45-MWt AVR[17] and the 10-MWt HTR-10.[18] The inherent safety at a commercial scale, such as the 200-MWt reactor power level, has not been verified before because the major bottleneck of decay-heat removal is managing the power level.

RESULTS

The first test began at 9:16 a.m. August 13, 2023. Before the test, #1 and #2 modules operated at the power levels of 200 and about 5 MWt, respectively. The test was started by switching off the power supply of the primary helium circulator and feed-water pump. As a result, the reactor protection system was activated,

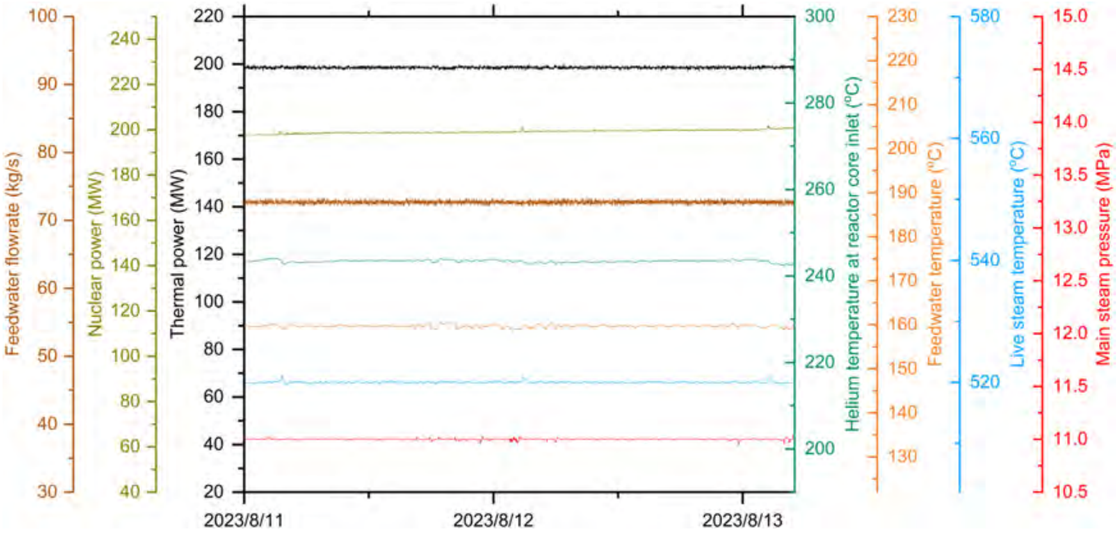

Figure 2. Operation status of #1 module from 0:00 a.m. August 11 to 9:00 a.m. August 13, 2023

triggering the emergency shutdown signal that induced the dropping of control rods. During this process, the helium circulator, feed-water pump, and the steam generator were halted and isolated, which means that the cooling through the steam generator was completely stopped. The only response of the operator was to regulate the helium pressure in the primary circuit in about 10 h to make sure that the pressure difference between the two sides of the steam generator remained within a specified value. Note that the pressure control action is not a safety-related activity; it is used to satisfy the operation requirement of steam generators for the protection of the equipment. The safety-related systems, including the reactor protection system, emergency shutdown signal, dropping of control rods, isolation of the steam generator, helium circulator, and feed-water pump, satisfy the single-failure criterion, and all these systems are fail-safe, except for the isolation of the steam generator.

The measured responses of nuclear power, primary helium flowrate, and control rod position of the #1 reactor module during the first test are shown in Figure 3. The helium flowrate began to decrease and reached a value of 20% in 20 s. Then, the nuclear power reduced to 2% within 20 s, during which the control rod positions were still at about 50% core height, indicating that the reactor shutdown was achieved mainly by the negative feedback mechanism of nuclear fission to temperature. The control rods descended by gravity from the top of the core to their lowest position in 70 s. The temperature profiles for the top reflector, upper part of the side reflector, the side reflector, metallic core internal, and the RPV outer surface at the height of the core middle are shown in Figure 4. The positions of the thermal couples for temperature measurement and the location of RCCS are illustrated in Figure 5. The total heat transfer rate of RCCS, the calculated decay heat at the current status of the core, and the pressure are given in Figure 6. The measured cooling gas radioactivity inventory in the primary circuit is indicated in Figure 7 for the 200-MWt operation. After the test, the radioactivity inventory decreased to a level below the lowest measurement limit of 15 GBq.

The second test was performed on September 1, 2023, and involved the #2 module. At 12:30 p.m., the reactor emergency shutdown was initiated, the helium circulator

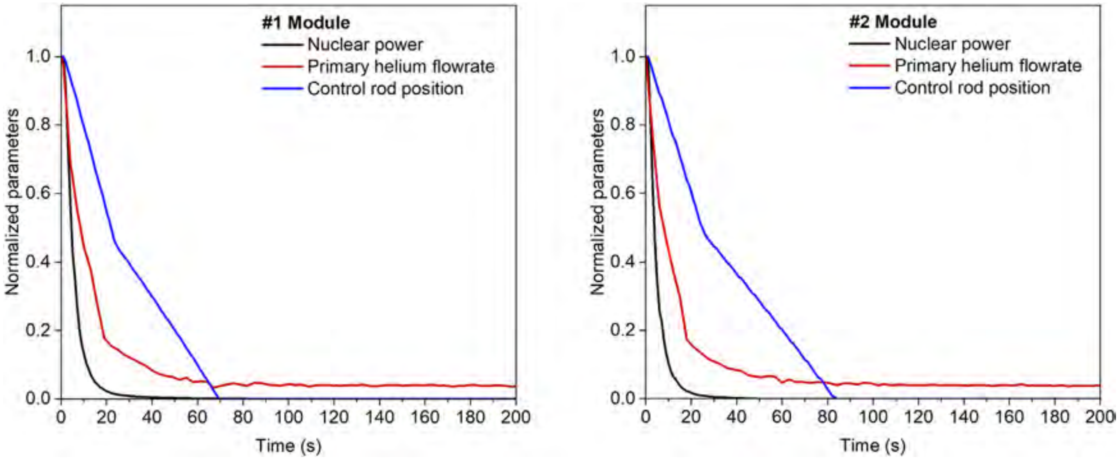

Figure 3. Responses of nuclear power, primary helium circulator speed, and control rod position

and feed-water pump were stopped, and the steam generator was isolated. The reactor was cooled down naturally in the same way as the previous test. The parameters of the process of the #2 module in the second test were shown in the same figures, closely resembling those observed during the #1 module test, thus confirming the consistent and repeatable nature of these features.

DISCUSSION

It can be seen from Figure 5 that after the reactor shutdown, a natural circulation was built up in the reactor core, of which the high-temperature helium at the bottom raised upward from the radial center due to buoyancy, whereas the low-temperature helium flowed downward along the reflector surface. As a result, the temperature of the bottom reflector decreased, whereas that of the top reflector increased. The top reflector temperature reached its highest value of 870°C after 3.5 h of the reactor trip. Subsequently, the temperatures of the top reflector decreased to about 520°C in 35 h. This signified the establishment of a stable condition for heat transfer, which involved the decay-heat generation and transfer in the core and heat transfer from side reflector to the RPV and from RPV surface to RCCS. Figure 6 illustrates that the calculated decay heat of about 4,000 kW was significantly higher than the RCCS power at the beginning. As fission ceased, it reduced quickly and reached the same number of RCCS power of 850 kW after about 13 h. During this period, the decay heat was stored inside the reactor structure, influencing the temperatures of various components. Afterward, the RCCS power surpassed the decay heat, and a stable heat transfer mechanism through the side reflector to the RPV surface was established. The bottleneck in the heat transfer process is the RPV surface. The temperature of all key components, systems, and structures, especially those located at the top of the reactor, remained within the predefined limits. The reactor module had been restarted again after the test. The results of the two tests are simple and clear, as indicated by the well-known laws of nature and as recognized by the world HTR community. It is confirmed that the HTR-PM reactor module could be cooled down naturally, or by the laws of nature, without depending on the emergency core cooling system.

Although the feasibility of inherent safety was verified on the test reactors, such as the 45-MWt AVR and the 10-MWt HTR-10, the verification results on the test reactors cannot manifest the existence of inherently safe commercial nuclear fission reactors, of which the biggest challenge is the highly lifted power. The two tests performed in

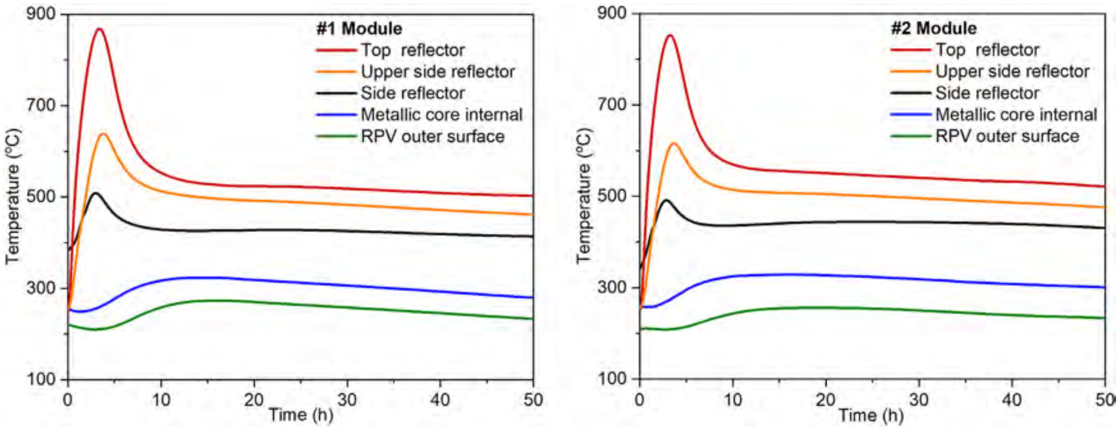

Figure 4. Temperatures of the top reflector, side reflector, metallic core internal, and reactor pressure vessel

the two reactor modules of HTR-PM plant operating at 200 MWt provided conclusive evidence that the reactors could be naturally cooled down by the laws of nature, significantly minimizing the operator actions and safety systems required in LWR designs.

In addition, the economic viability of the modular approach could be achieved by the multi-modular scheme,[19] where a set of standardized HTR-PM reactor modules collectively drive a common system of thermal load. In fact, the HTR-PM demo itself exemplifies this concept because it is composed of two reactor modules providing superheated steam for a single turbine. Although the current power generation cost of HTR-PM is still about 20% higher than that of commercial PWR plants, this could be managed by scheme cogeneration and further by the mass production of reactor modules. We, along with the industry partners, believe that the cost-effectiveness will be achieved after the mass supply chains are established.

In summary, the loss-of-cooling tests conducted confirm the inherent safety feature of the world's first demonstration plant of a HTR-PM. To fulfill the climate change mitigation goal, we have initiated new projects aimed at providing high-temperature steam up to 500°C and electricity to the petrochemical industry in China. The reactor modules for the commercial plants are designed to adhere to the same standardized design.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Zhe Dong (dongzhe@mail.tsinghua.edu.cn)

Materials availability

This work did not generate new, unique reagents.

Data and code availability

The published article includes all data generated or analyzed during this study.

The way to trigger emergency reactor shut down

The emergency reactor shutdown is the basis for performing the safety tests. During the rests, the emergency reactor shutdown was triggered indirectly by switching off

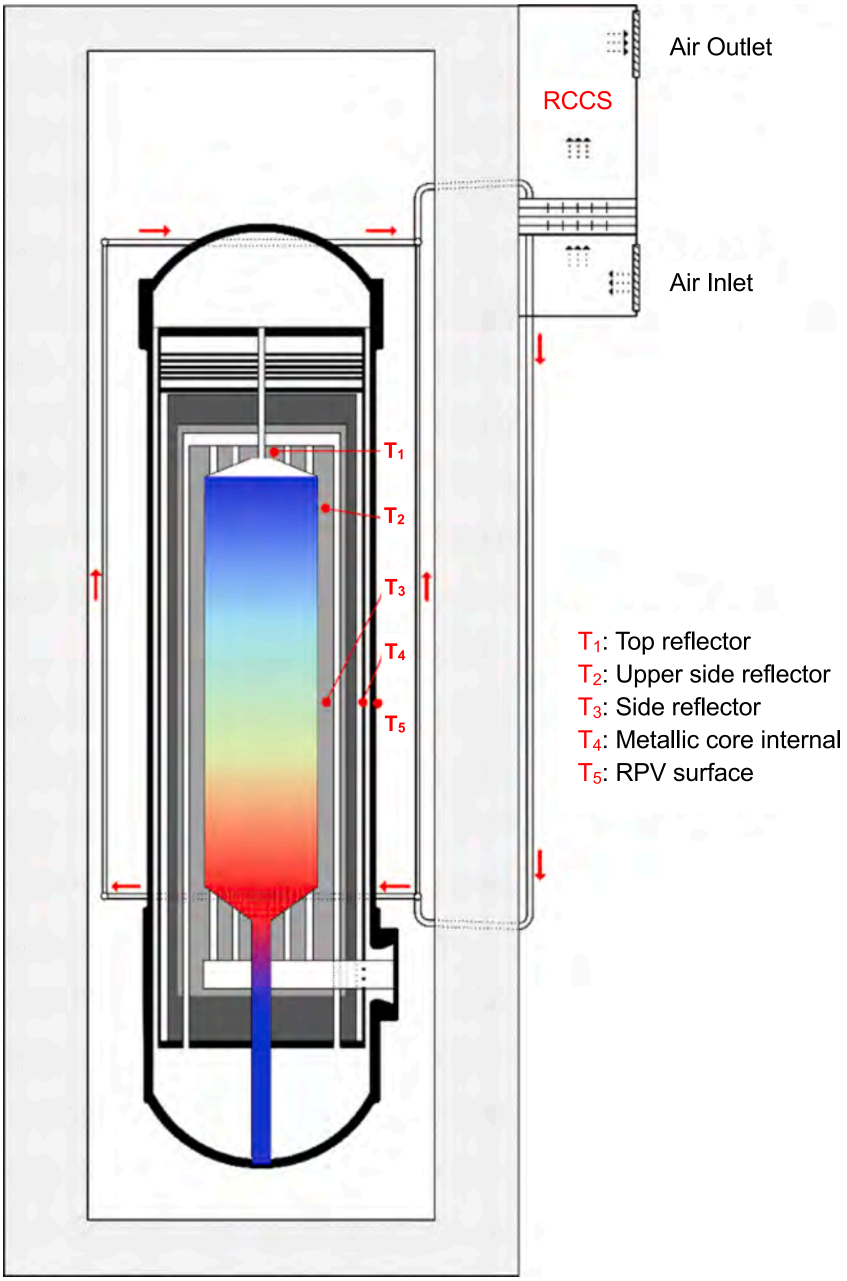

Figure 5. The position of the measured temperatures during the tests and diagram of RCCS

the power supply of the primary helium circulator and feed-water pump simultaneously. Due to the rapid decline of the helium and feed-water flowrates caused by the simultaneous stopping of the helium circulator and feed-water pump, the reactor protection system was activated, triggering the emergency shutdown signal that induced the drops of the control rods, as well as the isolation of the steam generator, helium circulator, and feed-water pump.

The logic to confirm the inherently safe reactors

The reactor power decreases immediately after the helium circulator stops due to negative nuclear fission power to core temperature feedback. This phenomena

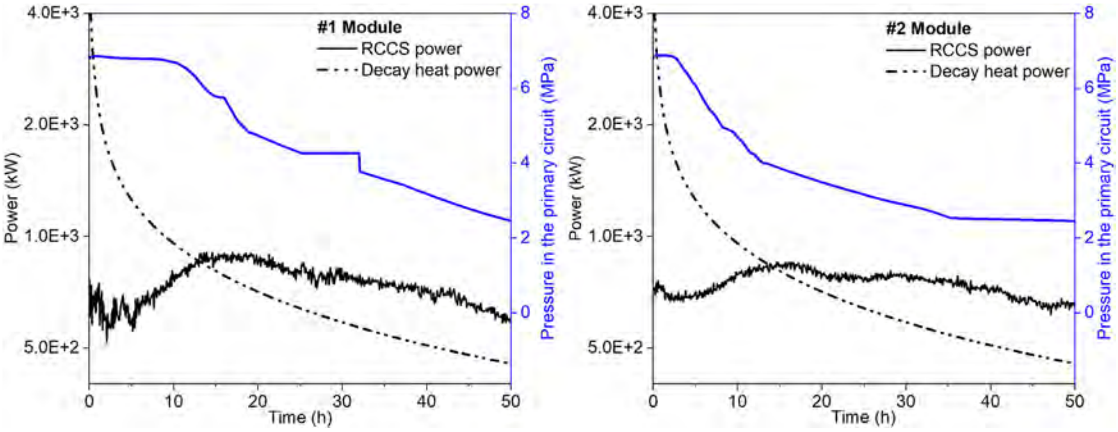

Figure 6. Responses of decay-heat power, RCCS power, and primary pressure

could be measured during the commissioning test of the core. The decay heat after the reactor shutdown could be determined by calculating the fission products inventory within the core based on the operation history and the decay of the fission products. The heat transfer in the core could be described by the natural convection of helium, heat conduction, and radiation in the pebble-bed core. The heat transfer in the graphite reflector, carbon block, metallic core internal, and RPV are mainly governed by the laws of heat conduction and radiation. The helium leakage between the gaps of the graphite and carbon structure could play a role, and it was estimated to be minimal based on the past analysis. These phenomena are governed by the well-known laws of nature. Furthermore, the inputs could be measured repeatedly and verified. The results are verified carefully during the licensing process.

The method to confirm the inherent safety or safety by the laws of nature is given by the following four logical principles:

(1) The input data are certain and measured repeatedly.

During the tests, all the measurement signals of nuclear power, temperatures, flowrates, pressures, etc. provided by the local instruments are collected at the plant digital control system (DCS) and saved to the historical data server of DCS. The sampling period of these important physical and thermal-hydraulic process variables is 1 s at most, and necessary filters are equipped to the measurement channels for attenuating noises. The responses shown in Figures 3, 4, 6, and 7 are all given by the practical measurement data saved in the historical server during the tests. In addition, to guarantee the certainty and repeatability strictly, the safety test of natural cooling down is performed on both reactors of HTR-PM plant. Figures 3, 4, 6, and 7 show that the responses in the two tests are in good accordance with each other, providing a basis for concluding that commercial-scale inherent safety is confirmed.

(2) Follow the well-known laws of nature.

Reliable shutdown, passive decay-heat removal, and strict containment of radioactivity are the three aspects of guaranteeing nuclear safety. The safety of the HTR-PM reactor is not provided in the sense of probability similar to that of commercial large-scale PWRs but is given inherently by the well-known laws of nature. The reliable

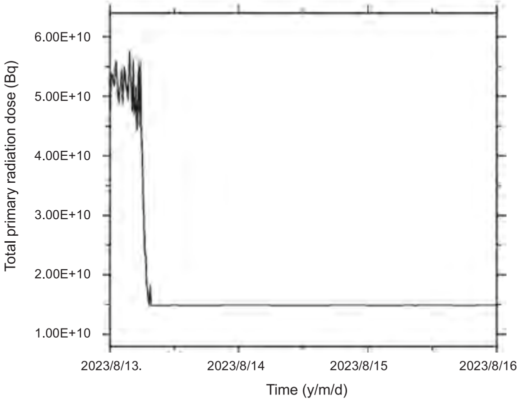

Figure 7. Total primary radiation dose measurement

shutdown of HTR-PM reactor is mainly guaranteed by the design feature of the strong negative temperature feedback effect. When the primary flowrate decreases quickly, the reactor core temperature increases, inducing a large negative reactivity that is enough to shut down the reactor reliably. The passive residual heat removal is mainly given by the design feature of low power density. Due to the limitation of residual heat by the low power density, the decay heat is removed totally and passively by the natural means of heat radiation, conduction, and convection. The strict containment of radioactivity is given by TRISO particle fuel elements. The radioactive products of fission reaction are firmly contained inside the particles under 1,620°C, being observably higher than the fuel temperature in any conceivable scenario.

(3) The results are inferenced by deductive logic.

The test results can be inferenced certainly by the deductive logic given by natural laws. It can be seen from Figure 4 that the nuclear power reduced to 2% within 20 s, whereas at that time, the control rod positions were still at about 50% of their initial value, showing the capability of reliable shutdown given by strong negative temperature feedback effect. Figures 4 and 6 show that, because the decay power is larger than the RCCS power right after the reactor shut down, the temperatures of coolant, reflector, and structural materials begin to increase. The temperature increase gave a higher temperature difference with respect to the environment, which further induces the rise of RCCS power. When RCCS power reaches its maximal value, all the temperatures have begun to decrease to their equilibrium value. The general trends of these process variables, including nuclear power and temperatures, are consistent with the theoretic self-stability and passivity analysis of HTR.[20,21] In addition, because the measured radioactivity inventory of primary coolant reduces to the level below the lowest measurement limit of 15 GBq, it can be seen that the radioactivity is strictly contained inside the TRISO particles during the procedure of natural cooling down.

(4) It can be verified through full-scale reactor tests.

Although the feasibility of realizing inherent safety were verified on some test reactors, such as the AVR and HTR-10, the existence of inherent safety in a commercial scale is still not confirmed until the safety tests are performed on HTR-PM reactors at the power level of 200 MWt. Actually, the most difficult task in verifying the existence of commercial-scale inherent safety is the construction and commissioning of the demonstration plant.

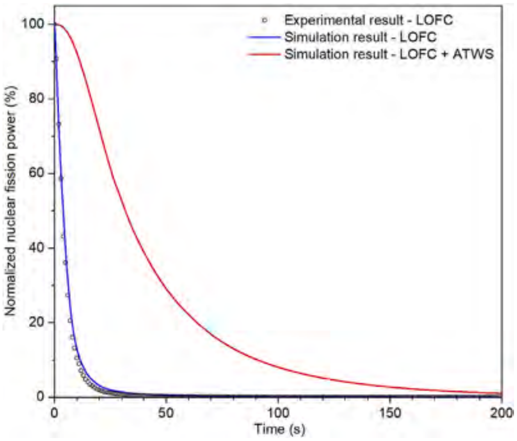

Figure 8. Responses of normalized nuclear power with and without control rod insertion
LOFC, loss of cooling; ATWS, anticipated transients with scram.

Even if the emergency shutdown does not work

Because the fuel spheres are continually loaded into and discharged from the pebble bed, the excess reactivity of HTR-PM reactors is quite low, given that the control rods are positioned at the top of the reactor core during the normal operation. Immediately after the stop of helium circulator, the reactor power decreases rapidly, steered by the negative reactivity from both the control rods and temperature feedback. Further, because the time for the control rods fully descending into the reactor core is nearly 70 s, the negative reactivity provided by temperature feedback dominates the initial stage of shutdown, as shown in Figure 2. These measured responses are adopted to tune the simulation code TINTE, and the comparison of measured and simulated responses are given in Figure 8, showing that the satisfactory precision of this simulation code. Then, the code is used to give the responses in the case that the malfunction of emergency shutdown is overlapped with the loss of cooling, and the corresponding response of normalized nuclear power is also given in Figure 8, showing that the negative reactivity given by temperature feedback is enough for shutting down the reactor, whereas the insertion of control rods speeds up the transition to subcriticality. This simulation result indicates that, even if the emergency shutdown through the control rods fails, the reactor can still shut down automatically as a result of the halt in the helium circulator's power supply.

If the decay heat increased to that of the equilibrium core or the module power increased up to 250 MW_t

The estimated decay heat of the tests is about the 70% of the equilibrium core's decay heat. The decay heat at the tests of the two modules can be estimated as 200 MWt × 0.004 × 0.7 = 560 kWt in 35 h, as indicated in Figure 5. If the test is performed in the equilibrium core, the temperature of the upper-side reflector will be increased about 100°C and to 520°C + 100°C = 620°C. It does not change the conclusions drawn from the tests. If the module power were to increase to 250 MW_t, it is estimated that an additional 100°C increase on the upper-side reflector would occur. The temperature will be in the range of 520°C + 100°C + 100°C = 720°C, which is still within the limit of the modular HTR estimation.

Even if the helium coolant is lost

The test was performed without loss of helium coolant. The natural helium convection will decrease the temperature difference inside the pebble-bed core. A simple way to consider the case with the loss of helium coolant is to estimate the fuel temperature difference in the core according to the formula:

$$\Delta T = \frac{Q\beta}{4\pi\lambda H}$$

where ΔT is the temperature difference between the core center and the core outer surface, λ is the effective heat conductivity of the pebble-bed core and was measured as about 15 W/(m°C) at minimum, H is the height of the core and is 11 m, β is a factor to indicate the power axial profile, and Q is the decay heat at the time that is estimated to be 800 kWt in 35 h based on the calculation 200 MWt × 0.004 = 800 kWt. Then, it is easy to calculate that $\Delta T = 620^\circ\text{C}$, meaning that in 35 h, the maximum core temperature in the case of the loss of helium coolant is about 620°C + 620°C $\leq$ 1,300°C. For 250 MWt, the temperature difference will be 750°C, and the maximum core temperature is about 720°C + 750°C $\leq$ 1,500°C. As shown in Figure 5, the pressure of the primary circuit decreased during the process because the helium was discharged to reduce the pressure difference between the primary circuit and the secondary side of steam generator. There will be no significant impact on the helium natural convection if the pressure is larger than 1.0 MPa.

Even if the malfunction of RCCS is additionally overlapped with the scenario of loss of coolant, the increase of fuel maximum temperature can be still limited to about 100°C because the radiation heat transfer in the pebble-bed core increases sharply when the temperature is higher than 1,000°C, taking into account that it is proportional to the fourth power of the temperature. The leakage of the radioactivity from the TRISO fuel particles is still very limited.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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