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Future HTGR developments in China after the criticality of the HTR-10

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Abstract

Nuclear power has a great potential to develop in China because of China's fast economic increase. HTGR will be the most promising nuclear reactor to apply in the future Chinese market. After the initial criticality of the HTR-10, subsequent research and validation of the HTGR performance is by hot commissioning tests and power operation, safety demonstration experiments, R&D of gas turbine and process heat application technologies, and promotion of industrial application of HTGR technologies. The commercial prototype HTR-PM is under study and conceptual design has started. These activities will result in the safe and economic development of HTGR technologies in China.

1. Introduction

The pebble bed high temperature reactor is seen as one of the best candidates for the next generation of nuclear power systems (DOE, 2000). Interest increased as the pebble bed modular reactor (PBMR) project was launched and the South African utility ESKOM made serious moves to be the initial customer (Nicholls, 1998).

The Chinese HTR-10 pebble bed reactor was initially fueled and went critical before the facility underwent hot commissioning tests (Zhong and Qin, 2001). Therefore, for the HTR-10 reactor, the hot tests and power-rise commissioning shall be the main tasks after its criticality. Power operation is necessary to study and verify the performance of various HTR-10 components and systems.

The inherent safety features are one of the striking advantages of modular helium cooled reactors (Lohnert, 1990). One of the purposes for building the HTR-10 is to demonstrate the unique safety features of this reactor technology. Therefore, safety demonstration experiments are planned after the reactor facility is commissioned.

The HTR-10 reactor, in its current system configuration, is coupled with a steam turbine power generation unit through a steam generator (SG) (Xu, 1999). In addition, in later project phases the test reactor facility will be reconfigured to allow R&D work with gas turbines and process heat application technologies.

With the successful construction and operation of HTR-10 as a pilot plant, it is time to study and

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promote industrial application of the modular HTGR technology. This technology has obtained drawn great interest from the Chinese government and the power industry, so additional development is likely to be carried out.

2. Requirements for future HTGR development in China

Chinese electricity capacity increased from 66 GW in 1980 to 277 GW in 1999. However, as a developing country, the electricity capacity per capita is still less than one half of the world average. Estimates by the State Power Corporation (SP, the biggest utility in China) indicate that the power demand will increase 400 GW by the year 2020 (State Power Corporation, 2000). It is expected that, at most 80 GW will be hydroelectric power, 30 GW will be generated using natural gas and 10 GW will come from renewable energy resources. An additional 280 GW will still be needed which obviously cannot all come from burning coal due to the pollution. Therefore, nuclear power has a great potential to be developed in China.

However, the difference between the potential and real situation is still large. Currently, 2.1 GW of nuclear power plants are in operation with another 6.60 GW under construction. More new projects are not yet approved. From the author's points of view, the major reasons for the difference seem to be:

2.1. Nuclear power should be competitive

In China, the major competitors to nuclear power is coal power plant. The capital cost of conventional coal power plants is about 500–800 USD kWe^{-1}, which is significantly lower than in other countries. The reason for the low cost is that the purchasing-power in a developing country is normally larger than in a developed country and coal power plants can be completely built by Chinese enterprises. In contrast, commercial nuclear power plants such as 1000 MWe light water reactors have to be imported. The capital cost of imported plants from France like in Daya Bay and Ling Ao is about 2000 USD kWe^{-1}, these costs are higher than in France. To compete with coal power plants, the capital cost of nuclear power plants should be in the range of about 1200–1400 USD kWe^{-1}. One solution to solve the problem is the localization of nuclear power plants including design, manufacturing, construction, and operation. Combined cycle gas turbine (CCGT) power plants using natural gas are not competitive in China right now, since the capital costs of imported CCGT is larger than the costs in American and European markets and natural gas is still expensive.

2.2. Safety concepts should be simple

Nuclear power is still accepted by the public of China, like it was accepted in the early 1990s in France and in Japan, or during the early 1970s in the United States, because the public confidence in China toward the nuclear field is still high and the energy supply needs are very high also. However, the government decision-makers frequently hear news from other countries like 'Germany phases-out nuclear energy', 'Tokaimura nuclear accident in Japan (Sep. 30, 1999)', conflicting information about the consequences of the Chernobyl accident, etc. The safety of current nuclear power plants is satisfactory from the science and engineering points of view. However, the safety concepts are still too complicated so they cannot be explained to people outside the nuclear field in a simple way.

The major interest in the nuclear power plants in China is still focused on LWRs, especially on PWRs. However, interest in the pebble-bed Modular HTGR is increasing since it could probably solve the major challenges we have just discussed, of nuclear power development in China. The major advantages include the localization of modular HTGRs, reduced investment for a single module of about 110 million USD, and easily to grasp 'inherent safety', as well as possible economic advantages, for example a low capital cost of around 1000 USD kWe^{-1}.

3. Second phase of the HTR-10

The HTR-10 second phase was planned several years ago. The plans for the second phase are reflected in the HTR-10 design; for example, the SG design includes space to install an intermediate heat exchanger (IHX) to operate at 950 °C, etc. It is highly probable that the government will continue to support the second phase of the HTR-10 if the first phase is successful.

The HTR-10 second phase will be finished in 5 years, and has been approved in the year 2001. The major tasks of the second phase are:
1. to perform operation and safety demonstration tests in the HTR-10;
2. to develop and test the fuel;
3. to develop a helium gas turbine cycle;
4. to test the process heat applications.

The HTR-10 is the only of pebble-bed HTGR test reactor in the world which can provide a useful environment to test and develop fuels and to test gas turbine systems in an integrated system. Therefore, INET is encouraging international involvement in the HTR-10 second phase to conduct joint research projects.

3.1. HTR-10 operation and safety demonstration tests

After installation and before initial criticality, the systems and components were tested using cold air as the circulating gas. Hot commissioning tests will take place after initial criticality with the primary helium circulator as the main heat source. The design operating performance of the systems and components under hot conditions will be tested and verified during this stage. The coolant will then be changed from air to helium to allow the start of various tests with helium.

The power-rise test will then step through the following power stages: 15, 30, 50, 75, and 100% of the 10 MW rated power. When the power-rise tests are complete, the test reactor plant as a whole will be fully commissioned. The power-rise tests will also include tests of some abnormal plant conditions such as load rejection, loss of off-site power, and fault shut-down of the primary helium circulator.

After the test reactor reaches full power, continuous power operation is necessary to study and verify the performances of various systems and components under reactor power operation. These systems and components include the fuel elements, the primary helium circulator, the reactor shut-down systems, the fuel handling system, the SG, the hot gas duct, I&C and protection systems, etc.

The most important advantage of modular high temperature gas-cooled reactors is their inherent safety features. These safety features include the passive decay heat removal and reactor self-shutdown under accident conditions through a negative reactivity temperature coefficient. Engineered safety features are not necessary to protect the reactor when accident conditions occur. The unique safety performance of the modular HTGR is an important selection factor for the government, the public and the utilities when they consider this reactor technology. The HTR-10 test reactor can be used to perform safety demonstration experiments to verify the safety features and to promote better understanding of these features.

Some of the safety demonstration experiments under consideration for the HTR-10 are:
- Loss of feed water supply
- Loss of helium flow
- Failure of primary isolation valve
- Loss of off-site power supply
- Failure of cavity cooling system
- Fault withdrawal of control rods
- Turbine trip
- ATWS
- Integral test of fuel bed up to 1600 °C.

Most of the safety demonstration experiments will be carried out after full power is reached and the reactor has been properly operated for some time.

3.2. Fuel development and verification

The HTR-10 is a modular pebble-bed type reactor with spherical fuel elements. Further work on fabrication of UO_2 kernels, coated fuel particles and spherical fuel elements is required to guarantee the fuel elements satisfy the requirements of future commercial high temperature gas-cooled reactors. These requirements may be demonstrated by testing graphite spheres that have been manufactured from the same lot of matrix graphite at the same time, using the same equipment and manufacturing parameters, and in the same furnace charges.

3.3. Gas turbine cycle

Recent developments in gas turbine equipment, high-efficiency heat exchangers and electromagnetic bearings have enabled the development and design of reactor plants combining a safe modular gas-cooled reactor and a power conversion system based on the high-efficiency gas-turbine Brayton cycle. The components of a gas turbine cycle, such as the turbine, compressor, magnet bearings, and effective recuperator could be found in other industries. The major challenge for a commercial direct helium gas turbine cycle for HTGR would be an integrated test with a real HTGR primary system environment. The questions concerning radioactivity deposition on the turbine blades, the influence of turbine shaft over-speed, as well as the system configuration, could be answered in the tests. The HTR-10 will be a very attractive reactor to perform these tests.

After successful operation and initial experiments on the HTR-10, the test reactor facility will be reconfigured for research and development work on gas turbines. The HTR-10 in its current system configuration consists of the 10 MW pebble bed reactor, the SG and the steam turbine-generator system. Space is reserved inside the SG pressure vessel for an IHX which will be installed later for future R&D tasks. Inlet/outlet nozzles for the secondary fluid that will be heated in the IHX are also in place on the SC pressure vessel. In principle, the HTR-10 reactor can be reconfigured in various ways.

Table 1
Major parameters for HTR-10 phase two power conversion unit

Reactor thermal power	10 MW
Core inlet temperature	250–300 °C
Core outlet temperature	700–950 °C
Size of steam generator cavity	$6.4 \times 6.4 \times 14.8$ m^3
Reactor pressure	1.0–3.0 MPa

The direct helium turbine cycle coupled with a high temperature gas-cooled reactor is presently being developed in several countries, for example, the PBMR and GT-MHR projects (IAEA, 2001). The direct cycle configuration promises to simplify the plant system design and should bring considerable cost benefits. Coupling of a direct helium cycle to the HTR-10 test reactor would be an attractive proposal.

This coupling would basically require the dismantling of the existing helium circulator and probably even the SG and its pressure vessel. In addition, any changes must consider that the design temperature of the HTR-10 carbon steel pressure vessel system is limited to 350 °C.

The major parameters for the HTR-10 phase two power conversion unit are shown in Table 1.

Coupling of a gas turbine cycle to the HTR-10 through an IHX would result in an indirect cycle. Coupling of an indirect helium turbine cycle to the HTR-10 test reactor would enable the installation of a nuclear driven helium turbine facility which would allow much more R&D work on the turbine part. An IHX together with the existing SG would also allow better optimization of the gas turbine and steam turbine parts. The IHX option would also allow the possibility of R&D of process heat application technologies.

Another option would be a direct gas turbine cycle combined with a steam turbine cycle using the existing SG.

Currently, these options for coupling gas turbine cycles to the HTR-10 are being studied and evaluated. An agreement has been signed between INET and OKBM of Russian to develop the preliminary design for the HTR-10 reactor power conversion unit. A concept layout for a direct gas turbine cycle is shown in Fig. 1.

4. Commercial prototype of a high temperature gas-cooled reactor

The HTGR development has been carried out so far within China's National High Technology Research and Development Program. Most

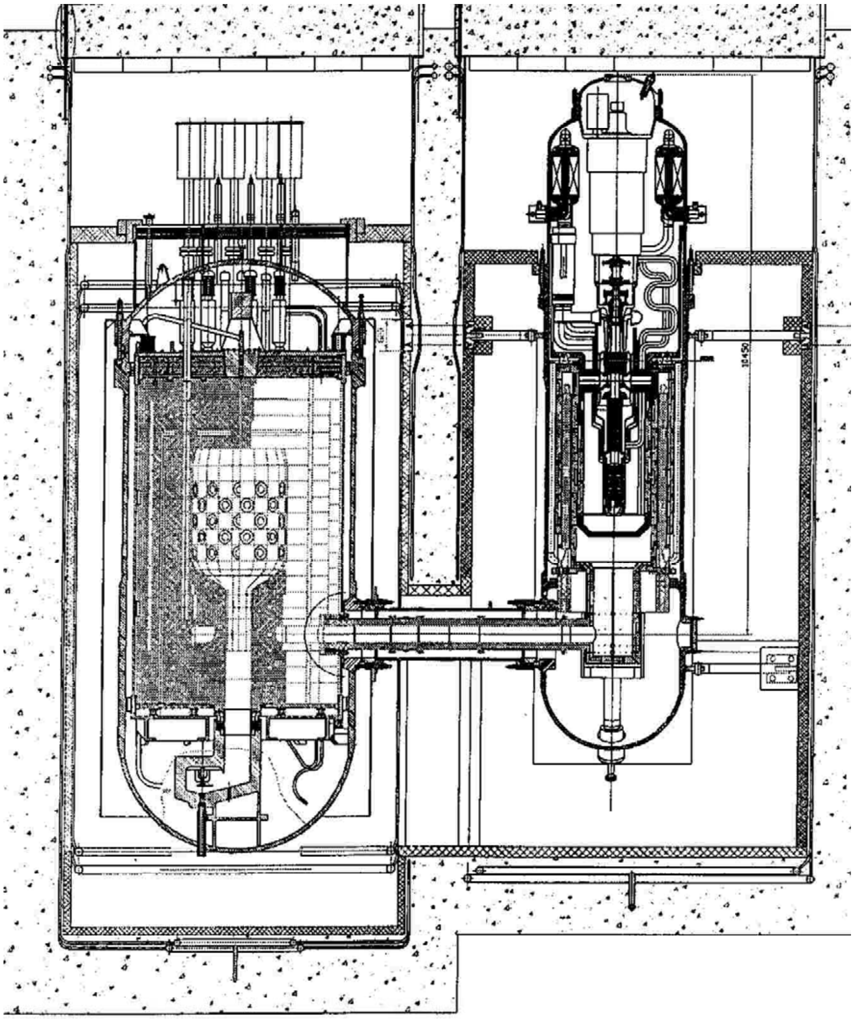

Fig. 1. HTR-10 layout with a direct gas turbine cycle in the steam generator vessel.

projects in this program are supposed to have strong industrial application potential. The HTR-10 is one of the most successful projects in the energy sector of the high-tech program. With the commissioning work currently underway, the industrial application of modular high temperature gas-cooled reactors can now be developed and promoted.

With the continuous rapid economic development in the past years which is expected to continue in the coming decades, the energy market requires the installation of additional power generation capacity. Many utilities are very positive towards the nuclear option. The State Power Corporation and some local utilities have shown particular interest in gas-cooled reactors. Both INET of Tsinghua University and the State Power Corporation have agreed to cooperate on building the first HTGR industrial demonstration plant for power generation, the 100 MWe High Temperature Reactor Pebble-bed Module (HTR-PM). The aim of this cooperative effort is to start erection of the demonstration plant near the end of the National tenth five-year plan (2001–2005) and then begin building plants in series. Current activities of the cooperative effort are focusing on feasibility studies. The cooperative effort is supported by the State Planning Commission and the State Ministry of Science and Technology.

The proposed HTR-PM has the following characteristics:

– Generation of electricity at lower cost. The design can generate more energy than existing nuclear plants with the same fuel consumption and radioactive waste.
– High level of safety in comparison with existing and upgraded nuclear plants. The unique safety characteristics of modular high-temperature reactors allow them to be located near towns.
– Minimal environment impact. The HTR-PM will not have any emissions to the air and can reduce the consumption of fossil fuel so that thermal remediation with the fossil fuels can be reduced too.

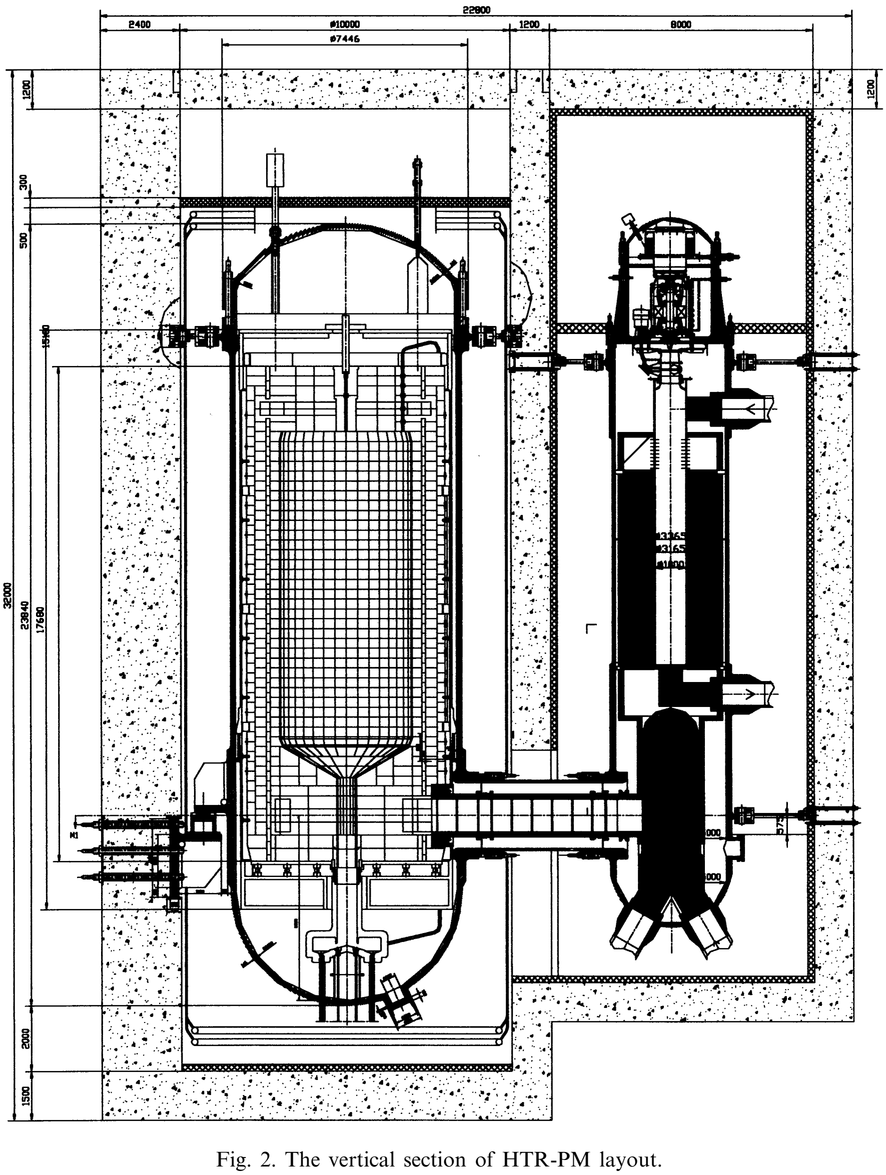

Fig. 2. The vertical section of HTR-PM layout.

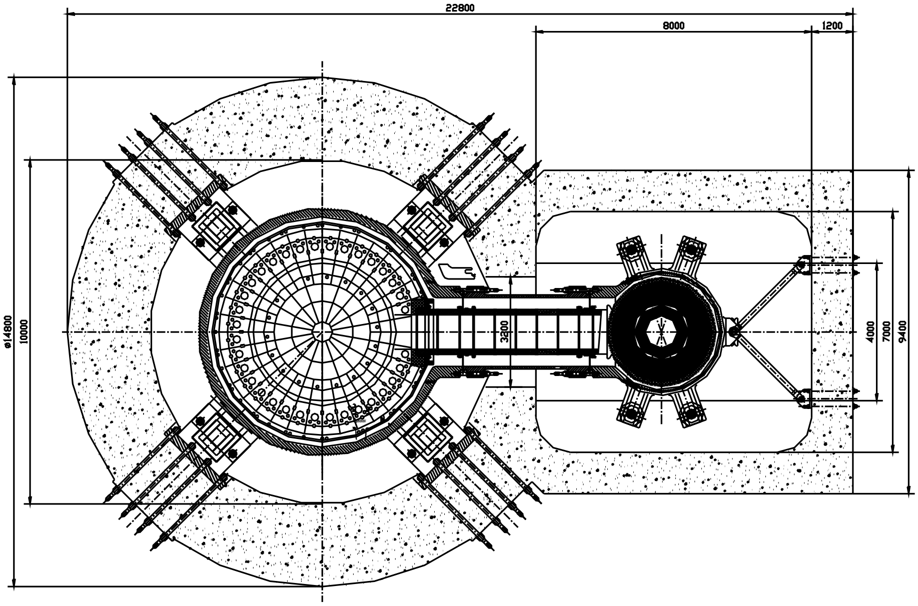

Fig. 3. The cross section of HTR-PM layout.

– Provides the ability to eliminate the use of fossil fuels to generate high-temperature heat required for petroleum refining and the chemical industry.

Development of the HTR-PM has already begun. Safety, Simplicity, and economy are the primary concern. Figs. 2 and 3 show the vertical section and the cross section of HTR-PM, respectively. The main specification of HTR-PM is listed in Table 2. For the power conversion unit, three options are under consideration, a steam turbine cycle, a direct helium gas turbine cycle and an indirect gas turbine cycle. The major parameters as shown in Table 3 are considered based on the following

4.1. Core inlet temperature

There are several core inlet temperature options. The core inlet temperature would determine the steel used in the reactor structure. Temperatures in the range of 250–350 °C would allow the use of conventional LWR material in the reactor pressure vessel which does not need a further verification program. The HTR-10 uses these materials. A higher core inlet temperature would require new materials for the reactor pressure vessel or a dedicated cooling system, which will influence plant efficiency and system configuration. The direct gas turbine cycle with a recuperator will require a higher core inlet temperature in the range of 490–600 °C if the core outlet tem-

Table 2
Main specification of the HTR-PM

Item	Unit	Amount
Thermal power	MW	320
Core diameter		
Central graphite zone	m	1.80
Annual fuel zone	m	1.80 to ~4.00
Average core height	m	9.43
Average core power density (fuel zone)	MW/m^{-3}	3.39
Spherical fuel element diameter	Mm	60
Fuel		UO_2
Average burn up	MWd/tu	>80 000
Control rod number		18
Absorber channel number		18
Helium pressure	MPa	7.0
Vessel diameter	m	~7.00

Table 3
Main parameters for the three power conversion cycles

Cycle type	Steam cycle	Indirect gas cycle	Direct gas cycle
Thermal power (MW)	320	320	310
Inlet temperature (°C)	250	400	550
Outlet temperature (°C)	750	850	900

Table 4
Preliminary comparison of different options

	Positive	Negative
Steam turbine	Uses current available technology	Need to connect several reactor modules onto one steam turbine Possible water ingress should be considered Efficiency is limited to 44%
Direct cycle	Advanced Potentially cheaper	No integration experience Uncertainty in some technologies such as magnetic bearings, catcher bearings, and turbine maintenance Change the vessel material or add a cooling system
Indirect cycle	Use conventional gas turbine technology	Intermediate heat exchanger should be developed Change the vessel material or add a cooling system Expensive

perature is 850–900 °C. Increases of the core outlet temperature will require an even higher core inlet temperature. The direct helium turbine and steam turbine combined cycle has the advantages that the core inlet temperature is in the range of 250–300 °C while maintaining high efficiency.

4.2. Technology availability

Use of the steam turbine cycle in HTR-PM will use the available technology tested in the HTR-10 project. However, steam turbines having powers of about 100 MWe have not been optimized for the plant efficiency due to the small blade height. Therefore 2–4 pebble-bed reactors will be connected to a steam turbine. This increases the system scale and complexity. The direct helium turbine will require an integrated test of the whole system, which would depend on the results of the HTR-10 second phase. The materials used in the HTR-10 may have to be changed which would require further verification. The use of an indirect gas turbine would relax the pressure requirements of the gas turbine systems. However, the IHX is expensive and complex. Table 4 gives a preliminary comparison of the options. INET, together

Table 5
Future HTGR development schedule in China

Duration	Activity
–2000.12	HTR-10 first criticality
2001.1–2002.12	HTR-10 hot commissioning, power operation, design performance verification
2001.1–2003.12	HTR-10 safety demonstration experiments
2001.1–2005.12	HTR-10 gas turbine cycle realization
2001.1–2004.12	HTR-PM feasibility study
2004.1–2005.12	HTR-PM project preparation & licensing
2006.1–2009.12	HTR-PM demo-plant construction

with the State Power Corporation, has formed a joint program to evaluate the above three options and will make a decision soon.

A preliminary time schedule, as indicated in the joint proposal to the Chinese government by INET and the State Power Corporation, for these activities is given in Table 5 (Sun, 2001).

5. Concluding remarks

The future direction of HTGR research and development in China falls into the following categories: hot commissioning tests and power operation of the HTR-10 and safety demonstration experiments with the HTR-10, R&D of gas turbine and process heat application technologies, and promotion of industrial applications of HTGR technology (HTR-PM). Most activities will be supported by the state and by the industrial sector.

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