ON THE ISSUES OF FUEL STORAGE AND DECOMMISSIONING OF THE HTR-10 TEST REACTOR

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Abstract

The HTR-10 is a helium cooled, graphite moderated test reactor using spherical fuel elements with coated fuel particles. The rated thermal power output is 10 MW. Average burn-up of the spent fuel is designed at 80,000 MWd/tU. Discharged spent fuel elements are stored in lead-steel containers. These spent fuel containers will be stored in a concrete compartment designed in the reactor building with the capacity of storing all the spent fuels of the reactor life span.

Decommissioning of the HTR-10 is subject to the Chinese national standards and codes for research and test reactors. China's national nuclear safety authority has issued the following documents which are applicable to the decommissioning work of HTR-10: Nuclear Safety Regulation HAF 1000-1 *Safety Regulations on the Design of Research Reactors*, Nuclear Safety Regulation HAF 1000-2 *Safety Regulations on the Operation of Research Reactors*, Regulatory Guide HAF 1004 *Decommissioning of Research Reactors and Critical Facilities*.

The paper discusses the following aspects concerning decommissioning the HTR-10: decommissioning considerations in the design and operational stage, facility characteristics and site features, preliminary activities of decommissioning. The key radioactive materials of the HTR-10 are spent fuel elements, core internals, pressure vessels and steam generators, components of fuel discharge system and helium purification system as well as some other auxiliary systems. Site of the HTR-10 is Institute of Nuclear Energy Technology, which is a nuclear research center and should exist for a long term. Designed plant life of HTR-10 is 20 years. Technical approaches of decommissioning the HTR-10 depends on a number of aspects, but mainly on the national strategies.

1. The HTR-10 test reactor

The HTR-10 reactor is a major project in the energy sector of China's national high technology programme. The reactor is a helium-cooled, graphite moderated test unit with a thermal output of 10 MW. It is one of the advanced reactors to be developed for the next century, when China's economy is expected to continually grow rapidly and the country's nuclear programme is planned to be greatly expanded.

The HTR-10 project is to be carried out in two phases. In the first phase, the reactor will be operated with a coolant outlet temperature of 700°C. It is coupled with a steam generator providing steam for a steam turbine cycle which works on electricity/heat co-generation basis. In the second phase, it is planned to raise the reactor coolant outlet temperature to 900°C. A gas turbine cycle will be coupled to the reactor in addition to the steam turbine cycle.

The key design parameters of HTR-10 are listed in Table I, and a cross-section view of the HTR-10 primary circuit is presented in Figure 1.

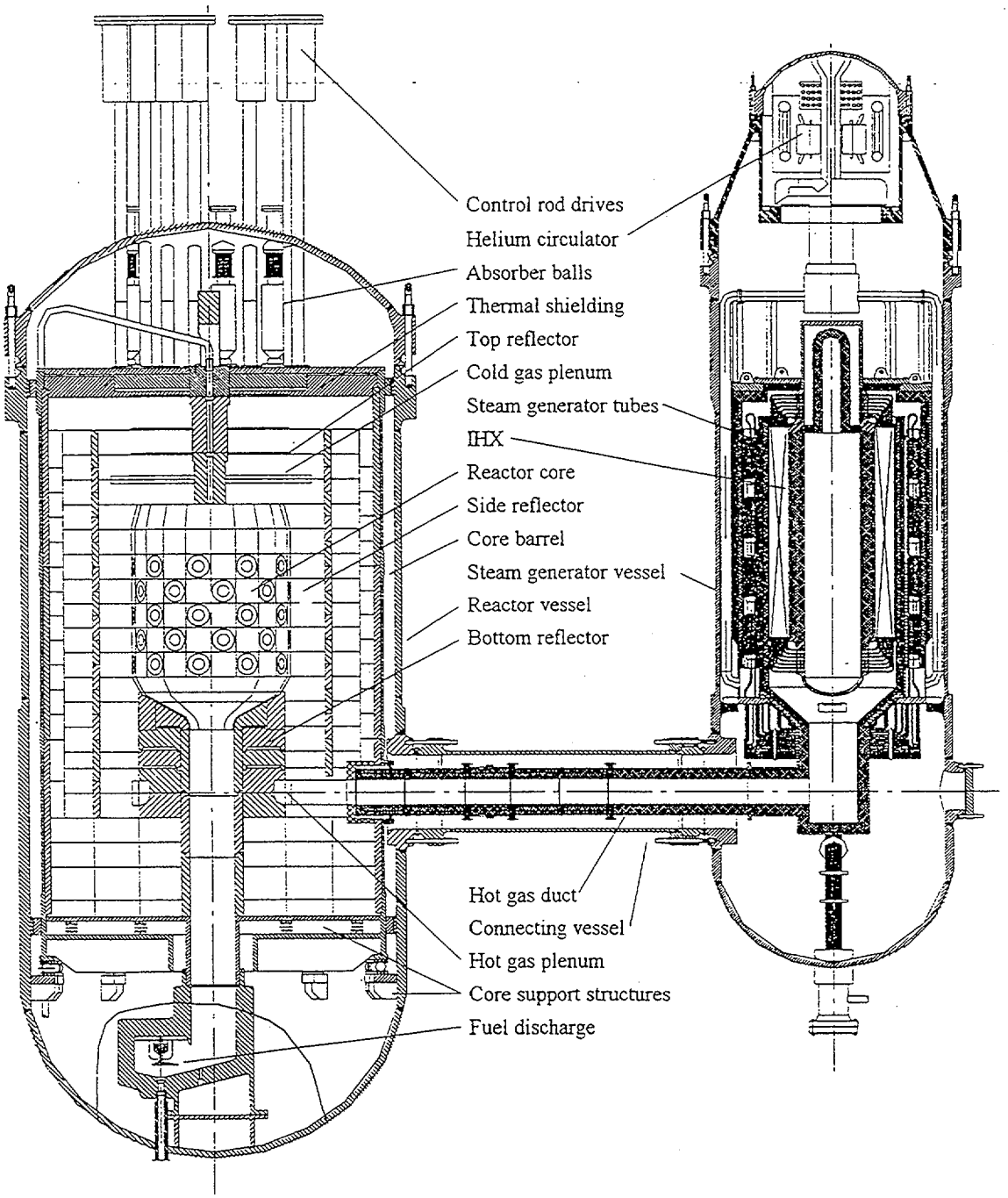

Figure 1 The HTR-10 Reactor and Steam Generator

The HTR-10 test reactor is now being constructed. First criticality is scheduled for 1999. When the test unit has been erected, following aims are expected to be met: acquiring know-how in the design, construction and operation of HTGRs; establishing an irradiation and experimental facility; demonstrating the inherent safety features of modular HTGR; testing electricity/heat co-generation and gas turbine technologies; carrying out R&D work on high temperature process heat application.

Table I Key Design Parameters of HTR-10

Reactor thermal power	10 MW
Primary helium pressure	3.0 MPa
Reactor core diameter	180 cm
Equivalent core height	197 cm
Average helium temperature at reactor outlet	700°C
Average helium temperature at reactor inlet	250°C
Helium mass flow rate at full power	4.3 kg/s
Main steam pressure at steam generator outlet	4.0 MPa
Main steam temperature at steam generator outlet	440°C
Feed water temperature	104°C
Main steam flow rate	3.47 kg/s
Number of control rods in side reflector	10
Number of absorber ball units in side reflector	7
Nuclear fuel / enrichment of fresh fuel elements	UO_2 / 17%
Form of fuel elements / diameter	spherical / 6 cm
Heavy metal loading per fuel element	5 g
Number of fuel elements in equilibrium core	27,000
Average discharge burn-up	80,000 MWd/tU
Fuel loading mode	multi-pass

2. Applicable national regulations

Decommissioning of the HTR-10 is subject to the Chinese national standards and codes for research and test reactors. China's national nuclear safety authority has issued the following documents which are applicable to the decommissioning work of HTR-10: Nuclear Safety Regulation HAF 1000-1 *Safety Regulations on the Design of Research Reactors*, Nuclear Safety Regulation HAF 1000-2 *Safety Regulations on the Operation of Research Reactors*, Regulatory Guide HAF 1004 *Decommissioning of Research Reactors and Critical Facilities*.

In these documents, concerning the decommissioning work, administrative procedures are described, responsibilities of the reactor owner are formulated, principal requirements and possible decommissioning approaches are described, the coverage and execution of the decommissioning programme are described.

3. Site features

The site of HTR-10 is located in the Institute of Nuclear Energy Technology (INET). INET is a national nuclear research center, founded in the early 1960's. It has about 620 employees and more than 20 divisions and laboratories of various disciplines, most of which are related to the research and development of nuclear technology. INET itself is located in the northwestern suburb of Beijing city, about 40 km from the city center.

On the area of INET, there exist already two reactors. One twin-core swimming pool reactor, with a total power of 3.8 MWt, was erected in 1964 and is still in service. The purpose of this reactor is to perform shielding and irradiation tests. In 1989, a 5 MWt water cooled reactor was erected in INET, mainly for the demonstration of district heating with nuclear energy. This reactor now is also used for performing tests on nuclear desalination and refrigeration.

The HTR-10 will be the third nuclear reactor facility in INET. Besides these reactors, the institute has a few laboratories which have to do with radioactive sources or other radioactive materials.

4. Facility characteristics

4.1 Reactor core internals

The reactor core internals consist of ceramic structures (graphite and carbon) and metallic structures.

The graphite internal structures, including top, side and bottom reflectors, are large graphite bricks which form a cavity for the pebble bed of fuel elements. All graphite reflector bricks are segmental. The top reflector is composed of three layers of graphite bricks. The side and bottom reflectors are composed of thirteen and five layers of graphite bricks, respectively. There are twenty segmental graphite bricks in each layer of the top and side reflector, while in each layer of the bottom reflector there are ten graphite bricks. In each layer of side graphite reflector there are twenty cold helium channels with a diameter of 80 mm, ten control rod guide holes with a diameter of 130 mm, seven slotted holes with the dimension of 160 x 60 mm for the small absorber ball system and three holes for irradiation and neutron sources purposes. The radial thickness of graphite bricks of the side reflector is 77.5 cm. The overall weight of the graphite internals is about 65 t.

The graphite reflectors are surrounded by boronated carbon bricks. These carbon bricks provide thermal and neutron shielding to the metallic internal structures and the reactor pressure vessel. The total weight of carbon bricks is about 46.5 t.

The metallic internal structures are composed of the core vessel, upper and lower support plates, holddown plates and a positioning plate. They provide support and housing to the ceramic internal structures and also transmit the mechanical loads coming from the fuel pebble bed and the ceramic internals to the reactor pressure vessel. 15CrMoR is selected as the material for most metallic core internal structures. The total weight of the metallic core internals is about 72.5 t.

4.2 Reactor pressure vessel

The reactor pressure vessel (RPV) consists of the upper closure head, the cylindrical vessel and the lower closure head. In terms of form, both closure heads are sections of semi-spheres. The lower head is welded to the cylindrical part, while the upper head is connected to the cylindrical vessel through flanges. The cylindrical part has two sections with the lower section thicker than the upper one. The plate and forging materials for the RPV are respectively SA516-70 and 15MnNi. On the upper head, control rod drives and absorber ball releasing mechanisms are mounted through tube nozzles. The RPV is supported to the reactor cavity concrete through four brackets.

The cylindrical vessel has an inner diameter of 4.2 m, thicknesses of the two cylindrical sections are respectively 80 mm and 120 mm. The overall height of the RPV is 12.58 m. The total weight of the RPV is approximately 167 t. At the end of the reactor life time, the fast neutron fluence of the RPV is estimated to be 1.26×10^{17} / cm^2.

4.3 Steam generator and its pressure vessel

The steam generator mainly consists of the steam generator pressure vessel (SGPV), heat exchanging tube bundle modules and internals. Thirty helical tube bundle modules are arranged in a circle between two insulation barrels inside the SGPV. Inside the inner barrel, the installation of an intermediate heat exchanger is planned for the second phase of the project. Each tube module consists of a helical heat exchanging tube, a central pipe, an outer case, fix and support structures as well as leak preventers. The tube dimension varies at different tube sections to improve hydrodynamic stability of steam/water two phase flow. The tube material is $2^1/_4$Cr1Mo. The total heat transfer area is about 55 m^2. Total weight of the tubes is about 2 t. The weight of the steam generator internals are 16 t.

The SGPV contains the steam generator, the intermediate heat exchanger and the helium blower. The same materials are used for the SGPV as for the RPV. The SGPV has an inner diameter of 2.5m and is approximately 11.37m in height. The weight of the SGPV is about 84.6 t. The SGPV and the RPV are connected by a so-called connecting vessel (CV), in which the hot gas duct is designed. The CV and the hot gas duct form the primary gas passages between the reactor and the steam generator.

4.4 Fuel handling system

The spherical fuel elements are successively fed to and removed from the reactor core by the fuel handling system. After passing through the core, the fuel elements are removed from the fuel element discharge tube via a pulse pneumatic single-exit gate, which is designed inside the reactor pressure vessel. With the aid of the separator, fuel elements which are not geometrically satisfactory drop into a fragments container, while the intact fuel elements are transported to the elevator set. From there, the fuel elements are either discharged to spent fuel containers when they have reached the discharge burn-up, or returned to the reactor core when they have not reached the discharge burn-up.

4.5 Helium purification system

The function of the helium purification system is to continuously remove, from the primary helium, dusts and particles, gaseous impurities including fission products. There is one purification train, which mainly consists of a filter, a molecular sieve trap, a copper oxide fixed bed, a cold charcoal trap and a compressor. The purification train must be regenerated after about 2,000 operation hours.

Dusts and particles are absorbed in the filter. Hydrogen and carbon monoxide are respectively converted to water vapor and carbon dioxide in the copper oxide fixed bed. The resultant water vapor and carbon dioxide are absorbed by the molecular sieve trap. Nobel gases, methane, oxygen and nitrogen are absorbed by the cold charcoal trap.

5. Fuel storage

The 6 cm spherical fuel elements of HTR-10 are made of TRISO type coated particles (CP) and graphite matrix. One CP consists of a UO_2 kernel with a diameter of 0.5 mm, which is successively coated with layers of low density pyrolytical carbon, inner high density isotropic pyrolytical carbon, silicon carbide and outer high density isotropic pyrolytical carbon, with thicknesses of respectively 90, 40, 35 and 40 μm. About 8,300 coated particles are dispersed in the graphite matrix, which is 5 cm in diameter, to form the fuel zone of a fuel

element. This fuel zone is surrounded by a 0.5 cm thick fuel-free graphite shell. As has been stated, each fresh fuel element contains 5 g uranium with an ^{235}U enrichment of 17%.

The fuel elements are designed to pass through the reactor core five times in average to reach an average burn-up of 80,000 MWd/tU after about 1080 effective full power days. According to calculation, the discharged spent fuel elements have a burn-up distribution between 74,300 and 87,100 MWd/tU.

The spent fuel elements are discharged into lead-steel containers. Each container is designed to receive 2,000 fuel elements. These spent fuel containers are stored in a concrete compartment inside the reactor building and are cooled by natural convection of the air. The compartment is big enough to store all the spent fuel elements of HTR-10 which is designed for 20 years operation on an average load factor of 50%. The storage of the spent fuel in the HTR-10 reactor building is surely the temporary storage. The issues of treatment, intermediate and final storage of the spent fuel elements remains to be studied.

6. Decommissioning considerations

Regulations require that the issues of decommissioning a reactor be considered already in its design and operation stages. The HTR-10 test reactor adopts the modular high temperature reactor design. It uses steel pressure vessels and, the RPV and SGPV are arranged in a "side-by-side" manner. They are separately housed in two concrete cavities. The spherical fuel elements can be easily removed from the reactor core into containers without opening the RPV. These factors, among other design features, make the decommissioning of HTR-10 relatively easier.

Important to decommissioning is that the design documents and related operational records should be well archived. Also important is that in the monitoring and surveillance programmes, aspects of decommissioning are also to be considered.

The following radioactive materials are relevant to the decommissioning work of HTR-10:

- Metallic materials: the reactor pressure vessel and the metallic core internals, the steam generator and its pressure vessel, the components of the fuel handling system and the reactor shutdown systems, some components and pipes of some auxiliary systems, mainly of the helium purification system and its regeneration system.

- Graphite and carbon bricks of the core internals including dusts.

- Filters and other absorbing components in helium purification system and its regeneration system as well as ventilation system.

- Routine liquid and solid radioactive materials which are produced during reactor normal operation.

Quantity of these materials and their radioactivity shall be evaluated before decommissioning starts based on the real reactor operation history.

The HTR-10 test reactor is designed for 20 year's operation. Presumably, the execution of its decommissioning is a matter around 2020. Till then, much development is expected in the national nuclear strategies, including the fuel cycle/waste disposal strategies. INET will also experience much development. The decommissioning programme of HTR-10 will be much dependent on the status of these developments then.

Independent from the above strategical development, following activities are believed to be performed when HTR-10 is to be put out of service.

- After sufficient cooling time, the fuel elements in the reactor core are to be removed into the storage containers. All the spent fuel storage containers are supposed to be transported to places, designated by the nation, for further treatment or storage.

- Removable radioactive materials, activated or contaminated, treated when necessary, are to be removed from the HTR-10 site and transported to the nation's regional waste repositories.

- For the remaining components and structures, decontamination are to be made as reasonably much as possible.

- Radioactive place or components are to be sealed or blocked, the facility is under appropriate monitoring and surveillance.

After the above activities, the facility is in safe conditions. Entrance to some places in the facility remains controlled. Further decommissioning activities would be much dependent on the situations then.