3. Reactor

3.1 Nuclear and Thermal-Hydraulic Design

The HTTR consists of core, main cooling system, auxiliary cooling system, vessel cooling system and related systems. The reactor pressure vessel, which is 13.2 m in inner height and 5.5 m in diameter, contains the active core, graphite reflectors, core support structures and core restraint mechanism as shown in Fig. 3.1.

The HTTR is a graphite-moderated and helium gas-cooled reactor with prismatic fuel elements of hexagonal blocks. The active core, which is 2.9 m in height and 2.3 m in diameter, consists of 30 fuel columns and 7 control rod guide columns. The active core is surrounded by columns for replaceable reflectors, control rod guide and irradiation test. The columns for the replaceable reflectors etc. are surrounded by permanent reflectors. The permanent reflectors are fixed by the core restraint mechanism.

The nuclear characteristics (power distribution, control rod worth, shut down margin, etc.) were calculated by the HTTR nuclear design code system which consists of the calculation codes (DELIGHT, TWOTRAN-II and CITATION-1000VP). The analysis of core characteristics was carried out considering the $^{239}$U enrichment and burnable poison zoning which was determined so as to minimize the maximum fuel temperature. The calculation flow is shown in Fig. 3.2. The DELIGHT code is a one-dimensional cell burnup code to produce the few-group constants for core analysis. The TWOTRAN-II is a two-dimensional transport code to produce the average group constants of the burnable poison and graphite block with the control rods. The analysis was conducted by the three-dimensional core analysis code CITATION-1000VP with group constants.

The thermal-hydraulic characteristics (distribution of coolant flow rate, fuel temperature, etc.) were calculated considering the main coolant flow in the graphite blocks, bypass flow in the inter-column gap, leakage

![Fig. 3.1 Cutaway view of a reactor pressure vessel and a core.](image1)

![Fig. 3.2 Calculation flow of nuclear and thermal-hydraulic design.](image2)
flow through the permanent reflectors and cross flow in the interface of graphite blocks. The distribution of coolant flow rate was calculated by the flow network analysis code FLOWNET with the network model.

Major nuclear and thermal-hydraulic specifications are summarized in Table 3.1.

### 3.2 Fuel

1. Structure of fuel assembly

A fuel assembly consists of fuel rods and a hexagonal graphite block, 360 mm across flats and 580 mm in height, as shown in Fig. 3.3. The fuel assembly has three dowels on the top and three mating sockets at the bottom to align the fuel assemblies. Trisoisotropic (TRISO)-coated fuel particles with UO2 kernel, about 6 wt% average enrichment and 600 μm in diameter, are dispersed in the graphite matrix and sintered to form a fuel compact. Fuel compacts are contained in a fuel rod, 34 mm in outer diameter and 577 mm in length. Fuel rods are inserted into vertical holes in the graphite block. Helium gas coolant flows through gaps between the holes and the rods.

2. Design requirements

In the safety design of the HTGR fuels, it is important to retain fission products within particles so that their release to the primary coolant may not exceed an acceptable level. From this point of view, the basic design criteria for the fuel are to minimize the failure fraction of as-fabricated fuel coating layers and to avoid significant additional fuel failures during operation. To meet the latter criteria for the first loading fuel, the fuel temperature is limited to below 1495 °C under normal operating conditions and below 1600 °C under abnormal
transient conditions, and also the fuel burnup is limited less than 33 GWD/t for the HTTR first loading fuel.

Based on the circumstances mentioned above, the safety design requirements for the HTTR fuel have been provided as follows.

(i) The initial failure fraction in the coating layers of the fuel particles shall be less than 0.2% in terms of the sum of heavy metal contamination and SiC defects.

(ii) The coated fuel particles shall not fail systematically under normal operating conditions, i.e., in the safety analysis,

- The penetration depth of the Pd/SiC interaction shall not exceed the thickness of the SiC layer of 25 μm, because the fully-penetrating Pd/SiC interaction is thought to lead loss of fission product retention in the SiC coating layer.

- The distance of kernel migration shall not exceed the thickness of the first layer plus the second layer of 90 μm to avoid failure of the SiC layer.

(iii) The fuel shall be designed so as to remain intact even with consideration of irradiation-induced damage and chemical attack through the full service period, that is, the additional failure fraction in the coating layers of the fuel particles shall be less than 0.2% through the full service period.

(iv) To avoid fuel failure, the maximum fuel temperature shall not exceed 1600 °C during any anticipated transient. Thus the coating layers of the fuel particles shall remain intact below 1600 °C during any anticipated transient.

An assessment has been made of failure mechanisms of the kernel migration, or so-called amoeba effect, and the corrosion of the SiC layer by a fission product of palladium. It can be clarified from the assessment that the maximum migration distance is 55 μm. This value is sufficiently smaller than the design limit of 90 μm, which is the sum of the thickness of the first and the second layers of coated fuel particles. The maximum corrosion distance of the SiC layer under HTTR conditions is evaluated to be 11 μm, which is smaller than the design limit of 25 μm, namely the thickness of the SiC layer.

(3) Fabrication result of the first-loading fuel
The fabrication of the first-loading fuel started in June 1995. A total of 66,780 fuel compacts, corresponding to 4,770 fuel rods, were successfully produced through the fuel kernel, coated fuel particle and fuel compact processes. The fuel rods were transferred to the reactor building of the HTTR, where the fuel rods were inserted into the graphite blocks to form the fuel assemblies. In December 1997, 150 fuel assemblies were completely formed and stored in new fuel storage cells.

High quality and production efficiency of fuel was established through many R&D activities and fabrication experiences of irradiation examination samples spread over about 30 years. The as-manufactured quality of the fuel has been improved by the modification of fabrication conditions and processes. The coating failure during coating process was mainly caused by the strong mechanical shocks to the particles given by violent particle fluidization in the coater and by the unloading procedure of the particles. The coating process was improved by optimizing the mode of the particle fluidization and by developing the process without unloading and loading of the particles at the intermediate coating process. Small fractions of the particles with defective coating layers were present during the fabrication process. Among several modes of defective coating layers, a defective SiC coating layer is the most harmful from the standpoint of fission product retention.

Next the fabrication process was modified to reduce the defective particle fraction during the compaction process before fabrication of the first-loading fuel of the HTTR. The compaction process was improved by optimizing the combination of the pressing temperature and the pressing speed of the overcoated particles to avoid direct contact with neighboring particles in the fuel compact.

Figure 3.4 shows measured dimensions and distributions of as-fabricated coated fuel particles. The thickness of the coating layers was measured by optical microscopy. The stresses acting on the coating layers during irradiation depend on irradiation conditions and coating layer thickness. The fabrication data showed that the deviations of thickness of the
PyC layers and the SiC layer were small, however, the deviation of the buffer layer thickness was relatively large. Since the internal pressure depends on the free volume in the buffer layer, an evaluation was carried out to confirm the coating layer intactness during operation. The crushing load of the coated fuel particles was measured in uniaxial compression tests to confirm the absence of so-called weak particles which have weak SiC layers. The 31 N of median load and 8.3 of the Weibull parameter were obtained and no weak tail was observed.

The free uranium fractions of the fuel compacts were measured by deconsolidation followed by acid leaching on four fuel compacts for each fuel compact fabrication batch (containing up to about 700 fuel compacts). The SiC-failure fractions of the fuel compacts were measured by the burn/leach method for six fuel compacts in each fuel compact fabrication batch. The HTTR first-loading fuel compacts were fabricated from 126 fuel compact batches. As shown in Fig. 3.5, as-fabricated fuel compacts contained almost no through-coatings failed particles and few SiC-defective particles. Average through-coatings and SiC defective fractions were 2 \( \times 10^{-6} \) and 8 \( \times 10^{-5} \), respectively.

At the beginning of fabrication, unexpected large SiC-failure fractions, about 3-5 particles in a fuel compact, were observed. Then, we analyzed relations between the measured SiC-failure fractions and fabrication parameters, such as coating layer thickness, overcoating layer thickness, pressing speed, etc. Finally, the following reasons for increase of the SiC-failed particle fraction were found.

(a) Decrease of SiC layer thickness

The SiC-failure fractions increased when the SiC-layer thickness decreased. The mechanism of the SiC-failure was considered to be as follows.

(i) A few coated particles were in direct contact with each other in the compaction process because of the relatively high packing fraction (30-vol%).

(ii) Since a coated particle with a thinner SiC layer is weaker, the SiC layers of contacting coated particles failed.

Another question was why the SiC layer became thinner although coating time and flow rate of the deposition gas (MTS) were controlled in the coating process. It was found that the filter of the MTS evaporator was partly choked and the concentration of the MTS gas gradually decreased during continuous operation of the coater which we had never experienced. Finally, from the viewpoint of the SiC-failure reduction, we confirmed that the SiC layer thickness was greater than 27 \( \mu \)m before the compaction process.

(b) Odd-shaped overcoated particle

A coated fuel particle (CFP) is overcoated to avoid direct contact with neighboring particles during the compaction process. We found odd-shaped overcoated particles in which two or three coated fuel particles were included. The fraction of the odd-shaped overcoated particles was about \( 10^{-4} \). We considered that the CFPs in the odd-shaped overcoated particles failed during the compaction process because they could not keep their distances from each other. To examine this failure mechanism, a compaction test was carried out. In the test, the fraction of the odd-shaped overcoated
particles was changed from 0 to 30-vol%. The result showed that the SiC-failure fraction increased with increase in the fraction of odd-shaped overcoated particles. In the fabrication process, the odd-shaped overcoated particles were removed.

(4) Fabrication of the second-loading fuel

The fabrication of the second-loading fuel started in October 2002. The specification of the second-loading fuel was settled the same as that of the first-loading fuel. Hexagonal graphite blocks for fuel elements, graphite sleeves for fuel rods, bottom replaceable reflector blocks and B.C pellets as the burnable poison were fabricated successfully by December 2003. Fabrication of fuel compact and fuel rod assembling is under way, which will be completed in March 2005. About 30,000 fuel compacts have been fabricated successfully at the beginning of 2004, of which average through-coatings and SiC defective fractions were $5 \times 10^{-6}$ and $1 \times 10^{-6}$, respectively, which shows as good quality as the first-loading fuel.

3.3 Reactor Internals

The reactor internals consist of graphite core-support structures, metallic core support structures and other components as shown in Fig. 3.6. The graphite support structures consist of hot plenum blocks, core bottom structures, core support posts etc. The hot plenum blocks provide lateral and vertical positioning and support of the core array. The blocks contain flow paths which guide the primary coolant from the outlet of the fuel columns and distribute it into the hot plenum beneath the hot plenum blocks. The core support posts are designed so as to support the core and hot plenum block arrays which form the hot plenum. The permanent reflector is a graphite structure surrounding the replaceable reflector and control rod guide column located in the circumference of the core. The metallic

Fig. 3.6 Structure of reactor internals.
core support structures are composed of core support plates, a core support grid and core restraint mechanisms. The core support plate and the core support grid are placed below the thermal insulation layers. The core restraint mechanism surrounds the permanent reflector blocks.

These components were assembled in a factory to check the assembly procedure and to test its sealing performance. After the test, these components were dismantled and transported to the site and assembled inside the reactor pressure vessel in September 1994.

3.4 Reactivity Control System

The reactivity control system of the HTTR is shown in Fig. 3.7. The control rods (CRs) are individually supported by control rod drive mechanisms (CRDMs) located in stand-pipes connected to the hemispherical top lid of the reactor pressure vessel. The CRs are inserted into the channels in the active core and replaceable reflector regions. Reactor shutdown is made at first by inserting 9 pairs of CRs into the reflector region, and then by inserting the other 7 pairs of the CRs into the active core region after the temperature is reduced, so that the CRs should not exceed their design temperature limit.

The CRDM withdraws and inserts a pair of the CRs. During normal operation, the position of the CR is sustained by the torque of the motor. The maximum withdrawal velocity is limited to a value below 70mm/s by the decelerator. At the reactor shutdown, the CRs are released from the CRDMs by separating the clutch gear teeth, and inserted into the core by gravity.

Reserve shutdown capability is provided by insertion of B,C/C pellets into holes in the CR guide blocks.
Various tests have been performed to evaluate the reliability of the reactivity control system. Figure 3.8 shows the typical reactor shutdown time under seismic conditions. The verification tests were performed to make sure that the CR should not be damaged after the reactor shutdown. The maximum temperature for the verification tests was about 1100°C. After the tests, inelastic deformation and creep-fatigue damage was observed, and little deformation and no cracks were observed.

Concerning the reactivity control system, various tests were carried out to assure the performance, for example, CR driving speed and detection of CR position. Installation of the reactivity control system into the stand-pipes was completed in March 1996.

3.5 Reactor Pressure Vessel

The reactor pressure vessel (RPV), 13.2m in inner height and 5.5m in diameter, is fabricated of 2⅔Cr-1Mo steel and consists of a vertical cylinder, a hemispherical top lid and a bottom dome. The RPV contains the core components such as fuel blocks, graphite reflectors, reactivity control system, core support structures, etc.

Figure 3.9 shows the schematic structure of the RPV. The top lid of the RPV is bolted to the flange of the vertical cylinder. Thirty-one stand-pipes, including the control rod and the irradiation stand-pipes, are welded to the top lid. A stand-pipe closure is installed on the top of each stand-pipe and is removed during refueling. Thermal shields are installed on the inner surface of the top lid to protect against high temperatures in accident conditions. Core support ribs and a core support ring are welded to the bottom dome to support the vertical load of the core components and reactor internals. The RPV is supported by a RPV skirt, stabilizers and a stand-pipe support beam. The RPV skirt is welded to the bottom dome. The stabilizers surround the vertical cylinder and are supported by the side concrete structure. The stand-pipe support beam is located near the top of the stand-pipes. Special stand-pipe fixing devices are located at the top of some of the stand-pipes to prevent the stand-pipe internal structure from being ejected in the event of a stand-pipe rupture accident.

As a material for the RPV, 2⅔ Cr-1Mo steel is employed because this steel has better creep strength at high temperature than Mn-Mo steel which is widely used in the pressure vessels of light water reactors. As the RPV constitutes a part of the reactor coolant pressure boundary and is subjected to a higher temperature than those of light water reactor plants, its integrity is of prime importance in the safety of the HTTR. Thus the high-temperature structural design guidelines for the HTTR have been established based on the well-established design guidelines for the fast breeder reactor plants taking into account the characteristics of the material and HTTR service conditions; as shown later in subsection 4.2.

3.6 Fuel Handling Equipment

The fuel handling equipment consists of a fuel handling machine (FHM), a door valve, a reactor isolation valve and a connecting pipe as shown in Fig. 3.10. The fuel blocks are refueled column-wise through a stand-pipe by the FHM automatically, and the FHM can handle fuel blocks which are located in a column underneath the stand-pipe and its surrounding columns. The positioning mechanism of the FHM gripper is equipped to adjust the gripper location by detecting the displacement of the columns. In case of unusual column arrangement, pneumatic cylinders push the inclined columns to prevent from stacking of fresh fuel. In case the link drive mechanism fails during the refueling procedure, the gripper and its housing can be retracted into a guide tube manually. These mechanisms were verified by simulation tests, life tests, etc.
Fig. 3.9 Schematic diagram of reactor pressure vessel (unit: mm).
Fig. 3.10 Fuel handling equipment of the HTTR.