3

Concept of a VHTR(Very High Temperature Reactor)

3.1 Principle overview on plant

Modular HTR can be applied as heat sources for the delivery of process heat in form of steam, or high temperature heat for different applications[1-11]. As will be explained in more detail in Chapter 4 and Chapter 10 the introduction of an intermediate circuit between the primary system and the process plant promises advantages, so far as contamination of products, safety and licensing conditions are considered. Figure 3.1 shows principle possibilities of flow sheets for process heat application.

The use of a steam transformer is a further option to decouple the nuclear and the conventional part of the plant to produce process steam, especially to avoid contamination of products. The important components for heat transfer following these simplified flow sheets are:

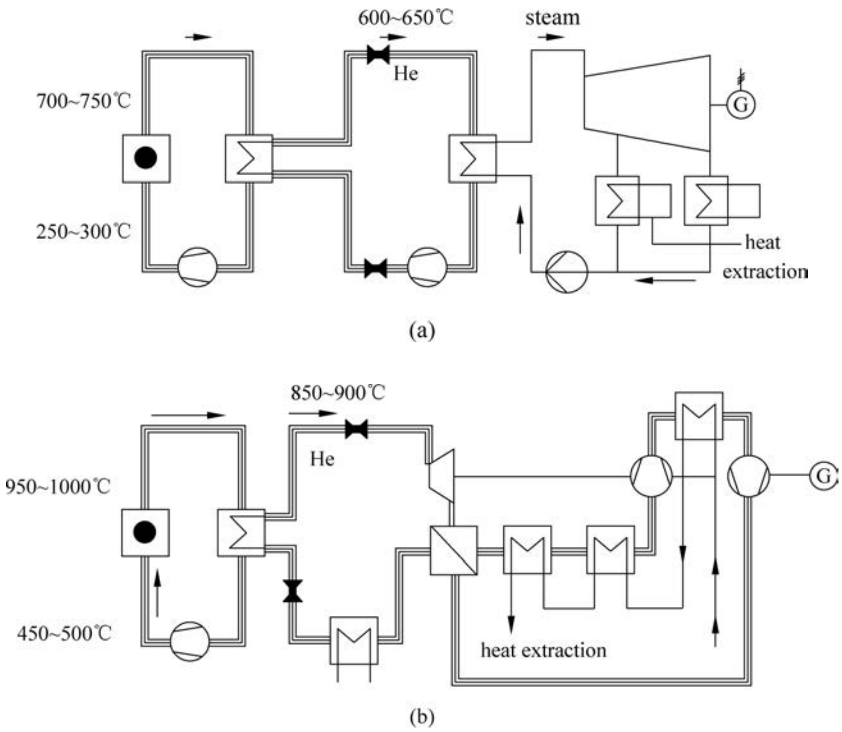
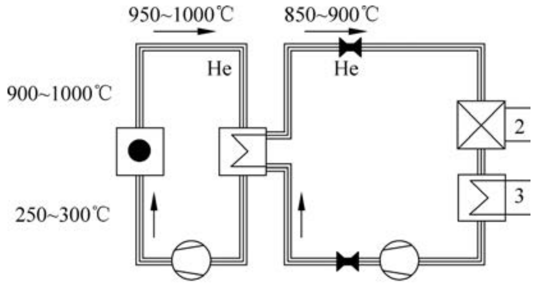


Figure 3.1 Flow sheets of VHTR-applications (with IHX)

(a) Process steam generation using a steam transformer behind a steam turbine; (b) Process steam generation using an IHX-circuit and a steam generator behind a recuperator of a gas turbine process; (c) High temperature process unit (steam reformer; steam gasifier; olefine furnace; reactor for thermochemical hydrogen production) and steam generator in IHX circuit

1—IHX; 2—process heat exchanger; 3—steam generator



(c)

Figure 3.1 (Continued)

- IHX (intermediate heat exchanger) for high temperatures (≈900℃ in secondary helium cycle);
- IHX for lower helium temperature (600～650℃ in secondary helium cycle);
- Steam reformers (≈800℃ on process side);
- Steam gasifiers(≈800℃ on process side);
- Steam generators (530～560℃ on process side);
- Steam transformers (350～400℃ on heating side);
- Steam superheaters (till 800℃ steam temperature);
- Special heat exchangers for oil heating (till 500℃);
- Heaters for air or nitrogen (till 800℃);
- Special heat exchangers for thermochemical water splitting cycles (till 850℃).

Details of these components and their status of development are discussed in Chapter 5 till Chapter 8. The modular HTR, which is suited to deliver the heat with the necessary high temperatures, offers different possibilities regarding the technical concept. It could be discussed corresponding to different phases. Here the primary enclosure and the concept of the reactor building are chosen as examples:

- Phase 1: use of existing and introduced technologies(as example: primary enclosure consisting from vessels made from forged steel; use of a reactor building above ground and an inner dense cell with a filter for radioactive substances).
- Phase 2: use of future technologies and options(as example: primary enclosure consisting from totally prestressed vessels; use of an underground arranged reactor building and an inner dense cell with a very efficient filter and storage for radioactive substances).

In the following sections firstly the technical solution corresponding to phase 1 is explained (Figure 3.2). At the end of this chapter one variant following the ideas of phase 2 is discussed explicitly. Figure 3.2 (a) allows a first overview on the modular HTR as a possible heat source. It was planned for process heat application, and designed for a power of $170MW_{th}$. The combination either with an IHX or with a steam reformer/steam generator combination was foreseen. New valuations on coupling nuclear reactors and process heat plants show that an IHX should offer advantages in all applications. Figure 3.2 (b) shows the combination of a steam reformer and a steam generator in a side by side arrangement, which can be integrated into the IHX-circuit. This combination of heat exchangers allows relatively easy access to the different components. The helium circulator can be arranged at the top of the component and all feed gas and product gas lines can be directly positioned at the top of steam reformer vessel. This arrangement has been proven successful in the EVA-Ⅱ plant.

Important data of the plant described before are given in Table 3.1. They are oriented on the development of the HTR-Module ($200MW_{th}$) for the realization of the steam generation process and are based on the experimental results of the EVA Ⅱ-plant (10MW) for the demonstration of the steam

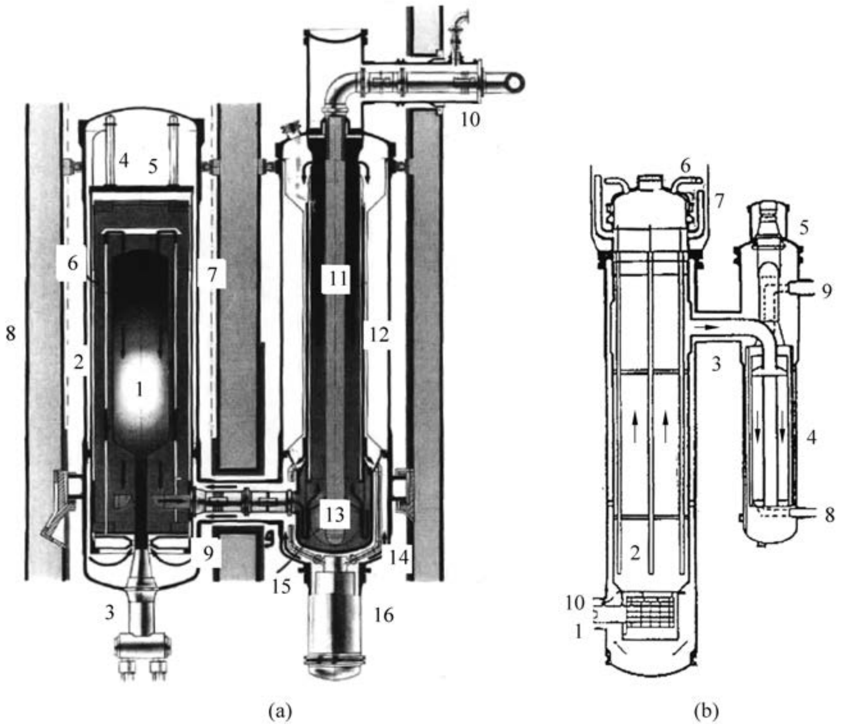


Figure 3.2 Primary system and heat utilization components for an VHTR (example: HTR-Module, $170MW_{th}$, $T_{He} = 950℃$, $p_{He} = 40bar$)[3,6]

(a) Overview on the primary system with IHX

1—core; 2—reactor pressure vessel; 3—discharge system for fuel elements; 4—second shut down system (KLAK = small absorber balls); 5—first shut down system (reflector rods); 6—graphite reflector; 7—surface cooler; 8—inner concrete cell; 9—hot gas duct; 10—helium duct (secondary); 11—hot gas sampler (secondary); 12—IHX (intermediate heat exchanger); 13—hot header; 14—cold gas pipes; 15—flow distributor; 16—helium circulator

(b) Variant of the steam reformer/steam generator combination (arrangement in the IHX-circuit)

1—hot helium inlet (secondary); 2—steam reformer bundle; 3—coaxial duct (helium); 4—steam generator; 5—helium circulator; 6—feed gas inlet; 7—product gas outlet; 8—feed water inlet; 9—steam outlet; 10—cold helium outlet

reforming process and on the results of the operation of the KVK-plant, in which the IHX and the IHX-circuit have been tested with a power of 10MW and maximal helium temperature of 950℃.

Table 3.1 Some data of the reactor system (example: reactor coupled to IHX; steam reformer and steam generator arranged in the IHX-circuit)

Parameter	Dimension	Value	Remark
Thermal power of reactor	MW	170	limited because of selfacting decay heat removal
Power of IHX	MW	170	maybe in two loops
Power of steam reformer	MW	65	in one component
Power of steam generator	MW	105	in one component
Power of primary helium circulator	MW	3.5	follows from optimization
Helium heat up in reactor	℃	300～950	
Mass flow of primary helium	kg/s	50	
Pressure of primary helium	bar	40	because of optimization of processes
Helium heat up in secondary circuit	℃	250～900	
Mass flow of secondary helium	kg/s	50	
Pressure of secondary helium	bar	41	maximal difference in operation should be $<2bar$

There is a connecting duct for the transport of the hot and cold primary helium between both components, reactor and IHX. These components are arranged inside an inner concrete cell, which is positioned in the reactor building and dense in normal operation. After depressurization accidents of the primary circuit the inner cell will be closed applying a special selfacting closure system to limit the amount of air, which could ingress into the primary system.

The steam reformer/steam generator combination is connected to the IHX by a secondary gas ducting system for hot and cold helium. Both components are placed in a separate building connected to the building for the primary circuit components via a room, in which helium valves to shut off the secondary helium circuit from the IHX are positioned. Figure 3.3 shows this principle of separation of circuits.

Some details of the arrangement of components of modular HTR, which can be transferred to VHTR-concepts, might be explained on hand of Figure 3.3 and Figure 3.4. The central part of the plant is the reactor building, which contains at least 2 modular units corresponding to the idea of modularization of the power on a site. In this central building additionally some auxiliary systems are installed as fuel handling system, gas purification, helium storage, helium supply systems.

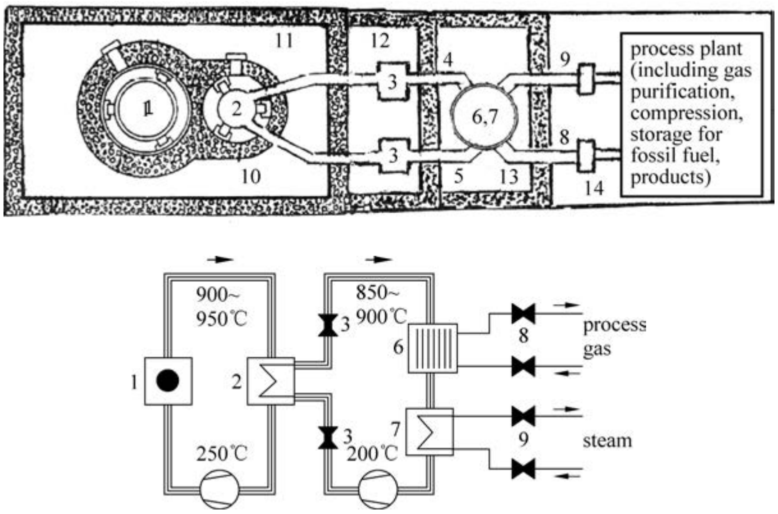


Figure 3.3 Principle arrangement of rooms for main components (example: IHX-application)

1—nuclear reactor; 2—IHX with primary helium circulator; 3—valves for secondary helium; 4—transport pipes for hot secondary helium; 5—transport pipes for cold helium; 6—steam reformer; 7—steam generator with secondary helium circulator; 8—pipes for process gas with valves; 9—pipes for process steam with valves; 10—inner concrete cell; 11—outer reactor containment building; 12—room for helium valves; 13—room for process heat exchanger; 14—rooms for handling process gas

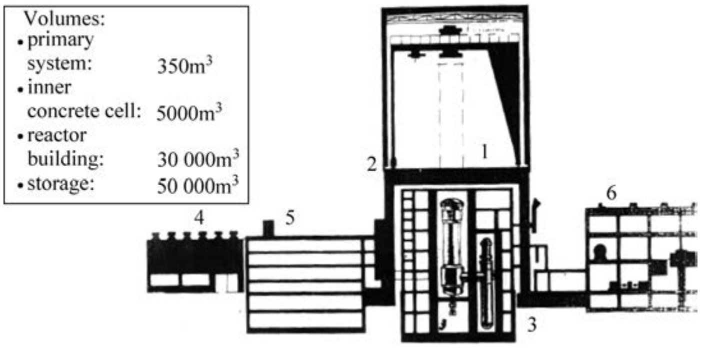


Figure 3.4 Arrangement of buildings of a HTR plant with two modular units (example: modular reactor of $200MW_{th}$): vertical section[11]

1—reactor hall; 2—protection building; 3—inner concrete cell; 4—building for intermediate storage of spent fuel elements; 5—reactor auxiliary building; 6—turbine hall

The reactor auxiliary building, positioned directly beside the reactor building contains some important systems like circuits for the start up or shut down of the reactor, intermediate cooling systems and the system, which is foreseen to depressurize the primary circuit and to condensate the water after a large water ingress accident into the IHX circuit in case of process heat application. The IHX-circuit has its own gas purification, which can remove contents of impurities.

Above the reactor building, which contains the inner cell with the primary system, there is a reactor hall which allows manipulation of components (Figure 3.4).

The plan of the total site gives more details on all other buildings and systems, which are necessary to operate a modular plant with two units. Here as an example the modular HTR with steam generator (Figure 3.5) is explained.

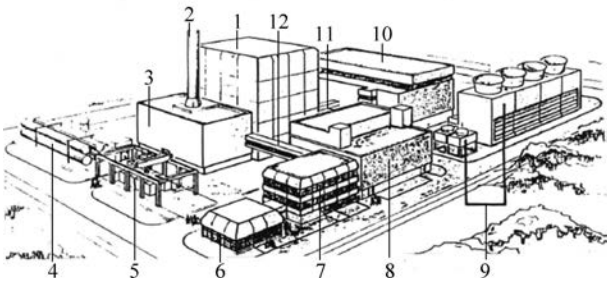


Figure 3.5 Site plan of modular reactor system with two units (example: application of steam generators without IHX)[11]

1—reactor building; 2—stack; 3—reactor auxiliary building; 4—gas supply station; 5—intermediate storage area; 6—entrance building; 7—administration and social building; 8—switchgear and emergency supply building; 9—cooling installations; 10—turbine building; 11—bridge for pipes; 12—connection to auxiliary building

In the reactor auxiliary building additionally to the systems which were already mentioned before some important further systems are installed: the air conditioning plant, the storage for fresh fuel elements, the storage of radioactive waste resulting from operation, and further rooms for hygiene and laboratory work.

In the switchgear building the control room, installations for control and regulation, the reactor-protection system, the emergency electrical supply systems and further components are arranged (computers, climate-and air-conditioning plants).

The transfer of heat or energy conversion takes place in the turbine building or in a special building containing the IHX circuit. The turbine and the electrical generator, all heat exchangers and pumps of the water/steam circuit and components, which decouple process steam for process heat applications are arranged in the turbine hall in case of the application for cogeneration.

A very important building is used for the intermediate storage of spent fuel elements. Here the vessels filled with spent fuel elements are set up and cooled by radiation, conduction and free convection. Eventually the time of operation of this storage system could be much longer than that of the reactor itself. The question how long the time of intermediate storage will be, is a topic of optimization between the aspects of final storage and of intermediate storage. Today time schedules of more than 5 decades for intermediate storage seem to be advantageous.

The plant possess a cooling installation, consisting from wet cooling towers operated with forced convection by blowers. There are some further buildings, as they are common use in all power plants: offices, buildings for special purposes and further. The reactor building itself fulfills all requirement, which today exists in the nuclear licensing process regarding impacts from the outside. As example in Germany today the following loads from the outside have to be assumed:

- Air plane crash (Phantom military machine);

- Gas cloud explosion ($\Delta p_{max} = 0.3$bar);
- Earthquake (acceleration$<0.3g$).

The planned modular concept has been designed against these accidents. Future planning will require the assumption of stronger loads (see Chapter 11).

The principle of the barriers which are available for the fission product retention in case of accidents contains the following elements (Figure 3.6).

- The coated particles with the graphite matrix of fuel elements;
- The primary enclosure consisting of vessels made from forged steel(basic safe);
- An inner dense cell consisting of concrete with a connected selfacting closure and filter.

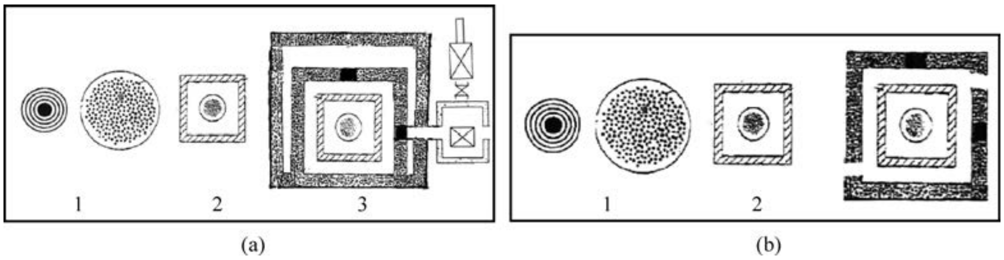


Figure 3.6 Concepts of barriers to retain fission products in the plant

(a) Nuclear reactor

1—fuel particle + fuel element; 2—primary enclosure; 3—inner concrete cell with storage and filter

(b) Intermediate storage for spent fuel elements

1—fuel particle + fuel element; 2—storage vessel

Some details of the reactor building are shown in Figure 3.7. The wall thickness of the inner cell amounts to be 2m and this is sufficient to tolerate an overpressure of 2bar for a short time after depressurization accidents with large breaks of primary circuit. After that, a closure system opens and reduces the pressure to normal values. The closure system closes selfacting after the depressurization and by this concept the mass of air, which could penetrate into the primary circuit is limited to very small values. In future plants maybe this inner containment can be filled with inert gas. Details of the accident of air ingress are discussed in Chapter 9 and Chapter 11. The outer reactor building has a wall thickness of 2m too and is designed against the impacts from outside, which today are assumed in the licensing process in many countries(airplane crash: Phantom military machine). The storage vessels for spent fuel elements are protected against these impacts too by the special design of the vessel and the storage building. This building is not dense, however.

The reactor concept discussed here follows the known principles of safety, which have been established for modular HTR. Following requirements expressed by stability, several safety characteristics of the reactor system have to be fulfilled. The goal is the retention of the radioactive substances in the nuclear plant (Figure 3.8) in all accidents, which can be reasonably assumed.

More details on safety and environmental questions are discussed in Chapter 11. Some relevant aspects, which are partly new in case of process heat application, are as follows:

- How can the decay heat removal of a process heat plant be realized?
- Can large amounts of process gas be handled in the neighborhood of nuclear plants?
- Which specific accidents are important for nuclear process heat plants?
- How can an operation concept be realized?
- What are the changes of the concept of selfacting decay heat removal for a core with higher helium outlet temperature?
- Which experiences are available for the operation of VHTR systems?
- Which special aspects of high temperature alloys are safety relevant?

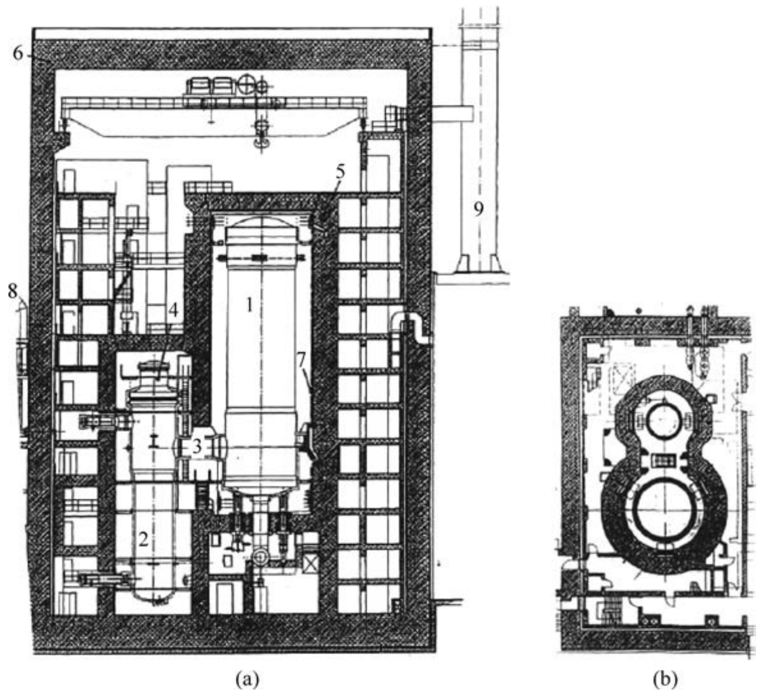


Figure 3.7 Primary system of the HTR-Module (200MW_{th}, process steam generation)[8]

(a) Vertical section

1—reactor pressure vessel; 2—pressure vessel for steam generator; 3—connecting vessel; 4—helium circulator; 5—inner concrete cell; 6—outer reactor building; 7—surface cooler; 8—annex building; 9—stack

(b) Horizontal section

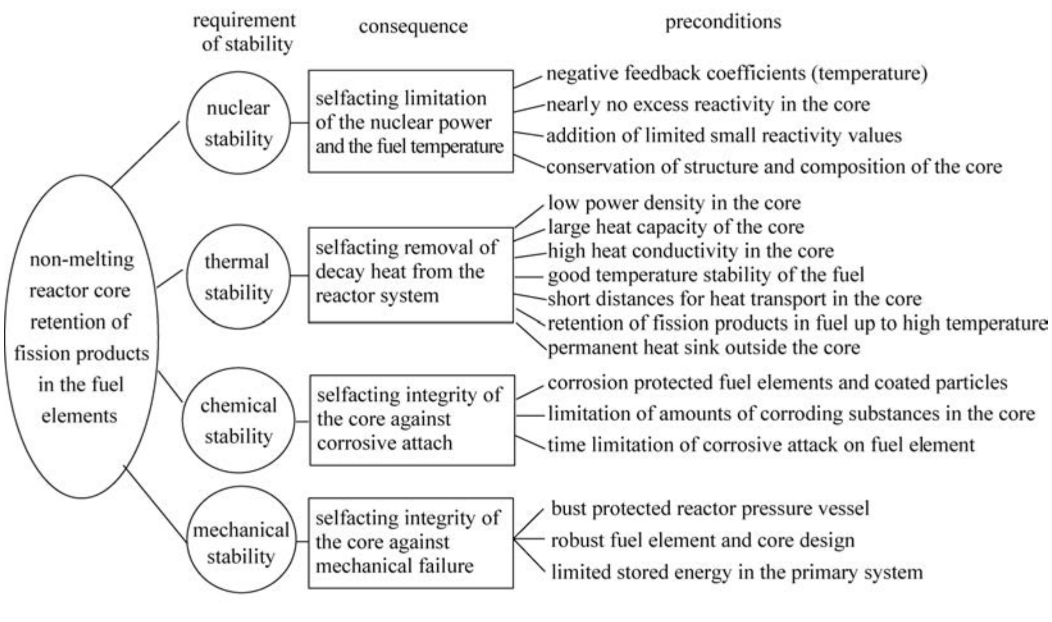


Figure 3.8 Concept of safety of modular HTR for process heat application

Besides these questions, which are related to the technical feasibility of a modular HTR for very high helium temperatures, there are some further aspects of coupling of nuclear plants to chemical processes. Some examples are:

- Is an IHX necessary or advantageous?
- Is the Tritium permeation tolerable and are countermeasures possible?
- Which media are optimal for the IHX?

- Which temperatures in the helium cycle are necessary for the different possible processes?
- Which layout and design of the process heat components, which consume heat, is optimal with respect to the area for heat exchange and necessary pumping power?

3.2 Fuel elements for the generation of high helium temperatures

The modular HTR following the pebble bed concept uses spherical fuel elements loaded with coated particles as fuel[12-22]. The LEU-cycle with around 8% enrichment and TRISO-particles is normally proposed. The content of heavy metal is 7g per fuel element and this material is contained as UO_2 in 11600 coated particles per fuel element. Figure 3.9 (a) and (b) show this concept of fuel elements.

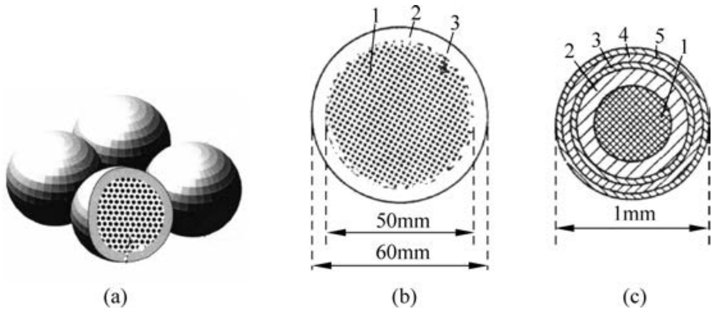


Figure 3.9 Spherical fuel elements of modular HTR(VHTR)

(a) Arrangement of spherical fuel elements in a pebble bed; (b) Section through a fuel element

1—coated particles; 2—graphite matrix; 3—outer fuel free shell

(c) Coated particle (TRISO)

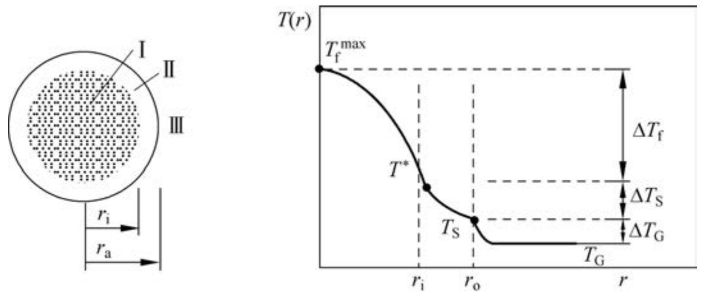
1—UO_2-kernel; 2—buffer layer of porous graphite; 3—dense pyrolytic carbon layer; 4—silicon carbide layer; 5—dense pyrolytic carbon layer

The diameter of the UO_2-kernel of the coated particle is 0.5mm and the kernel is surrounded by several layers, which have special functions. A first buffer layer (thickness: 90μm) can store fission products, which leave the kernel during the burn up in the core. This carbon layer is porous and has a relative low density.

The second layer is formed by pyrolytic carbon (thickness: 40μm) and the layer forms the first inner part of a very small pressure vessel, which retains the fission products. The third layer is made from silicon carbide and this has a high retention capability especially for some important solid fission products (thickness: 35μm). The fourth layer consists again from dense pyrolytic carbon (thickness: 40μm). TRISO-particle means a particle with three dense layers; the inner porous zone is not counted, because it does not retain fission products.

This system of different layers forms a very small pressure vessel, which can tolerate large internal pressures even at high burn up values. An outer overcoating protects this system of layers during the fuel fabrication process, in which the coated particles are embedded in a synthetic matrix. The fuel element is build up from an inner fuel zone (50mm diameter), which is surrounded by a 5mm thick fuel free shell consisting from the matrix material too. The shell and the inner fuel zone are directly connected. Some simplified equations for the temperature differences in the zones of the fuel element and between the surface of the fuel element and the gas indicate the conditions of heat transport inside this component (Figure 3.10).

The valuation of the equations for a VHTR with spherical fuel elements delivers results as shown in Table 3.2. Here the axial profile of power density of a MEDUL-cycle is applied and an average outlet temperature of the helium from the core of 950℃ is assumed as example.



(a) (b)

I	inner fuel zone	$\Delta T_f = \frac{\overline{\dot{q}_f'''} \cdot r_i^2}{6 \cdot \lambda}$
II	graphite shell	$\Delta T_S = \overline{\dot{q}_{fz}'''} \cdot \frac{r_i^2}{3 \cdot \lambda} \cdot \left(1 - \frac{r_i}{r_o}\right)$
III	surface-helium	$\Delta T_G = \frac{\overline{\dot{Q}_{FE}}}{4\pi \cdot a \cdot r_a^2}$

(c)

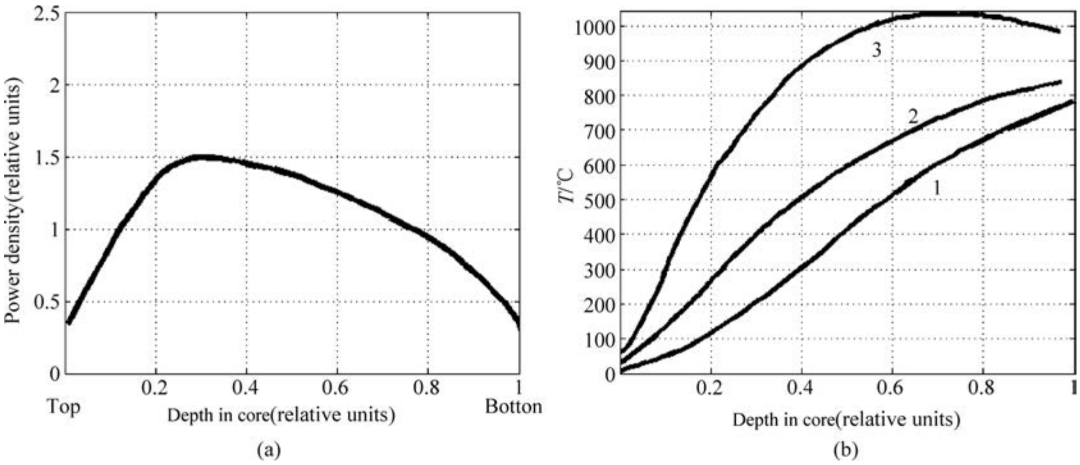
Figure 3.10 Temperature profiles in spherical fuel elements

(a) Spherical fuel element (diameter of fuel zone: 50mm; diameter of fuel element: 60mm); (b) Radial temperature profile (qualitative); (c) Temperature differences in the inner zone, the graphite shell and between the surface and the helium coolant

Table 3.2 Temperature differences in the fuel elements in some characteristic regions of core
(average core power density: 2.5MW/m^3; MEDUL-cycle; $\overline{T}_{outlet}$ = 950℃)

Position	Average power density /(MW/m^3)	ΔT_f/℃	ΔT_S/℃	ΔT_G/℃	T_{gas}/℃	T_{max}(fuel) /℃
in the upper part of core	3	130	40	30	300	<700
in the middle of core	4	170	50	40	600	<900
in the lower part of core	2	100	30	20	950	<1100

In the real reactor core the power density is axially and radially dependent in the core. Figure 3.11 shows this for the central hot "channel" in the reactor.



(a) (b)

Figure 3.11 Thermo-hydraulic conditions in a core for VHTR-application (P_{th} = 170MW; T_{He}(outlet) = 950℃; MEDUL-cycle)

(a) Power density dependent from height in core (several passages through core); (b) Temperatures dependent from height in core (maximal values)

1—helium; 2—surface of fuel elements; 3—center of fuel elements

During the normal operation the nominal maximal fuel temperature in the VHTR for process heat application stays below 1100℃, if the operation takes place at an average outlet temperature of the helium of 950℃. Just few coated particles arrive at these high temperatures as the histogram in Figure 3.12(a)explains.

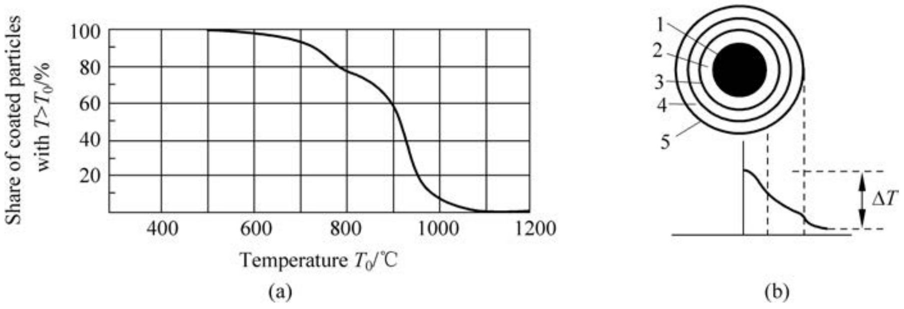


Figure 3.12 Some results of thermo-dynamic analysis of VHTR-fuel elements in normal operation

(a) Histogram of fuel temperatures in a VHTR core in normal operation with temperature above T_0 (P_{th} = 170MW; $\overline{q'''}$ = 2.5MW/m^3; T_{He}(out) = 950℃; MEDUL-cycle); (b) Temperature distribution in coated particle

1—UO_2-kernal; 2—C-layer; 3—SiC-layer; 4—C-layer; 5—graphite matrix

The temperature profiles inside the coated particles (Figure 3.12(b)) show very small differences, because these fuel zones are very small. Values of less than 10℃ between the center and the surface of the particle are characteristic.

The temperature limit for normal operation for today available TRISO-coated particle fuel is stated as 1250℃ till 1300℃. Therefore the thermal loads of fuel elements designed for the HTR-Module are far below technical limits of this type of fuel. In irradiation experiments much higher loads have been tested with great success. The experience today is furthermore, that the fission product release in normal operation at the thermal conditions of the HTR-Module is caused mainly by the fission of free (not coated Uranium) which could be contained in the matrix of the fuel element or on the surface of the coated particles. The content is small today (around 5×10^{-5}) and this explains the very low release rates measured in all HTR-plants and in irradiation experiments.

Because of the chosen core design and layout it is expected that the contamination of the helium circuit in normal operation will be very small in a VHTR-core using pebble bed fuel. The measurement of the activity content of the helium circuit as example of AVR confirms this analysis (Figure 3.13). A value of around 1 Ci/MW$_{th}$ as specific noble gas activity was characteristic for AVR, similar data are known from the other HTRplants. The result for operation at very high helium outlet temperatures (950℃) was not very different in AVR compared to that in the operation phase before, where the average helium outlet temperature was 850℃. Naturally during the operation time of 20 years of the

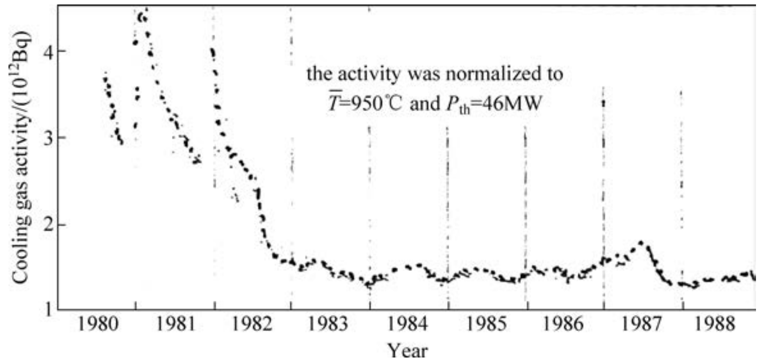


Figure 3.13 Activity of noble gases in the helium circuit of AVR during the operation time[22]