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# HIGH-TEMPERATURE NUCLEAR REACTORS
(Overview. Part 1)

J. Ekmanis, E. Tomsons, N. Zeltiņš

Institute of Physical Energetics
21 Aizkraukles Str., Riga, LV-1006, LATVIA

At the Generation IV International Forum (GIF) of 2001 the measures were approved which are necessary for the development of future generation nuclear reactors (NRs). Six best high-temperature NR technologies were selected, with the main criteria being the safe and economically profitable operation, long-term use, protection against the employment of nuclear material for military purposes and terroristic attacks as well as technologies of fuel close cycle in order to increase the amount of fission material and decrease the amount of highly radioactive waste. In four of the technologies, apart from electricity production also hydrogen is obtained. Part 1 presents a generalized description of the high-temperature NRs, their comparative characteristics and history, with the stopped and operational HTNRs outlined. The properties of different type nuclear fuels are described in detail.

**Key words:** *high-temperature nuclear reactors, close-cycle nuclear fuels, power plant.*

## 1 INTRODUCTION

Developmental conception for nuclear reactors (NRs) of the HTGR (High Temperature Gas Cooled Reactors) type was proposed in 1956 in Great Britain. A short time later, development of NRs of the type started in Germany and the USA.

In comparison with the water cooled NRs, the helium cooled high temperature NRs have several advantages [1, 2]:

- better economic indices due to greater utilisation of the NR heat (up to 50%), i.e. the efficiency of the power generating unit (PGU) is higher (approx. by 1.5% whenever the cooler temperature is increased by 50 $^{o}$C), lower building and maintenance costs because of a lesser number of the safety systems and a lower cost of the electric energy generated by the PGU;
- lower consumption of nuclear fuel due to deeper (more complete) combustion of nuclear fuel ((100–200) MW·d/t) and greater possibility for reprocessing of nuclear fuel;
- the possibility to use various types of nuclear fuel and its cyclic usage, as well as to use a less enriched uranium with a $^{235}$U isotope or thorium;
- lower heat release into the surrounding environment (~ 25% less) owing to lower consumption of water is less;
- the possibility to use gas turbines (the Brighton cycle);

- the possibility to use the produced high temperature heat for various energo-technological needs in industry (oil refining, water desalination, metallurgy, etc.) as well as for economical production of hydrogen from water;
- high safety (low radioactivity of the cooling contour, a remarkable negative feedback, weak sensitivity of the elements to temperature variations, etc.);
- higher safety of the nuclear power plant (NPP) as compared with the water cooled NRs, as well as lower impact of radiation upon the surrounding environment, which allows location of NPPs closer to the consumers;
- less radioactive waste as compared with the III and $III^+$ generation NRs.

## 2. STOPPED HIGH-TEMPERATURE NUCLEAR REACTORS

**The experimental nuclear reactor "DRAGON".** In April, 1960, construction of experimental NR "Dragon" of the HTGR type started in Winfrith (UK) with a 20 $MW_{th}$ heat capacity [3]. The NR active zone consisted of 37 blocks of nuclear fuel. Each block had seven six-sided prism graphite elements containing nuclear fuel, the cooling channels and the channels for the regulating rods of the reactor. The height and diameter of the active zone were 1.6 m and 1.08 m, respectively. Helium gas with a pressure of ~ 2 MPa was introduced into the NR active zone and heated from 350 $^oC$ to 750 $^oC$. The cooling was done supplying helium (9.62 kg/s) The NR was used 12 years (1964–1976) for experiments and tests. "DRAGON" belonged to the European Union of Nuclear Energy (Tables 1 and 2).

**The experimental nuclear reactor "AVR" in Jülich (Juelich).** In August, 1961, the construction of an experimental 51 $MW_{th}$ NR "AVR" (Arbeits-gemeinschaft Versuch Reaktor) of the HTGR type started in Jülich (Juelich), Germany [4]. The conception of an NR with spherical (globe-shaped) nuclear fission elements was proposed by Prof. Rudolf Schulten. The NR active zone was formed from 100 000 globe-shaped graphite elements of nuclear fuel 6 cm in diameter. The elements were freely poured into the active zone. This shape of nuclear fuel elements allows changing them continuously while the NR is running and achieve more uniform combustion since the balls are relocated several times in the active zone so that a smaller reactivity reserve is needed, which raises the NR safety. At the end of 1967, the 13 $MW_{e\ (net)}$ PGU was connected to the electric network. In order to produce electric energy, a steam turbine was used at the NPP in which steam was supplied under the pressure of 7.3 MPa and at the temperature of 505 $^oC$. Initially, the temperature of helium flowing out of the active zone was 850 $^oC$, but in 1974 it was raised to 950 $^oC$. After 21 year of running, at the end of 1988 the NR was stopped, having run 122 000 h. The NPP produced 1.5 $TW{\cdot}h_e$ of electric energy.

**The "PEACH BOTTOM-1" demonstration nuclear reactor.** In February, 1962, the construction of the "PEACH BOTTOM-1" NPP started in Pennsylvania, USA with a HTGR-type NR [5]. The graphite moderator of the NR active zone contained small particles of uranium-thorium carbide covered with protective layers. The height of the active zone was 2.28 m and the diameter 2.79 m. The heat capacity of the NR was 115 $MW_{th}$, and the electric capacity of the PGU – 40 $MW_{e\ (net)}$. The efficiency of the NPP was35 %, with the average energy density in the active zone being 8.3 $MW_{th}/m^3$. The incineration depth of the nuclear fuel

*Table 1*

**The main characteristics of the stopped high-temperature nuclear reactors**

| Country | Location | Name | Capacity | | Coefficient of efficiency η (%) | Helium temperature (°C) | | Helium pressure in the active zone (MPa) | Average energy density in the active zone ($MW_{th}/m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| | | | heat ($MW_{th}$) | electric ($MW_e$) gross/net | | entering the active zone | leaving the active zone | | |
| **Great Britain** | Winfrith | DRAGON | 20 | - | - | 350 | 750 | 1.96 | 14 |
| **USA** | Pennsylvania | PEACH BOTTOM-1 | 115 | 42/40 | 35 | 344 | 728 | 2.31 | 8.3 |
| **Germany** | Jülich (Juelich) | AVR JUELICH | 51 | 15/13 | 28.3 | 270 | 850 | 1.08 | 2.3 |
| **USA** | Colorado | FORT ST. VRAIN | 842 | 342/330 | 39.2 | 400 | 785 | 4.83 | 6.3 |
| **Germany** | Schmehausen | THTR-300 | 750 | 308/296 | 40 | 262 | 750 | 3.92 | 6 |

*Table 2*

**The operating time of the stopped high-temperature nuclear reactors**

| Country | Name of the NR | Construction started | Critical condition reached | Connected to the electric network | Commercial use started | Stopped | Produced electric energy ($GW \cdot h_e$) |
|---|---|---|---|---|---|---|---|
| Great Britain | DRAGON | 1960/04/01 | 1964/01/01 | - | - | 1976/01/01 | - |
| USA | PEACH BOTTOM-1 | 1962/02/01 | 1966/03/03 | 1967/01/27 | 1967/06/01 | 1974/11/01 | 1 350.3 |
| Germany | AVR JUELICH | 1961/08/01 | 1966/08/16 | 1967/12/17 | 1969/05/19 | 1988/12/31 | 1 505.74 |
| USA | FORT ST. VRAIN | 1968/09/01 | 1974/01/31 | 1976/12/11 | 1979/07/01 | 1989/08/29 | 5 419.76 |
| Germany | THTR-300 | 1971/05/01 | 1983/09/13 | 1985/11/16 | 1987/06/01 | 1988/04/20 | 2 756.1 |

reached 73 GW·d/t. At the beginning of 1967, the PGU was connected to the electric network. The NR used variously-shaped nuclear fuel elements. After 7.8 years of running, the "PEACH-BOTTOM-1" NPP was stopped (in November, 1974). The "PEACH BOTTOM-1" NPP produced 1.35 TW·$h_e$ of electric energy.

**The "FORT ST. VRAIN" high-temperature nuclear reactor.** In 1968, the USA started the construction of another "FORT ST. VRAIN" NR of the HTGR type [6]. The NR was built in Colorado (not far from Denver). The safe operation and the good operational indices of the NR ensured their further development. Its active zone was formed from blocks of six-sided graphite prisms. The blocks of the nuclear fuel contained 102 longitudinal channels for circulation of the helium gas heat carrier, 210 channels for disposition of the heat releasing elements (nuclear fuel) and the absorbents of incinerated neutrons. The height of the active zone was 4.75 m and the diameter – 5.94 m. The NR heat capacity and the PGU electric capacity was 842 $MW_{th}$ and 330 $MW_{e\ (net)}$, respectively, with PGU efficiency being 39.2 %. The incineration depth of the nuclear fuel reached 100 GW·d/t. The scheduled campaign of the reactor lasted 6 years, each year changing 1/6 (~ 250) blocks of nuclear fuel. The PGU operated 12.7 years (1976 – 1989) and produced 5.42 TW·$h_e$ of electric energy.

**The high-temperature thorium nuclear reactor "THTR-300".** In 1971, Germany (Schmehausen) started building the "THTR-300" NR of the HTGR type with a 750 $MW_{th}$ heat capacity. The PGU electric capacity was 296 $MW_{e\ (net)}$, with efficiency 40–41%. The NR used 675 000 globe-shaped 6 cm in diameter elements of nuclear fuel, which were disposed in the active zone of THTR-300 NR. The heat releasing element contained the nuclear fissile and the nuclear fuel reprocessing material (uranium dioxide ($UO_2$) and thorium dioxide ($ThO_2$)) in the form of particles 0.2–0.8 mm in diameter. The particles were protected by several coatings of the TRISO type (Fig. 1) and pressed in a 6 cm globe-shaped graphite matrix with a 0.5 mm graphite coating. Each element (ball) contained 1 g of $^{235}U$ isotope (93% enrichment) and 10.2 g of $^{232}Th$. The PGU was connected to the electric network in November, 1985, and stopped in April, 1988. The NPP was running ~ 16 000 h and produced 2.76 TW·$h_e$ of electric energy.

## 3. THE MAIN COMPONENTS OF THE HIGH-TEMPERATURE NUCLEAR REACTORS

### 3. 1. Nuclear fuel

The high-temperature helium cooled NR is the most successful solution among the gas cooled reactors. They differ from the other NRs by the fact that nuclear fuel and tiny particles of the reprocessing material ~ 0.5 mm in diameter are located in a graphite neutron moderator and covered with several layers protecting the particles from the coercion of the moderator and cooler (Fig. 1).

As nuclear fuel, uranium carbide dioxide ($UC_2$) or uranium dioxide ($UO_2$) is used, and the reprocessing material is $ThO_2$ or natural uranium ($^{238}U$) dioxide. The tiny particle of nuclear fuel is covered with a porous carbon layer (~ 0.095 mm) which absorbs the nuclear fission materials (mainly gaseous) and takes up the fuel swelling, then with a ~ 0.04 mm pyrolysis carbon layer – a so-called BISO-type (double) particle coating, which is designed for the work at the temperature in the centre of the particle up to 1000 $^oC$.

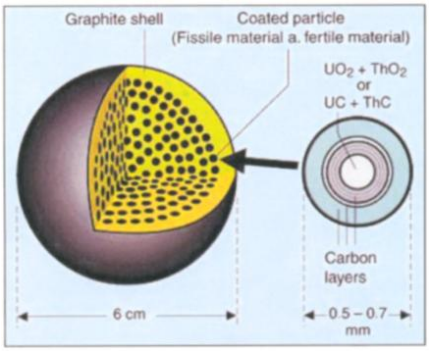


*Fig. 1.* A globe-shaped element of nuclear fuel.

If between the last two layers of the pyrolysis carbon a layer (~ 0.035 mm) of silicon carbide is placed, it is called a TRISO-type (triple) particle coating The temperature in the centre of a TRISO-type element may reach 1600 $^{o}$C. The AVR JUELICH and THTR-300 NR used globe-shaped elements of nuclear fuel.

The NRs "DRAGON", "PEACH BOTTOM-1" and "FORT ST. VRAIN" used the graphite elements of nuclear fuel of a six-sided prism with inserted tiny particles of nuclear fuel made by BISO- or TRISO-type particle coating technology (Fig. 2).

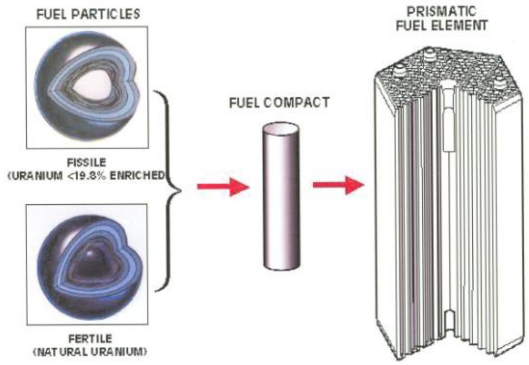


*Fig. 2.* A prism-shaped element of nuclear fuel.

The nuclear fuel in the form of tiny particles with several protective layers (as for the globe-shaped elements) is pressed in graphite rods [7, 8]. The graphite blocks with vertical channels of various sizes are used to insert nuclear fuel, control rods, absorbents of the incinerated neutrons, as well as to ensure the flow of helium gas. Such a disposition makes it possible to reach a low average density of the heat capacity in the active zone (2–10 $MW_{th}/m^3$). In comparison with the water cooled nuclear reactors, where it is much greater ($\geq$100 $MW_{th}/m^3$), this ensures a high operating capability of nuclear fuel and the running of reactor at high temperatures, thus allowing the use of gas turbines for electricity production (in Brighton's cycle) and of the obtained high-temperature heat for industrial needs (e.g. hydrogen production).

**Uranium** was discovered in 1789 by Martin Klaproth, a German chemist. Uranium is the only nuclear fission material found in nature. The natural uranium

has three isotopes: $^{234}$U, $^{235}$U and $^{238}$U (Table 3) [9]. The density of natural uranium is 19.1 g/cm$^3$, its melting temperature is 1132.2 $^o$C and its boiling temperature – 4131 $^o$C.

Table 3

**Properties of the natural uranium**

| Characteristics | $^{234}$U | $^{235}$U | $^{238}$U | Together |
|---|---|---|---|---|
| Atomic % | 0.0054 | 0.72 | 99.275 | 100 |
| Mass % | 0.0053 | 0.711 | 99.284 | 100 |
| Half-life period (years) | 244 500 | $703.8 \cdot 10^6$ | $4.468 \cdot 10^9$ | – |
| Specific activity (Bq/g) | 231.3 | 80.011 | 12.445 | – |
| Activity % | 48.9 | 2.2 | 48.9 | 100 |
| Activity of 1 g $U_{natural}$ (Bq) | 12 356 | 568 | 12 356 | 25 280 |

One kilogram of the uranium $^{235}$U isotope, if completely burned, can produce ~ 80 TJ of energy, which is equivalent to ~ 3000 t of burned coal.

In order to improve the mechanical and other properties of uranium, it is, as a rule, used in compounds with various physical properties, which allows making different nuclear fuel, thus satisfying many-sided application of the product.

**Plutonium.** When the NR absorbs neurons, uranium $^{238}$U isotope does not disappear but changes into plutonium.

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{239}_{92}\mathrm{U} \underset{23.5\,\mathrm{min}}{\overset{\beta-}{\rightarrow}} {}^{239}_{93}\mathrm{Np} \underset{2.356d}{\overset{\beta-}{\rightarrow}} {}^{239}_{94}\mathrm{Pu}\,.$$

Production of plutonium $^{239}$Pu isotope from $^{238}$U uranium isotope is called conversion, and in this case the $^{238}$U isotope is a raw material. Plutonium is automatically accumulated in all operating NRs in which the uranium nuclear fuel is used, since uranium contains the $^{238}$U isotope in a considerable amount. The $^{239}$Pu plutonium isotope produced in an NR extends considerably its operating time, being partly used as a nuclear fission material. Besides, $^{239}$Pu, when irradiated with neutrons, produces plutonium $^{241}$Pu isotope, the nuclei of which split well under the impact of neutrons [10].

The most important from 16 plutonium isotopes are $^{239}$Pu ($T_{1/2}$ = 24110 years), $^{240}$Pu ($T_{1/2}$ = 6 550 years), $^{241}$Pu ($T_{1/2}$ = 14.4 years) and $^{242}$Pu ($T_{1/2}$ = 37 630 years). One more – the $^{238}$Pu isotope has the half-life of 88 years. The nuclei of $^{239}$Pu and $^{241}$Pu isotopes, interacting with the thermal neutrons, split and throw out, on the average, 2.862 and 2.924 neutrons (for $^{235}$U this number is 2.416). Therefore, plutonium is an excellent nuclear fission material, particularly for the reprocessing (multiplication) of nuclear fuel for the fast neutron NRs. The NR active zone of the nuclear fuel multiplier was formed from $^{239}$Pu alternating with $^{238}$U uranium isotope ensuring conversion process. Currently, the only source of plutonium is the nuclear fuel reprocessed by separating plutonium from the remaining mass.

Plutonium is a silvery white metal whose melting temperature is 640 $^o$C and evaporation temperature is 3227 $^o$C. Its crystalline structure is very unstable, therefore in NRs plutonium dioxide ($PuO_2$) is used, which does not lose its mechanical

strength when temperature changes. It is of importance that the mechanical properties of $PuO_2$ are similar to those of $UO_2$ widely applied in the NRs. Therefore, mixture of the $PuO_2$ and $UO_2$ compounds are used. The $PuO_2$ melting temperature is >2300 $^oC$; it is radiation-resistant and does not combine with water and other heat carriers; the production of $PuO_2$ and of nuclear fuel is not complicated. Its density is 11.5 g/cm$^3$ (of $UO_2$ – 10.96 g/cm$^3$), and the melting temperature is 2760 $^oC$. Plutonium is a very toxic material, and for its treatment special equipment is used.

**Thorium** was discovered in 1828 by John Bercelius (Jöns Jacob Berzelius, Sweden). Thorium has one natural isotope $^{232}Th$ [11]. Pure thorium is a soft (lead-like) metal with a silvery shiny lustre. The metallic thorium is a chemically active element, in the air it oxidises and becomes opaque; in a powder form it is toxic. The density of thorium is 11.72 g/cm$^3$ (at 20 $^oC$), its melting temperature is 1842 $^oC$, its evaporation temperature is 4788 $^oC$. Thorium does not split when interacting with neutrons but is a material for reprocessing (recycling) the nuclear fuel:

$$^{232}_{90}\mathrm{Th} + {}^{1}_{0}n \rightarrow {}^{233}_{90}\mathrm{Th} \underset{23.4\,\mathrm{min}}{\overset{\delta-}{\rightarrow}} {}^{233}_{91}\mathrm{Pa} \underset{27.3d}{\overset{\delta-}{\rightarrow}} {}^{233}_{92}\mathrm{U}\,.$$

Thus obtained $^{233}U$ isotope is a good nuclear fission material which splits when interacting with neutrons. To derive this isotope, thorium is to be specially put into the NR where during operation it interacts with the neutrons producing the fissile uranium isotope ($^{233}U$). The HTGR type nuclear reactor fits well for this purpose.

### 3. 2. Heat carriers

The heat carriers employed by high-temperature NRs are: helium gas, liquid metals (sodium, lead or a lead-bismuth alloy), molten salts (Table 4).

*Table 4*

**Characteristics of high-temperature heat carriers**

| Heat carrier | Temperature ($^oC$) | | Density (kg/m$^3$) | Heat capacity, $c_p$ [kJ/(kg·$^oC$)] | Heat conductivity, λ [W/(m·$^oC$)] | Viscosity, ν·10$^6$ (m$^2$/s) |
|---|---|---|---|---|---|---|
| | melting | evaporation | | | | |
| Helium (7.5 MPa) | | | 3.8 | 5.2 | 0.29 | 11 |
| Sodium (700 $^oC$) | 97.8 | 883 | 796 | 1.27 | 55 | 0.23 |
| Lead (700 $^oC$) | 327.4 | 1750 | 10 200 | 0.147 | 18 | 0.13 |
| Bismuth (700 $^oC$) | 271 | 1500 | 9 530 | 0.151 | 18.1 | 0.096 |
| Lead-bismuth 44.5% Pb-55.5% Bi | 123.5 | 1670 | 9 880 | 0.147 | 16.1 | 0.114 |
| $Li_2BeF_4$ (FLiBe) | 459 | 1 430 | 1 940 | 2.34 | 1 | 2.9 |
| 0.58NaF–0.42$ZrF_4$ | 500 | 1 290 | 3 140 | 1.17 | ~ 1 | 0.53 |

**Helium** is a very good heat carrier with a considerable heat capacity (0.5 kJ/(kg·K) at 50 $^{o}$C), a low neutron absorption rate (0.007 barns) and the viscosity ensuring good circulation in pipelines. Helium has excellent heat conductivity; its density at the atmospheric pressure and 0 $^{o}$C is 0.1785 kg/m$^3$ and at 600 $^{o}$C – 0.0558 kg/m$^3$. Helium is a noble gas, i. e. chemically inert and resistant to radiation. Natural helium contains 0.000 137 % of $^3$He isotope which interacts with thermal neutrons in the NR after the (n, p) reaction. Considerable cross-section of $^3$He-neutrons interaction (5400 barns) results in arising of tritium – a β-radioactive irradiator with a 12.1-year half-life period. At temperatures below 1000 $^{o}$C helium is compatible with all materials used in the NR. In atmosphere, only a small amount of helium (~ 0.00013%) is present, while in natural gas 0.5–3%. For industrial needs helium is extracted from natural gas by deep cooling. Helium is a highly expensive gas.

**Sodium** has a higher boiling temperature (883 $^{o}$C) at the atmospheric pressure than water which is widely used for cooling contemporary NRs. Liquid Na has good heat exchanging properties. As compared with other liquid metals that are suitable for cooling NRs, sodium has a lower melting temperature and a lower energy consumption to ensure circulation. It is rather safe in use, yet inflammable.

**The lead–bismuth alloy** was used successfully in nuclear submarines**.** The melting temperature of lead is 327.4 $^{o}$C and that of bismuth 271 $^{o}$C. The eutectic Pb–Bi alloy (44.5% Pb+55.5% Bi, melting temperature 123.5 $^{o}$C, evaporation temperature 1670 $^{o}$C) can be used as a heat carrier in the NR. The thermo-physical properties of the alloy are close to the properties of its components. The alloy does not interact with water and is corrosion-resistant.

**Molten salts** with a small neutron absorption capacity (eg. combinations with fluorine) can be used for cooling the NR active zone. Fluoride $^7$Li in combination with beryllium fluoride is a promising alloy for cooling the NR. The solutions of thorium and uranium fluorides in the alloy can be applied as a liquid nuclear fuel. The melting temperature of the salts is above 500 $^{o}$C; however, the molten salt can be used at the atmospheric pressure. At a high temperature, fluorides are compatible with graphite used in the active zone as a neutron decelerator (moderator). The molten salts affect but slightly the materials of steel structures.

## 4. THE OPERATING HIGH-TEMPERATURE EXPERIMENTAL NUCLEAR REACTORS

Currently, two high-temperature helium-cooled experimental HTGR-type NRs exist (Table 5): a 30 $MW_{th}$ HTTR in Japan (since October, 1998; construction started on March 15, 1991), and a 10 $MW_{th}$ HTR-10 in China (since December, 2000; construction started on June 14, 1995). Because of the great radiation dose received by the NR elements and the very high operating temperature all-round research and improvement is going on presently of the materials, nuclear fuel, design solutions, application possibilities and the hydrogen production equipment.

**The high temperature engineering test reactor (HTETR)** of the Japan Atomic Energy Research Institute (JAERI) is situated 100 km to the north of Tokyo, near the Pacific Ocean. The NR uses a graphite neutron decelerator and helium gas for cooling the active zone. As nuclear fuel, uranium dioxide ($UO_2$) is

used, with 3–10% concentration of the $^{235}U$ isotope in uranium the tiny particles of which with a 0.92 mm diameter are made by the TRISO technology of the particle coating (see Fig. 2). Approximately 13 000 small particles of nuclear fuel are inserted in the cylindrical graphite element with a 26 mm diameter and 39 mm height.

*Table 5*

**The main characteristics of the operating high-temperature nuclear reactors**

| Country | Location | Name | Capacity | | Helium temperature ($^oC$) | | Helium pressure in the active zone (MPa) | Average energy density in the active zone ($MW_{th}/m^3$) |
|---|---|---|---|---|---|---|---|---|
| | | | heat ($MW_{th}$) | electric ($MW_e$) | entering the active zone | leaving the active zone | | |
| Japan | JAERI Oarai | HTTR | 30 | – | 395 | 850→ 950 | 4 | 2.5 |
| China | TSINGHUA University | HTR-10 | 10 | 4 | 250→ 300 | 700→ 900 | 3 | 2 |

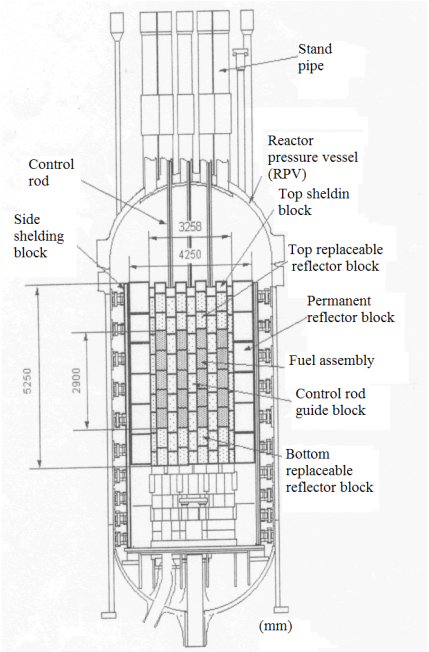


*Fig. 3.* Vertical cross-section of a nuclear reactor of the HTTR type.

These cylindrical elements are put into six-sided graphite prisms with a 36 cm length of a side and 58 cm height which have from 31 to 33 longitudinal channels in them (Fig. 3). For cooling the active zone under 4 MPa pressure 10.2 kg/s of helium gas is supplied. The temperature of the helium leaving the active zone reached 850 $^oC$ at the beginning of the operation but in 2004 it was raised to 950 $^oC$ (the temperature of gas entering the active zone was 395 $^oC$). The equivalent diameter of the active zone was 3.2 m and its height was 2.9 m [12, 13]. The HTTR-type NR is used for checking the already used materials and equipment, for the application of high-temperature heat, investigation of the gas-turbine cycle,

solution of the safety problems and industrial development of thermochemical processes.

**The high-temperature experimental NR "HTR-10"** is operating in China at the Tsinghua University, Institute of Nuclear Energy Technology (INET), approximately 40 km to the north of Beijing (Peking). It is the first China's high-temperature experimental nuclear reactor of the type [14], thus being the first step in the development of the HTGR-type NRs in China. The heat capacity of the NR is 10 $MW_{th}$. The diameter of the active zone of the reactor is 1.8 m, its height is 1.97 m (5 $m^3$); it is filled with 27 000 globe-shaped nuclear fission elements (D = 6 cm) (Fig. 4).

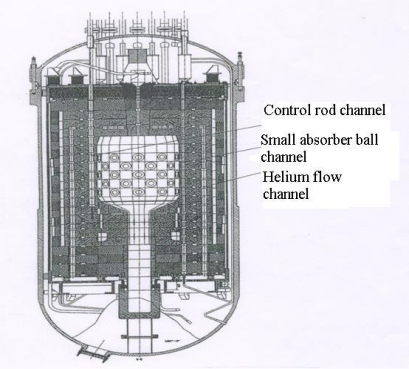


*Fig. 4.* Vertical cross-section of a nuclear reactor of the HTR-10 type

Each ball contains approximately 8 300 particles of uranium dioxide ($UO_2$) with a 0.5 mm diameter, made by the TRISO-type particle coating technology. Each ball has ~ 5 g of uranium in it with a 17 % enrichment of the $^{235}U$ isotope. The average incineration (combustion) depth of nuclear fuel (uranium) is 80 GW·d/t. The active zone is cooled by helium gas under a 3 MPa pressure. The temperature of helium when entering the active zone is from 250 to 300 $^oC$, but when leaving it – from 700 to 900 $^oC$. The HTR-10 is used for the investigations of high-temperature heat technologies and production of electric energy, as well as for testing the safety systems of the NR.

*ACKNOWLEDGEMENT*

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## AUGSTAS TEMPERATŪRAS KODOLREAKTORI
(Pārskata raksts)
1. daļa

J. Ekmanis, E. Tomsons, N. Zeltiņš

K o p s a v i l k u m s

Ceturtās paaudzes kodolreaktoru starptautiskā forumā 2001.gadā nolēma par nepieciešamiem pasākumiem nākamās paaudzes kodolreaktoru izstrādei. Ir atlasītas sešas reaktoru tehnoloģijas, kuras lietderīgi turpmāk izstrādāt. Tās atlasītas ņemot vērā to drošu un ekonomiski izdevīgu darbību, ilgtspējīgu izmantošanu, aizsardzību pret materiālu izmantošanu militārām vajadzībām un teroristu uzbrukumiem, slēgtā degvielas cikla izmantošanu, lai palielinātu kodoldalīšanās materiālu daudzumu un samazinātu augstas aktivitātes atkritumu daudzumu, kurus būs jāapglabā. Četras no plānotām tehnoloģijām bez elektroenerģijas ieguves varēs ražot ūdeņradi.

1. daļā ietverts vispārīgs apraksts par augstas temperatūras kodolreaktoriem, to salīdzinājums pēc raksturlielumiem, pēc attīstības vēstures. Apskatīti gan apturētie, gan strādājošie reaktori, to kodoldegvielas.

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