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5. Advanced designs of research reactors

In the middle 1980s, Russia dropped out of the international market as supplier of research reactors. For 25 years, the domestic companies either took no part in the bidding or had no success there. Meanwhile, the number of countries seeking to use nuclear technologies has been recently growing. The best first step in this direction is to build a research reactor and thus provide an opportunity for unhurried and thoughtful assimilation of the global experience in operation of nuclear facilities with proper safety management, and to train national personnel for the future nuclear power sector. This approach is being chosen by an increasing number of countries, which are thereby setting up a market for research reactors.

Another important application of research reactors is generation of isotopes for medical and industrial purposes. The present-day market for molybdenum isotope supply is almost fully shaped by research reactors. An attempt – unsuccessful for certain reasons – has been made already to build a tandem of purely isotope-production reactors in Canada. This failure does not eliminate, however, the need for an inexpensive and convenient isotope-production facility.

This and other factors call for special attention to the technical side of the situation. NIKIET specialists have analyzed the market for research reactors and have identified the power and functional characteristics in greatest demand. The results of this analysis have enabled them to come up with a number of basic engineering proposals.

Medical beam reactor cooled by natural circulation

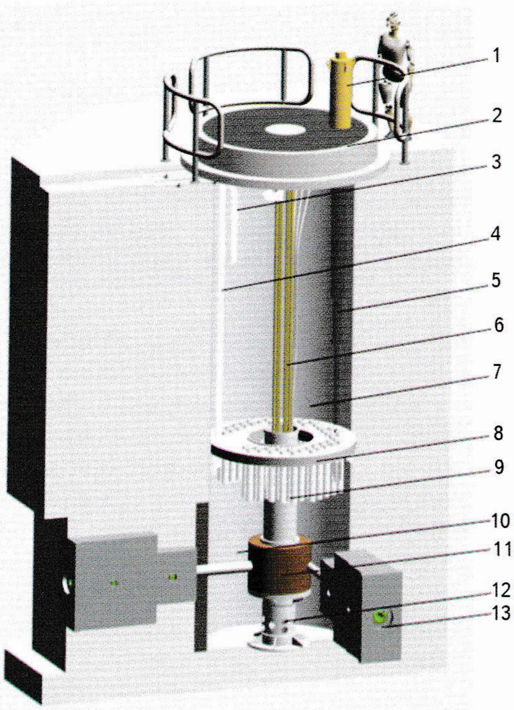
This pool-type reactor cooled by natural circulation of a coolant can be used for training purposes, but its primary application is cancer therapy with the use of neutron beams in horizontal experimental channels. Three beams are provided for, each intended for a particular type of therapy:

– fast neutron beam for ray therapy ($\Phi_f \geq 1 \cdot 10^9$ cm^{-2}s^{-1}, $E_f > 0.5$ MeV);

– neutron capture beam for treatment of superficial tumors, using thermal neutrons ($E < 0.5$ eV), $\Phi_{th} \geq 1 \cdot 10^9$ cm$^{-2} \cdot$s^{-1});

– neutron capture beam for treatment of deep tumors, using epithermal neutrons (0.5 eV $< E <$ 10 keV), $\Phi_{eth} \geq 1 \cdot 10^9$ cm$^{-2} \cdot$s^{-1}).

The reactor pool is divided into two parts by a horizontal partition – the balcony of the fuel bundle storage. The balcony is fixed in the reactor vault and has sockets for fuel assemblies and other core items. The upper part of the pool accommodates the reloading mechanism, brackets for securing vertical horizontal channels, CPS channels, and ionization chambers. Found in the lower part are the core with the beryllium reflector, horizontal channels with supports, and distribution header. The reactor core is comprised of VVR-M2 fuel assemblies with 19.7 % enrichment in



General view of the medical beam reactor cooled by natural circulation:
1 – transfer container; 2 – shielding cover; 3 – outlet nozzle; 4 – inlet nozzle; 5 – transfer channel; 6 – CPS channels; 7 – reactor pool; 8 – fuel bundle storage; 9 – upcomer well; 10 – experimental channel; 11 – reactor core with reflector; 12 – pressure header; 13 – experimental channel shutter

Main performance of the medical beam reactor cooled by water natural circulation

Thermal power	200 kW
Fuel assembly type	VVR-M2
Core height	600 mm
Thermal neutron flux (E <0.4 eV):	
in the trap	$1.0\cdot10^{13}$ $cm^{-2}\cdot s^{-1}$
in the separable beryllium blocks	$(2\ldots3.5)\cdot10^{12}$ $cm^{-2}\cdot s^{-1}$
in the stationary beryllium reflector	$3\cdot10^{12}$ $cm^{-2}\cdot s^{-1}$
Coolant temperature at the core inlet	40 °C
Coolant temperature at the core outlet	52.5 °C
Number of horizontal experimental channels	3
Number of vertical experimental channels, max.	8
including the central trap	1
Number of rabbit tubes	2
Absorber of CPS rods	Boron carbide
Number of control members	9
including:	
shim members (SM)	6
automatic control members (ACM)	1
emergency protection members (EPM)	2
BOC reactivity margin	8.1 % Δk/k
Cycle duration	4.8 years

uranium-235. Seven fuel assemblies in the core center can be replaced by a beryllium block with a water pocket – neutron trap – 80 mm in diameter. The radial reflector is made of beryllium. Desalted water is used as coolant, moderator, axial reflector and biological shielding.

Heat removal from the core relies on a cooling arrangement with intensification of coolant natural circulation. Having lost heat to the heat exchanger, coolant is pumped to the reactor tank up to the top edge of the upcomer well and is drawn off from the upper portion of the reactor tank. Part of the pumped water passes through the core, with the rest rising in the space between the tank wall and the upcomer well, then mixes with the water from the core and comes to the pump inlet.

The materials of the neutron beam shapers in each of the horizontal channels are selected with regard to the strict requirements imposed by the medical purposes of the channels.

Owing to the long reactor campaign and the possibility of simultaneous irradiation by different beams, the contribution of a radiation treatment procedure to the operating costs is substantially reduced.

Multipurpose 10 MW reactor

The reactor is meant for a broad spectrum of research and applied studies with the use of experimental devices and irradiation capsules installed directly in the reactor core and reflector as well as in the path of neutron beams. Its possible applications include:

- nuclear physics;
- solid-state physics;
- radiation material science;
- neutron activation analysis;
- neutronography;
- silicon doping;
- production of isotopes for medical and industrial purposes (^{99}Mo, ^{131}I, ^{125}I, ^{35}S, ^{32}P, ^{90}Y, ^{166}Ho, ^{60}Co, ^{153}Sm, ^{192}Ir);
- neutron capture therapy.

Main performance of multipurpose reactor

Parameter	Value	
	IRT-4M	VVR-KN
Thermal power, MW	10	10
Number of fuel assemblies in the core	16	26
Core height, cm	60	60
Core volume*, l	49.6	62.6
Specific power density, kW/l	201.61	158.93
Fuel enrichment in ^{235}U, %	19.7	19.7
Maximum neutron flux in the core, $\times 10^{14}$ $cm^{-2}\cdot s^{-1}$:		
thermal (E <0.625 eV)	2.1	2.17
fast (E > 0.82 MeV)	0.3	0.36
Maximum thermal neutron flux in the beryllium reflector, $\times 10^{14}$ $cm^{-2}\cdot s^{-1}$	2	2
Neutron flux in the silicon irradiation channel, Ø205 mm, $\times 10^{14}$ $cm^{-2}\cdot s^{-1}$:		
thermal (E <0.625 eV)	0.38	0.37
fast (E> 0.1 MeV)	0.003	0.003
Neutron flux at HEC outlet, $\times 10^{10}$ $cm^{-2}\cdot s^{-1}$:		
thermal (E <0.625 eV)	0.8…1.3	0.8…1.3
fast (E > 0.82 MeV)	0.0035…0.049	0.0035…0.049
Thermal neutron flux (E <0.625 eV) at pneumatic rabbit positions, $\times 10^{13}$ $cm^{-2}\cdot s^{-1}$:	0.2	0.2
Maximum water velocity between fuel elements, m/s	4.6	4.33
Coolant temperature, °C:		
at the core inlet	45	45
at the core outlet	59	56
Number of horizontal experimental channels:		
tangential	1	1
radial	3	3
Number of vertical experimental channels, including:	Up to 24	Up to 24
for silicon irradiation	1	1
in the replaceable reflector and in the core (only VVR-KN), Ø65 mm	Up to 8	Up to 8
in the stationary reflector, Ø48 mm	11	11
in the stationary reflector, Ø70 mm, Ø130 mm	1 in each	1 in each
rabbit channels	3	3
Absorber in the CPS members	B_4C	B_4C
Number of control members		
including:	11	10
shim members (SM)	8	6
automatic control members (ACM)	1	1
emergency protection members (EPM)	2	3
Average burnup in the core, %	23.6	38.5
Reactor cycle, eff. days	22	9…19**

** Total volume of cells accommodating fuel assemblies; ** Depending on reloading conditions*

For the above activities, the reactor is equipped with the following built-in and replaceable devices:

– vertical experimental channels (VEC), including a loop channel for in-pile tests of materials, fuel elements and mockup fuel assemblies of power reactors;

– channels of the pneumatic rabbit system of the activation analysis laboratory;

– horizontal experimental channels (HEC).

Core design studies were carried out for two types of fuel assemblies, namely: IRT-4M and VVR-KN.

The proposed reactor has an enhanced safety level due to the following design approaches:

– the core is found in a water pool which can be a good heat sink in emergencies;

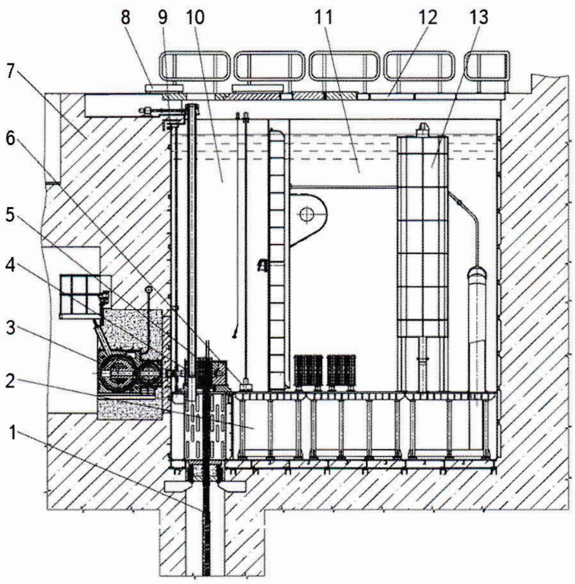
– the water column above the core is 7.5 m;

– the coefficients of reactivity are negative;

– the emergency cooling tank rules out the risk associated with component failures;

– the water column above the top core end, when the ECCS tank is full, is 6.2 m;

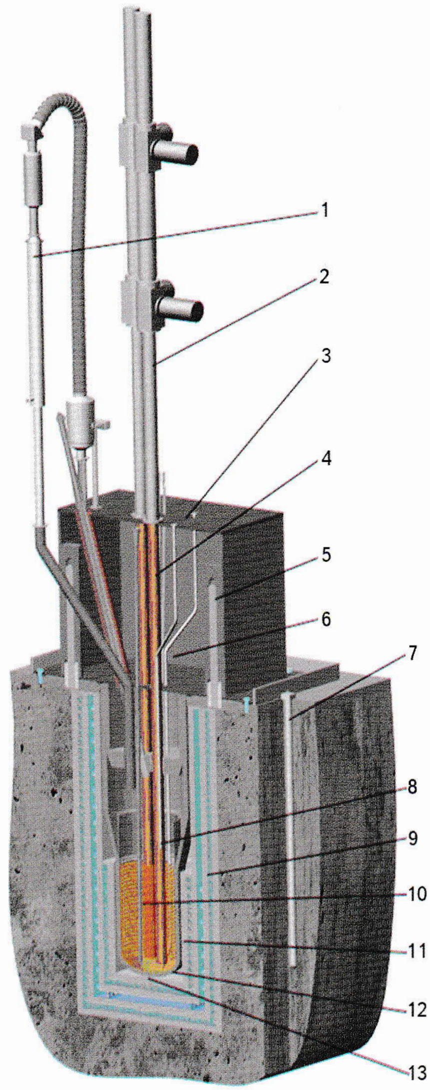
– the pipelines are provided with emergency flow limiters. Water height above the core during accidents with pipeline rupture outside the tank, is 2.6 m.



Arrangement of reactor components in the pool:
1 – CPS drives; 2 – retention reservoir; 3 – HEC shutter; 4 – reflector; 5 – core; 6 – natural circulation valve; 7 – biological shielding; 8 – rolling plate; 9 – tank; 10 – reactor pool; 11 – storage pool; 12 – top plate; 13 – ECCS tank

A tandem of isotope-production solution-type reactors with power levels up to 75 kW

This facility is being developed to produce medical isotopes – ^{99}Mo and ^{89}Sr – by an innovative fuel solution process as an alternative to the target-based technology. Application of the fuel solution process promises to reduce by orders of magnitude the neutron fluence and the thermal power of reactor required for production of a specified isotope quantity, and to reduce appreciably the resulting amount of radioactive



General view of the solution-type reactor for production of isotopes:
1 – recombiner; 2 – CPS member; 3 – lid; 4 – CPS channel; 5 – guide; 6 – solution charge/discharge tube; 7 – ionization chamber channel; 8 – instrumentation channel; 9 – iron and water shield; 10 – surveillance specimen channel; 11 – vessel; 12 – cooling coil; 13 – fuel solution

Performance of the solution reactor

Power	75 kW
Fuel	$UO_2SO_4 \cdot 3H_2O$ with addition of sulfuric acid
Enrichment	19.7 %
Moderator	Light water in fuel solution
Uranium concentration in the solution	400 g/l
Working volume of fuel	56.5 l
Temperature of fuel solution	80.7 °C
Fuel cycle	~10 years
^{99}Mo production output (at the time of separation from the adsorbing agent)	~$2.5 \cdot 10^3$ Ci/week
^{99}Mo separation cycle	6…7 days
Number of CPS channels	4
Primary coolant	Water
Coolant temperature gain	40 °C

waste. The development effort was undertaken together with specialists of the SRC "Kurchatov Institute".

The uranium salt solution, taking up 1/3 of the reactor volume, is characterized by high uranium concentration but low enrichment. The reactor vessel and the concrete vault serve as neutron reflectors.

The top-mounted recombiner provides processing of the detonating mixture resulting from radiolysis as well as additional cooling; downstream of the recombiner, water is fed into the solution. The recombination system has a gas loop connected to it for removal of ^{89}Kr from the operating reactor for production of ^{89}Sr.

The isotope production complex consists of two identical reactors connected to a sorption column where molybdenum is deposited.

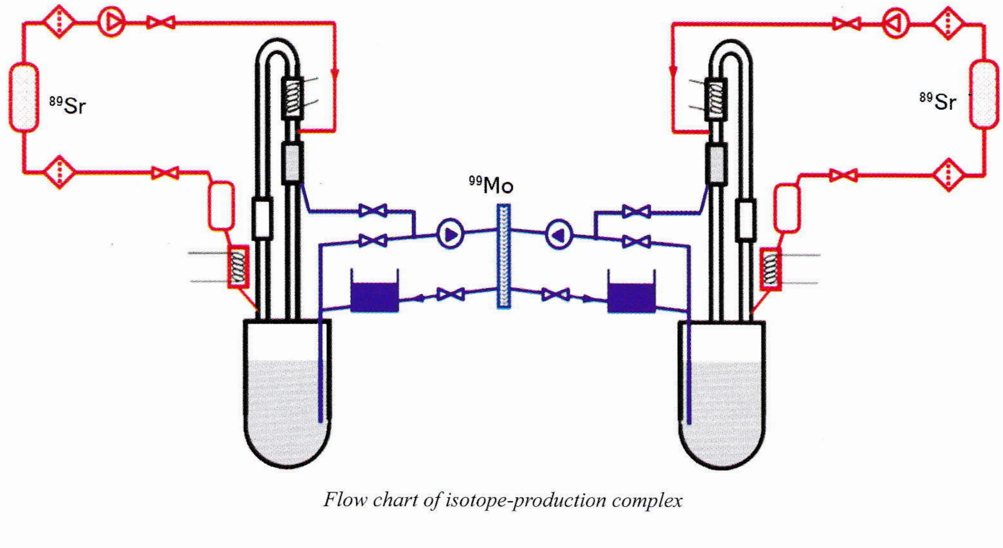
The simplicity of design and the modular configuration of the reactor facilities, the small reactor size as well as the nuclear and radiation safety provisions make it possible to site the complex in the immediate vicinity of medical centers while providing the planned production output and reliable supply of isotope products.

Dedicated isotope-production reactor of 15 MW power

This dedicated reactor is designed for production of isotopes, such as ^{99}Mo, ^{192}Ir, ^{71}Lu, ^{153}Sm, ^{131}I, etc., as well as for neutron transmutation doping of silicon and is expected to attract orders from domestic and foreign customers.

The reactor has a pool-type configuration with forced circulation of coolant in the core which consists of fuel assemblies with fuel of low enrichment (LEU). Desalted water is used as coolant, moderator, axial reflector and radiation shield.

The reactor components are arranged in a tank which serves as a metal lining of the concrete biological shielding vessel. The tank, filled

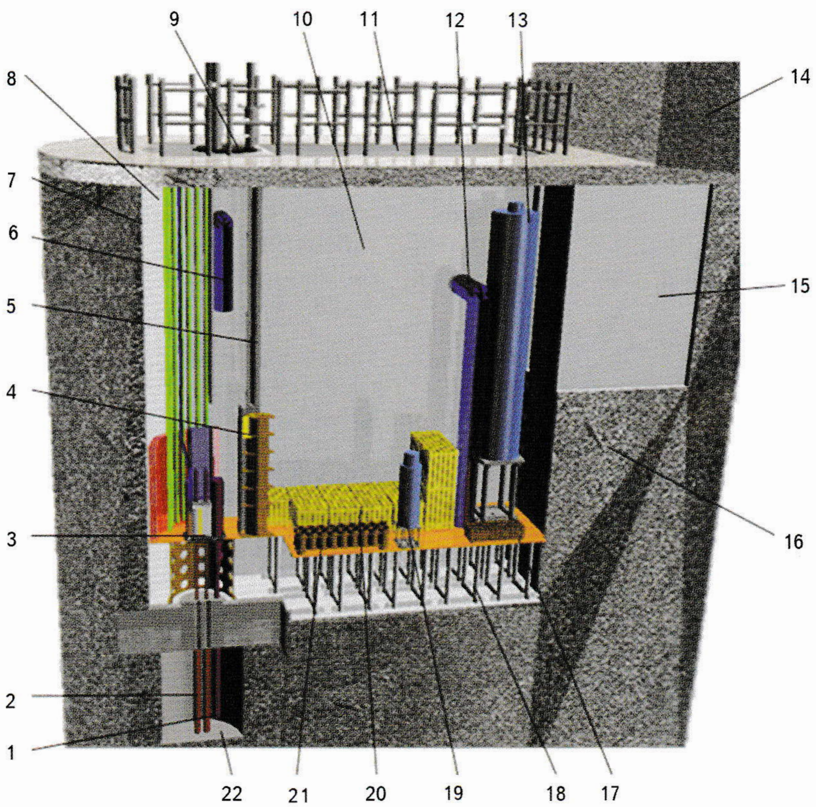


Flow chart of isotope-production complex with coolant, is divided by a leak-tight vertical partition into two parts – the reactor pool and the storage pool. The reactor pool contains the core with the reflector and the inlet pipeline, the storage pool accommodates structures for keeping fresh and spent fuel assemblies, irradiation devices and silicon ingots, as well as the tank of the forced circulation extension system (FCES), the heat exchanger of the emergency heat removal system (EHRS), and the outlet pipeline. The storage pool is covered with a dismountable deck and is connected to hot cells by two canyons for transportation of spent fuel assemblies and irradiation devices.

The bottom part of the reactor pool acts as a retention reservoir to reduce the oxygen and nitrogen activity of the water that has passed through the reactor core. Under the reactor pool there is a room for the drives of CPS members and neutron transmutation doping (NTD) devices, as well as for neutron detectors of irradiation devices, which can check the quality of generated products.

A biological shield above the reactor pool is constructed as two eccentrically installed rotatable plugs, which also perform the reloading functions. The reloading device in the rotating plug can be guided to any core cell. The lower part of the vertical partition has a niche housing a reloading drum with vertical cells, which can turn about its vertical axis. Once the irradiated component is inside the cell, the drum is rotated through a required angle so as to transfer it to the storage pool.

The figure presents the general view of the isotope-production reactor, while the table gives its main technical characteristics.



General view of the isotope reactor:
1 – NTD channel drive; 2 – CPS member drive; 3 – reactor core; 4 – reloading drum; 5 – vertical partition; 6 – inlet pipeline; 7 – tank; 8 – reactor pool; 9 – rotating plugs; 10 – storage pool; 11 – deck; 12 – outlet pipeline; 13 – FCES tank; 14 – hot cell; 15 – transport canyon; 16 – concrete biological shielding vessel; 7 – molybdenum holdup device; 18 – retention reservoir; 19 – EHRS heat exchanger; 20 – spent FA storage device; 21 – silicon ingot holdup device; 22 – room under the reactor pool

Main performance of the isotope-production reactor

Thermal power	15 MW
Coolant	H_2O
Reflector	Be
Number of fuel assemblies in the core	24
Core height	580 mm
Fuel enrichment in ^{235}U	19.75 %
Coolant pressure at the core inlet	$1.66 \cdot 10^5$ Pa
Coolant temperature:	
at the core inlet	45 °C
at the core outlet	52 °C
Number of control members	6
including:	
shim members (SM)	3
automatic control members (ACM)	1
emergency protection members (EPM)	2
Number of vertical channels	17
for:	
production of ^{99}Mo	11
production of other isotopes	2
NTD	2
hydraulic rabbit system	2
Maximum unperturbed neutron flux in the high-flux channels of the core:	
thermal (E <0.625 eV)	$5.07 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
fast (E > 0.82 MeV)	$0.77 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
Maximum unperturbed neutron flux in the 99Mo production channels: ^{99}Mo:	
thermal (E <0.625 eV)	$3.35 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
fast (E > 0.82 MeV)	$0.55 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
Unperturbed neutron flux in the rabbit channels:	
thermal (E <0.625 eV)	$(1.4 \ldots 1.8) \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
fast (E > 0.82 MeV)	$(0.15 \ldots 0.2) \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
Maximum unperturbed neutron flux in the beryllium blocks of the reflector:	
thermal (E <0.625 eV)	$1.1 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
fast (E > 0.82 MeV)	$0.09 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
Maximum unperturbed neutron flux in the beryllium blocks of the core:	
thermal (E <0.625 eV)	$1.6 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
fast (E > 0.82 MeV)	$0.2 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$
Maximum unperturbed thermal neutron (E <0.625 eV) flux at the silicon doping channel	$1.55 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$

Neutron capture therapy channel in a pool-type reactor

Research reactors have recently found wide application for medical purposes. An example of this trend is a neutron capture therapy (NCT) beam in a pool-type reactor, which can be set up for treatment of localized tumors, where other methods fail.

An NCT channel can be located in the niche of the thermal column of a small (2…3 MW) pool-type reactor and will be designed for reliable and safe neutron beam extraction to an irradiation room (experiment hall) with the following parameters at the channel axis (at ~2.5 m from the core center):

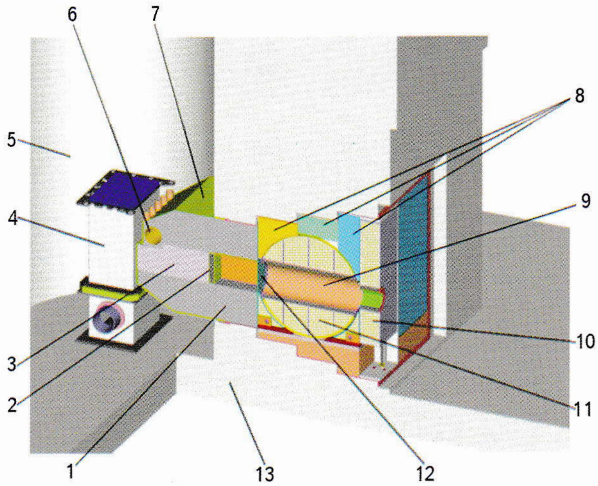
Thermal neutron flux...................... $\Phi_{th} = 2{,}2\cdot10^9$ cm$^{-2}\cdot$s^{-1}

Epithermal neutron flux .... $\Phi_{eth} = 1{,}3\cdot10^9$ cm$^{-2}\cdot$s^{-1}

Absorbed dose rate (ADR) caused by fast neutrons .... $D_n = 2{,}7\cdot10^{-13}$ Gy$\cdot$cm^2

ADR caused by photons .... $D_\gamma = 3{,}9\cdot10^{-13}$ Gy$\cdot$cm^2

The design studies of advanced research reactors described here make allowance for possible variations to meet the preferences of prospective customers.



NCT channel shifted laterally by 250 mm from the core center: 1 – graphite stack; 2 – lead shield; 3 – aluminum block; 4 – reactor; 5 – reactor pool; 6 – HEC-4; 7 – aluminum shroud; 8 – stationary biological shielding blocks; 9 – channel 300 mm in diameter; 10 – additional gate valve; 11 – main gate valve; 12 – aluminum screen (6 mm); 13 – concrete (biological shielding)