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ScienceDirect
Progress in Nuclear Energy 50 (2008) 314–319
PROGRESS IN NUCLEAR ENERGY
An International Review Journal
www.elsevier.com/locate/pnucene

Design concept of self-contained low power reactor master for heat supply

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Abstract

This paper demonstrates technical features and conceptual scheme of innovative self-contained low power reactor MASTER for heat supply. Neutron-physical and thermo-hydraulic characteristics of this reactor are analyzed. The possibility of power self-control and minimization of reactivity swing during fuel burnup are considered.

Keywords: Low power; Heat supply; Self-control; Long-lived; Natural circulation

1. Introduction

Nowadays, safe and reliable small power reactors are in growing demand as self-contained power sources. Such reactor facilities may be widely used in distant and hard-to-reach regions located far from the main power sources for electricity production, heat supply and sea water desalination.

Suggested reactor MASTER for heat supply has its advantages and own range of usage. The special feature of the facility is significant decrease of heat production cost as a result of high (up to 80%) fuel component of the capital costs in comparison with conventional power plants. Such effect is achieved due to power self-control and natural circulation of coolant in the primary circuit.

The reactor facility MASTER will be in demand because of its advantages: economically expedient, self-contained, passively safe, reliable for long operation time and simple by design. This reactor can be completely assembled at the plant-producer then transported to the place of exploiting and put into operation at the site of consumer.

To exclude theft of the fissile materials and to localize the radioactive products release in hypothetic emergencies the reactor is proposed to be located underground.

2. Requirements to the low power reactor facility

The present paper continues the scientific research (Kazansky et al., 2003) aimed to substantiation of design of self-contained extra small power ($P_{therm} = 300$ kW) reactor MASTER-IATE. It was proved that this reactor can operate in self-regulated mode during 60 years.

However, during elaboration of MASTER-IATE project it became clear that this facility might be upgraded due to improvement of its technical and economical characteristics.

The main directions of the facility improvements are:

- Increase of thermal power to reduce the cost of produced power;
- Replacement of $UBe_{13} + Mg$ fuel of low density with more dense UO_2 to reduce the core size;
- Decrease of uranium enrichment less than 20% to satisfy the international requirements of non-proliferation of nuclear materials;

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0149-1970/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.pnucene.2007.11.012

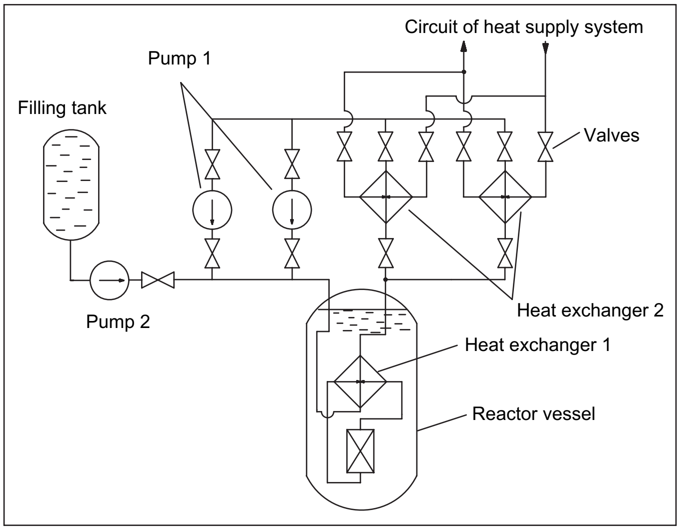

Fig. 1. Schematic hydraulic diagram of the reactor facility MASTER.

- Decrease of expensive Be content in the reactor core and reflector due to use of Al–Be alloy and more compact lattice of fuel pins; and
- Use of Dy burnable absorber to flatten the reactivity behavior during fuel burnup.

The above general thoughts may be considered as technical requirements to the reactor facility MASTER described in the present paper.

- Thermal power of the reactor facility is 1 MW;
- Core lifetime without refueling and permanent maintaining is up to 60 years;
- Self-control operation mode during whole lifetime;
- Inherent safety due to the negative feedbacks and absence of high pressure in the circuits;
- Elimination of hard emergencies and using the reactor as an explosive object;
- Three water circuits of cooling: with natural circulation (primary circuit) and with forced circulation (secondary and third circuits);
- Water temperature for consumers is 80–85 °C;
- Fuel UO_2 with enrichment of ^{235}U 17%;
- Any significant contamination of environment under any emergency is impossible;
- Underground location of the reactor facility; and
- Low cost of produced heat power.

3. Schematic diagram of the reactor facility master

Schematic hydraulic diagram of the reactor facility MASTER is presented in Fig. 1.

Facility consists of three circuits and the following main units: reactor vessel, heat exchangers 1 and 2, pumps 1 and 2, and filling tank.

Specific feature of this facility is location in the same strong vessel both the reactor core and heat exchanger of primary and secondary circuits.

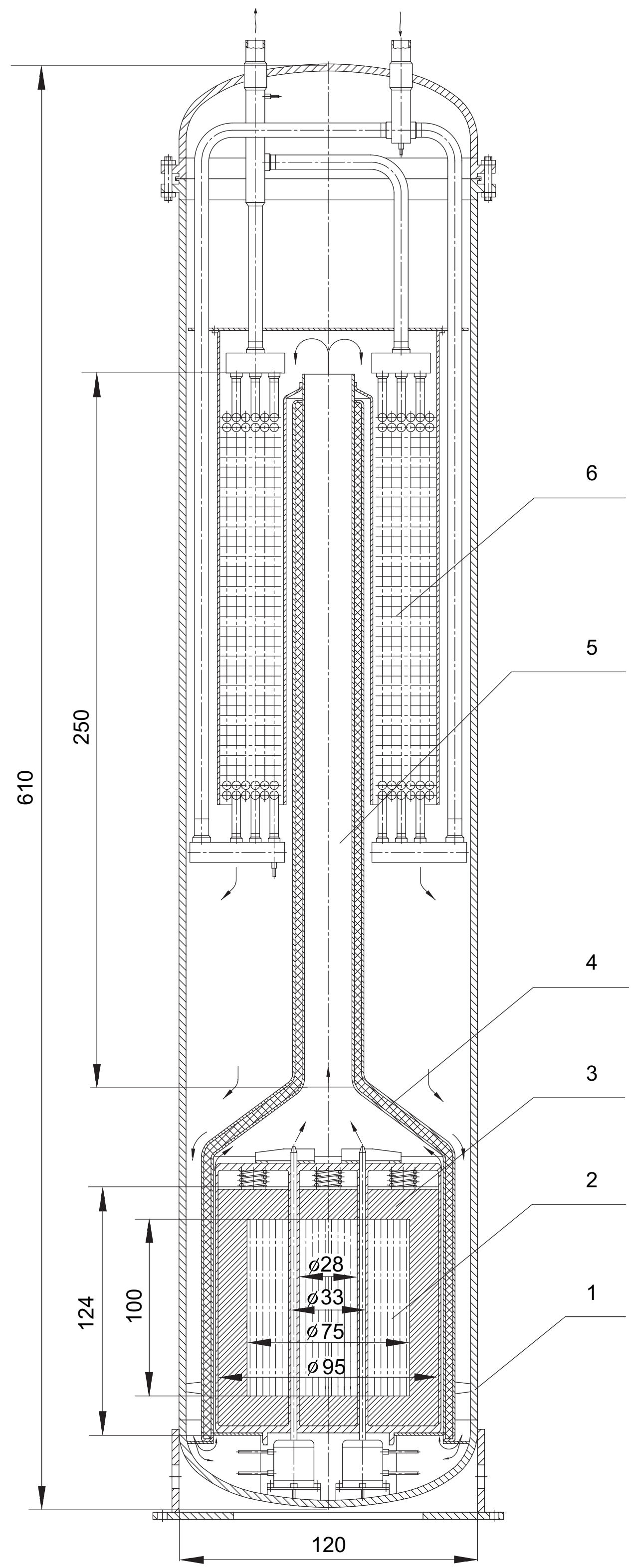

Fig. 2. Design diagram of the reactor facility MASTER (Dimensions are given in cm). 1, reactor vessel; 2, core; 3, reflector; 4, heat insulating shell; 5, draft tube; 6, heat exchanger.

Table 1
Main technical parameters of the reactor MASTER

Parameter	Value
Thermal power	1 MW
Reactor lifetime	60 years
Core active height	100 cm
Core equivalent diameter	75 cm
Core moderator and reflector material	Alloy Al–Be
Fuel type	UO_2
Fuel mass	1515 kg
Fuel enrichment	17%
Fuel pins lattice pitch	1.8 cm
Fuel pellet OD	1.17 cm
Thickness of fuel rod cladding	0.09 cm
Fuel pin cladding material	Alloy Zr–Nb
Fuel pin OD	1.35 cm
Thickness of top, bottom and side reflectors	10 cm
Core cladding and reactor vessel material	SS 12X18H10T
Core cladding OD	95 cm
Core cladding height	124 cm
Pressure of the primary coolant circuit at the reactor core half height	0.15 MPa
Height of the draft part	250 cm
Height of the primary circuit heat exchanger	160 cm
Temperature of the consumer water circuit at the heat exchanger inlet	50 °C
Temperature of the consumer water circuit at the heat exchanger outlet	80 °C

The vessel with the reactor core and heat exchanger is filled with water, which serves as a coolant of the primary circuit. Circulation of coolant in the primary circuit is natural. Heat is removed from the primary circuit heat exchanger by the secondary circuit water.

The secondary circuit is formed by two circulation pumps 1, two heat exchangers 2, pump 2 and filling tank. Water serves as coolant of the secondary circuit. Circulation in the secondary circuit is forced. First pump 1 and heat exchanger 2 operate in the main mode. Second pump 1 and heat exchanger 2 operate in standby mode. Filling tank with water is used for the forced priming of the secondary circuit.

Heat power of the secondary circuit is transferred through heat exchanger 2 into the circuit of the heating system (consumer circuit).

4. Design and main technical parameters of the reactor master

Design diagram of the reactor facility MASTER is presented in Fig. 2. The main parameters are summarized in Table 1.

The stainless steel vessel of the facility (outer diameter is 120 cm and height is 610 cm) contains the reactor core with reflector, heat insulating shell, draft tube and heat exchanger. The pipes supplying and removing the coolant of the secondary circuit are passed through the top cover of the reactor vessel.

The core is the main component of the reactor facility. It consists of two parts: central and periphery. The central part is manufactured as a cylinder with diameter of 28 cm and height of 124 cm. The periphery part is manufactured as a cylinder with inner diameter of 33 cm and outer diameter of 75 cm. Height of the periphery part is equal to the central part height.

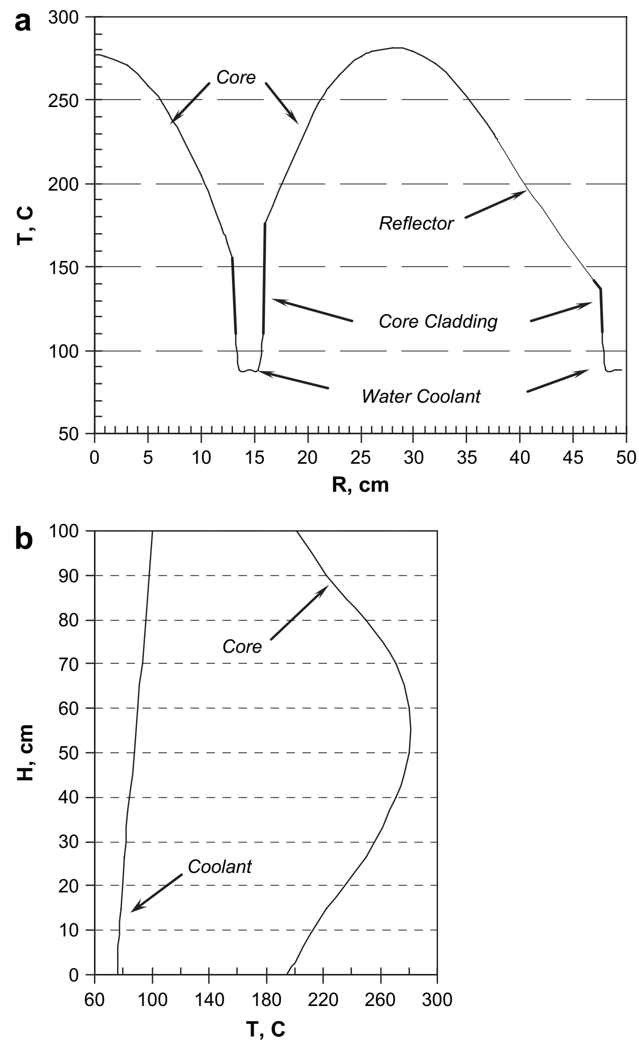

Fig. 3. Radial (a) and axial (b) core temperature distribution.

Components of the reactor core are chosen to ensure contact heat conductivity as a heat transferred from the fuel rods to the primary coolant circuit due to heat conductivity of core materials. So the following components are used for the core construction: fuel pins ($H = 100$ cm, $OD = 1.35$ cm) with UO_2 fuel are placed inside of Al–Be matrix with lattice pitch 1.8 cm. To reduce thermal resistance the gaps between fuel pellets and claddings and between claddings and Al–Be matrix are filled with helium.

The annular channels of the primary coolant circuit are placed between central and periphery parts of the core and between periphery part of the core and the heat insulating shell. Location of inside annular channel and its thickness (2.5 cm) is chosen so that heat conducting matrixes (fuel-moderator) have approximately equal temperature distribution both the central and periphery parts of the reactor core.

Internal part of the reactor vessel is filled with water which is the primary coolant circuit. The gas space at the top part of

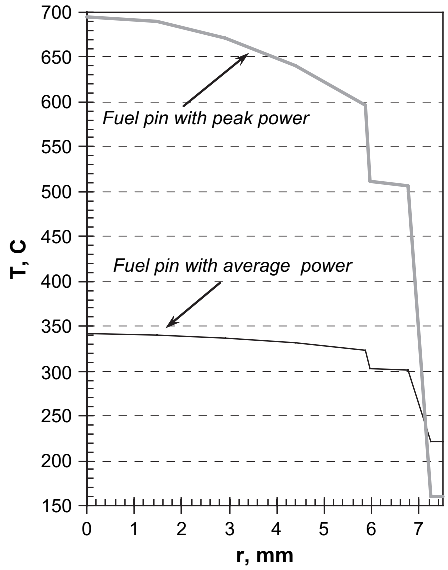

Fig. 4. Radial temperature distributions of the fuel pin for the average and for peak power.

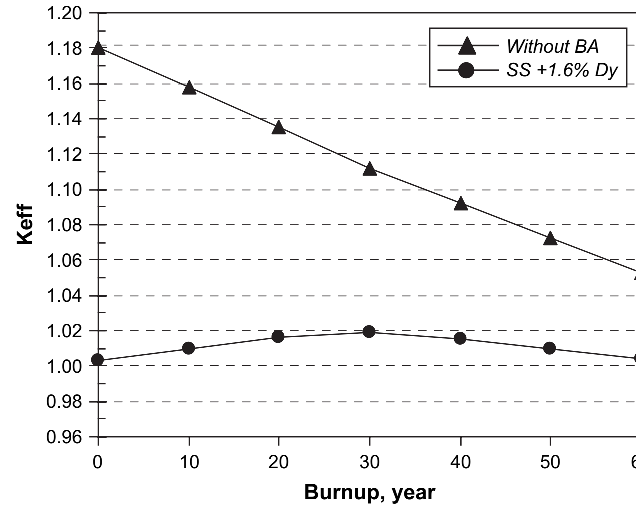

Fig. 5. k_{eff} as a function of burnup.

the vessel is reserved to compensate volume expansion of the primary circuit water.

5. Thermo-hydraulic and neutron-physical characteristics of the reactor master

Cooling system of reactor MASTER is designed with the aim to reduce maximum temperature of the core structure materials. For this purpose the water coolant flows through two annular channels located inside and outside of the reactor core.

Optimization of thermo-hydraulic characteristics is performed to make a choice of location and width of inside annular channel and width of outside cooling channel as it is shown in Fig. 2. It results in minimization of core centre temperature and equalizes the heating of water in both channels.

Fig. 3a demonstrates radial core temperature distribution with inside annular channel of width equal to 2.5 cm and outside annular channel of width equal to 1 cm. With such position of the cooling channels the central and periphery parts of the core produce heat power equal to 255 and 745 kW, correspondingly. In this case the maximum temperature of moderator matrix in the central and periphery parts of the core is practically the same and equal to 280 °C.

Calculated mass flow rates of coolant along the annular channels are equal to 5.9 kg/s for inside channel and to 4.1 kg/s for outside channel of the core. Coolant heating in the channels is equal to 25 °C and 23 °C, correspondingly.

Axial core temperature distributions of the moderator matrix and coolant at the inner annular channel are shown in Fig. 3b.

Fig. 4 demonstrates calculated radial temperature distribution of the fuel pin located in the central part of the core with average and peak heat power. Helium gap thickness of 0.5 mm between fuel pin and moderator matrix is assumed in calculations.

Table 2 summarizes calculated thermo-hydraulic parameters of the reactor facility.

Calculations demonstrate that the primary circuit coolant temperature does not exceed the water boiling temperature under nominal conditions of the reactor facility. Maximum temperature of fuel with maximum heat power is significantly less than the limit permissible value.

Neutron-physical characteristics of the reactor MASTER are analyzed on the basis of design diagram (see Fig. 2) in 3-D geometry. Monte-Carlo codes KENO-VI (ENDF/B-V constants library, 238 groups) and MCNP-4C (ENDF/B-VI constants library) are applied for calculations. The code ORIGEN is used for fuel burnup estimation.

Table 2
Thermo-hydraulic parameters of the reactor MASTER

Parameter	Value
Average temperature of core water inlet (primary circuit)	76 °C
Average temperature of core water outlet (primary circuit)	100 °C
Mass flow rate of water (primary circuit)	10 kg/s
Heat exchanger surface (secondary circuit)	47 m^2
Average inlet temperature of heat exchanger water (secondary circuit)	59 °C
Average outlet temperature of heat exchanger water (secondary circuit)	90 °C
Mass flow rate of water (secondary circuit)	7.7 kg/s
Heat exchanger surface (consumer circuit)	53 m^2
Average inlet temperature of heat exchanger water (consumer circuit)	50 °C
Average outlet temperature of heat exchanger water (consumer circuit)	80 °C

Table 3
Neutronics characteristics of the reactor MASTER

Parameter	Value
k_{eff}	1.0016 ± 0.0003
Doppler coefficient, pcm/K	−1.2
Coolant temperature coefficient, pcm/K	−0.2
Coolant density coefficient, pcm/%	−11.2

Table 4
Neutron fluence and potential Be swelling in 60 years of reactor operation

Zone	φ (En > 0.1 MeV), n/cm^2/s	Fluence, 1/cm^2	Be swelling, %
Central part of the core	8.88×10^{12}	1.68×10^{22}	0.31
Periphery part of the core	5.18×10^{12}	9.80×10^{21}	0.18
Reflector	5.37×10^{11}	1.02×10^{21}	0.02

Fig. 5 shows k_{eff} as a function of fuel burnup. Upper curve corresponds to the criticality behavior without burnable absorbers (BA) in the core.

Initial critical state of the reactor with $k_{eff} = 1$ is achieved due to homogeneous admixture of different burnable absorbers to the SS cladding.

Minimum deviation of reactivity from zero is observed with utilization of dysprosium (Dy) as a burnable absorber (lower curve in Fig. 5). Admixture of 1.6% (weight percent) Dy to the SS cladding suppresses the initial reactivity excess and reduces the reactivity swing from 10.5% (core without BA) to 1.7% $\Delta k/kk'$.

The average value of fuel burnup is 16.4 GWd/tHM during 60 years of the reactor operation.

Initial criticality and reactivity coefficients at the beginning of burnup cycle for hot full power conditions of reactor MASTER are summarized in Table 3. Calculation results demonstrate the negative coefficients of the main variable parameters. It gives a chance to organize self-control mode of the reactor MASTER operation.

Since the core conductivity matrix and reflector contain the Al–Be alloy, it is necessary to estimate possible beryllium swelling during core lifetime. As it is experimentally demonstrated (Kupriyanov et al., 1999) the swelling of small-grained Be under exposure to neutron fluence of 5.5×10^{21} 1/cm^2 and temperature of 700 °C does not exceed 0.1%.

Table 4 summarizes values of neutron fluence during 60 years of the reactor operation and calculated swelling of beryllium in the core and reflector. The most swelling of beryllium is observed in the central part of the core (0.31%). This estimation shows that damage of Al–Be matrix is not expected at the time of reactor operation.

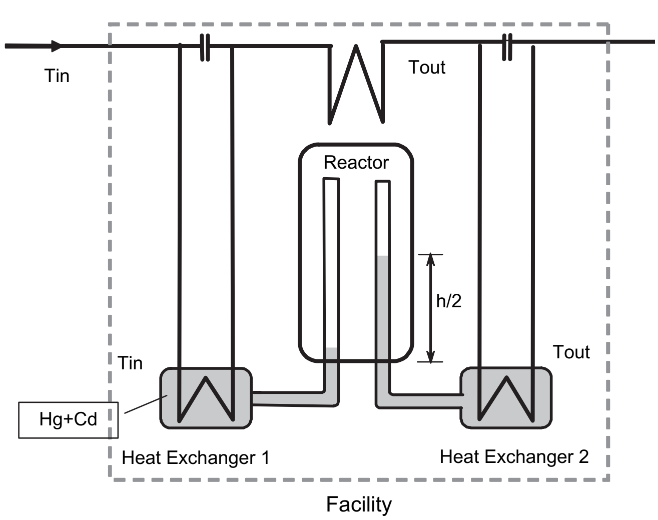

Fig. 6. Diagram of power self-control provided by inlet and outlet temperature of the consumer circuit.

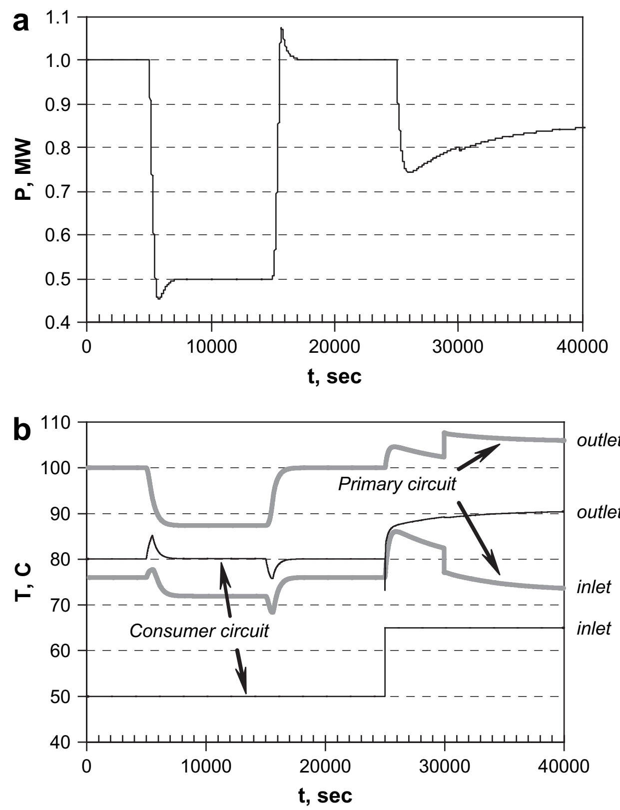

Fig. 7. Reactor power time behavior (a) and coolant temperature variations in the primary and consumer circuits (b) at the different perturbations.

6. Passive methods of reactor facility power control

During operation of MASTER reactor facility the seasonal change and diurnal variations of power may occur. It may be caused by consumer's number change and also by coolant flow rate changes through the consumer circuit. Besides that emergencies connected to loss of coolant or loss of coolant flow rate in the consumer circuit may happen. Compensation of such variations leads to increase or decrease of temperature in the reactor circuits. To realize self-control of reactor power it is suggested to use passive power control devices. These devices, in fact, are intensifiers of temperature reactivity coefficients (ITRC).

Technical realization of ITRC is shown in Fig. 6.

The reactor core contains two devices of power control according to work medium temperature at inlet T_{in} and outlet T_{out} of the consumer circuit. Work body of this device is cadmium amalgam (Hg + Cd) with coefficient of thermal expansion 1.8×10^{-4} 1/K in the work range of temperatures and with high absorption cross-section of neutrons. Control is realized by variation of liquid column in the core based on volume expansion of cadmium amalgam during increasing its temperature. This control channel is placed into the core and connected to the heat exchanger.

At the nominal reactor power free surface of the cadmium amalgam of the left channel (see Fig. 6) is at the lower core edge, and the liquid of the right channel is at defined height ($h/2$) of the core section level.

When coolant temperature of consumer circuit is increased, the negative reactivity is introduced into the core with rising of Hg + Cd level at the control channel. It leads to the reactor power decrease. And the opposite, when the temperature is dropped, the positive reactivity is introduced into the core that leads to the reactor power increase.

Fig. 7a demonstrates the reactor power as a function of time during introduction of perturbations. At the moment of 5000 s flow rate in the second circuit is twice reduced and then at the moment of 15,000 s flow rate becomes nominal again. The introduced ITRC devices operate and power at this time interval is automatically halved.

Then at the moment of 25,000 s water temperature at the outlet of consumer circuit is increased from 50 °C to 65 °C. Finally it leads to the reactor temperature increase and, consequently, to the reactor power reduction. Fig. 7b shows variation of the coolant temperatures in the primary and consumer circuits as a response to perturbations in self-control mode of reactor operation.

7. Conclusions

The current research resulted in technical foundation of self-contained low power (1 MW) reactor MASTER for heat supply. Conceptual design of the reactor facility is suggested, neutron-physical and thermo-hydraulic characteristics are optimized to save negative reactivity feedbacks and reduce maximum temperature of structure materials. Passive method of power self-control by using intensifiers of temperature reactivity coefficients is suggested.

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