NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 8(3): 179–185
DOI 10.3897/nucet.8.93907

Research Article

The concept of a thermionic reactor-converter with evaporative heat transfer*

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Academic editor: Georgy Tikhomirov ♦ **Received** 21 October 2021 ♦ **Accepted** 11 July 2022 ♦ **Published** 27 September 2022

Citation: Alekseev PA, Lazarenko GE, Linnik VA, Pyshko AP (2022) The concept of a thermionic reactor-converter with evaporative heat transfer. Nuclear Energy and Technology 8(3): 179–185. https://doi.org/10.3897/nucet.8.93907

Abstract

As a result of the analytical studies of the designs of thermionic reactor-converters, four groups of technical solutions have been identified that differ in the method of heat transfer from the fuel to the emitters of the thermionic converter: one option with direct in-core transfer (combining the fuel cladding with the emitter) and three options with thermionic converters taken away from the reactor core, in which case the heat is removed either by heat pipes (common or individual for each fuel element) or is arranged based on the principle of a steam chamber.

The article describes the advantages and disadvantages for each of these methods. It is shown that at present the most developed design remains the version with in-core power conversion and, in the future it will be based on the steam chamber since the ingress of gaseous fission products into the inter-electrode gap as well as the influence of fuel swelling on the inter-electrode gap size are excluded and it ensures constant temperature and heat flux density on the surface of all emitters of the thermionic converters, which makes it possible to select the optimal operating parameters for them.

A model of a thermionic reactor-converter with a steam chamber containing a reactor core and a zone of thermionic converters has been developed in which the fuel element of the reactor core and the power generating channels of the thermionic converter are separated in space, covered with a capillary porous structure and interconnected by a honeycomb capillary porous spacer plate to provide for circulation of the liquid metal coolant and to let its steam pass through.

Neutronic calculations have demonstrated the possibility of a duration for the reactor campaign in excess of ten years following the nuclear safety regulations when a gadolinium oxide coating is applied to the surface of the fuel rods and the reactor vessel in the area of the reactor core.

The assessment of thermal and electrical parameters shows that, due to the constant temperature and heat flux density on the surface of all emitters and optimization of the power conversion process for all the thermionic converters, one can expect to reach the maximum efficiency of 20%.

Keywords

Thermionic reactor-converter, steam chamber, duration of the campaign, design schemes

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2022, n. 1, pp. 118–129.

Introduction

Main period in the development of the direct energy conversion falls within the interval of the years 1960–1980 when ambitious projects of nuclear power installations (NPI) were elaborated to provide for power supplies of spaceships placed in close orbits with the purpose to carry out radar reconnaissance. In total two spaceships equipped with the NPIs based on the TOPAZ thermionic reactor converters (TRC) as well as 32 NPIs with thermoelectric generators BUK were in operation.

Subsequent operations in this direction were not carried out to the stage of space flight tests due to the lacking financial support, however, search for optimal designs of the TRCs and their systems are continued till the present time. Since the moment of the TOPAZ TRC development several fundamentally different design and layout solutions were proposed with the purpose to increase the TRC lifetime based on the spacing plate between the fuel rods and emitters of the thermionic converters (TC). Such technical solutions exclude the effects imposed by fuel rod deformations caused by fuel swelling exercised on the size of the TC inter-electrode gap which leads to short circuits and destruction of the TRC.

The aim of the present work is to compare technical parameters of the TRCs at various construction options which differ in the method employed to transfer the heat from the fuel to the emitters of the thermionic converter (by means of conductivity, radiation or evaporation-condensation processes). Cooling of the TFE collectors is based in all options on the convection of liquid metal (LMC) coolant.

Design options of reactor-converters

Design and layout schemes for the TRC design options are presented in Fig.1. All of them are in compliance with the four methods of heat transfer from fuel rods to the emitters of the thermionic fuel element (TFE):

- Conventional conduction method (fuel rod cladding is functioning as the emitter for the thermionic converter) (Gryaznov and Pupko 1991, Kukharkin et al. 1999);
- Heat-pipe method with separated installation of heat pipes (HP) and fuel rods in the high heat conductivity matrix (evaporation) (Zabudko et al. 2003, Zrodnikov et al. 2007);
- Heat-pipe method with installation of heat pipes (HP) in the fuel rod cavity or directly on its surface (evaporation) (Ovcharenko et al. 2005a, b);
- With installation of fuel rods and the TFE in the steam chamber (evaporation) (Fiebelmann 1966, Alekseev et al. 2020);

Let us consider specific features of the mentioned design and layout schemes.

The conventional scheme (See Fig. 1) with conductive heat transfer from fuel to the emitting surface through the fuel rod cladding (fuel rod cladding is playing the role of the TC emitter). The concept of the in-core TC installation is realized in the given TRC type. The surface of the fuel rods comprises the constituent part of the TFE.

Rather compact design of the TRC with low specific weight is achieved as a result of the combination of functions executed by the constructive elements. The TFEs are placed between the tube plates in the hermetic vessel filled with the LMC supplied via the pressure tube and removed through the discharge tube (the type of the shell-and-tube heat-exchanger). Commutation chambers are placed behind the tube plates where the inlet current conductors of the TFE and offsets of the Cesium system are located. Externally the core is surrounded by the reflector. Two options for the TRC of this type were developed: namely with single-cell TFEs (the "ENISEY" TRC) (Kukharkin et al. 1999) and multi-cell TFEs (the "TOPAZ" TRC) (Gryaznov and Pupko 1991). The single-cell TFE allows one to organize the removal of gaseous fission products (GFP) bypassing the inter-electrode gap (EG), while the multi-cell type provides for the higher output voltage due to serial connections of the TCs.

The heat pipe design with separated arrangement of HPs and fuel rods in the high heat-conductivity matrix (Zabudko et al. 2003, Zrodnikov et al. 2007) was initially proposed for the TRCs based on the SAFE-300 Stirling engine with subsequent substitution by a thermoelectric converter and only afterwards the option with thermionic converter (See Fig. 1b) was considered in view of the low efficiency of the thermoelectric converter. Such reactor design ensures stable heat transfer from each fuel rod in case of the damage of some of the HPs due to redistribution of heat flux from fuel rod claddings along the high heat conductivity matrix to the operating HPs. It was assumed to ensure the thermal contact between the matrix, fuel rods and HPs by means of brazing which is acceptable for the initial option in case of the Stirling engine, however, at present the replacement with the thermionic converter which is accompanied by the essential increase of the working temperature is not sufficiently elaborated and stability in relation to thermal mechanical loads needs to be substantiated.

The heat pipe design of the TRC with installation of the HPs in the cavity of fuel rods or directly on their surface (evaporation) was proposed for the "Elbrus" project (Ovcharenko et al. 2005a, b) (See Fig. 1c). The TRC reactor core is assembled of annular fuel elements placed on the external surface of lithium HPs which remove heat to the TFE assembly located outside the reactor core. The TCs are mounted on the HP surface; emitters of the TCs are separated from the HP surface by means of the layer of heat resistant electrical insulation. Such design ensures thermal and mechanical separation of fuel rods and TC emitters. It is assumed that along with swelling of the fuel inside the rods it is forced only to the outside the rods without mechanical loading imposed on the HP walls.

Within the frames of the concept under development the TRC design with transfer of heat from the fuel rods to the TFE based on the principle of the steam chamber

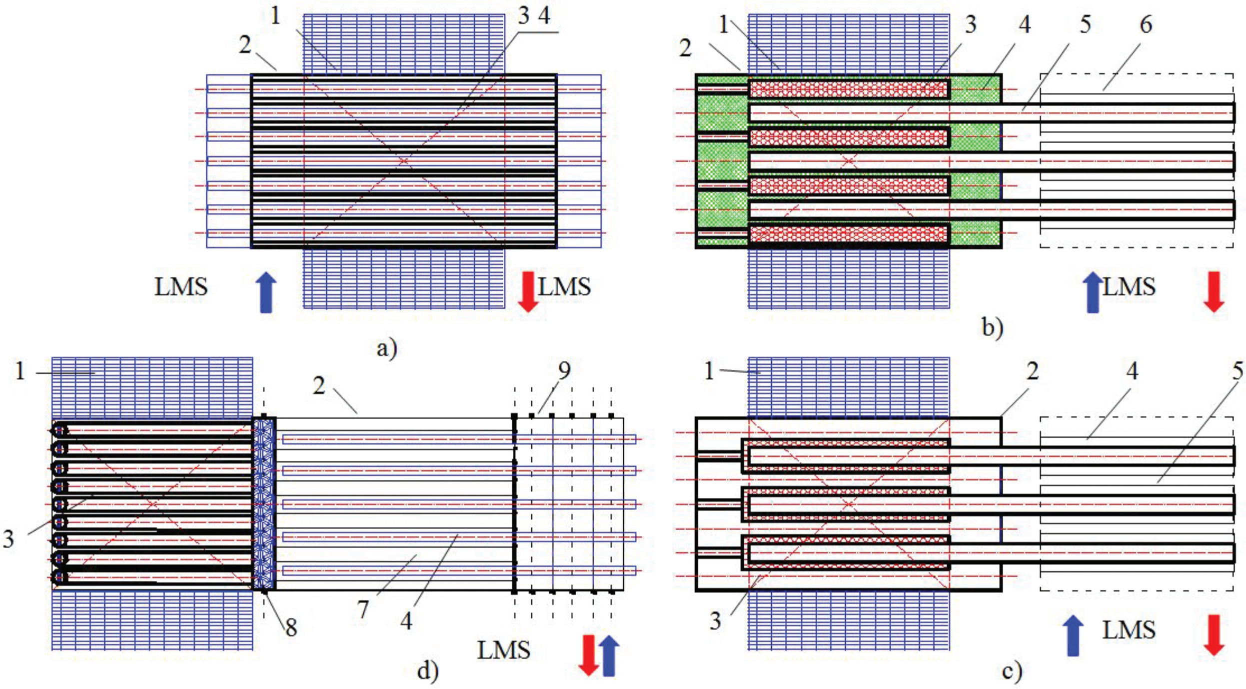

Figure 1. Design and layout schemes for the options of the TRC design: **a.** The “TOPAZ” type; **b.** The “SAFE” type; **c.** The “ELBRUS” type; **d.** Design based on the steam chamber principle. Legends: 1 – reflector, 2 – reactor shell, 3 – fuel rods, 4 – TFE, 5 – heat pipe, 6 – high heat conductivity matrix, 7 – steam chamber, 8 honeycomb partition made of capillary porous material, 9 – block of collectors and commutation chambers.

(Fiebelmann 1966, Alekseev et al. 2020) ensures the thermal and mechanical separation of fuel rods cladding and the TFE (See Fig. 1d) to the maximum degree. It includes two assemblies installed in the hermetic vessel – the reactor core assembled of such fuel rods with capillary structure on the surface constituting the evaporation zone, and the condensation zone formed of the TFE assembly which external surface is also covered with capillary structure. The capillary structures of fuel rods and the TFEs are interconnected by the capillary structure used to circulate the LMC condensate. The fuel rods are fixed at one end of the vessel, and the TFEs are fixed at another end which ensures access to them to remove the GFP (from fuel rods) and connection to the Cesium system, connection to the current carrying buses and inlet (outlet) of the LMC employed for cooling of the collector (in the TFEs).

Technological and technical features of the TRC design options

Each of the mentioned TRC options manifests both advantages and disadvantages. Let us point out the main of them for each of the options.

Features of the conventional design (Option a) include:

Advantages:

- technological maturity of the design including the flight development tests;
- minimum size of the TRC;
- maximum localization of high temperature zones (limited by the size of the fuel rod cladding);
- dense reactor core (which is important while considering the emergencies related to the TRC flooding);
- Mounting the electrical insulation in cold zones (outside the reactor core or on the surface of collector electrodes).

Disadvantages:

- Due to the uneven heat emission over the reactor volume it is impossible to ensure optimal conversion parameters for all TCs and, as a consequence, the NPI efficiency is as a rule several times lower than that electrode efficiency;
- Complicated removal of the GFP from fuel rods and pollution of the inter-electrode gap (EG) which is reducing the lifetime and effectiveness of the TCs;
- Limited lifetime due to swelling of the fuel and deformation of the cladding of fuel rods which are simultaneously functioning as the TC emitters up to the closure of the EG;
- The TFE includes fuel rods and TCs i.e. it contains fissile materials which is essentially complicating its manufacturing;
- Cooling of the reactor core is conducted using the LMC which toughens the requirements imposed both on the coolant purity and the choice of construction materials.

The remaining three design options were developed with the purpose to eliminate the mentioned drawbacks meanwhile new disadvantages inevitably appear, which are specific for the given construction.

The heat pipe design with separated installation of HPs and fuel rods in the high heat conductivity matrix demonstrates in principle the same advantages as those mentioned for the option “a”. The additional advantage is the continuation of the operation when cooling was interrupted in one of the TFEs. Disadvantage – casings of all the TFEs are grounded to the matrix which essentially complicates the requirements imposed on the stability of high temperature insulation of the TFE casing in relation to the electrical breakdown.

The heat pipe TRC design with installation of the HPs in the cavities of fuel rods allows one to eliminate uneven heat emission along the length and completely flattens the heat flux density on the converter emitters by means of the variable TC length depending on the distance from the central axis. The design disadvantage consists of the “loose” reactor core and presence of electrical insulation between the HP casing and emitters, high temperature of the HP coolant and, as a consequence, the enhanced requirements imposed on the material of fuel rod cladding and the HP casing.

The TRC design with heat transfer from fuel rods to the TFE based on the principle of the steam chamber elaborated in the frames of the proposed concept ensures maximum advantages in relation to the remaining design options:

- Possibility of separate employment of fuel rod elements and the TFE;
- Possibility to manufacture the TFE without fissile materials;
- Simplified manufacturing of the fuel rods;
- Transformation of heat flux density along with the heat transfer from fuel rods to the TFE (constant heat flux density on the surface of all TFEs is ensured independent on the heat flux density distribution along the fuel rod surface over the volume of the reactor core; the value of heat flux density is determined by the integral parameters – heat capacity of the reactor and total heated surface of the TFE);
- Possibility to optimize the TFE regarding the heat flux density at the given temperature;
- Simple solution of the problem to withdraw the GFP (it is assumed to use single-element fuel rods with the withdrawal of gaseous fission products through the elements of fuel rod holders);
- Possibility to use heat resistant alloys mastered by the industry in the fuel rod and TFE construction;
- Possibility of manufacturing based on the technologies mastered by the industry;
- Reduction of the fraction of construction materials in the reactor core;
- Increase of operation lifetime;
- Improvement of reliability due to the use of parallel schemes to include the fuel rods in the process of generation of the working fluid steam and its condensation in the TFE.

Main disadvantages are the same as in the heat pipe options plus the poor localization of the high temperature zone – the high temperature zone is embracing the whole space inside the reactor and the whole reactor vessel.

Option parameters are summarized in Table 1 for the sake of clearness.

Design options of the reactor-converter

Development of the TRC design was completed and calculation estimates were carried out in the frames of the concept under development. The TRC design is shown in Fig. 2. The TRC contains two functional blocks – namely the reactor and the thermionic converter which are separated by the capillary porous spacer plate and mounted within the common hermetic vessel.

The reactor core is assembled of 186 fuel rods mounted in a regular hexagonal grid. The control rod is located in the center of the reactor core. Fuel rods include the fuel made of highly enriched uranium dioxide, beryllium end-plate reflector and the molybdenum cladding; thin layer of burnable absorber (gadolinium oxide Gd_2O_3) is applied on the internal surface of the cladding. Molybdenum spacing

Table 1. Comparison of TRC parameters

RC type	Conventional	Heat pipe (fuel rods and HP inside the matrix)	Heat pipe (fuel rods inside the HP)	Steam chamber
Size	Minimum	Maximum	Maximum	Average
Weight	Average	Maximum	Average	Minimum
Volume of construction materials in the reactor core	Maximum	Average	Average	Minimum
Fuel density of the reactor core	Average	Average	Average	Maximum
Load and enrichment with U-235	Maximum	Average	Average	Minimum
Fuel lifetime	Reduced	Reduced	Average	Maximum
Localization of high temperature zone	Maximum	Average	Average	Minimum
Temperature and heat flux density flattening in the TC	Absent	Along the height	Along the height	Along the height and radius
GFP removal	Complicated	Available	Available	Available
Manufacturing technology	Mastered	Requires further development	Requires further development	Requires further development

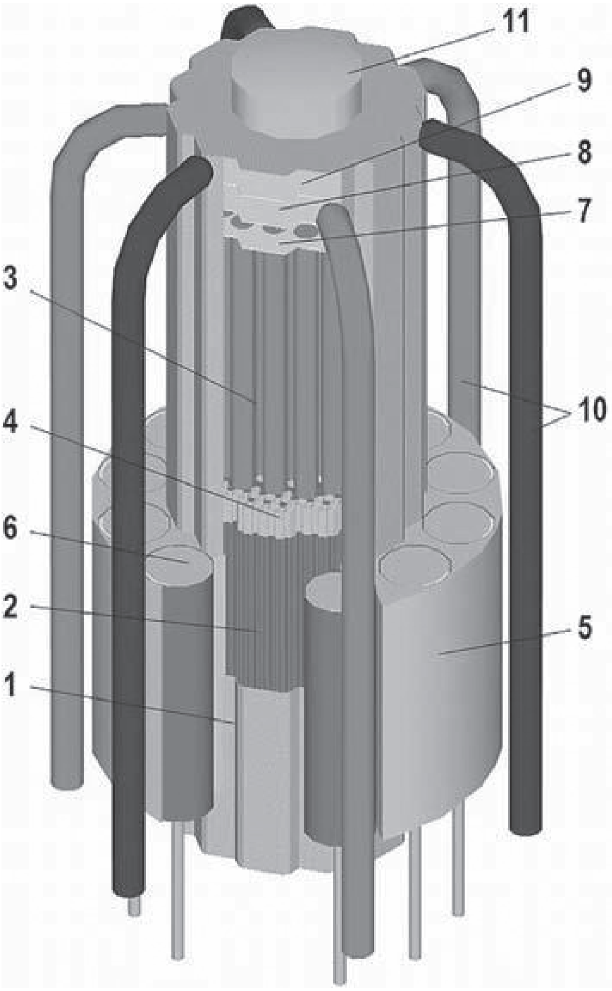

Figure 2. General view of the TRC: 1 – hermetic vessel, 2 – reactor core fuel rods, 3 – thermionic generators, 4 – capillary porous spacing plate, 5 – reflector, 6 – rotating drums, 7 – commutation chamber, 8 – discharge collector, 9 – pressure manifold, 10 – cooling system pipeline, 11 – cesium system.

plate is placed between the fuel and the end-plate reflector. The capillary porous structure filled with the LMC (lithium) is formed on the external surface of the fuel rod cladding. Under the working reactor conditions free space of the reactor core is filled with lithium steam.

The reactor core is contained within the molybdenum vessel; thin coating of the burnable absorber is applied on the external surface of the vessel. The vessel is separated from the reflector by a gap with a thickness of 2 mm where the thermal-vacuum heat insulation is placed.

The beryllium reflector with thickness 14 cm includes 12 rotating elements with sickle shaped inserts made of absorbing material (boron carbide B_4C) to control the reactor power.

The block of thermionic converters is assembled of 36 cylindrical current generating channels located in a regular hexagonal grid. The capillary porous structure filled with the LMC is applied on the external surface of the current generating channels.

Capillary porous spacing is made of a metal-fiber material (clinkered "felt" made of molybdenum fibers) in a form of a honeycomb structure with holders to provide for the tight fit for nozzles of the fuel rods and the current generating channels. A view of the capillary-porous spacing plate from the side of the reactor core is shown in Fig. 3 and its section across the fuel rod nozzles is presented in Fig. 4.

The function of the capillary-porous spacing plate is to ensure transportation of the LMC in the condensed state from the surface of the current generating channels to the fuel rods surface under the influence of capillary forces. Triangular channels are made in its body to let the gaseous LMC pass through the capillary-porous spacing plate. In addition to that the current generating channels are grouped in the center of the vessel with the purpose to improve thermal and hydraulic parameters of the current generating channels which opens the annular space between the package of current generating channels and the reactor vessel to let the coolant steam pass through in the area of the capillary-porous spacing plate.

Main thermal and hydraulic parameters of the TRC are presented in Table 2.

Table 2. Parameters of the TRC

Parameter	Value
Reactor thermal rating, kW	1000
Reactor electrical rating, kW	150
Lithium steam temperature, maximum, K	1800
Number of fuel rods, pcs	186
Number of generating channels, pcs	36
Fuel rod rating, kW	8.06
Generating channel rating thermal/electrical, kW	28/4.2
Number of steam channels in the reactor core	420
Number of steam channels in the TFE block	168
Fuel rating of first fuel rod channels, kW/cm^2	2.10
Fuel rating of first TFE channels, kW/cm^2	5.25

Assessment of thermionic converter operation efficiency

As it was shown in (Ushakov et al. 1974, Alekseev et al. 2017), due to the irregular heat generation along the height and radius of the core inherent to nuclear reactors (irregularity ratios may reach up to the value of 1.3) the thermionic converters are working in the conventional reactor-converters under the operation modes determined by their location in the reactor core which is not optimal both regarding their efficiency and the generated electrical power. Moreover, the total reactor capacity is limited due to the limitations on the maximum fuel temperature, and peripheral thermionic converters are operating under the strongly underloaded conditions which are also impacting their efficiency. Elimination of these drawbacks in the reactor converter designed in compliance with the concept under consideration ensures optimal organization of the energy conversion process for all thermionic converters (isothermality of electrodes, stability of heat flux density on their surface) and allows one to calculate the limiting value of the efficiency which is reaching up to 20% (Zherebtsov and Kasikov 2011).

The maximum values of the efficiency for energy conversion are presented in Fig. 5.

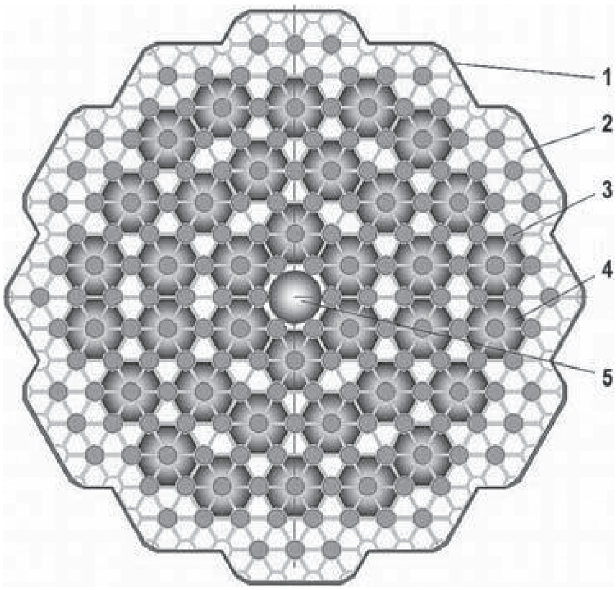

Figure 3. View on the capillary-porous spacing plate from the side of the reactor core: 1 – reactor vessel, 2 – capillary-porous spacing plate, 3 – fuel elements, 4 – module of the thermionic generator, 5 – safety rod.

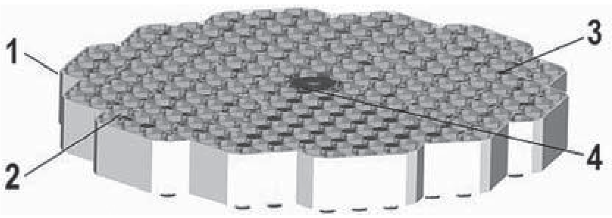

Figure 4. Section of the capillary-porous spacing plate across the fuel rod nozzles: 1 – reactor vessel, 2 – capillary-porous spacing plate, 3 – fuel rods, 4 – safety rod.

Nuclear parameters of the reactor

Calculation of nuclear parameters for the TRC was carried out using the MCNP program code (MCNP 1997) using the database ENDF/B-VII (Chadwick et al. 2006). The task of the calculation is to determine critical parameters for the reactor in routine and emergency situations and to make choice of the burnable absorber to prevent power excursions of the reactor in emergency situations.

Reactivity margin was determined for the cold reactor at the beginning of the reactor campaign, the reactivity of the shut-down reactor was estimated, effectiveness of the rotating safety and control system was determined, and emergency situations were assessed in case of the reactor flooding and filling of the reactor cavity with wet sand. The calculated results are presented in Table 3. The reactivity temperature coefficient is negative.

Dependence of variations of the reactivity margin on time is presented in Fig. 6. It is evident that initially the increase of the reactivity margin is taking place due to rather intensive depletion of the absorber in relation to the burning of the fuel in the reactor core, and the reactivity margin is reducing subsequently.

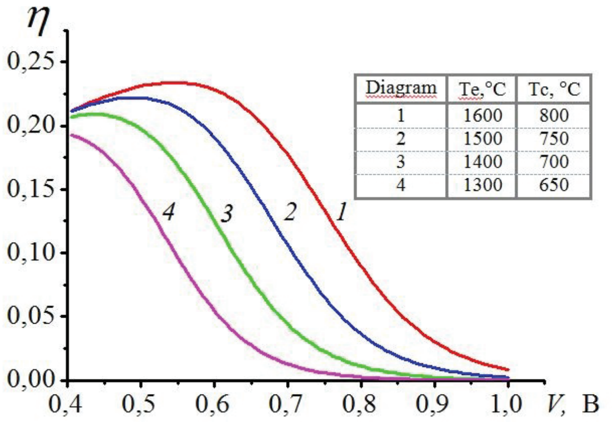

Figure 5. Maximum efficiency values for the TC arch mode depending on the emitter temperature (T_e) and the collector temperature (T_c).

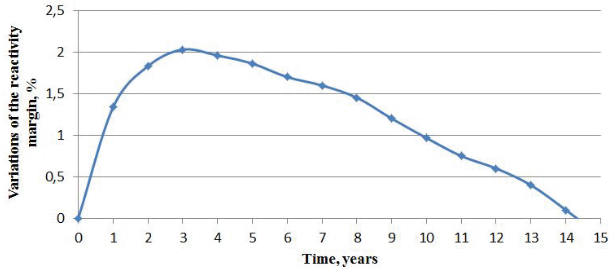

Figure 6. Variations of the reactivity margin during the reactor operation.

Table 3. Nuclear parameters of the reactor

Parameter	Value
Keff of the cold reactor	1.04734±0.00075
Keff of the shut-down reactor	0.88404±0.00076
Effectiveness of the rotating control devices, %	10
Keff of the reactor (water inside and outside the reactor), reflector is present	0.95379±0.00089
Keff of the reactor (water inside the reactor, wet sand outside the reactor), reflector is absent	0.95359±0.00090

Based on the conducted calculations one can derive the conclusion that the reactor satisfies the nuclear safety requirements when the gadolinium oxide coating is applied on the surface of fuel rods and on the reactor vessel. The estimated duration of the reactor campaign is 14 years (See Fig. 6) which allows one to use the considered TRC as a power source for telecommunication stations placed in the geostationary orbit.

Conclusions

The conventional TC construction with the TFEs which is combining the fuel elements and the TCs i.e. with the employment of the in-core energy conversion is the best developed technology. Therefore, in the nearest prospective one must follow the development of the NPI with TRCs specifically in this direction. In the prospective studies it is worthwhile to consider the possibility of the development of the TRCs designed based on the steam chamber principle which manifests a series of attractive features: enhanced efficiency of the conversion of the thermal to electrical power, improved reliability and operation lifetime, high degree of isothermality and absence of thermal and mechanical loads imposed on the construction elements related to that. Expansion of the high temperature zone up to the volume of the TRC vessel and reduction of the fuel nuclear density in the reactor core must also be related to the drawbacks.

References

- Alekseev PA, Krotov AD, Ovcharenko MK, Linnik VA (2017) Minimize of fission power peaking factor in radial direction in water-cooled thermionic conversion reactor core. Izvestiya Vuzov, Yadernaya Energetika 4: 27–34. https://doi.org/10.26583/npe.2017.4.03 [in Russian]
- Alekseev PA, Lazarenko GE, Linnik VA, Pyshko AP (2020) The Reactor-Converter. Patent RF. № 2724919. [in Russian]
- Chadwick MB, Oblozinsky P, Herman M, Greene NM, McKnight RD, Smith DL, Young PG, MacFarlane RE, Hale GM, Haight RC, Francle S, Kahler AC, Kawano T, Little RC, Madland DG, Moller P, Mosteller R, Page P, Talou P, Trellue H, White M, Wilson WB, Arcilla R, Dunford CL, Mughabghab SF, Pritychenko B, Rochman D, Sonzogni AA, Lubitz C, Trumbull TH, Weinman J, Brown D, Cullen DE, Heinrichs D, McNabb D, Derrien H, Dunn M, Larson NM, Leal LC, Carlson AD, Block RC, Briggs B, Cheng E, Huria H, Kozier K, Courcelle A, Pronyaev V, van der Marck SC (2006) ENDF-B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology. Nuclear Data Sheets 107(12): 2931–3060. [UCRL-JRNL-225066] https://doi.org/10.1016/j.nds.2006.11.001
- Fiebelmann Peter (1966) Nuclear reactor, British Patent. No 1149946.
- Gryaznov GM, Pupko VYa (1991) TOPAZ-1 – Soviet Space Nuclear Power Installation TOPAZ-1. Priroda 10: 29–36. [in Russian]
- Kukharkin NYe, Nechaev YuA, Samodelov VN, Khazanovich IM (1999) Energy and Resource characteristics of a Single-Cell TFE that have passed the Nuclear Power Tests as part of Topaz-2 Topaz-2 Reactor Units. Procedures of the V-th International Conference “Nuclear Energy in Space”. Podolsk. [in Russian]
- MCNP – General Monte Carlo N-Particle Transport Code (1997) LA-12625-M. Vers 4B.
- Ovcharenko MK, Almambetov AK, Vinogradov YeG, Zabudko AN, Ionkin VI, Lazarenko GE, Mikheev AS, Pyshko AP, Yarygin VI (2005a) The Concept of the Space Nuclear Power Plant with an External Fuel Arrangement. Procedures of the International Conference “Nuclear Energy in Space – 2005”. Moscow-Podolsk. March 1–3, 1: 240–246. [in Russian]
- Ovcharenko MK, Zabudko AN, Ionkin VI, Lazarenko GE, Mikheev AS, Pyshko AP, Yarygin VI (2005b) The concept of the Long-Life Nuclear Power Plane “Elbrus-400/200” with Effective Low Temperature Thermal Emission Converters Removed from the Core. Procedures of the International Conference “Nuclear Energy in Space – 2005”. Moscow-Podolsk. March 1–3, 1: 144–149. [in Russian]
- Ushakov BA, Nikitin VD, Yemelyanov IYa (1974) Fundamentals of Thermionic Energy Conversion. Moscow. Atomizdat Publishing, 288 pp. [in Russian]
- Zabudko AN, Yarygin VI, Ovcharenko MK (2003) Conceptual Development of a Space Nuclear Power Plant with a SAFE-300 Reactor and thermoelectric Energy Converters. Procedures of International Congress on the Advanced Nuclear Power Plants (ICAPP’03). Cordoba, Spain, 314 pp. [in Russian]
- Zherebtsov VA, Kasikov II (2011) Performance Limits of Thermionic Energy Converter. Atomnaya Energiya 110(1): 12–17. [in Russian] https://doi.org/10.1007/s10512-011-9384-6
- Zrodnikov AV, Yarygin VI, Lazarenko GE, Zabudko AN, Ovcharenko MK, Pyshko AP, Mironov VS, Kuznetsov RV (2007) Low Temperature Thermal Emission in Space Nuclear Power Plants with a Fast Reactor of the SAFE Type. Procedures of the International Congress on the Advanced Nuclear Power Plants (ICAPP’07). San-Diego, California, USA, 89 pp. [in Russian]