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# Micro-particles fuel autonomous melted salt reactor (MARS).

**Keywords:** micro-particle fuel, melted salt coolant, autonomous reactor for small nuclear energetic, natural circulation, gas turbine.

Present work provides main technical characteristics of conceptual project of micro-particle fuel autonomous melted salt reactor for small nuclear energetic. There are given two variants of the reactor with core campaign of 15 and 60 years, respectively. It is shown, that this concept satisfies fully all modern requirements for autonomous nuclear reactors of small power.

Reactors of small power can be used for production of electricity, heat, liquid engine fuel and fresh water. They can be prepared in short time. There are many places both in Russia and other parts of the world where need of electric power, heat and water exists. However, in practice, economically reasonable and reliable supply of organic fuel is impossible and there is no perspective transfer by lines of high-voltage from general or large regional electric systems. Reactors of small power can be both with thermal and fast neutron spectrums. Nuclear power plants with reactor unit less than ~150 MWt (thermal) are NPP of small power. The reactors of small power should be transportable. After delivery of a reactor to a customer, its installation and starting operation of the reactor without overload of fuel is planned not less than 10 -15 years in autonomous or controllable mode. The NPP owners will not have problems with the electric power cost changes in the world market, cares of operation termination and radioactive waste salvaging. After ending of reactor operation life the installation will be replaced by new one and the first will go to processing into "*internal*", "hidden" from the world part of nuclear fuel cycle (NFC) structure by safety barriers. NPP of various power from 1 up to 50 MW (electric), that can cover necessity of settlements and industrial plants of any size by several units assemmbly. As a source of electrical power and heat for шndustrial complexes the reactors to be used should possess self-defence. The period of NPP prefabrication should be minimum (3-4 years).

To the present time there are two approaches to NPP safety control.

**The first** is a traditional engineering approach based on increasing of number and efficiency of different protective and localizing systems and devices, which decrease probability of damages and their consequence hazards. Only this approach implementation gives in complicating and rising price of installation, aggravating its other characteristics and principally does not exclude an opportunity of disaster with heavy consequences. In this case the inner reasons are not eleminated, that can cause a damage.

For the proof of reactor safety at this approach it is necessary to use probability safety assessment (PSA), which conseders the failures of technical devices and operational

staff mistakes as casual events. Low probability of such simple (not statistical) events is proof of neither possibility of heavy damage nor its happen earlier, than through thousand or tens thousand years. Moreover, in case of sabotage or terroristic act such events will not be casual, and PSA loses its cogency in general .

**The second** is an approach based on conseption of reactor with inherent safety. In this case the reasons of serious damages are excluded by feedback inside reactor without using devices or elements of reactivity compensation, but using basic physical laws. This makes inherent safety reactor. However, feedback should be validated reliably. At this approach there is no need of protective and localizing systems, which in some cases could cause accidents themselves. These systems need complex confirmation of safety with huge numerical and experimental effort using unauthentic scenarios.

In RRC “Kurchatov Institute” (KI) the methodology of implementation of inherent safety reactor was developed [1]. During development of next generation reactor it seems necessary to use optimal combination of the approaches based on inherent safety and engineering facilities for increasing of plant safety.

New generation of nuclear small power plants for energetic of distant and hard-to-reach regions should satisfy the following requirements:

- Ultimate safety of reactor operation that secure radwastes blowout outside the NPP in permissible limits using natural and technological level.
- High ecological properties permit the low heat, radiation and chemical contamination of environment (airspace, water area, soil surface) and minimum change variation of its condition.
- High thermal efficiency of heat- electricity conversion ($\eta \geq 30\%$) and minimum auxiliary consumption ($\leq\sim 1\%$).
- High efficiency of nuclear fuel application.
- Long refueling period (more than 10 years).
- High level of coolant natural circulation in the first circuit.
- Independence from water resources.
- Plant assembling of reactor unit.
- Package dimensions.
- Acceptable costs and minimum maintenance period.
- Minimum personnel.
- Minimum decommissioning costs, for radwaste handling and spent fuel storage.

The plants with reactors on the base of micro-particles fuel and melted salt coolant refers to NPPs with inherent safety, which can be provides by self-security. The properties of such self-security reactors are determined mainly by properties of this heat coolant and fuel.

Not only design of small power NPP is proposed, but a whole class of NPPs for different purposes.

Among possible combinations of nuclear fuel, coolant and heat - electricity transducers that can solve tasks of NPPs for distant and semiarid regions the combination of graphite fuel elements on the base of micro-particles fuel, melted salt coolant on the base of Li, Na, Be, Zr fluorides and gas-turbine plant (GTP) using second circuit generator has a special place. Let us consider potential possibilities of such combination.

**Melted salt coolants** on the base of indicated above metal fluorides provide very good compatibility with graphite in a wide range of temperatures (up to $\sim 1200\div 1300^0$C) [2, 3]. Graphite impregnated by these salts becomes non-flammable practically in air [4]. The beginning of such coolant using could be 1950, when the research program for development of high temperature nuclear reactor with circulating fuel for aircraft engine was accepted in Oac Ridge national laboratory (USA) [5]. Within this program in 1954 a small research reactor ARE was built, and a few years later another larger one MSRE [6,7] was constructed. Later a series of conceptual projects and engineering proposals were executed in Japan [8], France [9], Russia [10], China [11]. Design parameters of melted salt NPP concerning coolant and structural materials choice of the 1 и 2 circuit are presented in Table 1.

**Table 1.**
**Coolants, structural materials for research reactors, NPP designs and ASPT with ZSR and VTRS type reactors.**

| Country | Design | Power, MW(т) | First circulation | | Second circulation | | Third circulation |
|---|---|---|---|---|---|---|---|
| | | | Consist of coolant and structural material, %мol. | Tinput/ Toutput, °C | Consist of coolant and structural material, %мol. | Tinput/ Toutput, °C | Consist of coolant and structural material, %мol. |
| USA | ARE | 2,5 | $53NaF-41,2ZrF_4-5,8UF_4$ Inconel (78Ni-15Cr-7Fe) | 655/860 | Helium | | |
| USA | MSRE | 8,0 | $66LiF-29BeF_2-5ZrF_4-0,2UF_4$ Hastalloy-N(66Ni-17Mo-7Cr) | 632/654 | $66LiF-34BeF_2$ Hastalloy -N | 546/579 | |
| USA | MSBR | 2250 | $71,7LiF-16BeF_2-12ThF_4-0,3UF_4$ Hastalloy -NM(70Ni-12Mo-7Cr-2Ti) | 566/705 | $8NaF-92NaBF_4$ Hastalloy -NM | 455/621 | |
| Japan | FUJI-II | 300 | $71,7LiF-16BeF_2-12ThF_4-0,3UF_4$ Hastalloy -NM | 566/705 | $8NaF-92NaBF_4$ Hastalloy -NM | 455/621 | |
| France | CCDP | 2000 | $71,7LiF-16BeF_2-12ThF_4-0,3UF_4$ Hastalloy -NM | 550/700 | Plumbum Chromecco3(leadFe-2,2Cr-1,0Mo) | 350/550 | |
| USSR | ГЖСР для ASPT | 2000 | $69LiF-30BeF_2-1,0ThF_4-0,1UF_4$ ChN80MTYu (80Ni-17Cr-Mo-Ti-Al) | 600/750 | $8NaF-92NaBF_4$ ChN80MTYu (80Ni-17Cr-Mo-Ti-Al) | 500/650 | $NaNO_2-NaNO_3-KNO_3$ LiCl-LiOH |
| USSR | HTPS | 300 | $66LiF-34BeF_2$ ChN80MTYu (80Ni-17Cr-Mo-Ti-Al) | 600/750 | Air | | |
| China | MSGR | 2250 | $57NaF-43BeF_2$/ Hastalloy -NM | 566/705 | $8NaF-92NaBF_4$ | 454/621 | |

In RRC "Kurchatov Institute" development of reactors with melted salt coolants began in the beginning of 70-s. The works were divided into two directions: reactors with liquid circulating fuel [12,13] similar to MSRE and reactors with salt composition and fuel on the base of micro-particles fuel and spherical fuel elements [14-16]. Basic thermophysical properties of the most known fuel-free salt coolants $LiF-BeF_2$ и $NaF-BeF_2$ [12] are given in Table 2.

Table 2.

| № | Parameter | Value | |
|---|---|---|---|
| 1 | Molar composition, mol.% | $NaF-BeF_2$ 57-43 eutectic | $LiF-BeF_2$ 48-52 eutectic |
| 2 | Melting temperature, $(t_{melt})$, $^0C$ | 360 | 350 |
| 3 | Specific heat, $(C_p)$, J/kg·K | 2172 | 2720 |
| 4 | Heat conduction, (λ), Wt/m·K | 1 | 1,19 |
| 5 | Density, (ρ), $kg/m^3$ | 2270-0,37·t | 2220-0,4·t |
| 6 | Dynamic viscosity, (μ), $n·s/m^2$ | $3,46*10^{-5}exp(5164/t)$ | $1,89·10^{-5}exp(6174/t)$ |
| 7 | Saturated vapor pressure, $(P_{sv})$, mm Hg | ≤1 at t≤$800^0C$ <br> $<10^3$ at t≤$1300^0C$ | $LgP_{sv}$=9,44-10130/t |

Melted salt coolants on the base of LiF, NaF, $BeF_2$ are characterized by high chemical and radiant resistance [4, 17-20]. Hence, they are chemical passive to reactor materials and environments (air, water). Also it gives high level of allowable flux in the reactor core.

Chemical passivity of salt coolant ensures its passivity to dangerous flame and combustion processes with outer materials. It also provides small amount of stored chemical and mechanical energy (~0,01 MJ/MW (el.)).

As construction materials compatible with fluorides under consideration up to T~600-850$^0$C it can be used the following [21-23]:

- steel Kh18N10T – up to T~650$^0$C;
- alloys EI-726 and EP-164 –up to T~750$^0$C;
- alloy KhN80MTYu (analogue to Hastalloy-H) – up to T~850$^0$C.

Nickel alloy of KhN80MTYu type was developed special as a base construction material for reactors with melted salt coolants. Its corrosion resistance is determined by presence of impurities in salt composition (soluble oxides, moisture traces, fission products etc.). It was noted specially that corrosion of this alloy at using fuel-free salt compositions of $LiF-BeF_2$ and $NaF-BeF_2$ in many times less than in fuel salt. Intergranular corrosion determined as a rule by fission products (mainly tellurium), is practically absent. Corrosion of this alloy at T≈750$^0$C (maximum temperature of operating salt) and heating Δt≈150÷200$^0$C (natural circulation) is practically absent. Safe fast neutron fluence (E>0,5 MeV) is more than $10^{21}$ n/cm$^2$ and safe thermal neutrons is ~5*$10^{21}$ n/cm$^2$ .

Rather important property is a wide range of salt coolant liquid condition (up to T≈1300$^0$C) with pressure of saturated vapour not higher than atmospheric. This allows to exclude reactor pressure vessel of high pressure at nominal operating conditions at temperature level of 700-850$^0$C. Inner pressure on pressure vessel will be determined only by column height of liquid coolant (hydrostatic pressure).

In melted condition these coolants are transparent and their thermal conductivity similar to water. Their thermophysical properties support high efficiency of heat removal at natural circulation, salt-wall heat transfer coefficient is close to water one. Negative feedback of temperature - hydroresistence guarantees unlocking of salt circulation channels in the core and, therefore there is no overheat of fuel elements.

Thermal diffusivity of salt is approximately in 300 times lower than natrium one. Hence, during other conditions being equal the relevant time of melted salt solidification is in 300 times longer than natrium one.
Comparably high temperature of salt coolant melting complexifies start up and operation of NPP. However, this fact allows to make conditions for skull formation, for example, on inner surface of reactor pressure vessel the skull excludes corrosion interaction with circulating salt. Conditions of salt containment in the reactor and operation of stop valves based on freezing are also better.

Neutron physical properties of the coolants under consideration allow to use coolants efficiently as neutron moderator and neutron reflector. Thermophysical and neutron properties of NaF-$BeF_2$ salt are worse than LiF-$BeF_2$, but formation of tritium is essential smaller at using this salt in reactor. In heat reactors cavity and density response ratios of salt have negative values, that is the main demand for inherent safety. However, for maintenance of these conditions at using LiF-$BeF_2$ coolants initial enrichment must be not less than 99,999% for making neutron balance better and decreasing of tritium formation.

**Graphite fuel elements with micro-particles fuel** can be arranged in the core as blocks of prismatic or cylindrical shape. Also they can be made as balls and arranged in the core as free or ranked filling. However spherical graphite fuel elements with micro-particles fuel [21] ensure high flexibility in technology of fuel elements production with different structure, diameter, fuel enrichment and micro-particles fuel content. At this core formation becomes much easier. The core consists of spherical graphite fuel elements, absorb elements and dummy elements, with their optimum arrangement in core region. Two-zoned spherical fuel element of 60 mm diameter contains graphite matrix with micro-particles fuel and a shell from dense graphite of 5 mm thickness. Average density of fuel element equals ~1,7 g/$cm^3$, that is lower than densities of melted salt coolant at operating temperature.

Micro-particle fuel structure includes the following components:
Fuel kernel, inner layer made from PyC, the second layer made from PyC, interlayer made from silicon carbide, outer layer made from PyC. It should be noted, that all reactor components made on graphite base (fuel elements, pels, hels etc.) soaked with melted salt coolant are non-flammable.

Not only graphite matrix and fuel element coating are barriers for fission products yield, but mainly coatings of micro-particles fuel. Warranted long serviceability of such fuel
elements is maintained at the following conditions: up to temperatures ~1250$^o$C, neutron fluence ~$2,2.10^{21}$ n/$cm^2$ (E > 0,18 MeV) on fuel coatings [21], depth of fuel depletion not less than ~100 GW*.day/tt and neutron fluence on graphite ~$10^{22}$ n/$cm^2$ (E≥50 KeV) [22,23].

Spherical fuel elements that are recommended for application as fuel elements in the reactor “MARS” have passed in-process and reactor tests. They are validated to application in high temperature gas cooled reactors as VG-400, VGM-50, and VGM-100. Micro-particles fuel which is the base of spherical fuel elements has passed a test in Pich Bottom, Fort St. Vrain USA reactors and in German AVR and THTR-300 ones. [24]. The spherical fuel elements reprocessing can be carried out on the base of gas-fluoride technology.

High efficiency autonomous power source with longtime operation without use of water for heat exhaust and cooling can be made on the base of **gas-turbine unit** (GTU) heat source of which is the nuclear reactor with micro-particles fuel and high temperature melted salt coolant.

GTU is of special interest because it works using open air cycle. Such GTU with different thermodynamic parameters were constructed on the base of aero-engines [25] and as an alternate heat source allows to use its built-in combustion chambers of organic fuel or hydrogen. It is important during NPP starting, outages and malfunction. Together with high efficiency and circuit simplicity the GTU makes easy also problems of seismic stability.

The specific weight of such GTU equals ~3,0 - 4,5 kg / kW, and specific volume ~ 0,04 - 0,17 $m^3$/kW. It is in 10 and more times less, than in advanced steam turbine units. The alternative design examinations of GTU parameters concerning different thermodynamic cycles and schemes have shown, that its efficiency can vary from ~31 % up to ~52 % at identical preheating of air up to Tg~700°C depending on the selected scheme and input air temperature. Thus, for example, efficiency increases from ~31 % to ~46 % at input air temperature drop from $T_{input}$ = + 50°C to $T_{input}$ = - 50 °C (at $T_{input}$=0 °C $\eta$=38,3 of %) for the simplest scheme (Fig. 1) with one compressor (optimum air compression index $\pi_k$=4), one preheater (up to Tg ~ 700°C), one turbine and one regenerator. For the most complex scheme (four compressors with three intercoolers, two preheaters, two turbines, regenerator (Fig. 2)) efficiency increases from ~35 % up to ~52 % in similar conditions. All set of physical and technical preconditions obtained on the base of selected combination of fuel, coolant and GTU ensures actual possibility of making ultimate safe, high efficient, economical, autonomous NPP for waterless and semiarid regions - MARS (micro-particles fuel autonomous melted salt reactor). Elementary diagram of MARS unit is presented in Fig. 3. Natural circulation circuit of melted salt coolant includes: core basket filled with spherical fuel elements, absorbing elements and dummy elements; upper, radial and lower reflectors; lifting (traction) section; heat salt - air exchangers. Reflector material is circulating melted-salt coolant. There is compensating tank above the lifting section. All heat salt - air exchangers (standing and reserve) are arranged along a reactor pressure vessel above the core. The pressure vessel is cooled outside by natural air circulation. All inlets - outputs are arranged only on its cover (rod gears of safety control system, input and output of air pipelines etc.). On inner surface of pressure vessel it can be frozen a thin salt layer (skull) that protects pressure vessel from corrosion. Screens with neutron absorbent, for example made from boron steel can be placed along inner surface of pressure vessel to lower neutron flux on it. For increasing of strength it is recommended to use double vessel. Absorbing material of safety control system rods is boron carbide ($B_4C$). The core is gathered from spherical fuel elements, absorbing elements and dummy elements. The core component parameters of reactor MARS are given in Table 3.

Table 3.

| **Core lement** | **Parameter** | **Value** |
|---|---|---|
| Spherical fuel element | **Outer diameter, mm** | 60 |
| | **Inner diameter, mm** | 50 |
| | **Fuel enrichment, %** | 10,0 |
| | Graphite density in fuel matrix, g/$cm^3$ | 1,65 |
| | Graphite density in outer layer of fuel element, g/$cm^3$ | 1,65 |
| Micro-particle fuel | **Diameter of kernel, μ** | 500 |
| | $UO_2$ density in the kernel, g/$cm^3$ | 10,0 |
| | **Thickness of the first coating layer of micro-particle fuel, μ** | 30 |
| | PyC density in the first layer, g/$cm^3$ | 1,0 |
| | **Thickness of the second coating layer of micro-particle fuel, μ** | 50 |
| | PyC density in the second layer, g/$cm^3$ | 2,0 |
| | **Thickness of the third coating layer of micro-particle fuel, μ** | 40 |
| Table 3 (continued). | | |
| | SiC density in the third layer, g/$cm^3$ | 3,2 |

| | | |
|---|---|---|
| | **Thickness of the fourth coating layer of micro-particle fuel, μ** | 40 |
| | PyC density in the fourth layer, g/cm$^3$ | 2,0 |
| Absorbing element (pel) | **Diameter of absorbing element,mm** | 45 |
| | **Absorbent** | $B_{nat}$ |
| | **Absorbing material** | $B_4C$ |
| | **Absorbent charge in absorbing element, g** | 0,1 |
| Dummy element (hel) | **Diameter of dummy element, mm** | 35 |
| | Graphite density in dummy element, g/cm$^3$ | 1,65 |

As an example the main parameters of MARS with power ~6 MW, natural circulation of $LiF\text{-}BeF_2$ coolant and GTU with simple open air cycle (Fig. 1) are given in Table 4 for 60 and 15 years campaign (variant 1 and variant 2, respectively).

Table 4.

| № | Parameters | Variant 1 | Variant 2 |
|---|---|---|---|
| 1 | Thermal capacity, MW | 16 | 16 |
| 2 | Thermal efficiency coefficient at $T_{inlet}=0^0C$, % | 37 | 37 |
| 3 | Core diameter/height, m | 3/3 | 3/3 |
| 4 | Average power density, MWt/m$^3$ | 0,75 | 0,75 |
| 5 | Reflector thickness, m | 0,4 | 0,4 |
| 6 | Coolant temperature $T_{outlet}/T_{inlet}$, $^0C$ | 750/550 | 750/550 |
| 7 | Coolant flow, kg/s | 29,4 | 29,4 |
| 8 | Height of lifting section, m | 5 | 5 |
| 9 | Total height of circulating circuit, m | 8,8 | 8.8 |
| 10 | Number of standing heat exchangers, pcs. | 3 | 3 |
| 11 | Full number of standing heat exchangers (including reserve), pcs. | 21 | 6 |
| 12 | **Heat exchanger diameter/height, m** | 0,5/4,6 | 0,5/4,6 |
| 13 | Fuel element charge, g | 31,58 | 7,90 |
| 15 | Maximal fuel temperature, $^0C$ | 1200 | 1200 |
| 16 | Fuel enrichment of $^{235}U$, % | 10,0 | 10,0 |
| 17 | Fuel burnable, GW·day/t | 98 | 98 |
| 18 | Fuel campaign, years | 60 | 15 |
| 19 | Fast neutron fluence (E≥0,183 MeV) to fuel element for a campaign, 1/cm$^2$ | $2,1*10^{21}$ | $0,53*10^{21}$ |
| 20 | Fast neutron fluence (E≥0,183 MeV) to reactor pressure vessel for a campaign, 1/cm$^2$ | $1,0*10^{21}$ | $0,33*10^{21}$ |

Table 4 (continued).

| | | | |
|---|---|---|---|
| 21 | Number of rods in safety control system, pcs. | 12 | 12 |
| 22 | Rod diameter of safety control system, cm | 7,2 | 7,2 |
| 23 | Turbine efficiency, % | 92 | 92 |
| 24 | Compressor efficiency, % | 88 | 88 |
| 25 | Air compression index in compressor | 6 | 6 |
| 26 | Air temperature before turbine, $^0$C | 700 | 700 |
| 27 | Pressure recovery coefficient in air circuit | 0,9 | 0,9 |
| 28 | Air temperature after regenerator, $^0$C | 232 | 232 |
| 29 | District heating capacity, MW | 8,5 | 8,5 |
| 30 | Heat regenerating coefficient | 0,85 | 0,85 |
| 31 | Weight of reactor unit, t | ~171 | ~132 |
| 32 | Weight of GTU with electrogenerator, t | ~26,4 | ~26,4 |
| 33 | Diameter/height of reactor unit, m | 4/10 | 4/10 |

Table 4 shows that reactor campaign for the first variant reaches 60 years, i.e. exceeds service life of modern NPP, and for the second one is 15 years. Integrated fast neutron fluxes in the core during campaign (fluences) do not exceed permissible limits for micro-particles fuel and graphite. Neutron fluences on reactor pressure vessel are also less than allowable values, even without possible shielding of reactor pressure vessel. Corrosion of pressure vessel can be practically stopped by the skull on its inner surface. On the other hand, there is practical opportunity to reserve necessary number of salt-air heat exchanges and GTU for all service life. Therefore, there are natural and technical premises for making installation, which one can operate as 15 years, so and 60 years without fuel re-loading. Taking into account rather low power of MARS, it is quite possible to maintain operation without power adjusting. In case of lowering external load or at open-phase fault the underused electrical power can be applied, for example, for hydrogen electrolysis or using fan heater it is thrown out in atmosphere.

However, the most effectively the power can be used for liquid air production with subsequent applying it for cooling air before the compressor of GTU input. It will allow to increase essentially efficiency of NPP by maintenance of low air temperature before the compressor.

Switching to reserve heat exchangers and GTU or to electrolytic baths and fan heaters can be carried out automatically or using remote control desk.

As a whole it allows to maintain MARS operation after starting without constant serving personnel and at the relevant technique without guarding.

In design operation condition the irradiation of air by neutrons that penetrates through the reactor pressure vessel and surface of salt - air heat exchangers results in rather low concentration of $^{41}$Ar, $^{14}$C, $^{16}$N, $^{23}$Ne, $^{19}$O radio-isotopes. As calculations show their concentrations in air on the edge of an exhaust tube more than in 10 times less than maximum permissible concentration (MPC). During mixture of hot and atmospheric air the concentrations drop further in tens times. The output of tritium produced in reactor is low. Tritium concentration in air on the edge of the exhaust tube approximately in 1000 times lower than tritium MPC.

Package dimensions of reactor unit MARS and GTU allow to carry it using practically all modes of transport (sea, river, railway, heavy motor -vehicle, airplanes such as «Ruslan») into any accessible for them region. GTU and reactor unit can be transported in completely assembled condition (practically) made by plant – manufacturer.

Experience of reactor development similar to MARS (particularly VTRS-50) has shown that there is no necessity to use a stationary system of salt coolant purification. It is stipulated by the following: there is no pumps in the circuit, that means that there is no wear debris; low speed of coolant circulation promotes lowering of erosion on surfaces of construction materials and core materials; high preheating of salt in the reactor in natural circulation conditions with low speed; dead zones and salt skull on the pressure vessel surface. These facts promote realization of known methods of coolant purification in 1 circuit - settling and cold traps. Complete or partial purification of salt can be carried out once in several years, for example, during fuel overloading on the special plant.

It is necessary to note, that long-lived serviceability of salt - air heat exchangers is not validated completely and there is a hazard of depressurization of heat exchanger surfaces with necessity of heat exchangers replacement on reserve ones during operation before exhaustion of the core resource (probably once in ~ 5-10 years). Therefore, in the designs of similar reactors a reserve of heat exchangers in active and passive condition are arranged near to working ones. In nominal condition three salt - air heat exchangers works constantly. Inside the pressure vessel a system of interior loops for realization of turning on the group of reserve heat exchangers and turning off ones out of the resource should be organized.

Therefore, for reactor with 15 years campaign it is recommended integrated assembling of the first circuit with heat exchangers placed inside reactor pressure vessel. And for reactor with 60-years campaign of non-stop operation, apparently, it is necessary to consider loop assembling of the first circuit with outrigger heat exchangers to simplify their break-in and out of operation. It will promote lowering of costs by improving technologies and development of new materials for heat exchangers during reactor operation.

Technical-and-economic index of small power NPP MARS essentially depends on its following features:

- absence of water treating, hydraulic engineering equipment and buildings in plant systems;
- absence of emergency reactor cooling (emergency cooling is executed by free convection of air along outer surface of reactor pressure vessel);
- absence of equipment for continuous purification of the first circuit coolant;
- absence of equipment for fuel re-load;
- absence of pumps in the first circuit.

Shutdown of the MARS can be very simple – without fuel elements discharge and coolant drain, i.e. start shutdown of the reactor, its cooling down to complete salt freezing and conservation of NPP. Salt heating-up during reactor starting is carried out using starting technology of BN type reactors.

It should be noted that the proposed concept of reactor for small energetic allows to use it and for main energetic, because fuel rating of the core can be increased up to ~ 20 $MW/m^3$ under condition of natural circulation maintenance of melted salt coolant and approximately the same weight and dimensions of the reactor unit. Model parameters of materials consumption of MARS equipment are presented in Table 5.

Table 5.

| Parameter | Value |
|---|---|
| **Dimensions of reactor pressure vessel (∅/ h/thickness), m** | 4/ 10/ 0,02 |
| **Coolant weight, t** | 65,7 |
| - in the core | 17,0 |
| - in radial reflector | 32,5 |
| - in edge reflectors | 11,3 |
| - in lifting section | 2,0 |
| - in compensator tank | 1,0 |
| - in three operating heat exchangers | 1,9 |
| **Weight of spherical fuel elements, т** | 21,63 |
| **Heat exchangers (dimensions ∅=0,5m, h=4,6m) for three operating heat exchangers, t** | 7,3 |
| - weight of pipe heater at heat exchanger surface 3×200 $m^2$ (KhN80MTYU), t | 5,4 |
| - weight of pressure vessel (KhN80MTYU), t | 1,9 |
| **Weight of KhN80MTYu, t** | 2,49 |
| - lifting section | 0,18 |
| - compensator tank | 0,21 |
| - basket and support grid of the core | 2,1 |
| **Weight of equipment from stainless steel, t** | 24,22 |
| - reactor pressure vessel | 23,5 |
| - air-channel pipes | 0,72 |
| **GTU** | |
| Weight of GTU with electric generator, t | 26,4 |
| Weight of regenerative heat exchanger, t | 47,8 |
| Weight of equipment for overheat utilization, t | ~ 50 |

The basic advantages and disadvantages of the present concept of small power NPP MARS are given in Table 6.

Table 6.

| Advantages | Disadvantages |
|---|---|
| Infrastructure in Russia*) | |
| NPP autonomy | |
| Complete assembling of the reactor unit on plant-manufacturer and its transportability | Need of heating system. |

| Table 6 (continued). | |
|---|---|
| Absence of water necessity | |
| A lot of barriers for keeping of fission products. | High tritium output as compared to LWR. |
| Ultimate safety of the reactor. | |
| Reactor pressure vessel of low pressure. | |
| Possibility of skull protective layer forming on the inner pressure vessel surface. | High melting temperature of the coolant. |
| GTU used with open air circuit. | |
| One-phase state of the salt coolant. | |
| Natural coolant circulation. | |
| Low probability of melted salt coolant leakage from the core. | Necessity of extra works concerning coolant technology. |
| High ecological properties of NPP permit low stage of heat, radiation and chemical contamination of environment. | Necessity of extra research and development works concerning construction materials. |
| High thermodynamic efficiency of heat-electricity conversion. | |
| Lowering of accident risk and increasing of plant reliability. | Rise in the cost of fuel production and processing. |
| Absence of problems with burial of radwaste and decommissioning of reactor. | |
| Long core campaign (up to 60 years). | Necessity to reserve some components of reactor unit. |
| Lowering of accident risk and increasing of plant reliability. | Rise in the cost of fuel production and processing. |
| Absence of problems with burial of radwaste and decommissioning of reactor. | |
| Long core campaign (up to 60 years). | Necessity to reserve some components of reactor unit. |
| High efficiency. | |
| Knowledge of engineering solutions. | |

*) Infrastructure:

- Scientific leader: RRC "KI", Moscow.
- Designer of reactor unit and NPP: OKBM, Nizhni Novgorod.
- Chief projector: VNIPIET, St. Petersburg
- Manufacturer of reactor pressure vessel: Izhora plants, St. Petersburg.
- Technology of fuel and coolant: VNIIINM.
- Manufacturer of: PO LMZ, St. Petersburg.
- Heat exchangers: VNIIAM.

The analysis of the given alternatives of NPP with reactors MARS has shown, that this concept of nuclear reactor units on the base of micro-particles fuel, melted salt coolant and GTU with open air cycle is completely fits to all requirements of autonomous nuclear power plants for semiarid regions. The selected type of nuclear reactor unit is ultimate safe, high ecological and high efficiency source of electricity, high and low temperature heats. The potential technical and economic indexes of the MARS stand out from other types of these class reactors.

The results obtained allow to conclude the following:

- using of micro-particles fuel and spherical graphite fuel elements allows to reach high depletion of high temperature nuclear fuel and ultimate low radioactive fission products yield into environment during all possible design and hypothetical accidents.
- application of fluoride salt fusion as high temperature coolant ensures natural coolant circulation, low pressure in reactor pressure vessel, practically complete impossibility of coolant output into environment and effective use of small-size gas-turbine units as energy transformer;
- using of GTU with open air circuit permits not to use water as heat absorbent of extra heat and in cooling systems, allows to use built-in combustion chambers of organic fuel or hydrogen as alternative heat source during transient and emergency modes; improves seismic stability of NPP;
- the proposed concept makes possible long reactor campaign (in the present work there are given two campaign variants of 15 and 60 years).

- simplified essentially problems of NPP decommissioning;
- reactor power can be increased in ~20÷25 times using increasing of core rating up to ~ 20 MW/m$^3$ under condition of natural air cooling maintenance of melted salt coolant and approximately similar weight and dimensions of reactor unit;
- reactor unit MARS has high level of technical solution knowledge, expends small quantity of energy for house set (< 1%) and needs minimum personnel;
- improvement of technical and economic indexes of small power NPP with the MARS is reached using its following features:
  - absence of water treating, hydraulic engineering equipment and buildings among plant systems;
  - absence of emergency cooling equipment of the reactor (emergency cooling is executed by free air convection along outer surface of reactor pressure vessel);
  - absence of equipment for continuous purification of the first circuit coolant;
  - absence of equipment for fuel re-load.

Therefore, reactor unit MARS can be one of the most perspective nuclear sources of small and mean power, especially for semiarid, distant and seismic areas.

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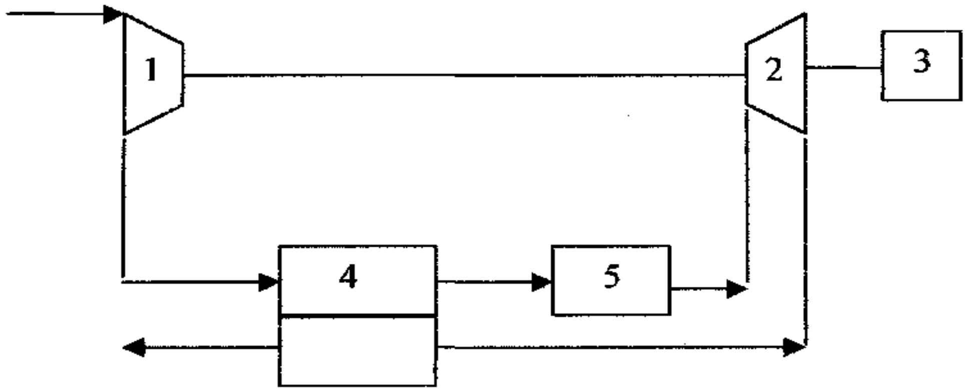


**Fig. 1 A scheme of GTP.**
1 - compressor; 2 – turbine, 3 - electric generator, 4 - heat exchanger: salt-air, 5 - regenerator (regenerating heat exchanger air-air).

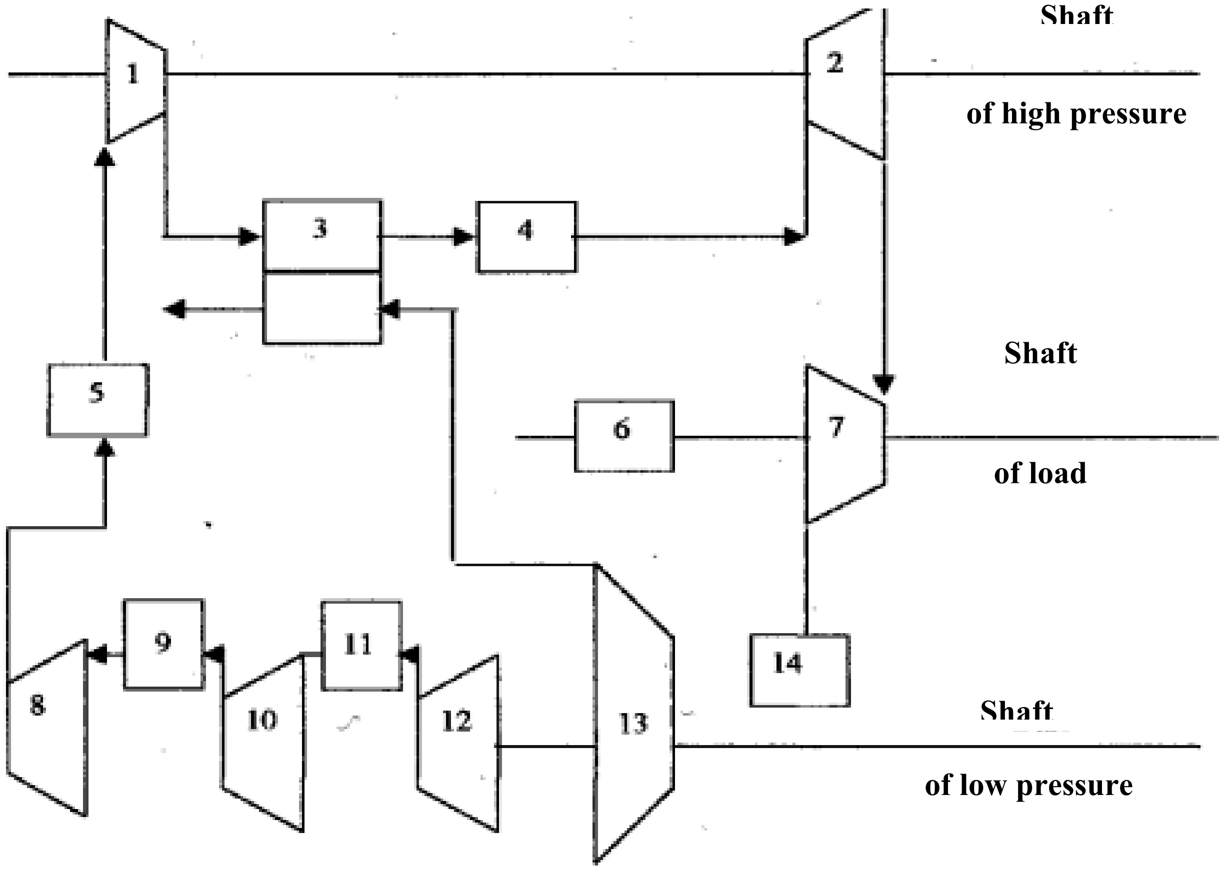


**Fig. 2 A scheme of GTP.**
1,8,10,12 - compressors; 5,9,11 - intermediate codlings; 2,7,13 - turbines; 4,14 - heat exchanger: salt-air; 3 - regenerator; 6 - electric generator.

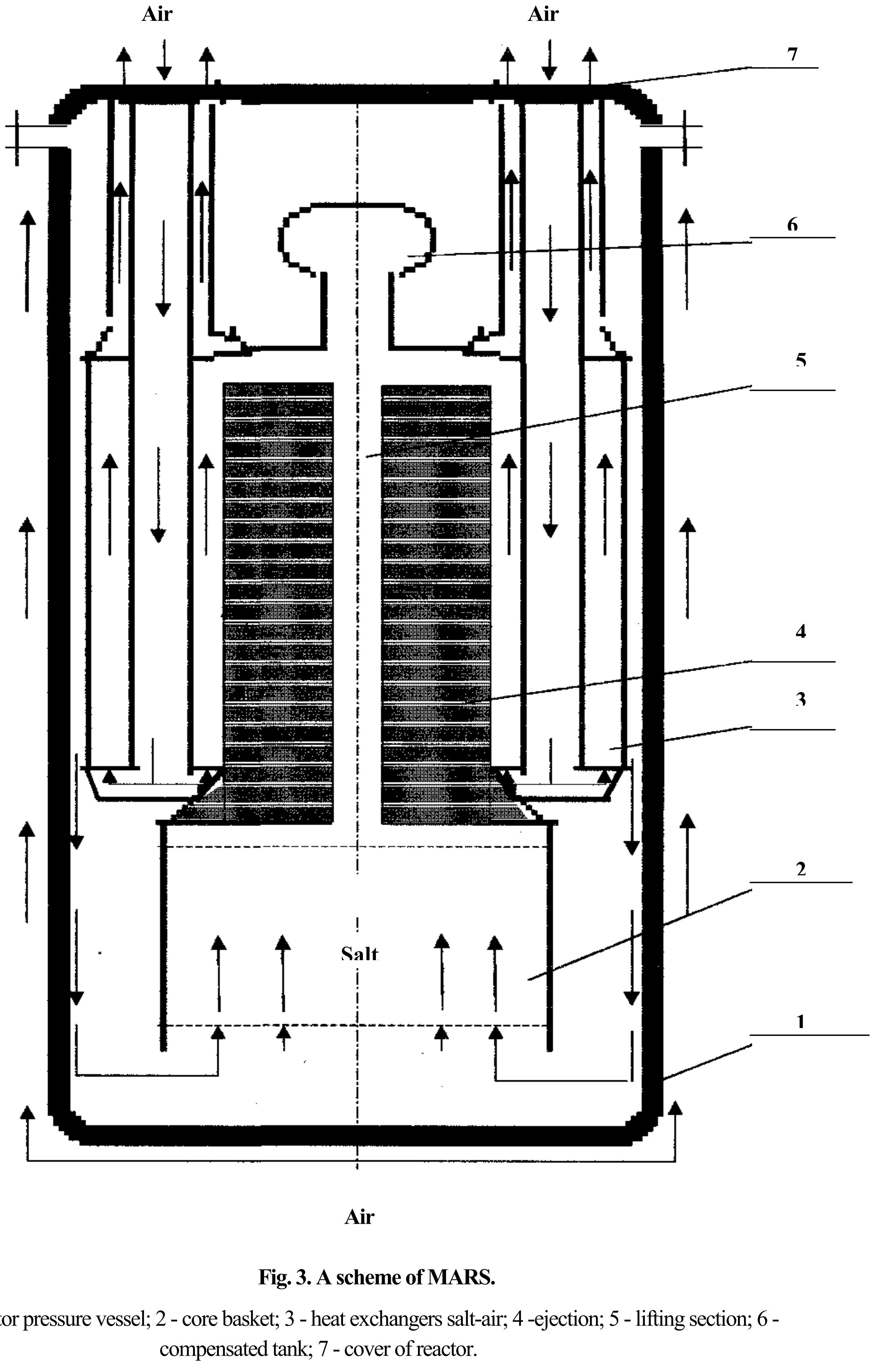


**Fig. 3. A scheme of MARS.**

1 - reactor pressure vessel; 2 - core basket; 3 - heat exchangers salt-air; 4 -ejection; 5 - lifting section; 6 - compensated tank; 7 - cover of reactor.