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THERMOPHYSICAL PROCESSES IN CRYOSPHERE

THE THERMAL IMPACT OF A SMALL UNDERGROUND NUCLEAR PLANT ON PERMAFROST

N.N. Melnikov, P.V. Amosov, S.A. Gusak, N.V. Novozhilova, S.G. Klimin

Mining Institute of the Kola Science Center RAS,
24 Fersman str., Murmansk region, Apatity, 184209, Russia; vosoma@goi.kolasc.net.ru

Analysis of results of numerical experiments on assessment of the permafrost thermal state taking into account the "ice–water" phase transition around a small underground nuclear power plant is presented. The thermal physics problem has been considered on the example of hypothetic location of a small reactor unit in a remote northern region of Eastern Siberia (Yakutia, Chukotka).

Small nuclear plant, permafrost, numerical modeling, phase transition, thermal impact

INTRODUCTION

A number of studies of the current state of the economy and of the fuel and energy sector of Eastern Siberia and of the Russian Far East attain a certain place to possible use of small nuclear power plants (SNPP). For example, in [*Saneyev et al., 2011*] prepared by the specialists of the Melentyev Institute of the Energy Systems of Magadanenergo Inc., a location plan of perspective small power plants is presented for the eastern regions of Russia, including SNPP. In particular, in ***Sakha Republic (Yakutia)*** the following areas are considered perspective for building small power plants by the year of 2030: Yuryung-Khaya (36 MW (el.)) for developing the Tomtor niobium-rare-earth-metals field; Ust-Kuiga (30 MW (el.)) for developing the Kyuchuss gold field; Tiksi (12 MW (el.)) to ensure power supply in resuming functioning of the North-Eastern Seaway (the latter has become topical due to the State Program for Development of Arctic and of the North-Eastern Seaway submitted by the Ministry for Regional Development to the RF Government [*Krivoshapko, 2013*]); in ***Chukotka autonomous district*:** Peschanoye (up to 200 MW (el.)) for developing the Peschanoye polymetallic field.

As basic and perspective for studies of SNPP technologies selection, various small nuclear power reactors are considered, for example, KLT-40C (150 MW (heat)), VK-50 (150 MW), ABV-6M (38 MW), Uniterm (15–50 MW) [*Sarkisov, 2011*]. Numerous developments of various reactor units (RU) carried out over the recent 20–25 years for small-scale power generation have never been implemented in this sector of power consumption. Having analyzed the situation, the specialists of Rosatom and Kurchatov Institute made a conclusion that the basic reasons were not in the area of design solutions but in the area of planning, organization, infrastructure, operation, servicing, responsibility, and ownership of the reactor units [*Krivitsky, 2005; Sidorenko, 2011*]. At the beginning of 2012, out of all the basic and perspective RU, only KLT-40C designed for a floating nuclear power plant was granted a license of Gosatomnadzor. According to the notice as of November 27, 2013 [*Positive opinion..., 2013*], the results of engineering survey conducted in the framework of planned construction of a prototype nuclear power unit with a fast-neutrons reactor unit with lead-bismuth coolant (LBC-100) passed the state examination proceedings. In the opinion of the CEO of AKME-engineering Vladimir Petrochenko, the conclusion obtained allows taking the next step of the state examination proceedings of the design documentation for the power unit construction.

One of the essential issues of nuclear power plants' operation is to ensure their safety and to assess their potential environmental impact. The Mining Institute of the Kola Research Center of the Russian Academy of Sciences, together with the other institutes of the Russian Academy of Sciences, has certain scientific potential and achievements in the solution of the issues of ensuring all-round safety of hazardous radiation objects [*Melnikov et al., 2010*]. At the turn of the 1990-s, the Mining Institute, as the head organization in cooperation with the leading research, design, and technological organizations of the country, conducted comprehensive R&D, aimed at substantiation of the major provisions of the concept of establishing underground power plants in the USSR under the state scientific and technological program "Environmentally Safe Power Plants".

Currently research is being conducted at the Mining Institute, the goal of which is to develop a concept, scientific and engineering foundations for design and construction of small module-type in-ground and underground nuclear power plants to provide power to mining enterprises and to settlements in remote hard-to-reach areas of Russia. Certain areas are considered for location of SNPP [*Melnikov et al., 2013*], meant for power supply of mining companies on perspective mineral fields, which actually coincide with the sites indicated in [*Saneyev et al., 2011*].

One of the tasks being solved by the Mining Institute of the Kola Research Center of the Russian Academy of Sciences is the study of the thermal impact of SNPP on the underlying rocks. The talk is about possible placement of SNPP in the geological formations of rocks and permafrost rocks (PR) in the mode of normal operation of a plant considering phase transitions and climatic characteristics of the areas considered. From the scientific point of view, a task is more interesting when a heat source (in this case, a SNPP module) is located in permafrost rocks (considering the ice–water phase transition). The results of the survey conducted are shown in this paper.

PARAMETERS OF THE SNPP AND PR MODELS

Assessment of the thermal impact of SNPP on PR allows the size of the melting area around a potentially hazardous underground radiation facility to be assessed and the movement rate of the phase transition border to be determined. In studying the thermal impact of a power plant on PR, a normal operation mode was considered. As noted in [*Melnikov et al., 2014*], to describe the site for an underground SNPP, a representative set of thermophysical parameters may be used. It should be pointed out that the values of the major parameters used in digital solution of thermal tasks (the geothermal gradient, the extreme values of seasonal temperature fluctuations, SNPP capacity, the average air temperature) are rather close but practically they are always indicated within ranges.

All the potential areas of SNPP location refer to the permafrost regions with the ground temperatures at the depth of 10–15 m varying from –10 to –5 °C [*Brown and Grave, 1981*]. For further calculations, we will use the data from [*Karapetyan et al., 2012*] (for the regions of Bilibino nuclear power plant, located north of Peschanoye). The value of the seasonal fluctuation is taken to be about 12 m, with the temperature at this depth being –6 °C. The PR thickness in this region is 250–450 m.

Based on the typical permafrost rock temperature distribution with the depth shown in [*Kershengolts et al., 2008*], the following conclusion was made: to make numeric calculations of the temperature fields, such parameters will necessarily be required as the geothermal gradient, the borderline of the depth of seasonal fluctuations, and the PR thickness. In a number of calculations, the average air temperature is important. It is noted in many publications on the permafrost zone of Siberia that the geothermal gradient varies from 0.015 to 0.025 °C/m [*Brown and Grave, 1981*; *Kershengolts et al., 2008*; *Karapetyan et al., 2012*]. We used the value of 0.020 °C/m in our computations.

In our opinion, in order to study thermal interaction between the underground SNPP modules and the thermal condition of the surrounding rock, it is sufficient to consider the non-stationary heat problem, taking into account ice–water phase transitions in a two-dimensional setting. The schematic view of an underground nuclear power plant placed in PR at the depth of at least 50 m (in accordance with the construction regulations for the Extreme North regions [*Underground facilities..., 2012*]), is shown in Fig. 1. A simplified schematic of an underground SNPP consists of the following modules: a reactor hall (RH) sized 14 × 60 m, a swimming pool (SP) 4 × 10 m in size and two modules with reactor units, the sizes of which correspond to the sizes of the selected small reactors. The distance between the reactor unit modules is 20 m. In the given model, the dimensions of the modules indicated in Fig. 1 generally correspond to the similar premises of facilities containing reactor units of the KLT-40C type.

The SNPP model includes two layers of the embedding mass: PR 1 the mass above the seasonal fluctuation borderline (approximately 12 m, the temperature is –6 °C) and PR 2 the lower mass with constant geothermal gradient (at the level of 0.02 °C/m). Porosity of PR 1 is 0.15 and that of PR 2 is 0.10.

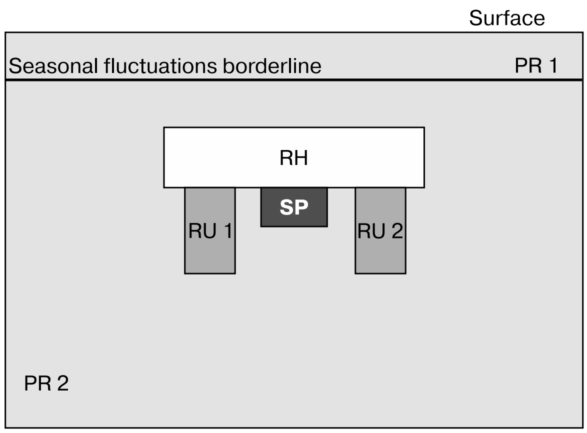


Fig. 1. The schematic view of an underground nuclear power plant model (see the details in the text).

PR – permafrost rocks; RH – reactor hall; SP – swimming pool; RU – reactor units.

Table 1. **Thermal physical characteristics of materials**

Material	λ, W/(m·K)	c_m, J/(kg·K)	ρ, kg/m^3
Permafrost	1.8	800	2200
Lining	2.0	840	2500
Heat insulator	0.03	1200	100

Note. λ – thermal conductivity; c_m – specific heat capacity; ρ – density.

The 1 m thick lining (for the 0.5 m swimming pool) and the thermal insulation layer on the example of 0.5 m thick polystyrene are assumed. The thermal physical characteristics of the layer are shown in Table 1.

Unlike [*Melnikov et al., 2014*], a situation is discussed in the present study when the temperature in all the SNPP modules is within the range from 60 to 10 °C. It seems that low temperatures may be ensured by improving the ventilation system (taking practically inexhaustible cold supplies into account).

The following boundary conditions were determined for solution of the heat problem:

1) on the surface – the third-order condition (the heat exchange is 10 W/(m^2·K) and the temperature is −11.6 °C, which corresponds to the average annual temperature in the area in question);

2) on the side boundaries – the null bias;

3) on the lower boundary – the fixed temperature determined by the boundary depth and by the geothermal gradient.

The initial temperature for a SNPP is the temperature of the middle of the model layers, for the lining layers it is 10 °C. The modeling period is 10 years. Additionally varied is the thermal conductivity coefficient λ = 2.0; 0.5; 0.05 W/(m·K). Two options of the SNPP are considered; without a heat insulation layer and with a heat insulation layer in the reactor unit modules.

The main tool for performing numerical experiments was the *COMSOL* code (by *COMSOL*). It was possible to use either the *PORFLOW* software product (by *ACRi*) or the software program developed by the authors for assessing the impact of small underground nuclear power plants on the surrounding rocks under permafrost conditions. These software products allow heat processes to be simulated considering the ice–water phase transition. As in [*Kazakov et al., 1997*], the codes used by the authors are built on the following presumptions:

– "the environment is presumed to be macroscopically uniform by all characteristics; its porous space is filled with ice, and after the phase transition – with water";

– "dependence of the thermal physical properties of the rock mass on temperature is not taken into account, both in the permafrost and in melted condition" (*p. 38*).

For example, the developers of the *PORFLOW* software product use the model by J.A. Wheeler [*PORFLOW..., 1997*]. The *COMSOL* code and our software program are implementing the known method of transforming the initial nonlinear system of equations to the quasi-linear type by the Dirac Δ (delta)-function, which during numerical implementation is substituted with a δ-function, different from zero in the phase transition interval and satisfying the standard normalization requirement. In addition to the classical work by *Samarsky and Vabishevich* [*2003*], we found an exhaustive description of this phenomenon the collective monographs of the researchers from the Chersky Mining Institute of the North, Siberian branch of the Russian Academy of Sciences [*Kurilko et al., 2011a,b*] and implemented this algorithm in our software program.

Comparative analysis of the results of test calculations conducted with the said software programs showed their acceptable agreement [*Amosov, 2013*]. However, it is the *COMSOL* code that allows fast and effective representation of information in a convenient graphical form.

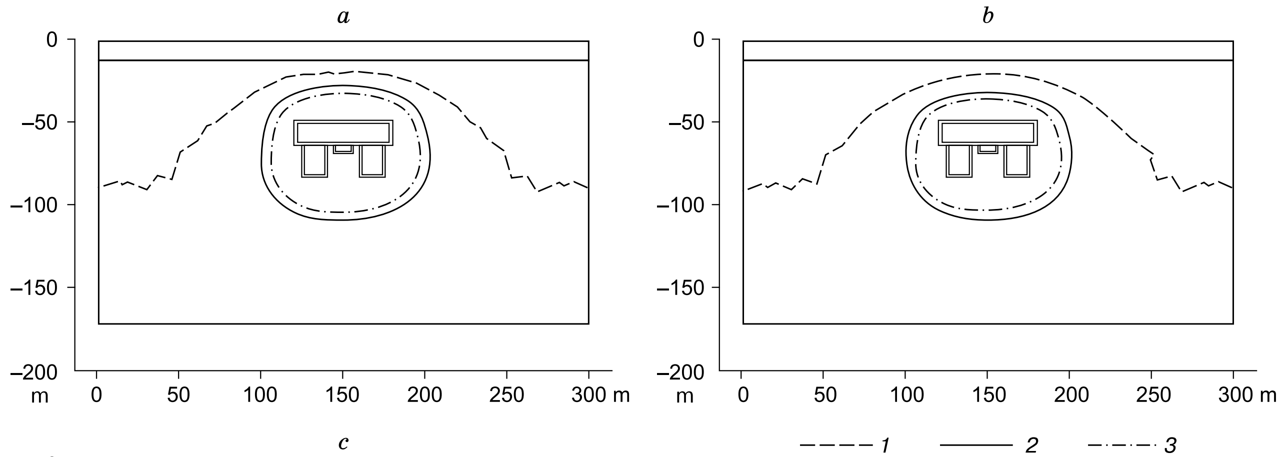
ANALYSIS OF THE COMPUTATION RESULTS

Consider several examples of the results of the numerical experiments. The graphical representation of spatial distribution of the temperature contour lines with the values of −5, 0 and +5 °C across the entire simulation area at the temperature of 60 °C in the SNPP modules for the option without heat insulation is shown in Fig. 2. The heat conductivity coefficient of the lining λ = 2; 0.5; 0.05 W/(m·K). Shown in Fig. 3 is spatial distribution of the same contour lines at the temperature of 10 °C for the option when there is a heat insulation layer as a sheet of polystyrene 0.5 m thick.

Analysis of the computation results shows that practically with all the indicated values of the thermal physical parameters, the porous space around the SNPP modules is filled with water. Even availability of a heat insulation layer does not keep the water away from the porous space of the rock around the modules of the underground SNPP. The vastest "moist" areas are naturally predicted to exist at the maximum temperature values in the modules and of the heat conductivity of the lining.

Decrease in the temperature and thermal conductivity values diminishes the "moist" area. When using the coefficient λ = 0.05 W/(m·K) in calculations, the size of this zone significantly decreases, and its contours approach the surfaces of the modules of RH, SP, and RU. However, the "moist" area practically disappears only at minimum values of both parameters (Table 2).

Knowing the dimensions of the SNPP modules, it is not difficult to evaluate the melting depth by the Table 2 data in the horizontal (the distance as far as



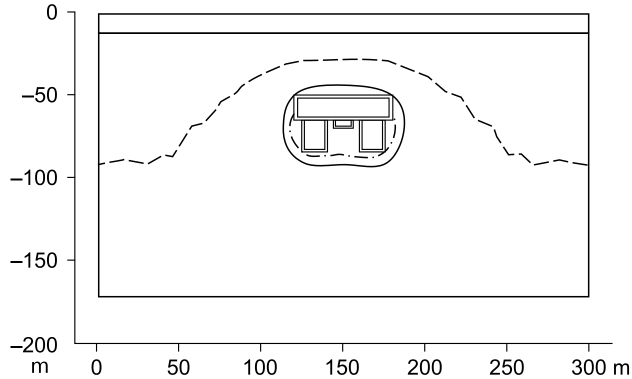
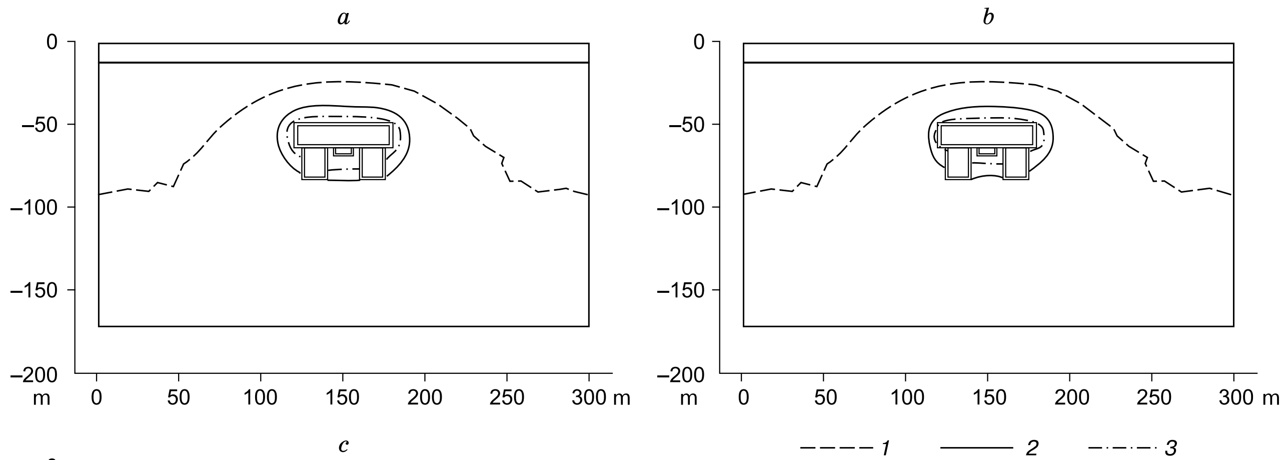


Fig. 2. Spatial distribution of isotherms at the temperature of 60 °C in a SNPP module for the option without a heat insulation layer.

Thermal conductivity coefficient of the lining: *a* – 2 W/(m·K); *b* – 0.5 W/(m·K); *c* – 0.05 W/(m·K); temperature contour lines: *1* – T = –5 °C; *2* – T = 0 °C; *3* – T = +5 °C.



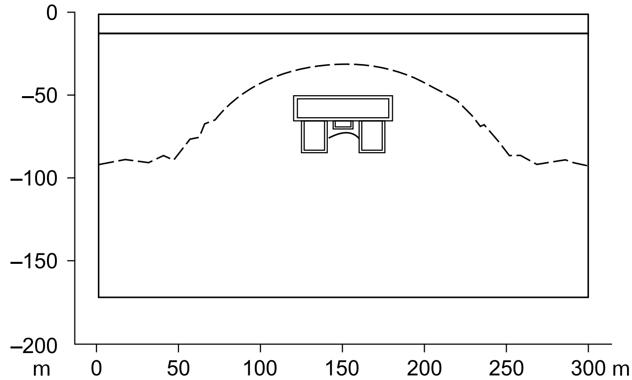


Fig. 3. Spatial distribution of isotherms at the temperature of 10 °C in a SNPP module for the option with a heat insulation layer.

Thermal conductivity coefficient of the lining: *a* – 2 W/(m·K); *b* – 0.5 W/(m·K); *c* – 0.05 W/(m·K); temperature contour lines: *1* – T = –5 °C; *2* – T = 0 °C; *3* – T = +5 °C.

Table 2. **Estimated sizes of the "moist" area with the model parameters varying for two options, m**

λ, W/(m·K)	T_m, °C	Insulation option	No-insulation option
2	60	116 × 82	108 × 68
	40	110 × 81	98 × 65
	20	100 × 70	88 × 59
	10	86 × 58	76 × 45
0.5	60	110 × 75	95 × 65
	40	106 × 72	92 × 63
	20	94 × 64	83 × 54
	10	84 × 53	68 × 43
0.05	60	86 × 50	77 × 45
	40	78 × 47	71 × 44
	20	72 × 40	61 × 39
	10	60 × 35	60 × 35

the contour line 0 °C from the middle of the left module of the reactor unit) and vertical (the distance down as far as the contour line 0 °C from the middle of this module's foundation) directions. Both the graphic presentation of the prediction (Fig. 4) and the table data (Table 2) convincingly demonstrate the effect of the heat insulation layer (its presence and absence) and the impact of the thermal conductivity coefficient of the lining.

Fig. 4 illustrates dependences of the melting depth in the horizontal and vertical directions on the thermal conductivity coefficient of the lining and the temperature in the SNPP modules for the option without heat insulation.

Note the behavior of the predicted melting depths:

– non-linearity of the system's response to changes in the thermal conductivity coefficient;

– different sensitivity to the temperature parameter in the module for different values of the thermal conductivity coefficient;

– the effect of reducing the horizontal size of the "moist" area depending on the choice of material with a varying thermal conductivity coefficient of the lining in the option without heat insulation is from 26 to 32 m, whereas in the option with insulation it varies from 16 to 31 m;

– reduction of the vertical size of the "moist" area depending on the choice of material with a varying thermal conductivity coefficient of the lining in the option without insulation varies from 23 to 34 m, whereas in the option with insulation it varies from 12 to 23 m.

Additionally, the impact of porosity of permafrost on the melting depth was studied. The only module of a reactor unit was considered. The lining layer thickness was 1 m. The main parameter of the study, permafrost porosity (ε), was 1, 5, 10, 15, 20, 25, and 30 %. The temperature in the module was taken to be equal to 60 °C.

Analysis of the results shows that, with the assumed thermal pysical parameters of the model, 10 years after the thermal impact of a SNPP on permafrost, the melting depth in the horizontal direction (h) is described by a quadratic function. The variation range of the melting depth is about 18 m, while the value itself by the quadratic dependence $h = 0.017\varepsilon^2 - 1.1\varepsilon + 36.352$ with the confidence coefficient of 0.986 monotonously decreases from 36 to 18 m for the indicated porosity range.

It can be stated that the high value of porosity results in reduction of the melting depth. This is explained by significant energy expenditures on the "ice–water" phase transition.

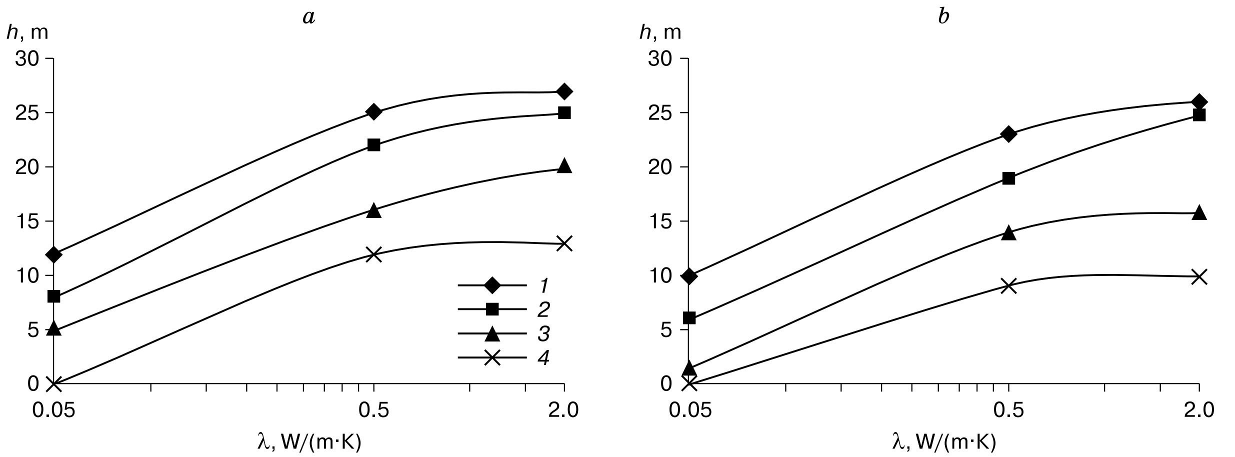


Fig. 4. Dependence of the melting depth (h) in horizontal (a) and vertical (b) directions on thermal conductivity coefficient of the lining (λ) and the module temperature (T_m) of a SNPP (the no-insulation option).

1 – T_m = 60 °C; *2* – T_m = 40 °C; *3* – T_m = 20 °C; *4* – T_m = 10 °C.

CONCLUSIONS

The results of the studies of assessing the thermal impact of a hypothetical underground SNPP on the embedding permafrost allow the following conclusions to be made.

Two-dimensional numerical models have been developed, considering the “ice–water” phase transition, in the *COMSOL* code for proposed options (without heat insulation and with heat insulation of the RU module) of a hypothetical underground SNPP established in permafrost at the depth of 50 m from the earth surface. Series of computations have been made for the varying thermal conductivity coefficient of the lining and the temperature in the SNPP varying from 60 to 10 °C.

Analysis of the results of numerical modeling experiments has been conducted. The sizes of the melting area around the SNPP modules have been predicted for the cross section considered:

– the maximum size (~116 × 82 m) is predicted for the use of the highest values of the variation of the thermal conductivity of the lining (2 W/(m·K)) and the temperature in the modules 60 °C;

– the minimum size of the “moist” area (at the level of the geometric characteristics of the SNPP modules) is ensured by the use of materials with a varying thermal conductivity coefficient of the lining at the level of hundredth of a watt per meter-Kelvin and the temperature 10–20 °C in SNPP modules.

The impact of permafrost porosity (the variation range 1–30 %) on the melting depth has been assessed. It has been demonstrated that the melting depth in the horizontal direction with a high confidence coefficient of approximation is described with a quadratic function.

In general, the calculation results allow a conclusion to be made regarding the necessity of design and mining solutions directed at reduction of the negative impact of the thermal factor on the physical and technological properties of the embedding permafrost rocks and on stability of the design elements of an underground SNPP.

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