1. Introduction

The prospects of using of porous heat-insulating materials in the industry don’t in doubt [1–3]. New porous materials appear every year. Such materials are used as heat-insulating for houses, constructions, pipelines, furnaces, dryers and other industrial equipment. In [4] the creation of new porous heat-insulating heat-proof material on the basis of composite binder and gas agent was described, but thermal properties of such material weren’t given and the possibility of porosity regulation wasn’t described. Despite the fact that porosity (quantity, size and pores form) influences on the effective thermal conductivity [5, 6].

The generalized equation of thermal conductivity is needed for assessing of the future effective thermal conductivity of porous material, but it doesn’t exist. Also the generalized equation will allow controlling the thermal conductivity of porous material at the pores formation stage without numerous experiments. So, finding of the generalized equation of thermal conductivity of porous heat-insulating materials is an actual scientific task, which is useful for the industry.

2. The object of the research and its technological audit

The object of research is the heat transfer through porous insulating materials. The most famous problem is the lack of generalized equation of thermal conductivity; it doesn’t allow to predict the effective thermal conductivity of the material at the structure formation stage. The reason of it is lack of complex entrance independent factors of porous structure that influence on the effective thermal conductivity. For determining of these factors the computer simulation was used, results of it was confirmed by laboratory experiment. For finding of the generalized equation of thermal conductivity of porous heat-insulating materials the experimental design method was used. Disadvantages of the obtained equation are the narrowed application boundaries, the pore size of 2 mm, the thermal conductivity of the basic material without pores is 0.95 W/(m·K).

3. The aim and objectives of the research

The aims of this work creation of the generalized equation of thermal conductivity of porous heat-insulating materials and give the practical recommendations for structure formation of such materials.

To achieve that aims, next objectives must be solved:
1. Research the influence of the convection in the pores on the thermal resistance by the computer simulation.
2. Confirm the obtained dependencies by the practical experiment in the laboratory.
3. Identify the main factors which influence on the coefficient of effective thermal conductivity of porous materials.
4. Find the regression equation of thermal conductivity of porous heat-insulating materials by the experimental design method.
5. Analysis of the regression equation to give the practical recommendations for structure formation of heat-insulating materials.

4. Literature review

Before this time the effective thermal conductivity could be solved by the difficult systems of equations, which taking into account radiation and convection inside the pores [7, 8]. These equations have many simplifications and semi-empirical factors (i.e. only suitable for specific materials). Therefore, they aren’t suitable for controlling the thermal conductivity of porous material at the production stage.

In [9] the microporous structure of ceramic insulation material is considered as a fractal. Looking at fractal structure the size and the location of pores can be taking into account, although pore form wasn’t considered. The idea, which was proposed in the work is scientifically interesting, but it doesn’t allow proposing practical recommendations for the creation of porous insulating material. Also in the work the structure and the equations, which are effective only for microporous structures, were considered. Calculation of thermal resistance was made by
electro-thermal analogy. But in this method convective and radiation components were neglected, phonon thermal conductivity wasn’t considered (which for ceramic products has significant value).

In [10] three mathematical models of the porous gars were made and was proven that for this material the pore form (cylindrical, conical, elliptical) doesn’t matter, the main thing — the total porosity of the material. But in the conducted research the convection in pores and the number of pores weren’t considered. Therefore, the conclusion that only porosity of the material will influence on the effective thermal conductivity, can be real only for the equally spaced micropores. The proofs are given in [11, 12]. Also in [12] the conclusion that the pores form is important (big difference of the coefficient of thermal conductivity between elongated and flattened pores) was made.

The influence of convection in the pores is very difficult task, in which many scientists take part [13, 14]. The characteristic feature of many investigations of the convection in closed pores is their use only for a narrow specific material. So, the decision of three-dimensional task of the gravitational convection in the Boussinesq approximation was given in [15]. But the obtained results are permissible only for specific sizes of the air layer.

In the literature are plenty information about the impact of the porous materials structure on their thermal properties, but there are no practical recommendations for the formation of structural indicators of macroporous thermal insulation materials. Some articles are controversial and needed clarification. Therefore it is necessary to create the generalized equation of thermal conductivity of porous heat-insulating materials and on its basis give practical recommendations for creation of new porous thermal insulation materials.

5. Materials and methods of research

Methods of research were computer simulation and empirical method.

For researching the influence of the convection on the thermal resistance of porous thermal insulating materials were built following computer models. Cube with sides of 0.04 m was modeled. In the center of the cube was spherical pore. Pore was simulated with different diameters. On one of the surfaces of the cube was set heat flux 100 W/m² and 10 W/m². The opposite surface of the cube was set with convection cooling and with an initial temperature 22 °C. Other cube surfaces were adiabatic. The material in the pore was ideal air with pressure of 1 atm. The gravitational force was set to an axis which was parallel to the heating and cooling surfaces, and was equal to 9.81 m/s².

In the laboratory research was used the polystyrene foam of the firm «TechnoNikol ekoplit» with thermal conductivity 0.035 W/(m·K), density 2.6 kg/m³ and heat capacity 1.45 kJ/(kg·K). The thermal conductivity was measured by the thermal conductivity meter ITP-MH4 of the company «SKB Stroyprybor». The samples were made with closed and open porosity. The open porosity was made by through holes. The diameter of the pores and holes in the samples was 4, 6, 7, 8 and 10 mm. The probe of the thermal conductivity meter before every measurement was anointed with thin layer of the thermal paste KPT-8.

6. Results of the research

6.1. Research of the influence of the convection in pores on the thermal resistance of the porous thermal insulation materials. The mesh was consisted of tetrahedrons. Physical preference was made for the method of calculation hydrodynamics. The boundary layers of the mesh were chosen in number of five both for pore and for material. The material and pore of diameter 20 mm with mesh is shown in Fig. 1.

The allocation of convective lines velocity in the closed spherical pore of diameter 20 mm is shown in Fig. 2. Fig. 2 shows that the convection in the pore of diameter 20 mm is perpendicular to the heat flow and along of the lower and upper spherical poles. This is due to the fact that the driving force of convection is the gravitational force. The velocity of air in the pore is low and doesn’t exceed 0.00008 m/s. Also velocity near pore center is the smallest and close to zero.

The changing of the convective lines velocity in the closed spherical pore of diameter 10 mm must be marked. The allocation of convective lines velocity in the closed spherical pore of diameter 10 mm is shown in Fig. 3. Fig. 3 shows that the convective lines velocity is allocated spirally. The velocity of air in the pore of diameter 10 mm lower than in the pore of diameter 20 mm. The spiral motion of the convective lines velocity can be explained by
self-organization of the convective cell like the Rayleigh-Bénard convection cell. In the Rayleigh-Bénard cell heat flow is directed along the vector of gravity but in Fig. 3 heat flow is directed perpendicular to gravity.

Smaller air velocity in the spiral motion of convective lines means that for increasing the thermal resistance of insulation materials the spiral motion of convective lines in a closed spherical pore is better than the transverse motion with partial flow along the lower and upper spherical poles.

Fig. 4 shows the temperature distribution in the body with pore diameter of 20 mm. Also it shows that the temperature of air in the pore is approximately the same. The temperature on the surface of pore is differs maximum of 7°C, while the temperature difference on the either sides of the material is more than 60°C. Also Fig. 4 shows that the pore of diameter 20 mm for set conditions has a good heat resistance to heat flow even in porous materials.

For researching of the influence of convection on the thermal resistant of heat insulation materials, with different pore size, computer models of samples with different pore diameters were made. The diameters of the closed spherical pore were 2, 5, 10, 15, 20 mm. For each diameter, the computer simulations of convection in the pores and the heat static analysis of thermal insulation material were made. As an insulation material was chosen polystyrene foam with a density 40 kg/m³, thermal conductivity 0.036 W/(m·K) under 20°C, and heat capacity 1.34 kJ/(kg·K). The minimum number of iterations for the convective analysis was 1100. The maximum estimated error by balance was 10.5.

Fig. 6 shows the dependence of the thermal resistance of thermal insulation material on the pore diameter. Bar dotted purple line shows the thermal resistance of the material with absolute vacuum in the pore. The dotted green line shows the thermal resistance of the material with air in the pore, but without convection. Black horizontal line shows the thermal resistance of the material without pore. The solid blue and red lines show the changing of the material resistance on the diameter of pore with the influence of convection.

The analysis of Fig. 6 shows that without convection, the increasing of pore diameter (as total porosity of material) increases thermal resistance of thermal insulation materials. But convective motions inside the pore significantly reduce thermal resistance. With a diameter of 2 mm pore convection is almost absent. The convection occurs with pore diameter of 5 mm, but the thermal resistance of the thermal insulating material with pore above the resistance of the thermal insulation material without it. For a given pore diameter the effect of temperature is essential. Thus, with
Если тепловая мощность составляет 10 Вт/м², то термическое сопротивление меньше чем термическое сопротивление с тепловой мощностью 100 Вт/м². Это можно объяснить температурным градиентом на поверхности пор.

Диаметр пор более 10 мм приводит к значительной конвекции и уменьшает термическое сопротивление, что делает его меньше, чем термическое сопротивление материала без пор.

Для создания пористого изоляционного материала рекомендуется использовать поры меньше 8 мм с небольшим температурным перепадом (10 °C).

Рис. 6 также показывает, что зависимость термического сопротивления от диаметра пор логарифмическая.

Для подтверждения полученных зависимостей был проведен лабораторный эксперимент. Лист пенопласта был вырезан в виде прямоугольных параллелепипедов. Экспериментальная высушенная часть состояла из таких 5 параллелепипедов. Перед сборкой, два параллелепипеда были пронумерованы симметрично расположенными отверстиями. Чтобы устранить контактное сопротивление, контактные поверхности были забиты тонким слоем термического пасты MX-4. Сборка была выполнена при клее на стороне. На конце образца был прорублен слепой канал диаметром 5,1 мм и длиной 76 мм под пробник для измерения теплопроводности. Схематично сборка показана на Рис. 7.

Рис. 7. Схема сборки экспериментальной пробы

Согласно результатам эксперимента зависимость коэффициента теплопроводности от диаметра пор была получена (рис. 8). Черная горизонтальная линия показывает теплопроводность материала без пор. Объединенные зависимости подтверждают, что поры размером менее 7 мм увеличивают тепловое сопротивление изоляционного материала. В эксперименте, поры размером 7 и 8 мм увеличивают тепловое сопротивление изоляционного материала на 2,86 %. Это можно объяснить тем, что поры форму не имеют цилиндрической (не сферической) и погрешность измерительного прибора составляла 7 %.

Также Рис. 8 показывает, что коэффициент теплопроводности материала с открытой пористостью выше, чем с закрытой пористостью, за исключением диаметра 4 мм. Это можно объяснить увеличением конвективной составляющей в случае с открытой пористостью.

Снизление коэффициента теплопроводности термического изоляционного материала с пористостью и диаметром 4 мм происходит из-за общей пористости в открытом пористом случае выше, чем в случае закрытой пористости (в этом эксперименте) и конвективная составляющая отсутствует.

Результаты эксперимента подтверждают точность полученных компьютерных моделей зависимостей.

Также можно заключить, что с диаметром 4 мм и при работе материала при температуре 50 °C конвективная составляющая внутри пор полностью отсутствует.

6.2. Нахождение обобщенной зависимости теплопроводности для пористых теплоизолирующих материалов. Для создания обобщенной зависимости теплопроводности для пористых теплоизолирующих материалов необходимо определить основные параметры, влияющие на теплопроводность материалов. Эти параметры должны быть независимы друг от друга. Исследования в этом разделе позволяют определить следующие основные параметры: температурный градиент на поверхности пор, тепловая мощность материала без пор, диаметр пор, длина пор, температура пор, температура материала.
flow were chosen because they have the most effect on the changing of effective thermal conductivity. Other geometric dimensions of pore (forms, which are closed to sphere) don’t significantly affect the effective thermal conductivity. Since the dependence of thermal conductivity of porous material on the pore diameter is logarithmic, the logarithms of diameters were used. The values and coding factors are given in the Table 1.

Since the dependence of the function on the factors $X_1$ and $X_2$ is linear, then for these factors will be enough the second order plan, for other factors will be enough the third order plan. The mixed composite plan of the second and third order was used. Number of pores was varied in a plane which is perpendicular to the heat flow. The analysis of results was made in the trial version of the program Statistica. After regression analysis the coefficients of generalized equation of thermal conductivity for porous heat-insulating materials were obtained (Table 2). Regression equation was chosen with linear, quadratic and paired coefficients. In the first column next factors are indicated: $L$ – linear coefficients, $Q$ – quadratic coefficients. Also in the Table 2 is set Student’s t-test. Important coefficients are marked by italics.

The Pareto distribution of the influence of initial factors shows that the biggest influence on the coefficient of effective thermal conductivity have the pore diameter along to the heat flow and the total impact of the pore diameter perpendicular to the heat flow with temperature gradient.

The generalized equation of thermal conductivity for porous heat-insulating materials without unimportant factors will be the next:

$$
\lambda = 0.046 + 0.02X_1 - 0.0255X_3 - 0.0178X_3^2 + 0.0023X_2X_3 + 0.034X_3X_2.
$$

The analysis of equation (1) shows that the thermal conductivity of initial material without pores $\lambda_{\text{mat}}$ in investigated range of 0.05 to 0.95 W/(m·K) isn’t a significant factor. The increasing of the pore diameter along the heat flow significantly increases thermal conductivity of the material. The temperature gradient doesn’t linear and not directly proportional impact on the thermal conductivity of the final material. Number of pores is directly proportional impact on the effective thermal conductivity of material by the coefficients of pair interactions.

The encrypted coefficients of the regression equation in the program Statistica

| Factor | Effect Estimates; Var.lambda R-sq=0.81775; Adj. R-sq=0.79723; 2 2-level factors, 3 3-level factors, 54 Runs; DV. lambda= MS Residual=0.000348 |
|--------|---------------------------------------------------------------------------------------------------------------------------------|
| $X_1$  | Effect Std.Err. $t$ | P  | -95% Cnf.Limit | +95% Cnf.Limit |
| 0.005 | 0.00395 | 11.0157 | 0.00003 | 0.03723 | 0.05462 |
| 0.005 | 0.03995 | 0.179 | 2.8784 | 0.00929 | 0.05855 |
| 0.005 | 0.00551 | 0.00603 | -2.6493 | 0.1538 | -0.0456 | -0.0542 |
| 0.005 | 0.02286 | 0.01021 | 2.2389 | 0.03669 | 0.0156 | 0.04417 |
| 0.005 | 0.02032 | 0.01021 | 1.986 | 0.08048 | -0.0098 | 0.04163 |
| 0.005 | 0.01956 | 0.00834 | 2.3445 | 0.02948 | 0.00215 | 0.03695 |
| 0.005 | 0.01907 | 0.01021 | -1.8672 | 0.07659 | -0.0438 | 0.02023 |
| 0.005 | 0.01861 | 0.01021 | 1.8218 | 0.08347 | -0.0399 | 0.00269 |
| 0.005 | -0.01777 | 0.00834 | -1.2056 | 0.04571 | -0.0516 | -0.00397 |
| 0.005 | 0.01714 | 0.01021 | 1.4534 | 0.1616 | -0.04174 | 0.07746 |
| 0.005 | -0.01635 | 0.01021 | -1.6012 | 0.125 | -0.03786 | 0.0495 |
| 0.005 | -0.01568 | 0.00834 | -1.8776 | 0.07509 | -0.0305 | 0.0173 |
| 0.005 | 0.01559 | 0.01021 | 1.5267 | 0.14249 | -0.00571 | 0.0369 |
| 0.005 | -0.01464 | 0.00834 | -1.7556 | 0.09445 | -0.03204 | 0.02075 |
| 0.005 | -0.01301 | 0.00884 | -1.2547 | 0.05435 | -0.0206 | 0.04044 |
| 0.005 | 0.01301 | 0.00834 | 1.5604 | 0.13434 | -0.0413 | 0.05041 |
| 0.005 | 0.01273 | 0.00884 | 1.4391 | 0.16585 | -0.05672 | 0.03518 |
| 0.005 | 0.01047 | 0.00884 | 1.84 | 0.25288 | -0.00797 | 0.02892 |
| 0.005 | -0.01023 | 0.00884 | -1.1686 | 0.25628 | -0.02879 | 0.00911 |
| 0.005 | 0.00099 | 0.01021 | 0.9744 | 0.34146 | -0.01133 | 0.03126 |
| 0.005 | -0.00961 | 0.00884 | -1.1097 | 0.28027 | -0.02872 | 0.00863 |
| 0.005 | 0.00947 | 0.00884 | 1.0711 | 0.29864 | -0.00897 | 0.02793 |
| 0.005 | -0.00994 | 0.01179 | -0.7976 | 0.43441 | -0.03401 | 0.01519 |
| 0.005 | 0.0115 | 0.01021 | 1.5267 | 0.14249 | -0.0571 | 0.0369 |
| 0.005 | 0.00386 | 0.00834 | 0.4639 | 0.6477 | -0.01352 | 0.02126 |
| 0.005 | 0.00386 | 0.00834 | 0.4639 | 0.6477 | -0.01352 | 0.02126 |
| 0.005 | 0.00386 | 0.00834 | 0.4639 | 0.6477 | -0.01352 | 0.02126 |
| 0.005 | 0.00386 | 0.00834 | 0.4639 | 0.6477 | -0.01352 | 0.02126 |
| 0.005 | 0.00386 | 0.00834 | 0.4639 | 0.6477 | -0.01352 | 0.02126 |

The encoded simplified equation will be the next (from the Table 3):

$$
\lambda = 0.04065 + 0.014d_i - 0.00527 \cdot \text{grad}(t) + 0.03423 \cdot \text{grad}(t)^2 + 0.01143 \cdot d_i \cdot n + 0.01697 \cdot \text{grad}(t) \cdot n.
$$

| Table 1 |
|---------|
| The conditions of the experiments |
| Factor | Code | Levels of factors |
| $X_1$ | 1,386 | 1.733 | 2.079 |
| $X_2$ | 1,386 | 1.733 | 2.079 |
| $X_3$ | 10 | 50 | 90 | 40 |
| $X_4$ | 0,05 | 0,5 | 0,95 | 4,5 |
| Number of the pores per unit volume $n$, num./m$^3$ | 1 | 5 | 9 | 4 |

| Table 2 |
|---------|
| The encrypted coefficients of the regression equation in the program Statistica |
The pore dimension perpendicular to the heat flow should be 8 mm, but by extrapolation was found that reducing of the thermal conductivity of material also will be if this parameter increase up to 15 mm (extrapolation to 95 %).

**7. SWOT-analysis of the research results**

**Strengths.** Among the strengths of this research, results which were obtained by analyzing of generalized equation of thermal conductivity should be noted. These results allow to obtain the necessary thermal conductivity of porous material, by setting of its structural characteristics. Using of these data can significantly reduce the thermal conductivity of modern macroporous heat insulating materials that will increase energy efficiency of equipment.

**Weaknesses.** Among the weaknesses of this research is the uncertainty of factors impact, which was considered, on the strength of the final material. The thermal conductivity of the material is the main characteristic for heat insulation, but if porous material has low end strength this is significantly narrows area of it application. Also weaknesses include the complexity of manufacturing the material with specific size and location of pores.

**Opportunities.** The prospect for future research can be upgrade of the found regression equation of thermal conductivity by expanding the input parameters range.

**Threats.** The complexity of using obtained results is a large capital costs for creation of new porous heat insulating material. For the production of the refractory bricks by semi-dry method, needs to change the mold and the heat treatment mode. For changing the refractory slip production, need creation of the complex spill form and increasing time for spill pouring. For the production of foam glass — the large costs associated with developing a new method of creating the desired porous structure.

**8. Conclusions**

1. By computer simulation was obtained that decreasing of pore diameter to 10 mm change the motion of the convective air lines in the pore. They become spiral. In this case air velocity in the pore of diameter 10 mm less than air velocity in the pore of diameter 20 mm. The spiral motion of the lines can be explained by self-organization of the convective cell like the Rayleigh-Bénard convection cell. Smaller air velocity in the spiral motion of convective lines means that for increasing the thermal resistance of insulation materials, the spiral motion of convective lines in a closed spherical pore is better than the transverse motion with partial flow along the lower and upper spherical poles.

The heat flow gets maximum values on the front surface of the pore and becomes greater than the heat flow in the material. The increasing of the heat flow is due to the influence of convection. Because the heat flow under the influence of convection is moved of the poles and part of it goes back, where it combines with heat flow that goes to the front of pores.

2. In laboratory, by practical experiment, was found that in the insulation material with spherical pores of diameter 2 mm convection is virtually absent. If pore diameter is 4 mm, convective component inside the pore during the operation of material to a temperature of 50 °C is completely absent. The convection occurs with pore diameter of 5 mm, but the total resistance of the thermal insulating material with pore above the resistance of the thermal insulation material without it. For a given pore diameter the effect of temperature is essential. With pore diameter of 10 mm or more, convection becomes significant and reduces the thermal resistance, so that it becomes smaller than the thermal resistance of the material without pore. For creation of porous insulation material is recommended to use the pores less than 8 mm with a small pore temperature difference (to 10 °C).

3. The main parameters, which influence on the coefficient of effective thermal conductivity, were found: temperature gradient of pore grad T, thermal conductivity of

### Table 3

The encoded coefficients of the regression equation

| Factor | Regression Coef. | Std.Err. | t(20) | p | -95%, % Cnf.Limt | +95%, % Cnf.Limt |
|--------|------------------|----------|-------|---|-----------------|-----------------|
| Mean/Interc. | 0.00465 | 0.01719 | 2.3644 | 0.02828 | 0.00478 | 0.07655 |
| (1)ln(d1)(L) | 0.014003 | 0.01103 | 1.2691 | 0.21897 | -0.00601 | 0.03701 |
| (2)grad(t)(L) | -0.00527 | 0.01076 | -0.4901 | 0.63073 | -0.02773 | 0.01718 |
| (3)ln(d2)(L) | -0.01278 | 0.01103 | -1.1582 | 0.26039 | -0.03579 | 0.01023 |
| (4)lambda_m(L) | -0.00751 | 0.01076 | -0.6977 | 0.49337 | -0.02997 | 0.01494 |
| lambda_m(L) | -0.0091 | 0.01865 | -0.4881 | 0.63073 | -0.048 | 0.02979 |
| Mean/Interc. | 0.00232 | 0.01076 | 0.2157 | 0.83134 | -0.02013 | 0.02478 |

The encoded coefficients of the regression equation
material without pores $\lambda_{\text{mat}}$, pore diameter along to the heat flow $d_1$, pore diameter perpendicular to the heat flow $d_2$, number of the pores per unit volume $n$.

4. The regression equation of thermal conductivity of porous heat-insulating materials was found. The encoded simplified equation will be the next:

$$\lambda = 0.04065 + 0.014d_1 - 0.00527 \cdot \text{grad}(t) + 0.03423 \cdot \text{grad}(t)^2 + 0.01143 \cdot d_2 \cdot n + 0.01697 \cdot \text{grad}(t) \cdot n.$$ 

5. The analysis of the regression equation was showed that the most influence (80 %) on coefficient of effective thermal conductivity have the pore diameter along to the heat flow and the total impact of the pore diameter perpendicular to the heat flow with temperature gradient. The thermal conductivity of initial material without pores $\lambda_{\text{mat}}$ in investigated range of 0.05 to 0.95 $\text{W/(m-K)}$ isn't a significant factor. The increasing of the pore diameter along the heat flow significantly increases thermal conductivity of the material. The temperature gradient doesn't linear and not directly proportional impact on the thermal conductivity of the final material. The number of pores is directly proportional impact on the effective thermal conductivity of material by the coefficients of pair interactions.

The new macroporous heat insulation materials must have the following parameters: the pore dimension along the heat flow 2–4 mm; the pore dimension perpendicular to the heat flow more than 8 mm (15 mm); the number of pores 9 pcs. to $6.4 \cdot 10^{-2}$ $\text{m}^3$.

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НАХОЖДЕНИЕ ОБОБЩЕННОГО УРАВНЕНИЯ ТЕПЛОПРОВОДНОСТИ ПОРИСТЫХ ТЕПЛОПРОВОДЯЩИХ МАТЕРИАЛОВ

Изучено влияние конвекции в замкнутых порах на коэффициент эффективной теплопроводности теплоизоляционных материалов. Определен общий характер распределения скоростей течения в замкнутой сферической поре с диаметрами 2–20 мм. Установлены наиболее значимые факторы, влияющие на коэффициент эффективной теплопроводности с помощью регрессионного анализа. Предоставлены рекомендации по созданию новых крупнопористых теплоизоляционных материалов.

Ключевые слова: конвекция, замкнутая сферическая пора, регрессионный анализ, эффективная теплопроводность.

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