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Thermal energy storage in granular deposits

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Abstract. Energy storage technology is crucial for the development of the use of renewable energy sources. This is a substantial constraint, however it can, to some extent, be solved by storing energy in its various forms: electrical, mechanical, chemical and thermal.

This article presents the results of research in thermal properties of granular deposits. Correlation between temperature changes in the stores over a period of time and their physical properties has been studied. The results of the research have practical application in designing thermal stores based on bulk materials and ground deposits. Furthermore, the research results are significant for regeneration of the lower ground sources for heat pumps and provide data for designing ground heat exchangers for ventilation systems.

1 Introduction

Due to the increasing demand for energy, combined with the development of energy based on renewable energy sources (RES), which, as is commonly known, generate energy in an inconsistent manner, the issue of storing energy in its various forms is becoming increasingly significant. It is usually done by using devices and media which store energy and allow to use it at different time.

Energy storage issue is not new. For many there have been various techniques and substances used for storing energy in various forms. In order to achieve the best efficiency of the system, it is most beneficial to store energy in the form it was obtained, or the form it will be used. Each transformation of energy generates losses and impairs the efficiency of the installation.

Storing energy involves a lot of technical problems associated with the storage time, the source of acquisition, and the destination. Thermal energy, regardless of time, can be stored in passive low-temperature systems, heating systems supplies, and systems used to power conventional thermal power plants where high temperatures are required [1].

1.1 Thermal energy storage

Thermal energy needs to be stored both short- and long-term, in a wide range of temperatures. It can be accumulated through a change in the internal energy of the medium, with the use of the specific heat of the substance, by applying to the phase change (using the latent heat), through physical processes, in thermo-chemical processes or through combinations of processes.

Accumulation of thermal energy with the use of the specific heat of the substance can be used for solids and liquids. Solid-liquid and liquid-gas phase changes are most common in the case of heat accumulation through phase change [2]. Methods of accumulation of thermal energy are presented in Fig. 1.

Development of effective and economical methods of storage of thermal energy obtained from RES is today a key issue for the development of renewable energy. This area requires close cooperation of both scientists and engineers, as well as investors. In order to design and execute cost-effective heat stores, extensive research is conducted throughout the world, covering all methods presented on Fig. 1. Mekhamer [4] pointed out raw saudi bantonite as an effective material to store heat energy, with a capacity of 30 kJ/g when heated to a temperature of 200° C. The material is also easily available and cheap.

A lot of research is being carried out on phase change materials, e.g. the research on using solar salt [5] as a good accumulator of solar energy in power plants CSP (concentrated solar power). The basis research into the mechanism of material melting around the heating pipe was undertaken in [6]. In paper [7] it was proposed to add PCM (Phase Change Materials) to concrete, and in the research financed by the Spanish Government [8], it was proposed to fill bulkheads with PCM. It indicated, like in this paper, that buildings should also be used as the storage of heat and that the research had a broad practical use. A lot of research is conducted on the sensible heat storage in natural materials, both in the ground and in the materials used as fillers. Paper [9] presents the results of execution of a heat store introductory project in Kerava, Finland. The subject of research presented in paper [10] is similar to the one presented in this paper, however, the storage material there is not the sand, commonly used to fill the foundation walls, but rocks which may be used for the storage of energy in the power plants CSP. The thermal properties of 5 rocks were presented. And the authors also stressed the ease of availability and low price of the material used to build the heat store.

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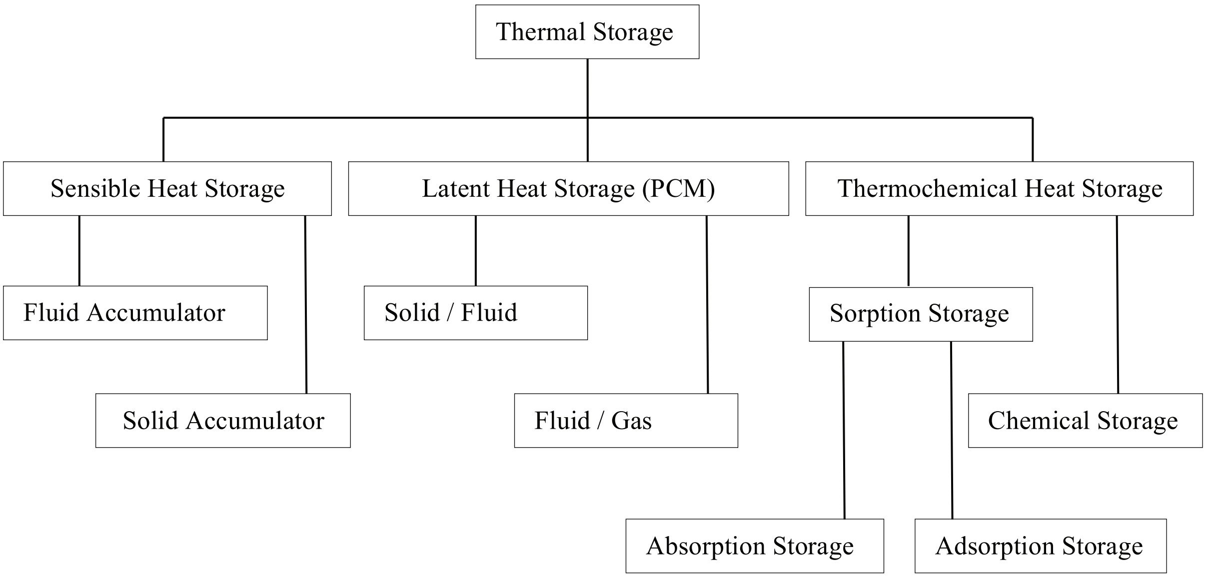

Fig. 1. The classification of thermal stores in relation to the thermodynamic properties [3].

This paper presents the results of research into bulk materials that can be used in the construction of sensible heat stores used for heating buildings. This research is part of the project, whose goal is to develop data and guidelines for designing this type of storage. In buildings without basement the space between the foundation walls is filled with compacted sand. This space can be used for sensible heat storage. The advantage of such store is the low cost of its construction. The store uses the construction elements of the building for the housing and the filling. The extra costs need to be incurred for a system of pipes to transfer heat, together with the power supply, and for padding the thermal insulation. These are small costs in comparison to the cost of the construction of a separate store, and they only slightly increase the cost of the entire house.

1.2 Accumulation of sensible heat using specific heat

This is the simplest and most common form of accumulation of thermal energy. Thermal stores that use specific heat of the substance accumulate energy by an increase in the temperature of the medium (a solid or liquid). This system operates on heat capacity and change in the temperature of the material during accumulating and discharging energy from the store [2]. The following substances can be considered as working media for sensible heat accumulation: water, air, oils (e.g. silicon), glycols, molten wax, refrigerants, as well as solids: rocks, grainy materials, soil; best suited, however, for this type of accumulation are deposits of rock, grainy deposits (soil, aggregates) and water tanks.

The amount of thermal energy accumulated in a homogeneous material depends on its specific heat, temperature changes, and the amount of heat-accumulating material according to the following formula:

$$Q = m\int_{T1}^{T2} c_w(T)dT \tag{1}$$

The substance that has the very good storage properties using the specific heat is of course water. The downside of this medium is low temperature of accumulation and a fairly narrow temperature range (0-100°C at atmospheric pressure).

As can be observed in the picture (Fig. 2), substances with relatively good storage property are metals, natural deposits and materials - stone and soil, as well as concrete. These materials are suitable for high-temperature accumulation which means the store can accumulate considerable amounts of thermal energy, and co-operate with systems using renewable energy sources - solar collector systems for thermal energy accumulation, and heat pumps, for which the store may be the bottom source. This makes it possible for the energy stored in the summer to be used in the heating period, in the winter.

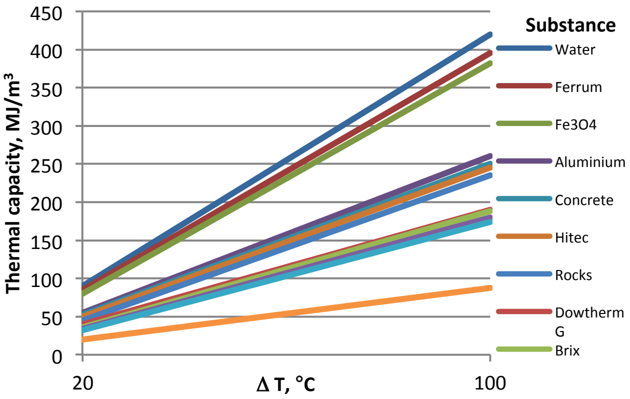

Fig. 2. Thermal capacity as a temperature rise function for certain liquids and solids - at constant specific heat [1].

Practical issues of the design and research relate primarily to the calculation of the heat capacity of the store, heat-exchange area linked to the cross-section and the length of the pipes of the heat exchanger, pressure drop, i.e. selection of circulation pumps and distribution of the heat exchanger pipes in the deposit.

1.3 Heat transfer characteristics

The basic issue, however is to determine the heat exchange method. In granular deposits it depends on the type and alignment of the particles (porosity of the deposit) and on how the heat is supplied. Different mechanisms will be applied for a deposit heated with a flowing liquid, and for a deposit with the pipe heat exchanger, in which the air is trapped in the voids between the grains. For such deposits where the particles are surrounded by stagnant fluid, heat transfer is assumed to occur in the vertical direction by the following mechanisms [11]:

1. Heat transfer through the fluid in the void space by conduction and by radiation between adjacent voids (when the voids are assumed to contain a non-absorbing gas).
2. Heat transfer through the solid phase.
    a) Heat transfer through the contact surface of the solid particles.
    b) Conduction through the stagnant fluid near the contact surface.
    c) Radiation between surfaces of solid (when the voids are assumed to contain a non-absorbing gas).
    d) Conduction through the solid phase.

Mechanisms 1 and 2 are parallel with each other. Conductivity is given by k_ε= (ΔT/ΔL) = heat flux in void space + heat flux through solid phase.

Therfore [11]:

$$-k_\varepsilon \frac{\Delta T}{\Delta L} = -k\varepsilon \frac{\Delta T}{\Delta L} + \alpha_{rv}\varepsilon\left(-\Delta T\right) \tag{2}$$

Allowing for the temperature drop in the particle which is the sum of temperature drop in the solid phase and temperature drop near the contact surface, and flux in the solid phase, a general heat transfer equation for a granular deposit in which the fluid is stationary can be applied: (by stagnant fluid) [11]:

$$k_\varepsilon = \varepsilon\left[k_g + \alpha_{rv}\Delta L\right] + \frac{(1-\varepsilon)\Delta L}{\dfrac{1}{k_g/l_v + \alpha_p + \alpha_{rs}} + \dfrac{l_s}{k_s}} \tag{3}$$

Both thermal conductivity and thermal resistance for the deposit depend on the grain material properties, void fraction of deposits and the heat transfer coefficients [12]. The research results presented here show that with the increase in porosity thermal resistance decreases, regardless of the heat conduction factor for grains of the granular material. It also shows that the relationship between the thermal resistance and the thickness of the barrier for low porosity of the deposit is not linear. For example, at porosity 0.1 thermal resistance initially grows fairly quickly with the increase in the width of the barrier, until it reaches approximately 0.7 m; for such width the resistance is almost 8 times higher at porosity factor 0.1 than at factor 0.9. Furthermore, the differences in the heat conduction factors of the granules did not have a strong effect on the thermal resistance when the barrier width exceeded 1 meter. However, the impact of the ratio of penetration of heat into the grains for the air filtering the granular material to the thermal resistance decreases when the thermal conductivity rises above 40 W/mK at specific parameters.

It is clear that at the low penetration coefficient resistance decreases very quickly with the increase in conductivity coefficient [12].

These data are essential for the appropriate design of placement of the tubes of the heat exchanger in granular deposit, as well as for the selection of the material and the construction of the deposit.

The paper [13], presents the heat exchange mechanism that can be used in the design of thermal stores, in which heat is supplied by a stream of the flowing fluid. Papers [14,15] describe the heat exchange for such deposits at high temperatures, in which radiation plays a larger role.

2 Material and Methods

Temperature changes have been studied in a heated granular deposit depending on the degree of its humidity. A tests results measurement system was constructed, as shown in Fig. 3.

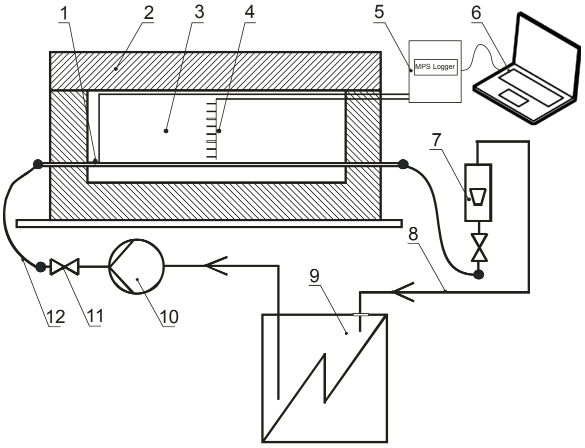

Fig. 3. The design of the laboratory workstation: 1 - pipe heating the deposit equipped with the inlet temperature sensor PT-100, 2 - thermal insulation of the measuring chamber, 3 - measuring chamber filled with loose material, 4 - temperature sensors TS-2 DM (8 pieces), 5 - measuring unit with MPS Logger, 6 - computer working with measuring module, 7 - rotameter, 8 - return of the heating water, 9 - electric thermostatic water heater, 10 - circulating pump, 11 - valve, 12 - flexible cable connecting the units of the workstation.

It consists of the measuring chamber filled with the tested granular material, the heat supply unit of a boiler with a thermostatic temperature control system for the feed water, and a measuring unit for measurement of the flow of the liquid, and the temperature in various areas of the deposit.

A temperature measurement was based on a measuring and control unit equipped with a data logging function, configured for multi-point measurement and temperature monitoring. In the project, the control device was connected to 8 digital temperature sensors TS-2 DM and 1 sensor PT-100 for monitoring the temperature of feed water as it may exceed the measuring range of sensors TS-2 DM.

Tests were carried out for the deposits of quartz sand 1-1.6 mm: dry, and at about 10% moisture content. The test chamber was filled with sand, and temperature sensors were installed; sensor PT-100 was placed on the heating water inlet and digital sensors were positioned vertically at 15 mm intervals. This allowed to measure the change in temperature of the deposit depending on the distance from the place of heat supply. The heating water temperature was 65 °C.

3 Tests results and discussion

The results of the measurements for the tested deposits are shown on the charts: Fig. 4 and Fig. 5.
As evident, the temperature increased in all sensors with a very similar trend - initially it grew faster, but after a while it stabilizes at a certain level for each sensor.

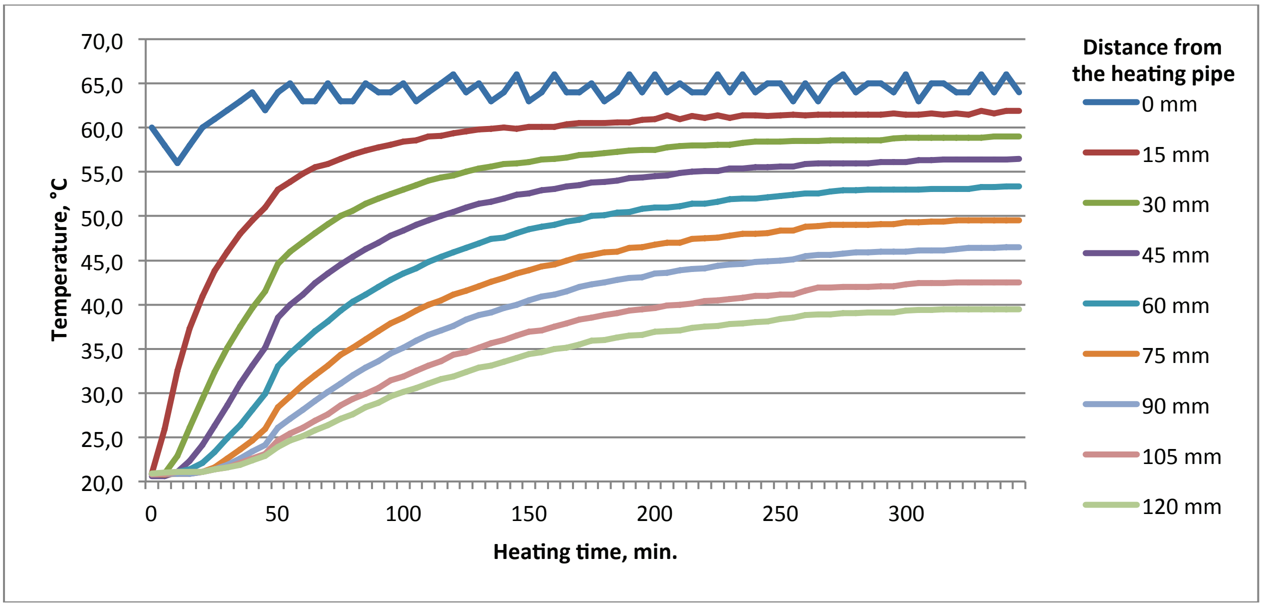

Fig. 4. Temperature chart for the deposit at different heights depending on the time of heating – quartz sand 1-1.6 mm, dry.

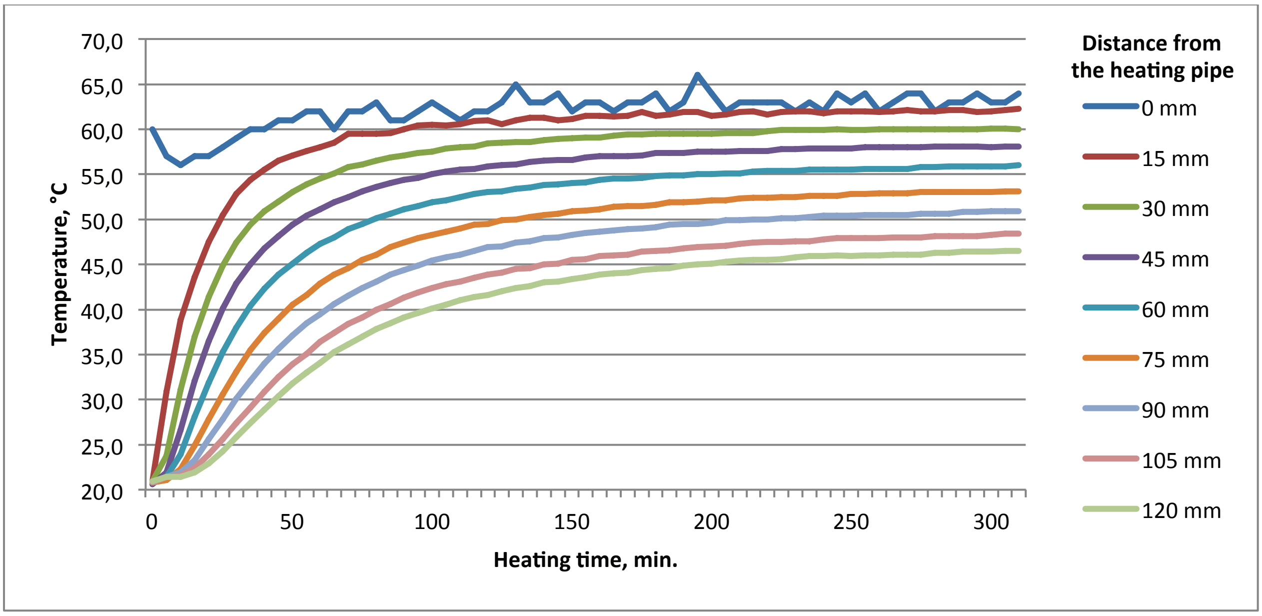

Fig. 5. Temperature chart for the deposit at different heights depending on the time of heating –quartz sand 1-1.6 mm, moist.

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Temperature differences between the sensors depend on sensor placement (Fig. 6): higher temperatures were taken by sensors located closer to the heating pipes, and conversely, the further the sensor was placed (sensors were placed in succession every 15 mm) the lower temperature it showed. Sensor, PT-100, which was located directly on the heating water inlet heated up quickest and the temperature stability was achieved. Small temperature fluctuations detected by sensor PT-100 were caused by starting or stopping of the thermostat of the warming device.

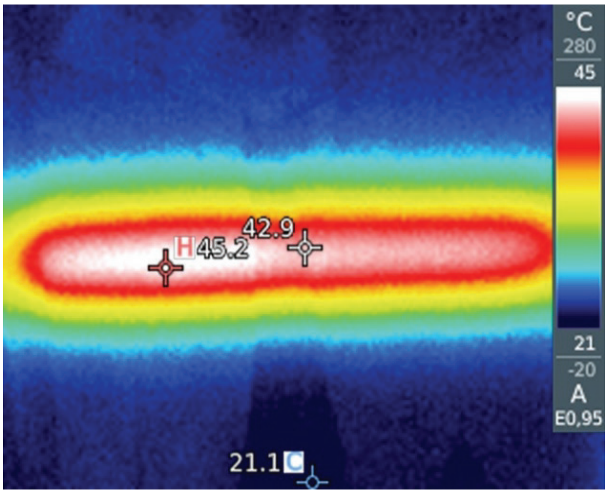

Fig. 6. Thermal photography of a granular deposit heated by a pipe exchanger. Symmetrical temperature distribution can be observed.

Charts show changes in one direction, however, it should be noted that in a granular deposit, in which the fluid flow is not possible, the temperature distribution around the heating pipe is symmetric, as is shown in the picture taken with the help of a thermal imaging camera.

4 Conclusions

The results of the tests show that for deposits of moist sand changes in temperature at various points of the deposit are faster, which is related to a higher heat transfer coefficient for radiation between the grain material and the air filling the void space in solid surface. In the deposit of 10% moisture content higher temperature is achieved faster than in the dry sand deposit; however, the temperature distribution is similar.

Areas of deposits more remote from the place of heat supply reach the balance temperature which is lower than the temperature of the supply medium. For the test material the temperature dropped by 18 Celsius degrees in the moist deposit, but more than 25 Celsius degrees for the dry deposits as detected by the sensor fitted at a distance of about 120 mm from the heating pipe. The sensor is located at a distance of 15 mm from the heating pipe recorded temperature 1.5 Celsius degrees lower. These values determine the distribution of (distance between) pipes of the heat exchanger in the proposed thermal store. Because the temperature distribution around the heating pipe is symmetric, these tubes must be distributed evenly throughout the volume of the storage and must not be placed only in the bottom area.

Tests were carried out also for other materials, such as sands of 0.5 mm grain, gravel, and garden soil. The results will be used in developing guidelines for designing sensible heat stores based on granular deposit with no liquid flow.

Finally, it should be pointed out that, taking into account the density of the stream of the stored energy, sensible heat stores are not competitive to PCM ([16]) stores using chemical reactions or sorption. There is a point, however, in doing research on sensible-heat storage because of the prevalence of granular deposits in construction - as foundation walls filling, substructure of public squares, etc. To build a sensible-heat store in such areas requires, therefore, only small investment costs, which in turn positions such stores high in terms of economic criteria. Not without significance is also the volume of the space filled with a granular material, which can easily allow of storing the appropriate amount of heat for the building. Therefore, this solution should be popularized in the construction industry.

The research results presented in this paper are part of the above mentioned area of research into using the commonly available and inexpensive materials for energy storage. It should be noted that this area of research is closely related to engineering activities, and thus it fits into the current trend of cooperation between science and industry.

Notation

Q - stored thermal energy [J],
m - mass [kg],
c_w - specific heat, J/kg·K
T - temperature, K
k_ε - stagnant conductivity, that is effective thermal conductivity of porous media filled with stagnant fluid for both unconsolidated and consolidated particles, W/m·K
k_g - thermal conductivity of fluid, W/m·K
k_s - thermal conductivity of solid, W/m·K
ΔL - effective lenght between centers of two neighboring solid particles in direction of heat flow, m
l_s - effective lenght of a solid particle for heat transfer in a bed of unconsolidated particles, m
l_v - effective thickness of the fluid film adjacent to the surface of two solid particles, m
α_p - heat transfer cofficient representing the heat transfer rate through the contact surface between solid particles in a bed of unconsolidated particles or between two clogged particles in a consolidated bed, W/m^2·K
α_{rv} - heat transfer cofficient for thermal radiation, void space to void space, W/m^2·K
α_{rs} - heat transfer cofficient for thermal radiation, solid surface to solid surface, W/m^2·K
ε - void fraction of a packed bed of unconsolidated particles

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