World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:8, No:2, 2014

Thermal Properties of the Ground in Cyprus and Their Correlations and Effect on the Efficiency of Ground Heat Exchangers

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Abstract**—**Ground Coupled Heat Pumps (GCHPs) exploit effectively the heat capacity of the ground, with the use of Ground Heat Exchangers (GHE). Depending on the mode of operation of the GCHPs, GHEs dissipate or absorb heat from the ground. For sizing the GHE the thermal properties of the ground need to be known. This paper gives information about the density, thermal conductivity, specific heat and thermal diffusivity of various lithologies encountered in Cyprus with various relations between these properties being examined through comparison and modeling. The results show that the most important correlation is the one encountered between thermal conductivity and thermal diffusivity with both properties showing similar response to the inlet and outlet flow temperature of vertical and horizontal heat exchangers.

Keywords**—**Ground heat exchangers, ground thermal conductivity, ground thermal diffusivity, ground thermal properties.

I. Introduction

GROUND Coupled Heat Pumps (GCHPs) perform better than Air Coupled Heat Pumps for heating and cooling because the ground has a lower temperature than the atmosphere in the summer and vice-versa in winter. To exploit effectively the heat capacity of the ground, Ground Heat Exchangers (GHEs) are used. Depending on the mode of operation of the GCHPs, GHEs dissipate or absorb heat from the ground. Therefore, the thermal properties of the ground are very important and need to be known when sizing the GHE.

Additionally, the temperature of the ground is mostly affected by the structure and physical properties of the rocks. For better understanding, some definitions of the main properties of the ground are introduced. According to ASHRAE Terminology of Heating, Ventilating, Air Conditioning and Refrigeration [1]:

Density is defined as the mass per unit of volume of a substance and is measured in kg m^{-3}.

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Thermal conductivity is the time rate of steady-state heat flow through unit thickness of unit area of a homogeneous material, induced by a unit temperature gradient in a direction perpendicular to that unit and is mainly measured in $Wm^{-1}K^{-1}$.

Thermal diffusivity is the physical quantity that determines the rate of heat propagation in transient-state processes. It is the ratio of thermal conductivity and the product of density and specific heat, and it is measured in $m^2\ s^{-1}$.

Specific heat is the quantity of heat required to raise the temperature of a given mass of any substance by one degree. Specific heat is measured in kJ $kg^{-1}\ K^{-1}$.

Another important factor is the porosity of a substance. Porosity describes the fraction of the volume of all the pores in a material, where the pores may contain air, water or a combination of both. In the case that the pores are air-filled, the substance is said to be at its dry state (0% degree of saturation). In the case where the pores are water-filled, the substance is said to be at its saturated state (100% saturation). Between the dry and saturated state of a substance, water and air or moisture may exist to some extent, defining its degree of saturation.

It is obvious that the most important property of the above, which determines the heat exchange process, is *thermal diffusivity.*

II. Thermal Response Test

In small plants such as for residential house applications, the thermal properties are usually estimated or calculated with the aid of empirical models. In such a case, the morphology of the ground in the area, the thermal conductivity, density and specific heat capacity of the different lithologies as well as the temperature of the ground at various depths are usually available from the National Geological Surveys or by geologists that perform geotechnical studies in the area. Unfortunately, in Cyprus data are limited due to the limited interest, during the previous decade, in the exploitation of geothermal energy for heating and cooling applications.

For the design of large scale applications it is important that the thermal properties of the ground should be measured on site. A pilot borehole is drilled and a GHE is installed of approximately the size (in diameter and depth) of the actual GHE. Water or heat-transfer fluid heated at a constant rate is circulated in the GHE and data are collected. This method for the in-situ determination of the thermal properties of the ground is known as the Thermal Response Test (TRT).

Information on the thermal properties of the borehole and its surroundings can be obtained by evaluating the increase or decrease of the temperature of the heat transfer fluid versus time. The greater the change in the temperature of the heat transfer fluid between the input and output leg of the GHE, the more conductive the borehole is. Also, the thermal resistance of the borehole can be obtained by evaluating the temperature difference between the heat transfer fluid and the surrounding ground. As the difference in the temperature between the heat transfer fluid and the surrounding ground increases, the borehole becomes less conductive. Mogensen [2] is reported as the first investigator who proposed the TRT as a method to determine the in-situ values of ground thermal conductivity. He circulated chilled heat-transfer fluid through the GHE at a constant heat extraction rate. The outlet fluid temperature was recorded continuously during the test and was compared with the results of a mathematical model simulating the heat transfer process of the borehole and its surroundings. From the TRT method the value of the thermal conductivity can be easily determined together with the borehole thermal Resistance for different fluid temperatures. The above procedure also requires knowledge of the ground specific heat and density, which can normally be deduced from the geological data of the site.

Another method for estimating the thermal properties of the ground is to collect rocks or drill chipping samples from the borehole, or obtain rock samples from locations that are lithologically identical to the conditions of the borehole. The collection of rock samples from the borehole may not always be feasible. Sometimes, the necessary equipment is not available, and most often the small diameter of the borehole (around 15–20cm) and its depth (usually over 100m) obstruct the extraction of the required samples. Samples can be easily collected from other locations but their thermal properties, and especially the thermal conductivity, may not always match the values for the actual borehole due to differences in density and saturation levels.

Yun and Santamarina [3] investigated the effect of thermal conduction in dry soils. According to their study, the contact quality and number of contacts per unit volume in granular materials, in relation to the presence or not of liquids or cementing agents in the pores, are the main factors affecting their thermal conductivity. Although, the thermal conductivity of minerals is larger than 3 $Wm^{-1}K^{-1}$, the thermal conductivity of dry soils made of minerals is less than 0.5 $Wm^{-1}K^{-1}$. This is due to the presence of air in the dry soils and its low thermal conductivity of 0.026 $Wm^{-1}K^{-1}$. The improvement of the interparticle contacts of dry soils and the reduction of their porosity enhance their thermal conductivity. Table I shows the factors that determine the thermal conductivity of soils as presented by Yun and Santamarina [3], based on selected previous studies.

Because of the above mentioned variations, the TRT gives more accurate results concerning the thermal properties of a borehole in relation to the sample collection method. A number of approaches can be employed for the case of TRTs to determine the thermal characteristics of the borehole and hence of the ground. These methods are based on the line source method, the cylindrical heat source method and the numerical method [4].

TABLE I
FACTORS THAT DETERMINE THE THERMAL CONDUCTIVITY OF SOILS

Factor	Features
Mineralogy	As the thermal conductivity of the solid increases the bulk thermal conductivity increases as well
Particle size	The bigger the particle the higher the thermal conductivity
Applied pressure	The higher the contact pressure the higher the thermal conductivity
Density/Gradation	The decrease of porosity leads to higher thermal conductivity
Water content	The higher the water content the higher the thermal conductivity
Pore fluid	The higher the thermal conductivity of the saturating pore fluid the higher the bulk thermal conductivity

III. The Geology of Cyprus

The topography of the island is controlled by the lithology and tectonic structure of its four terrains (Fig. 1). The Troodos Terrain forms the highest peaks in the central part of the island and the Keryneia Terrain forms the Pentadaktylos mountain chain on the northern coast. A juxtaposed suite of rocks in the south-western part of the island is referred to as the Mamonia Terrain. The Circum-Troodos autochthonous sedimentary succession covers all of these geological terrains. The following section attempts to give an account of the lithologies that are represented in the various formations that make up these terrains.

The Troodos Terrain (which here is considered to include the smaller Arakapas Transform Sequence, the Troulli inlier and the Akamas ophiolite) is the central bedrock unit of the island, consisting of a 90 million years old ophiolite complex. Its core consists of highly fractured harzburgite and serpentinized harzburgite making up the mantle sequence. Cumulate rocks such as dunite, wehrlite, pyroxenite, gabbro and plagiogranite make up the plutonic sequence. High peaks and ridges of hard diabase bedrock is the predominant feature in the western and eastern mountains. The lower ranges on the outer periphery of the complex consist mainly of a volcanic sequence of basaltic lava flows and pillows, topped with iron and manganese rich sediments.

The Mamonia Terrain in the southwest consists of groups of 200–70 million year-old formations. These formations include igneous, sedimentary and minor occurrences of metamorphic rocks. Deformation within the zone is quite intense as they have been severely broken and folded during their placement. Their juxtaposition formed thick and extensive melanges with a clay-rich matrix, referred to as the Mamonia Melange in the west and the Moni formation in the south. The northeastern peninsula of Karpasia and the rest of the Keryneia Terrain consist of an assemblage of allochthonous crystalline limestone blocks and thick sandstone beds.

The Circum-Troodos sediments consist of autochthonous, mostly carbonate sediments. The base of the succession is marked by the 750 m thick Kannaviou Formation consisting of bentonitic clays and volcaniclastic sandstones. The Troodos and Mamonia zones are topped with massive chalks, bands of chalk and marl and chalks with cherts of the Lefkara Formation, the first carbonate sediments. Equivalent to the Lefkara Formation in the south is the Lapithos Formation in the northern part of the island (which contains intrusions of pillow lava) being the oldest autochthonous unit in the Keryneia Terrain.

The depositional environment of the lower Miocene (constituting the beginning of the deposition of the Pachna Formation) is marked by a thick bed of reef limestone, the Tera Member, very well-developed in western Cyprus. Repetitive off-white chalk-and marl bed morphology dominates the rest of the Pachna formation which is intercalated with calcarenites and is topped by another reef limestone, the Koronia Member. In the central and southern lowlands, sequences of gypsum beds are known as the Kalavasos Formation and mark an important rock sequence found in most coastal Mediterranean regions, deposited during the Messinian Salinity Crisis, a 2000m drop in the Mediterranean Sea level which occurred about 6–5 million years ago. Reestablishment of the Mediterranean sea-level 5 million years ago is responsible for marly deposits across the whole Mediterranean basin. Locally, the marls were deposited in the shallow seas which today form the central and coastal lowlands.

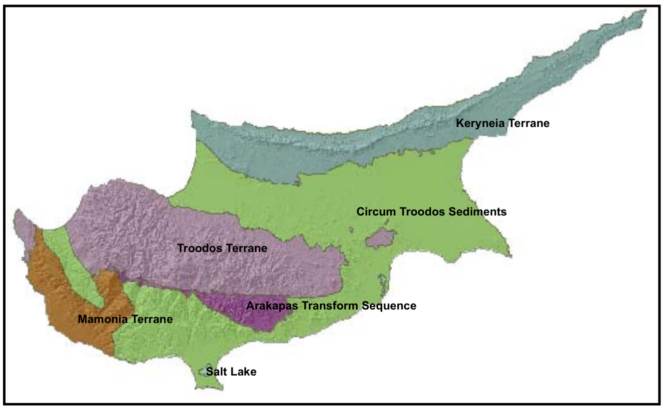

Fig. 1 Major terrains of Cyprus

IV. Thermal Properties of the Lithologies of Cyprus

For the direct measurement of the thermo-physical properties, thermal conductivity and volume heat capacity of the lithologies found in Cyprus, the Isomet 2104 portable heat transfer analyzer was used. The accuracy of the instrument when measuring thermal conductivity in the range of 0.015–0.7 W m^{-1} K^{-1} is 5% of the reading +0.001 W m^{-1} K^{-1}, while in the range 0.7–6.0 W m^{-1} K^{-1} is 10% of the reading. The instrument has a repeatability accuracy of 3% of the reading +0.001 W m^{-1} K^{-1}. The measurements were performed on various samples in their dry and water saturated state. All results measured with the Isomet 2104 portable heat transfer analyzer with a surface probe are shown in Table II.

TABLE II
Isomet 2104 Portable Heat Transfer Analyzer Results of the Thermal Properties of Ground Samples (In Gray Shade Are Shown the Samples Used in the Simulations)

Formation/ Lithology	λ W/m K	c_p J/kg K	ρ kg/m^3	α ×10^{-6} m^2/s	Condition
Tera limestone	1.22	654	2232	0.835	dry
	1.74	906	2347	0.818	saturated
Koronia limestone	1.51	718	2125	0.989	dry
	1.94	962	2234	0.902	saturated
Lefkara chalk	1.58	729	2304	0.940	dry
	1.70	733	2402	0.965	saturated
Pachna marly chalk	0.75	1020	1591	0.462	dry
	1.22	961	1862	0.681	saturated
Nicosia marl	0.50	806	1832	0.338	dry
	0.99	767	2155	0.598	saturated
Kalavasos gypsum	0.78	784	2075	0.479	dry
	1.19	757	2461	0.638	saturated
Nicosia calcarenite	0.36	296	1359	0.894	dry
	0.80	527	1777	0.854	saturated
Kalavasos gypsum	1.23	717	2301	0.745	dry
	1.19	753	2301	0.686	saturated
Ochre	0.72	690	2174	0.479	dry
Lower pillow lava	0.80	751	1997	0.533	dry
	0.97	805	2020	0.596	saturated
Upper pillow lava	0.82	749	2119	0.516	dry
	0.98	756	2225	0.582	saturated
Lava (Basal Group)	1.45	596	2728	0.891	dry
Gabbro	1.97	675	2749	1.061	dry
Wehrlite	2.65	630	2941	1.430	dry
Harzburgite	2.34	645	2708	1.339	dry
Plagiogranite	2.81	586	2893	1.657	dry
	3.16	703	2893	1.553	saturated
Diabase	3.76	522	3264	2.206	dry
	3.73	603	3264	1.895	saturated
Iron pyrite	9.06	392	4093	5.646	dry
Umber (silicified)	2.97	642	2773	1.668	dry
	3.14	690	2773	1.641	saturated
Pyroxenite	2.02	660	2718	1.126	dry
Serpentinite	2.29	641	2588	0.835	dry

The thermal conductivity of each sample is not constant but varies. This is due to the fact that the specific weight of the collected rocks also varies. Therefore, in Table II the mean values are presented.

V. Formulation of Mathematical Model for Geothermal Heat Exchangers

For time-dependent convection–diffusion the representative one dimension equation is

$$\frac{\partial \varphi}{\partial t} + u\frac{\partial \varphi}{\partial x} - \frac{\partial}{\partial x}(D\frac{\partial \varphi}{\partial x}) = S \quad (1)$$

where D = mass diffusion coefficient, u = horizontal velocity, φ = function under consideration, S = source or sink term [5]. Equation (1) was used to formulate the heat transferred from the fluid to each of the legs of the geothermal heat exchanger and through them to the borehole and soil material.

The heat equation representing the heat flow in the borehole and ground material per unit volume is

$$\rho_g c_g \frac{\partial T}{\partial t} + \frac{\partial}{\partial z}(-\lambda_g \frac{\partial T}{\partial z}) = 0 \tag{2}$$

where ρ_g = ground density, c_g = ground specific heat, λ_g = ground thermal conductivity, T = temperature and t = time. From (2) one can deduce the importance of the heat transfer process on the properties of the ground.

Details of the formulation and validation of the numerical models for the vertical and the horizontal GHEs can be found in [6].

VI. Results and Discussion

As a first step, the correlations between the various ground properties are investigated. As it is observed in Fig. 2, when plotting the relevant properties of Table II for dry and wet samples, there is a positive correlation between ground density and ground thermal conductivity, with an *R*-squared value of 0.81.

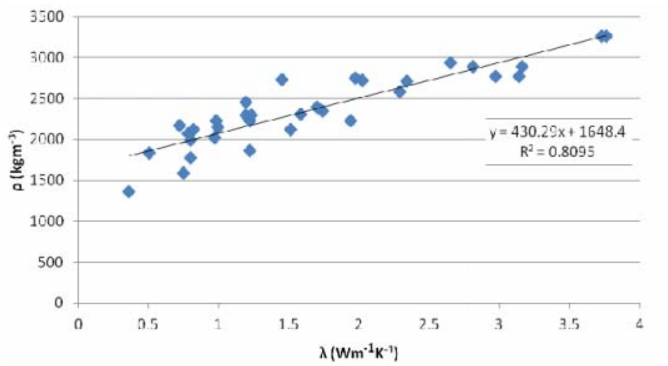

Fig. 2 Correlation between ground density and ground thermal conductivity

An even better correlation is observed between ground thermal diffusivity and ground thermal conductivity with an *R*-squared value of 0.88, as shown in Fig. 3.

All other combinations show weaker correlations as indicated in Table III. This could indicate that the most "important" property of a sample is its thermal conductivity, and studying its effect on the temperature of the GHE should be equivalent to studying the effect of thermal diffusivity. For the reason above, the effect of the ground material on the inflow and outflow temperatures of two types of GHEs (vertical and horizontal) is studied through simulations with respect to thermal diffusivity and thermal conductivity of different materials. Since thermal diffusivity, $\alpha = \lambda/(\rho c)$, is a measure of the rate at which heat travels through a material, it is expected that a material with high thermal diffusivity allows heat to propagate more rapidly. For the simulations a number of materials, as shown in Table I (shaded rows), were used.

The results show that diffusivities below a value of 16×10^{-6} m^2 s^{-1} are very significant since the lower their value the greater the temperature of the GHE is. Diffusivities above this value do not contribute further to the effect of the vertical GHE because they do not produce any appreciable difference on the fluid temperature flowing out of the GHE. As observed in Fig. 4, the effect may be an increase in the outflow temperature of about 6.5 K for a value of 3.4×10^{-6} m^2 s^{-1}. By plotting on the same figure the corresponding thermal conductivity of each ground layer versus the temperature of the inflow and outflow of the vertical GHE we observe a similar behavior as for the thermal diffusivity. In this case the critical value above which no additional effect is observed is 2.6 W m^{-1} K^{-1}.

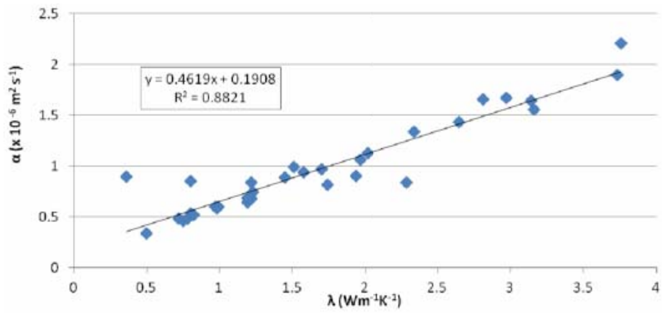

Fig. 3 Correlation between ground thermal diffusivity and ground thermal conductivity

TABLE III
Correlations between Various Ground Properties for Dry and Wet Samples

Plot of:	vs	*R*-squared value
$1/\rho_g$	α_g	0.66
α_g	ρ_g	0.60
$1/c_g$	α_g	0.40
$1/(\rho_g c_g)$	λ_g	0.34
c_g	α_g	0.23
$1/(\rho_g c_g)$	α_g	0.22
ρ_g	c_g	0.07
c_g	λ_g	0.06

α_g = ground thermal diffusivity, ρ_g = ground density,
c_g = ground specific heat and λ_g= ground thermal conductivity

For all other ground properties combinations a similar analysis shows, as expected, that the there is no agreement in behavior (see for example Fig. 5, where the thermal diffusivity and the inverse of the product of density and specific heat are plotted against the inflow and outflow temperatures of the vertical GHE).

For the horizontal GHE (Fig. 6) the critical value of thermal diffusivity is about 20×10^{-6} m^2 s^{-1}, while a lower value of 3.4×10^{-6} m^2 s^{-1} will produce a temperature difference in the outflow temperature of about 3 K. The corresponding thermal conductivity of each ground layer shows again (as for the vertical GHE) a similar behavior with thermal diffusivity versus inflow and outflow temperatures. The critical value of thermal conductivity for which no additional effect is observed is 3.2 W m^{-1} K^{-1}. For all other ground properties combinations a similar analysis shows, as expected, that the there is no agreement in behavior (see for example Fig. 7).

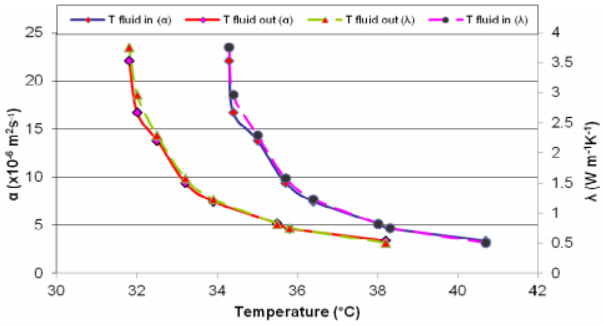

Fig. 4 Thermal diffusivity α, and thermal conductivity λ of the ground samples against inflow and outflow temperatures of the vertical GHE

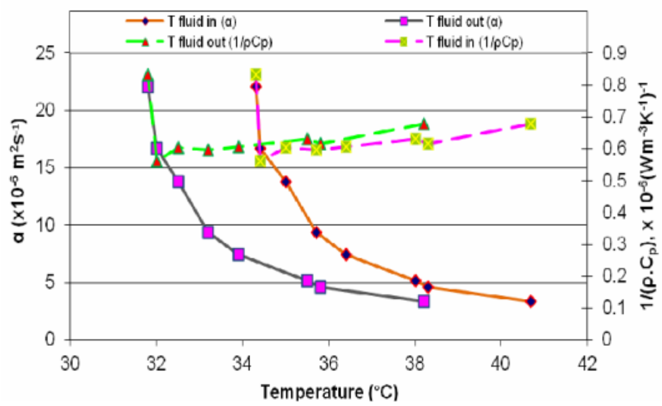

Fig. 5 Thermal diffusivity α, and the inverse of the product of density and specific heat $1/(\rho c_p)$ of the ground samples against inflow and outflow temperatures of the vertical GHE

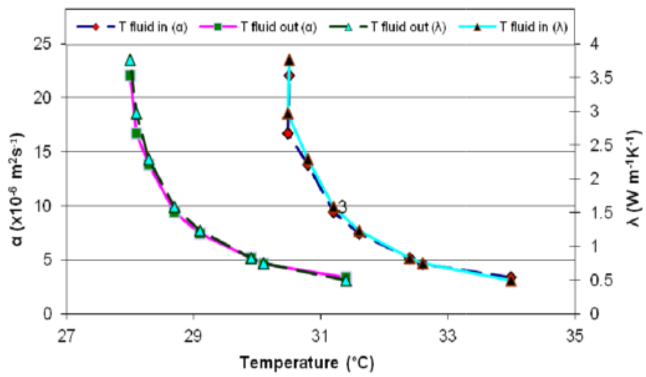

Fig. 6 Thermal diffusivity α, and thermal conductivity λ of the ground samples against inflow and outflow temperatures of the horizontal GHE

VII. Conclusions

Knowledge of the thermal behavior of the ground at various locations and depths is important for the design of geothermal applications as it determines the efficiency of ground coupled heat pumps for heating and cooling of buildings.

The line source method [4] is an easy way for determining the thermal conductivity of a borehole but knowledge of the ground specific heat and density is also required, which can normally be deduced from the geological data at the site.

Studying the correlation between various properties of ground samples showed that a very good correlation exists between ground thermal diffusivity and ground thermal conductivity and between ground density and ground thermal conductivity. All other correlations are less evident.

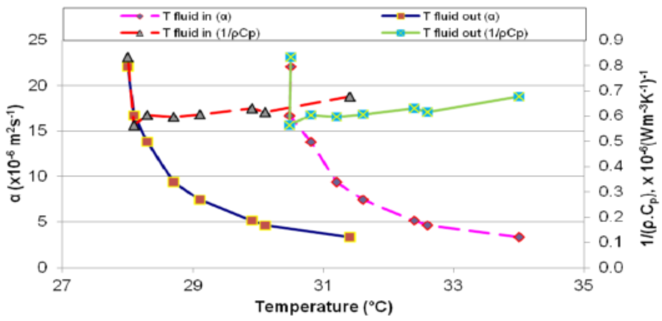

Fig. 7 Thermal diffusivity α, and the inverse of the product of density and specific heat $1/(\rho c_p)$ of the ground samples against inflow and outflow temperatures of the horizontal GHE

Studying the corresponding thermal conductivity and thermal diffusivity of each ground layer versus the temperatures of the inflow and outflow of the vertical GHE, we observe a very good agreement in behavior. For any other ground property combinations, the corresponding behaviors do not agree.

The above work will be enhanced in the near future with the study of over 100 rock samples that will enable more reliable conclusions to be drawn about the correlations between the thermal properties of the lithologies of Cyprus.

Acknowledgment

This work was carried out as part of a research project co-funded by the Research Promotion Foundation (RPF) of Cyprus under contract ΤΕΧΝΟΛΟΓΙΑ/ΕΝΕΡΓ/0311(ΒΙΕ)/01 and the European Regional Development Fund (ERDF) of the EU.

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