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Temperature increase of the elastic element determined to reduce vibrations due to its compression

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Abstract: Rubber material is very often used to dampen vibrations and reduce noise. Rubber as a material is one of the frequently used materials in mechanical engineering. This article will deal with elastic elements made of rubber. These elements are used in various transport and mechanical devices. The article will investigate the temperature increase during the hardening of such an elastic element. For these investigations, we will use our device, which we have completely designed, constructed and manufactured at our workplace. Due to the hardening of the elastic element, the pressure in the elastic element will increase and probably the temperature as well. We will find out whether this temperature increase has an effect on the function of the device.

Keywords: temperature. pressure, elastic element, vibrations

Przyrost temperatury element elastycznego w wyniku kompresji jako istotny czynnik redukcji drgań

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Streszczenie: Guma jest powszechnie stosowana do tłumienia drgań i redukcji hałasu, będąc jednym z najczęściej wykorzystywanych materiałów w inżynierii mechanicznej. W niniejszym artykule skupimy się na elementach elastycznych wykonanych z gumy, które znajdują zastosowanie w różnego rodzaju urządzeniach transportowych i mechanicznych. Przeanalizowano wzrost temperatury powstający podczas procesu utwardzania takich elementów. Do przeprowadzenia badań wykorzystano autorskie stanowisko badawcze. Proces utwardzania powoduje wzrost ciśnienia w elemencie elastycznym, co prawdopodobnie skutkuje także wzrostem temperatury. W pracy sprawdzono, czy ten wzrost temperatury wpływa na działanie urządzenia..

Keywords: temperature. pressure, elastic element, vibrations

1. Introduction

Rubber as a material is one of the frequently used materials in mechanical engineering. This article deals with rubber, or flexible pneumatic elements, the main part of which is rubber. We determine the effect of alternating stress on the temperature change in the flexible pneumatic element under this variable load. We describe a device that serves this purpose. This device was designed and manufactured in our department. We also determine the effect of the air pressure of the flexible element on the temperature of the air and the temperature of the flexible elements. We need to

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find out the magnitude of these temperatures so that we can determine whether these flexible elements can work without significant negative changes in physical properties.

Rubbers are widely used in industry due to their scalable mechanical properties and low masses [1, 14]. It serves as a raw material for various industries, including automotive, construction, medical, and consumer goods Such as vehicle tires, footwear, surgical gloves, and parts and components for agricultural and industrial machinery. And also natural rubber plantations contribute to the environment sustainability as rubber trees absorb carbon dioxide from the atmosphere, helping mitigate climate change [2]. However it is well known that natural rubber has the disadvantages of low elasticity, low tensile strength and low abrasion resistance, which is its limit applications. In our department, rubber is used in flexible pneumatic elements. These flexible elements, which we use in flexible pneumatic shaft couplings and in various working and mechanical devices [3, 4, 5, 6, 7, 8, 9], dampen vibrations well. If there is a reduction in vibrations, we know that there is also a reduction in noise. These flexible elements are filled with air or other gaseous medium, which we have already studied in various other publications [10]. By being stressed, the air is heated and the rubber itself is heated, which can affect the properties of both the rubber and the mechanical device [11].

The values obtained during static loading are used for the basic classification of rubber materials. In static tests, time is of considerable importance (the values apply only to the normalized loading rate), the shape and dimensions of the test specimen, and the influence of temperature (at temperatures below –40 °C, rubber's properties approach those of metals, at temperatures around 100 °C many properties of rubber deteriorate significantly compared to the same properties at normal operating temperatures around 20 °C).

Overheating failure is one of the important problems restricting the operation ability of rubber track under high speed and heavy load condition [12]. In industry, natural rubber is widely used in manufacturing rubber track matrix with its excellent comprehensive mechanical properties. However, NR presents viscoelasticity, which lead to severe heat build-up under high frequency and high amplitude alternating stress during high speed and heavy load operation. Because NR processes poor thermal conductivity [13], the heat cannot dissipate in time, resulting in temperature sharply increasing inside the rubber track. Furthermore, the high service temperature seriously impairs the performance and life of rubber track. Therefore, the preparation of natural rubber materials with high thermal conductivity and low heat build-up is of great significance for the development of high-speed rubber track, and it is a technical problem to be solved urgently.

Elastic elements consist of rubber metal and mainly the load is transmitted by air pressure. It is important for us to know how this rubber or air will heat up.

The aim of this article is to determine the increase in temperature of the elastic element and the increase in temperature in the elastic element due to regular compression of this element. In our department, we have made a device to perform this measurement. We will dynamically load the elastic elements depending on time and monitor whether the temperature of the rubber does not increase to such a value when the rubber loses its properties. Because if the rubber loses its properties, the pneumatic shaft coupling may be damaged, as well as the device in which this coupling is located. This can cause a risk of injury or in the event of damage to the device, great financial damage to the device. It can also cause the device to be shut down, which nowadays can also cause great financial losses for the company that uses the device [13,15, 17].

2. Materials and Methods

In this part of the article, we will describe our measuring equipment and also describe in detail the flexible elements that we tested in our measurements.

2.1. Measuring device

The measuring device that we used to measure the temperature during dynamic stressing of elastic elements was developed in our department. We designed it as simply as possible to fulfill its purpose and at the same time to be simple and economical to manufacture. We assembled the entire device in our laboratory.

Testing rig consists of a frame (1), in which the pneumatic flexible member is mounted (2), oscillating mechanism (3), an electric motor (4) with continuous frequency control between 0 and 50 Hz. Digital multimeters M-3870D METEX with temperature probe ETP–003, and measurement range −50 °C to +250 °C have been used. Temperature probes were set up in three locations where temperature was measured. The following temperatures were measured:

▪Air temperature inside the flexible member Tair

▪Temperature of the inner surface of the flexible member Tin
▪Temperature of the outer surface of the flexible member Tout
Testing rig was thermally insulated. In Fig. 1, the part of thermal insulation of testing rig is visible. During experiments, a stable temperature was maintained in isolated volume around the testing rig.

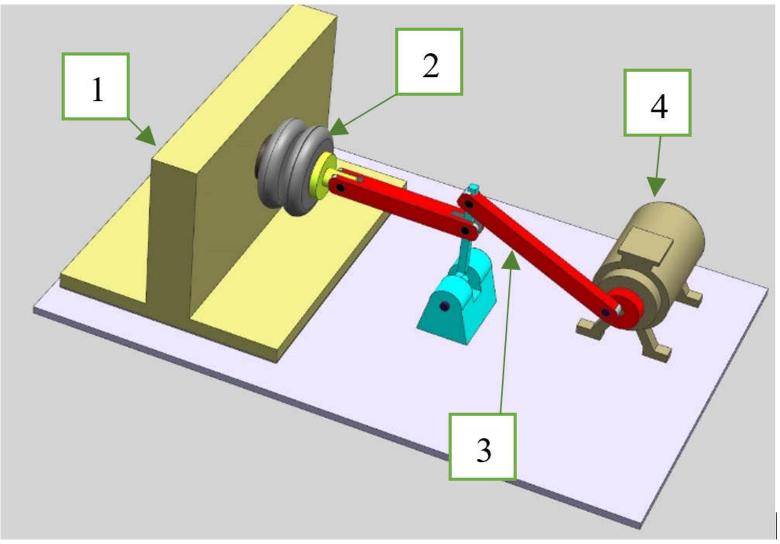

Figure 1. 3D model of measuring device

Temperature of the surroundings (which is the same as all the temperatures throughout the system at time t = 0 s) was T_0 = 22 °C. Sampling resolution was 1 min. Temperatures were recorded at times t = 1, 2, 3, … 30 min at constant frequency and amplitude of oscillations and varying air pressure. During experiments, the influence of the environment was minimized by the use of thermal insulation and by maintaining stable temperature conditions around the testing rig. The maximum resolution of temperature probes was 0.5 °C. The reference value of frequency in the experiment was f = 13.5 Hz. This operating condition represents the resonance condition (resonance frequency and amplitude) of the device where the pneumatic tuner was employed.
The amplitude of linear displacement at the flexible member was constant: A = 4 mm.

2.2. Pneumatic element

For the measurement, we used a double corrugated elastic element shown in Fig. 2. We use these elastic elements in flexible pneumatic shaft couplings that we design at our workplace. These elements are structurally simple and absorb shocks and vibrations well [16]. The main part is a flexible rubber element whose 3D model is shown in Fig. 3. The diameter of this flexible element is 700 mm and the height is 90 mm. This rubber is attached between the lower and upper flanges shown in Fig. 4. The flanges are fastened together with 8 screws as shown in Fig. 5. We can easily disassemble and assemble the simple structure.

Figure 2. Flexible pneumatic element.

Figure 3. 3D model of the rubber used in the flexible element.

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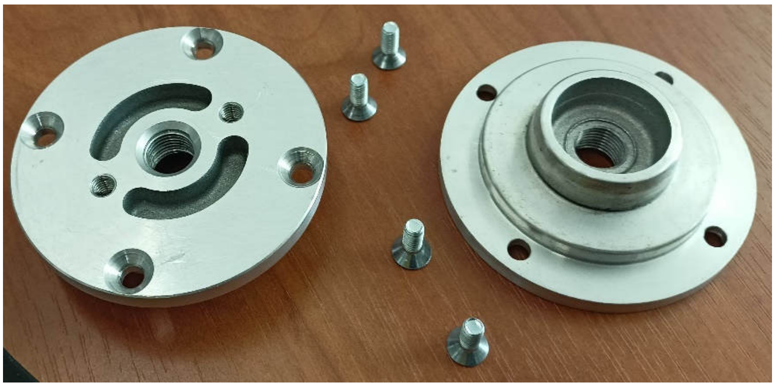

Figure 4. Top and bottom flange of the flexible element with used screws.

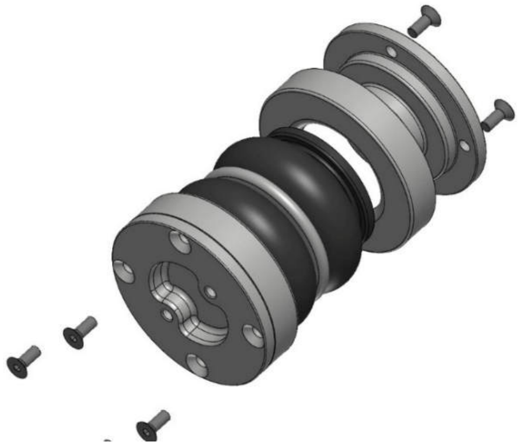

Figure 5. Disassembled structure of a flexible pneumatic element.

We loaded this double-corrugated element with alternating stress in the direction of the force +F and in the opposite direction –F. The directions of these forces can be seen in the schematic representation of the element in Fig. 6.

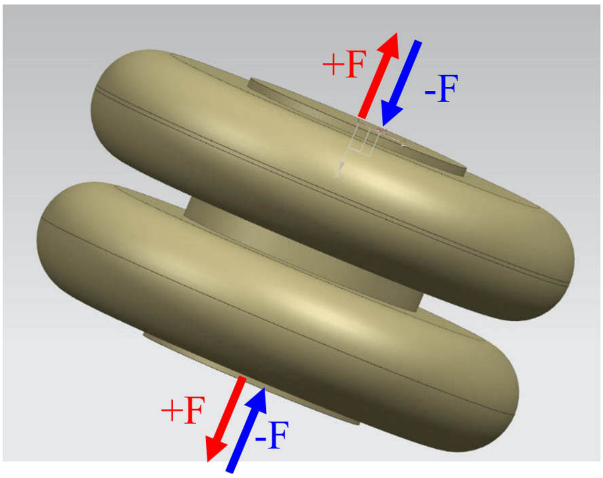

Figure 6. 3D model of an elastic element with the direction of force loading.

3. Analysis of heat conduction in an elastic element

We stressed the elastic element dynamically as indicated in Fig. 6. As a result of compression and expansion, the air and rubber heat up. The heating of the rubber-cord material of the elastic element during its periodic compression has two sources.

The first source is the air enclosed inside it. During periodic compression, it is alternately heated and cooled - these temperature changes then affect the material in which the air is enclosed [8]. However, it has been proven that, due to the high frequency of volume changes (200 - 600 min^{-1}) and low thermal conductivity, this fluctuation in air temperature affects only a thin surface layer (less than 0.1 mm) of the inner part of the material. Nevertheless, the heat exchange between air and material is important and must not be neglected - otherwise we would end up in a physically absurd situation where air with the original (and lower) temperature would be enclosed inside the heated rubber-cord material. The second process present here is the heating of the rubber material due to heat losses during its periodic deformations. For the sake of completeness, let us add that in addition to heating, there is also heat transfer to the air around the elastic element. Balancing the heat balance of all the processes involved results in achieving an equilibrium temperature in the system.

A certain complication is the low thermal conductivity of the rubber material. This causes the inner and outer surfaces of the elastic element to have different temperatures (experimental measurements clearly show this). Therefore, we cannot assume the same temperature value for the entire volume of the elastic element at time t.

The amount of heat transferred by conduction is proportional to the cross-sectional area through which the heat flows. Since the cord fibers woven into the rubber form only a negligible part of its volume, they will probably be insignificant for heat conduction.

The heat conduction equation describes the heat conduction in the environment - a partial differential equation that relates the instantaneous temperature distribution in the volume T(x, y, z, t) and its time evolution (thus giving the value of the time derivative of the temperature at each point in the volume). The aforementioned equation has the form:

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=\rho c\frac{\partial T}{\partial t}, \tag{1}$$

Where:

c – is the specific heat capacity of the rubber material (J/kgK),

ρ – its density (kg/m^3),

λ – heat conduction coefficient (W/Km).

In the numerical solution, we will further investigate the heat conduction in a pneumatic-elastic element as a one-dimensional problem. We assume that heat in its cross section flows only in the direction normal to the surface. In addition, there are two other directions in which heat could flow along the surface of the element in the circumferential direction (in Figure 4) and perpendicular to it (in Figure 7, the y direction).

The x direction is excluded due to the symmetry of the element - it heats up equally everywhere along the circumference, so there is no reason for any temperature differences and heat flow to arise in this direction.

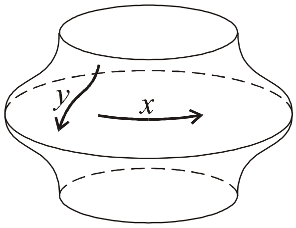

Figure 7. Directions of heat propagation in an elastic element

The y direction is more complicated. If we consider the generation of heat in the volume of rubber, it follows from the theory that the amount of heat generated depends on the magnitude of the changes in the deformation of the elastic environment. Looking at a deforming element, it is clear that not every part of its surface is stressed equally during deformation, and therefore individual parts will heat up differently. However, in all calculations we give a single number for the surface temperature. It is therefore necessary to bear in mind that the actual value will fluctuate around it and will not be the same for all parts of the element. Fortunately, the differences in mechanical stress of individual parts of a flexible element probably do not differ many times. Moreover, the generation of heat during the stress of the rubber is not the only factor; often the generation of heat during turbulent air flow in the hoses connecting the flexible elements has a much greater influence. It can be stated that the temperature differences on the surface of the element should not be too large and by not considering them we are not making a fundamental mistake.

4. Results of experimental measurements

Testing rig was thermally insulated. Temperature of the surroundings (which is the same as all the temperatures throughout the system at time t = 0 s) was T_0 = 22 °C.

Sampling resolution was 1 min. Temperatures were recorded at times t = 1, 2, 3, 4, 5… 30 min at constant frequency and amplitude of oscillations and varying air pressure. During experiments, the influence of the environment was minimized by the use of thermal insulation and by maintaining stable temperature conditions around the testing rig.

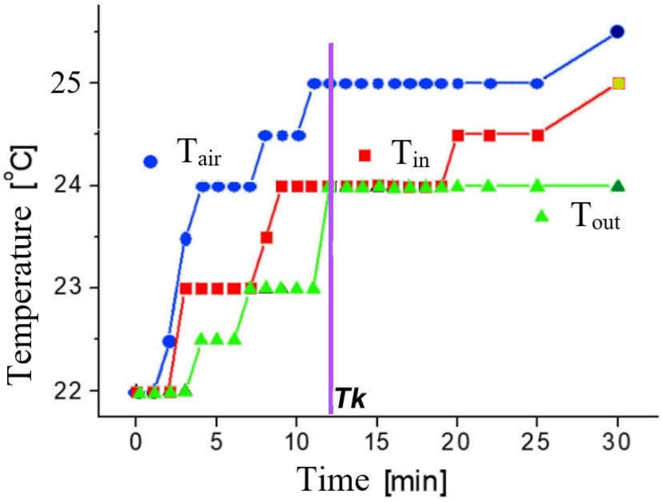

Figure 8. Temperatures as a function of time at pressure changes of 200kPa in the elastic element.

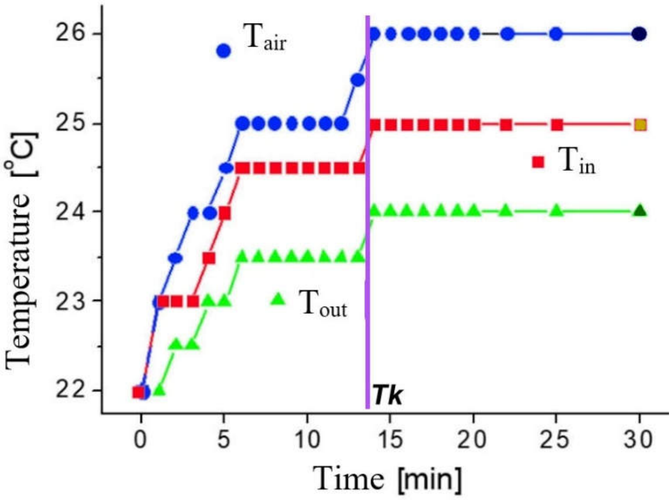

Figure 9. Temperatures as a function of time at pressure changes of 600kPa in the elastic element.

The maximum resolution of temperature probes was 0.5 ° C. The reference value of frequency in the experiment was f = 13.5 Hz. This operating condition represents the resonance condition(resonance frequency and amplitude) of the device where the pneumatic tuner was employed. We performed the measurements at 2 pressures. This means that the flexible pneumatic element was pressurized to a pressure of p=200kPa and then we tested the maximum pressure of p=600kPa.

In Fig. 8 and Fig. 9 we have shown the time Tk. We have called this time the stabilization time. It is the time when all temperatures have stabilized and no longer change significantly. For a pneumatic element pressurized to a pressure p=200kPa, this time Tk=12 min. For a pneumatic element pressurized to a pressure p=600 kPa. this time Tk=14 min. After reaching this limit, the temperature no longer changes.

Air pressure inside the pneumatic flexible member took up discrete values: p = 200 and 600 kPa. The amplitude of linear displacement at the flexible member was constant: A = 4 mm. The results of measurements were plotted. Fig. 8 and Fig.9 display the temperature evolution recorded by all three probes at oscillation frequency of f = 13.5 Hz and at different values of air pressure inside the pneumatic flexible member.

At 200 kPa pressure (Fig. 8), the temperature evolution was similar. The first temperature equilibrium occurred after 12 min for air temperature T_{air} at 25 °C. Subsequently, the temperature of the outer surface Tout was stabilized at 24 °C. Finally, the temperature of the inner surface Tin was stabilized at 24.5 °C.

At 600 kPa pressure (Fig. 9), the evolution of temperatures is similar to the evolution of temperatures at 500 kPa and 400kPa and 300kPa pressure. All three temperatures stabilized at the same time. Maximum temperatures are T_{air} = 26 °C for air inside, T_{in} = 25°C for inner surface and Tout = 24 °C for outer surface. If we compare the results from the measurements presented in Figs. 5–7, we can say that the air temperature inside the tire flexible member T_{air} reached maximum values in the range 25–26 °C.

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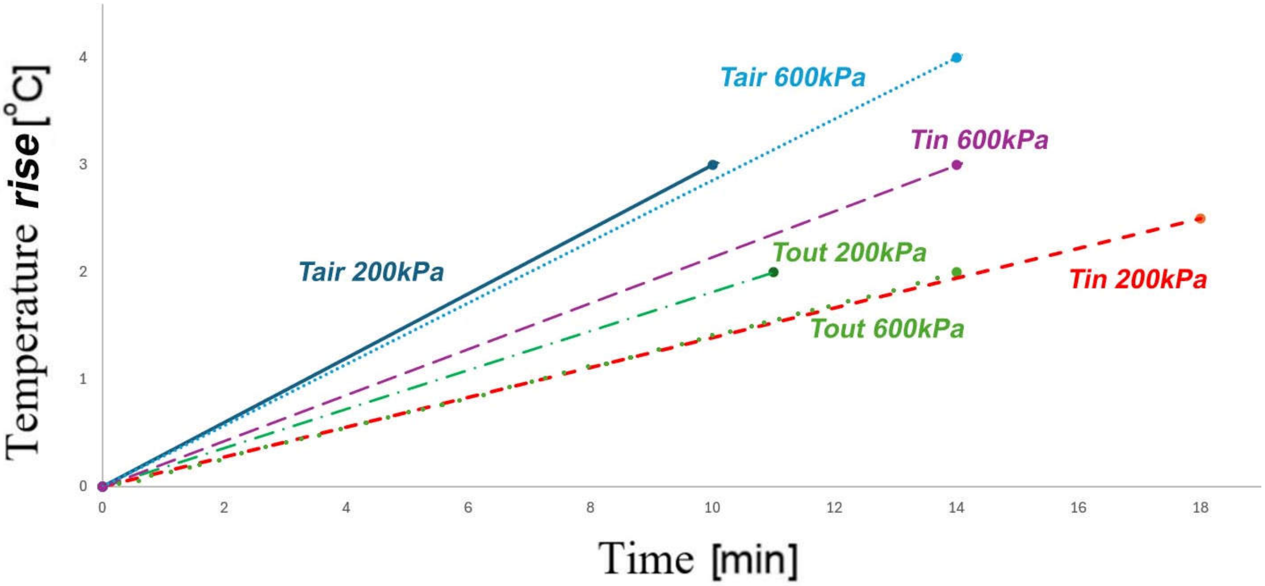

Figure 10. Temperature increase when compressing the elastic element for pressures of 200kPa and 600kPa.

At low pressures 200 kPa the air temperature T_{air} reached the maximum value 25.0 °C after 10 min of measurement already. At higher pressures (600 kPa), a stable temperature of 26 °C was reached only after 15 min of measurement. Interestingly, at these higher pressures the temperature throughout the system stabilized at the same time. On the contrary, the biggest difference in measured stabilization times was recorded at low pressures.

The temperature increase as a function of time can be seen in Fig. 10. The maximum values of the temperature increase vary depending on the pressure. These values are different at a pressure of 200kPa and different at a pressure of 600kPa. However, we can state that the maximum temperature increase is the increase in air temperature. The elastic elements heat up less and more slowly. The temperatures do not reach extreme values and thus do not affect the properties of the rubber.

5. Results

This article examines the increase in temperature of an elastic element, the temperature of air when compressing this elastic element. After performing the measurement on the test device that this article describes and also describes the flexible element used in this device, we can state several conclusions. For the measurement, we chose a low pressure of 200kP and a high pressure of 600kPa. During the measurement, the temperature stabilized after 10 to 15 minutes and then did not change. From the measured values, we can conclude that the pressure does not have that much influence on the temperature change. The temperature differences at low and high pressure are not that great. The measurements also show that during dynamic stress, the pneumatic element as well as the air heat up to a maximum temperature of 26°C. The increase in temperature was a maximum of 4 °C, as shown in the last graph in fig. 10. This temperature is not at all critical for us because it does not endanger health and also does not change the properties of the rubber that could cause malfunction or damage. We can therefore conclude that the flexible elements handle dynamic loads and there is no significant increase in temperature, which would be dangerous for us. The temperature increase will also be influenced by the stress frequency of the elastic element, which we want to address in our next research. From the measurements so far, we can conclude that the conditions are favorable, the increase in temperature is not extreme and does not have a significant effect on the functionality of the flexible elements. Flexible elements will work without problems and will not have a reduced ability to dampen vibrations in the device, which is very positive.

Acknowledgments

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