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ENERGY ABSORBED BY A MICROWAVE-IRRADIATED POTATO TUBER

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Abstract. The study aimed at the determination of the power absorbed by a potato tuber during its microwave-heating with regard to its electrical properties and biometric characteristics. Seed-potatoes, put in the microwave cavity with the capacity of 15.7 dm^3, were irradiated for 10 seconds with microwaves at frequencies of 2.45 GHz generated by a 100 W magnetron. The results showed that the method adopted in the experiment allowed for the estimation of microwave energy absorbed by the irradiated potato tuber and for its expression as the amount of absorbed power.

Key words: microwave, energy, potato

INTRODUCTION

The concept of power is defined, among others, as a scalar physical quantity determining the energy emitted in a particular unit of time. In connection with the issues related to the effects of electromagnetic radiation on the seed material it is necessary to determine the energy absorbed by the plant tissue. Such an approach to this type of experiments is required for the reasons of standardization of research, mainly because of their repeatability and comparability of results, and so that the achieved results were not only of the phenomenological character. In the case of exposure of biological objects to microwave radiation, a direct measurement of energy (induced power) in the irradiated material is not possible. This limitation has forced researchers to look for and to apply indirect methods of expressing the energy absorbed by biological objects during their exposure to electromagnetic radiation. Kubacki et al. [2007], Pietrzyk [2006] and Szarycz [2001] have determined the energy absorbed by a living organism by formulas taking into account, among others, electric field strength, conductivity and permittibility of an object, density of irradiated tissue, frequency of the electromagnetic wave and coefficient of dielectric losses. According to Lisowski [2004] and Łuczycka [2009], in the microwave frequency range (10^8–10^{12} Hz), the measurements of dielectric perme-

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ability of an object (ε) and tangent of loss angle (tg δ) of a dielectric with a low dielectric loss factor (tg $\delta \leq 1 \cdot 10^{-2}$) are performed only in the resonator cavity, setting the detuning and changing of the resonator quality after the introduction of the tested sample. To determine ε and tg δ of dielectrics with tg $\delta \geq 1 \cdot 10^{-2}$, measurements of the impedance in the slotted coaxial lines and waveguides are carried out [Barba et al. 2008]. In their experiments related to the irradiation of potato plants (*Solanum tuberosum* L.) with microwaves, in order to determine the energy absorbed by the bulb, Marks et al. [2003] used the parameters which were the compilation of the power of microwave generating device (P_0), the exposure time (t) and the mass of the heated material (m_B). This resulted in two parameters expressing the theoretical values: the total dose (D_C) of microwave radiation (which is the product of the present power generating device and the microwave exposure time) and the unit dose (D_J) of microwave radiation (obtained by dividing the total dose of microwave radiation by the mass of potato tubers).

In the studies of Marx et al. [2003] and Jakubowski [2010], the actual values of microwave radiation doses, taking into account the losses associated with exposure of potato tubers, were determined on the basis of the information presented in the work of Miki and Kasprzak [2004]. The way to determine energy (in unit dose) proposed by Marx et al. [2003] is a simple, non-invasive method of assessing the impact of microwaves on the subsequent processes of progeny plants ontogeny. It is important, however, that energy absorbed by a biological object should be expressed with regard to the electrical properties of the irradiated biological material [Szarycz et al. 2002, Pietrzyk 2006, Łapczyńska-Kordon 2007, Łuczycka 2009]. Such parameters are the values of electric field strength in the dielectric placed in the microwave cavity as well as the dielectric loss factor of the irradiated material. The overall objective of this study was to determine the power absorbed by a potato tuber during its microwave heating, taking into account its electrical properties. The value of power absorbed by the potato tuber during microwave heating was related to its biometric characteristics. Subsequently, the correlation connections were tested between the calculated values of the power absorbed by the potato tuber and its biometric properties as well as the absorbed unitary doses of microwave radiation.

MATERIAL AND METHODS

The study was performed on the material derived from the field experiment performed by the author in 2007–2009, which investigated the effect of the time of microwave stimulation of seed-potatoes on the growth and development of very early potato varieties Bona Felix, Rosara and Velox [Jakubowski 2010]. The choice of empirical data was dictated by the results of analysis of variance, which did not confirm a significant impact of the year of research or the applied variety on the tested dependent variable (plant growth and development). In this experiment, seed-potatoes were irradiated with microwaves at fixed parameters (microwave frequency $f = 2.45$ GHz generated by the magnetron power of $P_0 = 100$ W for the time $t = 10$ s). A single potato tube was placed on a rotating bed in the microwave cavity (with the capacity of $V_k = 15.7$ dm^3). Microwave generator was equipped with a precision timer. To conduct pilot studies for the presented experiment, 150 (N_P) empirical data were randomly selected from the above-described experiment. On the basis of the results of pilot studies, using Statistica 8.0, the minimum sample size was calculated for the designation of power absorbed by the potato tuber during its microwave heating, considering its electrical properties. During the determination of the minimum sample size, t-test was used for a single sample (with known values of the average of 2.39 in the population and the standard deviation 8.9), an output target of 0.9 test power and the test error probability of the first kind $\alpha = 0.05$. The minimum sample size of 148 (N_{MIN}) was received at the standardized effect of 0.27. Considering that $N_{MIN} < N_P$, in further calculations the value of N_P was assumed. The study involved the author's earlier research [Jakubowski 2010], which included the results of measurements of length, width, thickness and weight of potato tubers. The length of a tuber was determined as the distance from the stolon root to the tuber tip, the width as the higher dimension of the largest horizontal section and the thickness as the smaller dimension of the largest horizontal section. Using a laboratory balance with the 0.1 g accuracy, before placing a potato tuber in the cavity of the microwave-generating device, its mass m_B was defined (the range of seed-potatoes weight, considering the year of research and variety, did not exceed 14.1%). The regression curves were matched with the empirical variables by the method of least squares. It was assumed that the delivery to the empty cavity (microwave resonance cavity), of microwaves of the power P_0 will generate the electric field of the strength E_0 in the cavity (1).

$$E_0 = \sqrt{\frac{P_0}{2\pi f \varepsilon_0 V_k}} \ (\mathrm{V \cdot m^{-1}}) \tag{1}$$

At the same time, after placing the dielectric (potato tuber) in the cavity, the compensating field of the sign opposite to the field E_0 will be created in the tuber. Irradiation of the potato tubers located in the microwave cavity in the initial phase of the process will be associated with bringing the power P_{B0} to the cavity (2), and then the tuber will produce the electric field with the intensity of E_B dependent on the value of dielectric loss coefficient ε''_B of the stimulated material (3).

$$P_{B0} = \frac{m_B \cdot c_{wB} \cdot \Delta T}{t} \ (\mathrm{W}) \tag{2}$$

$$E_B = \frac{E_0}{\varepsilon''_B} \ (\mathrm{V \cdot m^{-1}}) \tag{3}$$

The tuber electrical field will cause the reduction of its power. The value of the reduction can be expressed by the following dependencies (4 and 5):

$$P_B = 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot (E_B)^2 \cdot V_B \cdot \varepsilon''_B \ (\mathrm{W}) \tag{4}$$

$$P_B = 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot (E_B)^2 \cdot \left(\frac{m_B}{\rho_B}\right) \cdot \varepsilon''_B \ (\mathrm{W}) \tag{5}$$

The energy issues involved in the discussed process are essential for technological reasons. In this case, the energy question concerns the power of the electric field turned into heat in the elementary volume of the irradiated dielectric. Such an approach should oblige to account for the varied moisture contents of the tubers irradiated with microwaves. On the other hand, according to Szarycz [2001], the humidity of the material is included in the calculations in the case when in the irradiated biological object the rise of the temperature inside the dielectric is accompanied with the rise of internal pressure (inside each particle in addition to the gradient of temperature and humidity there is also a pressure gradient).

Potato tuber is a highly hydrated biological material with the capillary-porous construction, so in the case of internal pressure gradient presence the process of diffusion would be speeded up, and internal pressure differences (designated on the basis of the chemical potential of cell sap and the temperature of the particles) would account for the internal mass transport. The above-described phenomenon occurs in the case of drying processes which use different operating parameters of a microwave generator and much longer irradiation times, and when the applied magnetrons operate with much higher power values [Metaxas and Maredith 1983, Szarycz 2001, Lewicki and Jakubczyk 2004].

Taking into account also the author's own research [Jakubowski 2009 a, b], during the microwave irradiation of potato tubers (for minimizing the losses associated with the storage as well as for potential stimulation of seed-potatoes before placing them in the soil), the thermal effect occurs to a very limited extent (ΔT does not exceed 1°C). The fraction of biological materials has a poor ability to form bipolar connections, with the result that the absorption of microwave energy depends predominantly on their water content. On the other hand, the potato tuber is characterized by a lack of uniformity of distribution of dry matter versus water, which suggests taking it into account in the calculations in which the two parts are not separated. Apart from the above-mentioned parameters, the following values were assumed in the calculations:

c_{wB} = 3440 (J·kg^{-1}·°K^{-1}) – specific heat of potato tubers [Lewicki 1999],

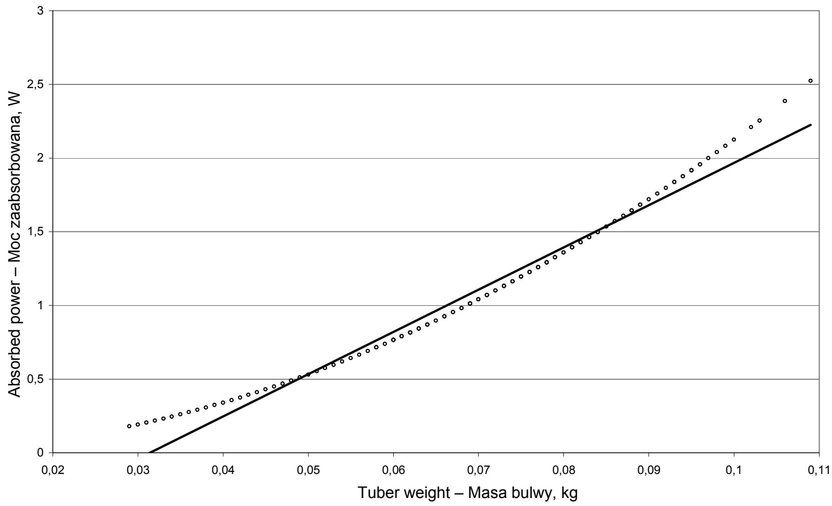
ε_0 = 8,85 · 10^{-12} (F·m^{-1}) – permittivity of vacuum,

ε''_B = 20 (-) – dielectric loss factor of the potato tuber [Barba et al. 2008],

ρ_B = 1,11 (kg·m^{-3}) – (mean) density of the potato tuber [Sobol 2006].

RESULTS AND DISCUSSION

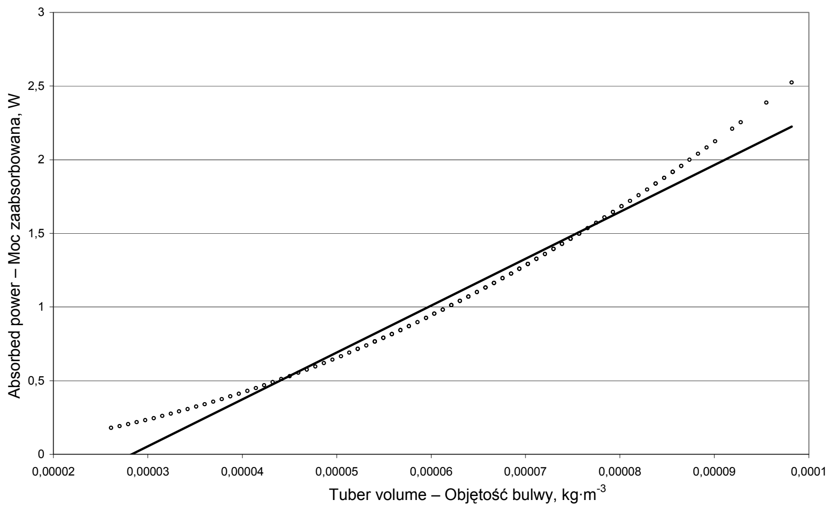
The presented equations (1–5) allowed for the calculation of the energy flux of micro-waves, emitted by a magnetron in a given unit of time (the absorbed power), received by the potato tuber with specific biometric characteristics. Inter-dependencies between the power absorbed by the potato tuber during its microwave irradiation and its biometric traits can be described by means of linear equations (figs. 1–3, tab. 1).



$$y = 28.7x - 0.9$$

Fig. 1. The relationship between the power absorbed by the microwave-irradiated potato tuber and its weight

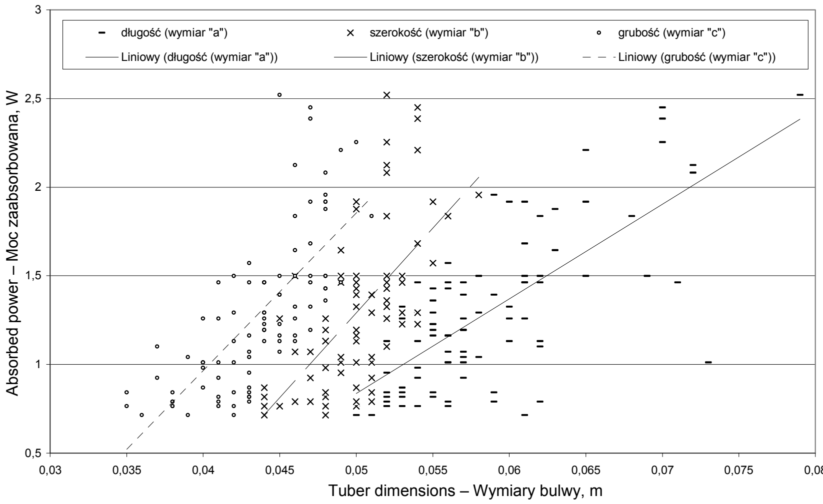
Rys. 1. Zależność między wartością mocy zaabsorbowanej przez napromienianą mikrofalami bulwę ziemniaka a jej masą



$$y = 31839x - 0.9$$

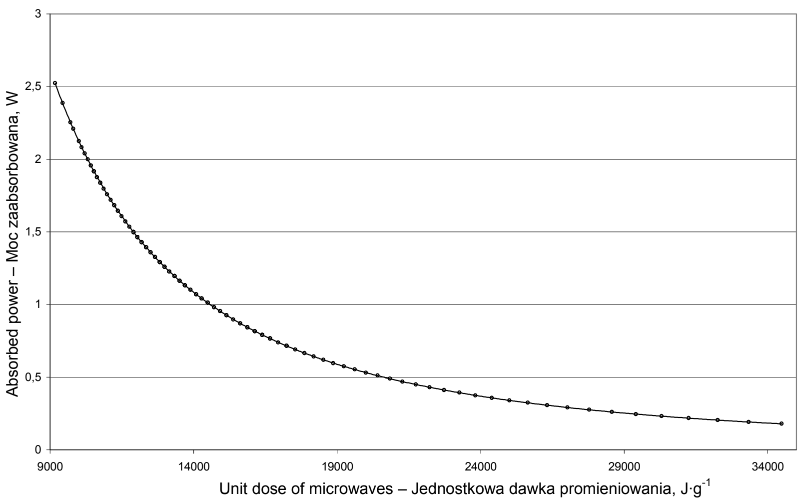
Fig. 2. The relationship between the power absorbed by the microwave-irradiated potato tuber and its volume

Rys. 2. Zależność między wartością mocy zaabsorbowanej przez napromienianą mikrofalami bulwę ziemniaka a jej objętością



$y = 53.4x - 1.8$ $y = 95.5x - 3.5$ $y = 88.9x - 2.6$

Fig. 3. The relationship between the power absorbed by the microwave-irradiated potato tuber and its dimensions
Rys. 3. Zależność między wartością mocy zaabsorbowanej przez napromienianą mikrofalami bulwę ziemniaka a jej wymiarami



$y = 2E + 0.8x^{-2}$

Fig. 4. The relationship between the value of power absorbed by the irradiated potato tuber and the unit dose of microwaves
Rys. 4. Zależność między wartością mocy zaabsorbowanej przez napromienianą bulwę ziemniaka a jednostkową dawką mikrofal

A strong dependence, determined by the value of the Pearson correlation coefficient, was shown by the relation of the power absorbed by the potato tuber to its weight and volume. A weaker relationship was found out between the power absorbed by the potato tuber and its length, width and thickness (tab. 1). This result is dictated by the specific character of the impact of electromagnetic radiation energy which is the sum of electric and magnetic fields as well as by the principle of conservation of energy in the electric and magnetic fields defined by the Poynting theorem and Maxwell's equations (and also, indirectly, by the Gauss theorem). These laws clearly show that the energy of electromagnetic radiation is absorbed within the considered volume. However, it should be noted that all these dependencies were characterized by statistically significant values of the Pearson linear correlation coefficients. The relationship between the power absorbed in the irradiated potato tuber and the unit dose of microwaves is described by power equation whereas determination and correlation coefficients are close to unity (fig. 4, tab. 1).

Table 1. The statistical relationships between the value of the power absorbed by the potato tuber and its biometric characteristics and the value of a unit dose of micro-wave radiation
Tabela 1. Statystyczne zależności między wartością mocy zaabsorbowanej przez bulwę ziemniaka a jej cechami biometrycznymi i wartością jednostkowej dawki promieniowania mikrofalowego

Type of dependence Rodzaj zależności	Equation describing the dependence Równanie opisujące zależność	Value of the coefficient of Wartość współczynnika	
		determination determinacji	Pearson linear correlation korelacji liniowej Pearsona
Absorbed power– tuber weight Moc zaabsorbowana – masa bulwy	$P_B = 28.7m_B – 0.9$	0.97	0.98
Absorbed power– tuber volume Moc zaabsorbowana – objętość bulwy	$P_B = 31839V_B – 0.9$	0.97	0.98
Absorbed power– tuber length Moc zaabsorbowana – długość bulwy	$P_B = 53.4a – 1.8$	0.51	0.72
Absorbed power– tuber width Moc zaabsorbowana – szerokość bulwy	$P_B = 95.5b – 3.5$	0.40	0.63
Absorbed power– tuber thickness Moc zaabsorbowana – grubość bulwy	$P_B = 88.9c – 2.6$	0.52	0.72
Absorbed power – the unit dose of microwave radiation Moc zaabsorbowana – jednostkowa dawka promieniowania mikrofalowego	$P_B = 2E{+}08D_j^{-2}$	0.99	-0.87
Pearson linear correlation coefficients significant for α = 0.05 Współczynniki korelacji liniowej Pearsona istotne dla α = 0,05			

The presented power equation was explained in 99% by regression, and the determined regression model can have a utilitarian value. The significant relation of the value of power absorbed in the irradiated potato tuber to the unit dose of microwaves will probably be involved in the setting of similar variables – sample weight (volume), exposure time and generator power – in both the presented parameters.

Therefore, it can be assumed that in the presented experiment these very variables determine the microwave energy absorption process by the irradiated potato tuber. Research related to energy issues, defined as the energy of electromagnetic radiation absorbed by an elementary volume of the irradiated dielectric should be, according to the author, continued. Subsequent experiments on potato plants should include the different varieties and take into consideration not only whether they are early ones or what their application is going to be, but also the tubers maturity and their storage conditions. These variables have an impact on weight loss of potato tubers (water content) and their density. The latter parameters, in turn, are included in the calculation of energy absorbed by the irradiated potato tuber. Due to the fact that the relationship between the energy absorbed by the potato tuber during its microwave irradiation and its size was significant (fig. 3 and tab. 1), it would be recommended in successive experiments also to take into account the shape of the tubers (shape coefficient). The amount of absorbed energy and its spatial distribution in a biological object depend on the frequency of radiation and electrical parameters of the irradiated tissues (conductivity and dielectric constant – both of these parameters show the dispersion characteristics and depend on the degree of tissue hydration).

Bearing in mind that microwave radiation is subject to all the physical phenomena characteristic of wave motion, and during interaction with matter it can undergo reflection, fracture, absorption, diffraction, transmission, interference or polarization, further research should also take into account the loss of energy resulting from these phenomena.

In the case of research using other frequencies in the microwave range, it should be taken into account that the microwave radiation also exhibits quantum properties – clearer with the shorter wavelength, and with increasing frequency of radiation the value of the relative dielectric permittivity decreases and the true conductivity increases.

With the increase of the latter values, there is a greater absorption in the particular medium and lower penetration of microwave energy and the depth of microwave penetration into a tissue is inversely proportional to the amount of water it contains. Also, it is helpful to try and estimate the energy absorbed by the potato tuber by the SAR (Specific Absorption Rate) factor, as the biological effects associated with absorption of microwave radiation depend both on the amount of absorbed energy and the speed of its absorption.

The SAR is defined as the rate of energy absorption by the body mass, and it can be calculated by measuring the strength of electric field in tissues or by calorimetric methods [Olchowik 2002, Ciosk et al. 2005, Kieliszek and Kubacki 2006]. In the case of an electromagnetic wave, according to Maxwell's equations, the electric and magnetic fields are inextricably linked. On the basis of the presented formulas (1–5), it can be concluded that the microwave energy absorption by the irradiated potato tuber is mainly due to the electric field.

Such an approach probably stems from the specific activity of the magnetron that generates waves with the frequency of 2.45 GHz [Dvurechenskaya et al. 2010, Ziaja and Ozimek, 2010]. An essential part of the magnetron is an anode block with vacuum cavities, whose number and shape imply the desired characteristics of the microwave lamp. The anode is placed between the poles of a strong magnet, so that the tracks of electrons flying out of a hot cathode are curved. Electric vibrations induced in the cavities convert the resulting cloud of electrons into the electromagnetic standing wave and the electrons remaining in the cavities give away their energy (in the form of microwaves) outside in the electric field of the cavities [Marton and Marton 1980, Czarczyński 2003]. It follows that the essential task of the magnetic field is to modify the magnetic tracks and speed of electrons between the magnetron cathode and the anode. It is necessary to take into account that the potato tuber as a dielectric is subject (its dipole is) to polarization both by the magnetic and electric field but in practice it is assumed that the polarization of the electromagnetic wave is determined for its electric component (the magnetic component is perpendicular to it). It should also be taken into account that the potato tuber is a diamagnetic, therefore the magnetic field inside the bulb is comparable to the field outside. Most researchers, however [Metaxas and Meredith 1983, Lewicki 1999, Szarycz 2001, Lisowski, 2004, Łapczyńska-Kordon, 2007, Barba et al. 2008, Łuczycka 2009], in relation to the microwave processes used in the agri-food industry, uses formulas which take into account the electric field (without magnetic field). Notably, Pietruszewski [1999], conducting research on the magnetic biostimulation of spring wheat, specified the value of the exposure dose absorbed by the seed material and expressed it by the time of exposure in the magnetic field and the value of magnetic induction (neglecting the electric field).

CONCLUSIONS

1. The method adopted in the experiment allows for the estimation of microwave energy absorbed by the irradiated potato tuber and its expression as the amount of absorbed power.

2. The value of power absorbed by the potato tuber, as expected, during its irradiation with microwaves at frequencies of 2.45 GHz in the accepted work parameters of the generator of microwaves (100 W and 10 s) depended on the weight, volume and dimensions of the exposed material (Pearson's correlation coefficients took value in the range 0.63–0.98).

3. The relationship between the power absorbed in the irradiated potato tuber and the unit dose of microwaves can be described by means of power function.

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ENERGIA ABSORBOWANA PRZEZ BULWĘ ZIEMNIAKA W TRAKCIE JEJ NAPROMIENIANIA MIKROFALAMI

Streszczenie. Praca miała na celu określenie mocy absorbowanej przez bulwę ziemniaka w trakcie jej mikrofalowego ogrzewania z uwzględnieniem jej właściwości elektrycznych i cech biometrycznych. Sadzeniaki ziemniaka, umieszczone we wnęce mikrofalowej o pojemności 15,7 dm^3, napromieniano przez 10 s mikrofalami o częstotliwości 2,45 GHz generowanymi przez magnetron o mocy 100 W. Wyniki badań wskazują, że przyjęta w doświadczeniu metoda pozwala na oszacowanie energii mikrofal, pochłoniętej przez napromienianą bulwę ziemniaka, i wyrażenie jej poprzez wielkość mocy absorbowanej.

Słowa kluczowe: mikrofale, energia, ziemniak

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