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GENERAL EXPERIMENTAL TECHNIQUES

Magnetic-Field Strength Measurements in Ferromagnetic Materials for Determining the Orthogonal Biasing Effect

Yu. E. Adamian and S. I. Krivosheev*
St. Petersburg State Polytechnical University, ul. Politekhnicheskaya 29, St. Petersburg, 195251 Russia
**e-mail: ksi.mgd@gmail.com*

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Abstract—The mutual influence of orthogonal magnetic fields on ferrite magnetic characteristics was experimentally studied. Experiments were performed in a pulse mode using a compound specimen. An induction probe positioned in the gap between its parts was used in magnetic-field measurements. A numerical simulation showed that the field strength in the central part of the gap corresponds to the field inside the ferromagnetic material with an accuracy of 5–7%, if the gap width is substantially smaller than its length. The analysis of the measurement results demonstrates a substantial difference (by 30–50%) in the dependences of the magnetic permeabilities on the magnetizing-field strength in the collinear and orthogonal directions.

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INTRODUCTION

The structure of the magnetic field in ferromagnets may have a complex spatial character. Typical examples of the situations where it is necessary to consider for the joint action of several spatial magnetic-field components are ferrite antenna devices [1], elements of magnetic circuits of electric machines, and ferromagnetic elements of transforming devices and automatics. Such situations take place when developing magnetic nondestructive-testing methods [2, 3] and determining the force fields in ferromagnets [4].

To correctly take the material properties into account in such cases, it is insufficient to use the dependences $B(H)$ that are obtained under standard testing conditions. The necessity of taking the tensor character of the permeability into account, which is displayed in both isotropic and laminated materials, was shown in many studies [5, 6]. Because of the complexity of the experiments and representation of the measurement results that were obtained in this field, the experimental data may be somewhat contradicting (e.g., [7, 8]).

In connection with this, an urgent task that provides obtaining reliable and comparatively easily interpreted data is to perform experimental studies in a sufficiently simple geometry. Such a task may involve investigations of the influence of an external field, which is orthogonal to the operating magnetic flux, on a toroidal core with a rectangular cross section. The influence of the orthogonal component does not directly result in the induction of spurious voltages in the circuit but may influence the effective permeability of the core.

TASKS OF THE STUDY

The objective of this study was to investigate the influence of a transverse magnetic field on the effective magnetic permeability of a toroidal ferrite core, which is measured along the operating axis (toroidal field). Paper [4] is of methodological interest for the arrangement of measurements, because a facility for creating a field in a specimen using an external magnetic circuit is used in it.

One of the main problems in such investigations is a correct measurement of the magnetic-field strength in a specimen, which is magnetized by an external circuit. The technique used in the aforementioned papers to measure the ac magnetic-field strength consists in the use of a thin flat induction probe, which is placed in the immediate vicinity of the specimen wall. It is assumed that owing to the continuity of the vector $\mathbf{H}$ component that is tangential to the interface between the ferromagnet and external medium, the field strength, which is measured by an external probe near the interface, corresponds to the field strength inside the ferromagnet. Thus, from the standpoint of the probe geometry, the conditions under which the thin probe is positioned as close to the ferromagnet surface as possible, are optimal.

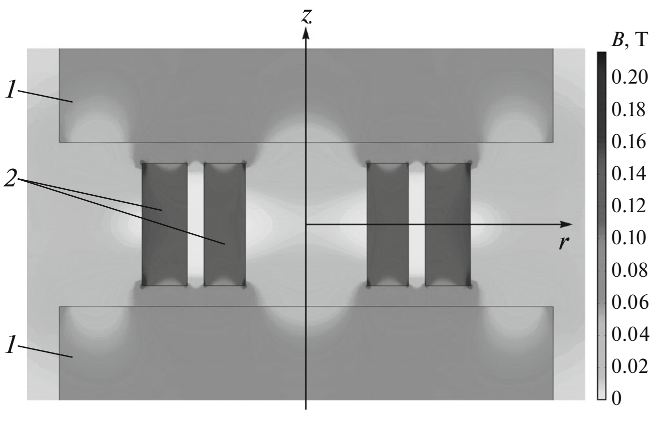

Fig. 1. Geometry of the calculated region: (*1*) magnetic circuit and (*2*) investigated specimen.

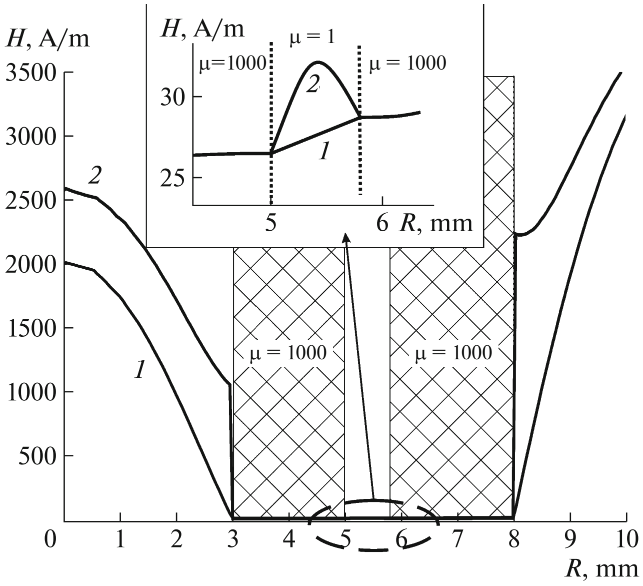

Fig. 2. Radial distributions of the magnetic-field strength in the specimen: (*1*) in the central cross section of the calculated region and (*2*) at a distance of ±1 mm from the central cross section.

The minimum probe thickness is limited by the technological possibility of its manufacturing and the small value of the obtained signal, especially at low frequencies. In the aforementioned study devoted to investigations of 3D characteristics of soft magnetic composites, small-thickness (0.5 mm) flat magnetic probes with a large number of turns (200) were used to measure the magnetic-field strength. The probes were placed on the central part of the specimen side surface.

It is obvious that the magnetic-field strength measurements using induction probes near the vacuum–ferromagnetic material (FM) interface does not allow unambiguous determination of the magnetic-field strength inside the FM. This is determined by large magnetic-field gradients near the boundaries and fixed dimensions (which are determined by the technical possibilities) of the measuring probes.

It becomes possible to determine the magnetic-field strength in a ferromagnet, if the approach proposed below is used. The magnetic-field strength measured outside of the FM will be close to the strength inside it, if the strength is measured in the gap between two parts of a specimen. In this case, the transverse size of the gap must be much smaller than its length. Let us illustrate this using an example of the results of a numerical simulation, which was performed for a system of two concentric ferrite rings.

SIMULATION OF CONDITIONS OF MAGNETIZING-FIELD STRENGTH MEASUREMENTS

The magnetic circuit consists of an external magnetic circuit with exciting windings, air gaps, and an investigated specimen. The axially symmetric magnetostatic problem was solved using the finite-element method at a constant relative permeability of all ferromagnetic elements of the circuit, which is equal to 1000. Figure 1 shows the geometry of the calculated region that contains investigated specimens—concentric ferrite rings—and the poles of the external magnetic circuit. The calculation is based on the geometrical parameters of a specimen that is prepared for measurements. The radial gap between rings is 0.75 mm at radial thicknesses of the inner and outer rings of 2 and 2.3 mm, respectively.

The distribution of the magnetic-field induction that was obtained in calculations is illustrated by a change in the brightness of the half-tone pattern in Fig. 1. The radial distributions of the magnetic-field strength near the central cross section of the calculated region ($Z = 0$) are shown in Fig. 2. Curve *1* corresponds to the central cross section, and curve *2*, to the cross section positioned at a distance of 1 mm from the central one along the vertical axis. According to the obtained data, the radial strength gradient at the outer and inner specimen surfaces is unacceptably large for measuring with a probe whose dimensions are implemented under laboratory conditions without application of special expensive technologies.

At the same time, the expected measurement error in the region of the gap between specimens near the central plane is small (curve *1* in the inset in Fig. 2). The calculation showed that an acceptable value of the measurement error holds in a region of ±0.15 of the specimen height along the vertical axis. In the region of the gap, the deviation of curve *2* from curve *1* reaches approximately 15%. If a probe with a vertical size of 2 mm, which is located in the middle of the gap,

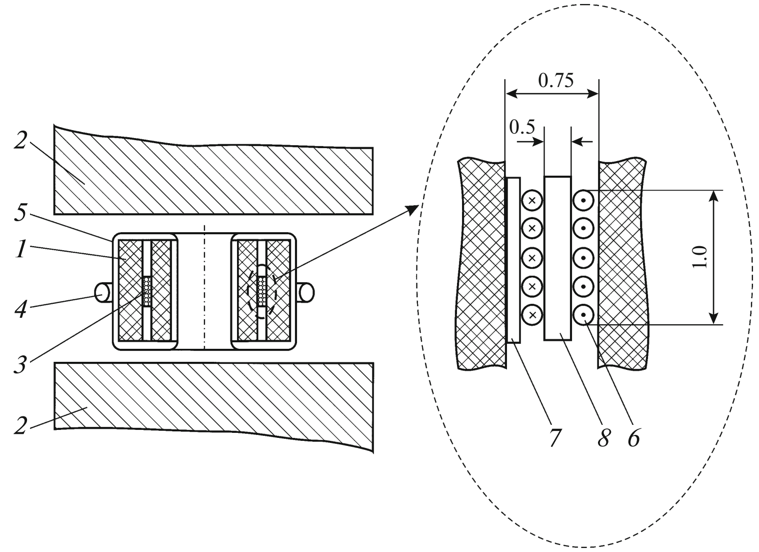

Fig. 3. Arrangement of the element in the measuring scheme: (*1*) investigated specimen; (*2*) external magnetic circuit; (*3*) probe; (*4*) turn for measuring the transverse induction; (*5*) exciting and measuring windings of the toroidal induction component; (*6*) coil of the field-strength-measuring probe; (*7*) plastic frame; and (*8*) plastic spacer.

is used, the field-strength measurement error averaged over the entire probe volume is no more than 5–7%.

EXPERIMENTAL TECHNIQUE

The experiment on the study of the influence of an external orthogonal magnetization of a specimen on its effective permeability $\mu_{\text{tor}} = B_{\text{tor}}/H_{\text{tor}}$, which is measured from the flux along the toroidal axis of the core, was planned taking the numerical-simulation results into account. The diagram of the arrangement of elements in the experiment is shown in Fig. 3.

Specimen *1* consisting of two concentric 1000HM ferrite rings was placed between the poles of external magnetic circuit *2*, the calculated gaps along the *Z* axis being provided. Probe *3* with a height of 1 mm for measuring the field strength, which consisted of two counter-wound coils *6* (5 turns in each) was placed inside the measuring gap between the parts of the specimen. The coils were wound with a 0.08-mm-diameter PEV2 wire on plastic frame *7* so as to provide a radial gap between the coils that determines the field-strength-probe sensitivity.

The gap value between the coils was determined by 0.5-mm-thick cylindrical plastic spacer *8*. The coil terminals are made in the form of a twisted pair for reducing spurious coupling to the other elements of the magnetic circuit. Windings *5* for exciting and measuring the toroidal induction component are wound in two wires and contain 10 turns each.

The vertical axis of the specimens is encompassed with turn *4* for measuring the transverse (biasing) induction. The magnetic flux measured using a signal of this turn contains a spurious component, which is associated with the field concentrated in the paraxial region that contain no FM. However, simple estimates show that the influence of this component is negligibly low at all possible states of the core in the experiment. The signal from the turn that measures the biasing induction together with the field-strength signal is required for monitoring the dependence *B*(*H*) for the specimen, which is obtained in the biasing circuit.

The external magnetic circuit is composed of 0.25-mm-thick transformer-steel layers. The magnetic circuit contour contains air gaps of significant lengths and has a high magnetic resistance. To attain a transverse-field induction that exceeds the material-saturation induction (~0.3 T) in the specimen, the magnetomotive force was created in the magnetic circuit via a discharge of a capacitor with a capacitance of 180 μF with a charging voltage of up to 100 V into the exciting winding. The number of turns in the exciting winding is 10, and the cross section of the external magnetic circuit is 45×22 mm^2. Because of the presence of gaps, which reduce the field strength in the ferromagnet, and the discharge-current shape in the form of decaying oscillations in the magnetic-circuit material, no appreciable residual magnetization effects were observed. The first half-period of the discharge current lasted ~300 μs.

The exciting winding of the toroidal field was supplied from a G3-112/1 sine-wave generator (AOOT Radiopribor, Russia, Velikie Luki) with an output impedance of 50 Ω through a matching transformer with a transformation ratio of 1:10. The amplitude of the toroidal magnetic field in the specimen was much

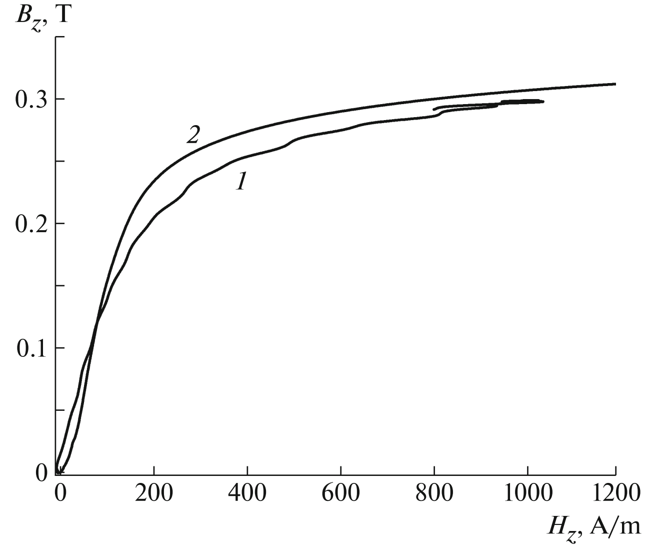

Fig. 4. Magnetization curves in the direction of the specimen's transverse axis that were obtained using (*1*) the standard technique and (*2*) measurements in the gap.

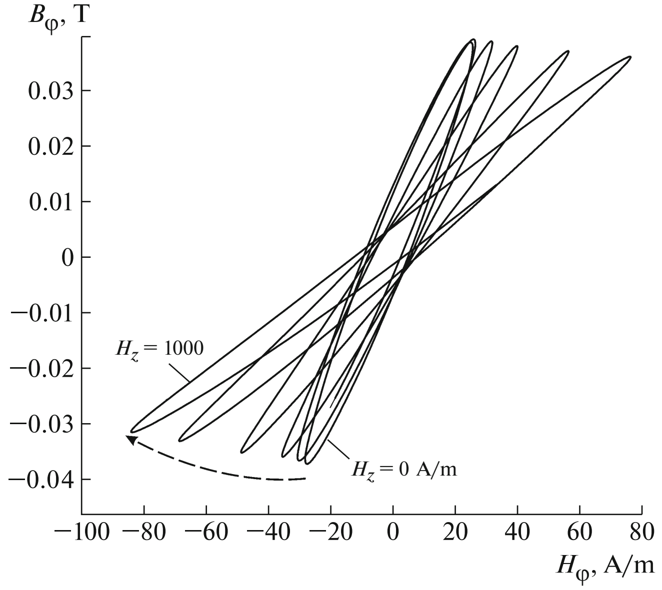

Fig. 5. Evolution of the dependence $B_\varphi(H_\varphi)$ along the specimen's toroidal axis for the transverse-field strength H_z changing from 0 to 1000 A/m.

lower than the ferrite-saturation induction and had an insignificant effect on the specimen magnetic state. A frequency of 50 kHz that was chosen for measurements allowed observation of the dynamics of changes in the ferrite permeability upon application of an external field, which was produced by the magnetic circuit.

A signal that was proportional to the value of the toroidal field was picked off the measuring winding, which was identical to the exciting winding. The current in the exciting winding was measured with a low-inductance shunt with a resistance of 0.078 Ω. The measured current value was used to determine the toroidal component of the magnetic-field strength.

Signals were recorded with a 4-channel DPO3034 oscilloscope (Tektronix). Signals from the induction and transverse-field-strength probes, as well as current and toroidal-field-induction signals, were simultaneously recorded. Signals from the induction and strength probes were integrated during processing of the recorded signals.

ANALYSIS OF THE EXPERIMENTAL RESULTS

The branch of the specimen-magnetization characteristic that corresponds to the transverse field is shown in Fig. 4 (curve *1*). Curve *2* corresponds to a test experiment on magnetizing the core along the toroidal axis using a discharge of a capacitor with a capacitance of 0.15 μF without application of an orthogonal field. Comparing the obtained dependences $B_z(H_z)$ of the material demonstrates the coincidence of the results with an accuracy of no worse than 10%, thus indicating the sufficient accuracy of measuring the transverse (biasing) field strength.

Figure 5 shows an evolution of the dependence $B_\varphi(H_\varphi)$ of the toroidal field in the core during magnetization with an external orthogonal field. Because the toroidal-circuit power supply has a quite low internal impedance, the amplitude of the toroidal-field induction changes slightly during the magnetization. The corresponding change in the strength amplitude is related to a change in the equivalent permeability of the specimen material, which leads to both a reduction of the inductive resistance of the toroidal-field winding and an increase in the current in this winding.

To determine the equivalent magnetic permeability along the toroidal axis, the points were used that corresponded to the maximum values of the toroidal-field induction magnitude. Curve *1* in Fig. 6 corresponds to the values of μ_r that were determined from the ratio of the induction to the field strength along the biasing-field direction. Curve *2* in Fig. 6 demonstrates the change in B_φ/H_φ as a function of H_z and coincides at $H_z = 0$ with the μ_r value, which is determined by the dependence $\mu(H_\varphi)$ (curve *3* in Fig. 6). The latter was obtained in the test experiment on magnetizing the core along the toroidal axis by a capacitor discharge without application of an orthogonal field. All dependences $\mu(H)$ were obtained upon application of a magnetomotive force from a demagnetized state using a demagnetization technique with a decaying alternat-

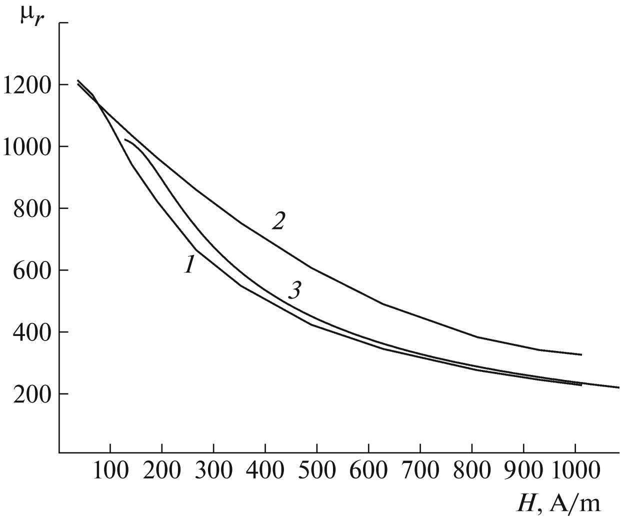

Fig. 6. Dependences of the relative permeability of the specimen on the transverse-field strength: (*1*) along the transverse axis; (*2*) along the toroidal axis; and (*3*) obtained in a test experiment.

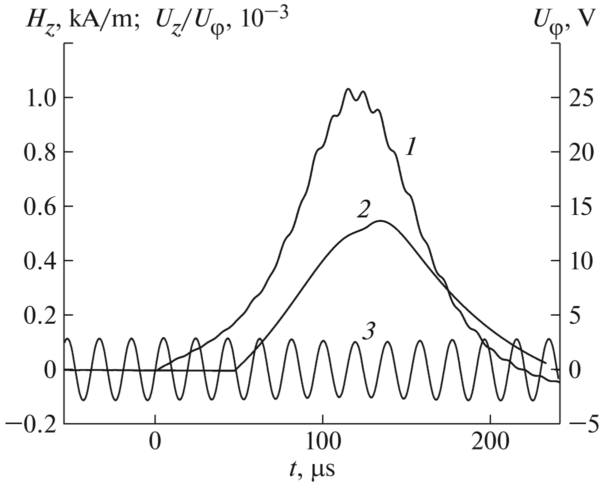

Fig. 7. Time dependences of the (*1*) transverse-magnetic-field strength in the ferromagnet, (*2*) relative amplitude of the first harmonic component of the toroidal-field frequency for a signal from the field-strength probe, and (*3*) voltage of the toroidal-field winding.

ing current of a discharging capacitor, which is close to the standard technique [9]. As was mentioned above, curves *1* and *3* in Fig. 6 correspond to a permeability change as a function of the value of the field component applied along the μ measurement direction. These curves virtually coincide for the transverse and toroidal axes; this can be interpreted as the absence of a material-permeability orthotropy. However, comparing these curves to curve *2* shows that the dependences of the ferrite permeability on the magnetic-field strength are substantially different for the cases where the permeability is measured along and across the magnetizing field. Analogous data were obtained when measuring the permeability μ_r using a frequency of 30 kHz, thus indicating that the frequency does not influence the measurement results.

The obtained results testify to the fact that attaining identical values of μ in the longitudinal and transverse (with respect to the measurement axis) magnetization modes requires substantially different field strengths. Thus, the orthogonal-magnetization strength must be 30–50% higher than the longitudinal strength. This difference is considerable and far exceeds the limits of the possible measurement error. Processing the curves that are presented in [7] yields similar results.

In the recorded signals of the field-strength probe (curve *1* in Fig. 7) that are proportional to the time derivative of the magnetic flux along the probe axis, a component with a substantial amplitude at frequencies that are multiple of the toroidal-field frequency is present. This component is absent in the signal before the magnetizing field was applied and abruptly increases with an increase in H_z. In the final form of the strength signal H_z obtained after the integration, this component has virtually no effect on the final curve. However, its nature may be of interest for understanding details of the processes in the investigated circuit.

Figure 7 (curve *2*) shows the time dependence of the relative amplitude, which is selected via filtering of the harmonic component of the signal from the field-strength probe at a frequency of 50 kHz (specified by the external oscillator). The amplitude value is normalized to the voltage amplitude at the terminals of the toroidal-field measuring circuit (curve *3*). Its comparison to curve *1*, which represents the time-dependent strength H_z, shows that the abrupt increase in signal component (*2*) correlates with the transition of the specimen material to the saturated state.

Under the condition of this experiment, a change in the magnetic resistance of the specimen upon a change in the magnetic state (unsaturated–saturated and back) under the action of the toroidal field leads to a change in the strength distribution in the biasing circuit, which is observed in the signal from the field-strength probe. The numerical-simulation results correspond to the experimentally observed processes.

REFERENCES

1. Vendik, O.G. and Parnes, M.D., *Antenny s elektricheskim skanirovaniem (Vvedenie v teoriyu)* (Antennas with Electric Scanning (Introduction into the The-

ory)), Bakhrakh, L.D., Ed., Moscow: SAINS-PRESS, 2002.

2. Bakunov, A.S., Gorkunov, E.S., and Shcherbinin, V.E., *Magnitnyi kontrol'* (Magnetic Testing), Moscow: Spektr, 2011.
3. Vasilenko, O.N. and Kostin, V.N., *Russ. J. Nondestr. Test.,* 2013, vol. 49, no. 9, pp. 510–518.
4. Adam'yan, Yu.E., Vyrva, E.A., Krivosheev, S.I., and Titkov, V.V., *Tech. Phys.,* 2013, vol. 58, pp. 1397–1403.
5. Guo, Y., Zhu, J., Lu, H., Lin, Z., Wang, S., and Jin, J., *Proc. Australasian Univ. Power Eng. Conf. (AUPEC'08)*, Sydney, Australia, 2008. P-079, Faz, R., Ed., Sydney: Univ. New South Wales, 2008, p. 1.
6. Sande, H.V., Henrotte, F., De Gersem, H., and Hameyer, K., *IEEE Trans. Magn.,* 2005, vol. 41, no. 5, pp. 1508–1511, DOI: 10.1109/TMAG.2005. 845077
7. Li, Y., Yang, Q., Zhu, J., and Guo, Y., *IEEE Trans. Industry Appl.,* 2012, vol. 48, no. 1, pp. 88–91, DOI: 10.1109/TIA.2011.2175677
8. Cardelli, E. and Faba, A., *Phys. B: Condens. Matter,* 2014, vol. 435, pp. 11–15, DOI: 10.1016/j.physb. 2013.06.010
9. *GOST* (State Standard) *29004-91 (MEK367-1-82). Cores for Inductance Coils and Transformers Used in Long-Range Communication Equipment. Part 1. Methods of Measurement.* http://www.gosthelp.ru/gost/gost10360.html

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