Controlled Thermosensitivity of the Poly(*N*-isopropylacrylamide-*co*-*N,N*′-dimethyl(methacryloyloxyethyl)-ammonium propane sulfonate) Hydrogels

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Summary: The N-isopropylacrylamide (NIPAM) and N,N′-dimethyl-(methacryloyloxyethyl) ammonium propane sulfonate (DMAPS) copolymer networks having monomer units with an opposite thermoassembling ability are synthesized and analyzed. The network composition is of crucial importance for their degree of swelling (Q) and Q-Temperature (T) dependences. After the Q normalization these dependences outline two classes of networks which hydrogels expel or imbibe water with T. The boundary network (with 0.39 mole fraction of DMAPS monomer units) defines a critical T (T_{cr}) at which Q is the same as that at the initial T (T_o), but with a structure organization, different than that at T_o. The hydrogels thermoreversibility at the stepped T change, and the salt effect on the Q-T dependences are demonstrated also.

Keywords: hydrogels; radical polymerization; self-organization; stimuli-sensitive polymers; thermoresponsibility

Introduction

In the double-hydrophilic N-isopropylacrylamide (NIPAM) -N,N′- dimethyl(methacryloyloxyethyl)ammonium propane sulfonate (DMAPS) copolymers (p(NIPAM-co-DMAPS)), the NIPAM monomer units are responsible for a thermosensitivity with LCST (around 33 °C), while the DMAPS monomer units – for thermoresponsive properties with UCST. This combination is an example of a new type amphiphilicity. The NIPAM monomer unit association is a result of the hydrophobic interaction, while the DMAPS monomer unit self-assembling ability is a result of a specific for polyzwitterions (PZ) dipole-dipole interaction (Figure 1) - the fundament of their anti-polyelectrolyte properties.[1–9] Depending on the relative positions of UCST and LCST, the design of such double-hydrophilic copolymers could result in a copolymer association at low and high temperatures, but in copolymer dissolution at intermediate temperatures.[10] For the chemically crosslinking networks of such copolymers, the mentioned above association results in an additional (physical) junction point formation and water expelling (gel contraction) from the gel.

Designed by this way copolymer networks afford an opportunity for an effective control of thermosensitive hydogels with an expanded application as biomaterials.[11,12] The studied up to now hydrogels of this type have a small mole fraction of DMAPS monomer units (m_{DMAPS}).[13–17] In the work presented, the properties of the p(DMAPS-co-NIPAM) double-hydrophilic hydrogels with a wide range values of m_{DMAPS} are investigated.

Experimental Part

Materials

The both monomers, NIPAM (Aldrich, 97%) and DMAPS (Merck-Schuchardt, >98%) were used as received. Potassium

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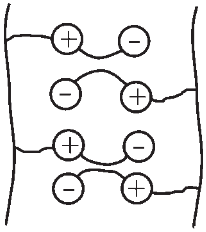

Figure 1.
Dipole-dipole self-assemblies of oppositely oriented dipoles - zwitterionic side groups of PZ macromolecules.

persulfate (PPS) (Sigma-Aldrich, 99%, A.C.S. reagent) and N,N,N′,N′-tetramethylethylenediamine (TEMED) (Merck, 99%), copolymerization initiator and accelerator were used without further purification. N,N′-Methylenebisacrylamide (MBAA), a crosslinking agent, was delivered from Fluka-Chemie AG. Tetrabutylammonium bromide (TBAB) was used as low molecular mass salt and it was supplied by Merck-Schuchardt (Darmstadt, Germany).

Hydrogel Preparation

The homo- and copolymer networks were prepared by a free-radical polymerization in a double distilled water. Different networks with various molar ratios of both monomers (NIPAM/DMAPS) were synthesized. The total monomer concentration was 0.5 M. The quantities of 1wt. % MBAA (a crosslinking agent), 0.1wt. % PPS (an initiator) and 0.1wt. % TEMED (an accelerator) were calculated on the base of the total monomer concentration. The reaction was carried out in a glass tube (0.8 cm inner diameter) at room temperature for 24 h under an inert atmosphere. The hydrogels obtained with a cylindrical shape were cut into small pieces with 0.8 mm thickness. The cut pieces were immersed in an excess of distilled water at room temperature for several days to remove the residual monomers. These samples were dried under vacuum at 40 °C to a constant weight.

Elemental analysis

The copolymer network compositions were calculated from the elemental analysis of S, using Vario EL III elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). The results obtained were summarized in Table 1.

Swelling Degree Determination

The swelling degree (Q) of the homo- and copolymer networks in distilled water in a temperature interval 18–50 °C was measured gravimetrically:

$$Q = \frac{W - W_0}{W_0} 100, \qquad (1)$$

where W_0 is the initial weight of the dry network and W is the weight of the swollen one.

Results and Discussion

Network Swelling Kinetics and Degree

The swelling kinetics of p(NIPAM) and p(DMAPS) ($m_{DMAPS} = 0.00$ and 1.00) and copolymer (DMAPS-NIPAM with different m_{DMAPS} values) networks are presented in Figure 2. The parallel decrease

Table 1.
Composition of the used p(NIPAM), p(DMAPS) and p(NIPAM-co-DMAPS) networks.

Network number	DMAPS (mole percent in the monomer feed)	S in the copolymers (%)	DMAPS (mole percent in the copolymers)
1	0	0	0
2	5	1.38	5.24
3	10	2.28	9.11
4	15	3.11	13.07
5	50	7.03	39.00
6	70	7.18	40.38
7	90	9.57	66.98
8	100	10.23	100

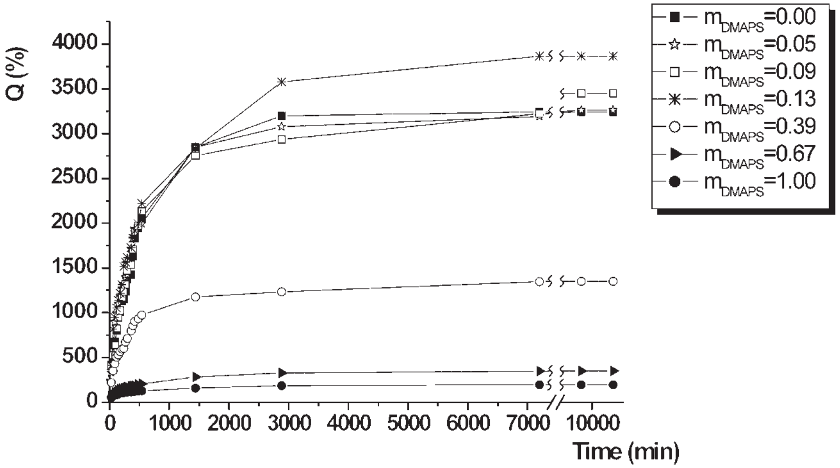

Figure 2.
The swelling kinetics of p(NIPAM) and p(DMAPS) ($m_{DMAPS} = 0.00$ and 1.00) and p(DMAPS-co-NIPAM) ($0 < m_{DMAPS} < 1$) networks in distilled water at temperature 18 °C.

of both initial swelling rate and the equilibrium degree of swelling (Q_{eq}) with m_{DMAPS} is a general peculiarity of these results. It could be explained with the formation increase of the dipole-dipole clusters from opposite orientated dipoles (Figure 1) with the m_{DMAPS} growth. The function of these clusters as additional network junction points is a possible reason for this tendency. Q_{eq} values (determined from Figure 2) as a function of networks composition are presented in Figure 3. As it could be seen, Q_{eq} increases in the interval $0 < m_{DMAPS} \leq 0.13$ and just after that, it decreases sharply. The mentioned above explanation for Q_{eq} decrease with m_{DMAPS} is related to copolymer networks with $m_{DMAPS} > 0.13$. At lower m_{DMAPS} the formation of dipole-dipole clusters is hindered. In this case the hydrophilic DMAPS units incorporated in copolymer chain lead to expand the hydrophilicity

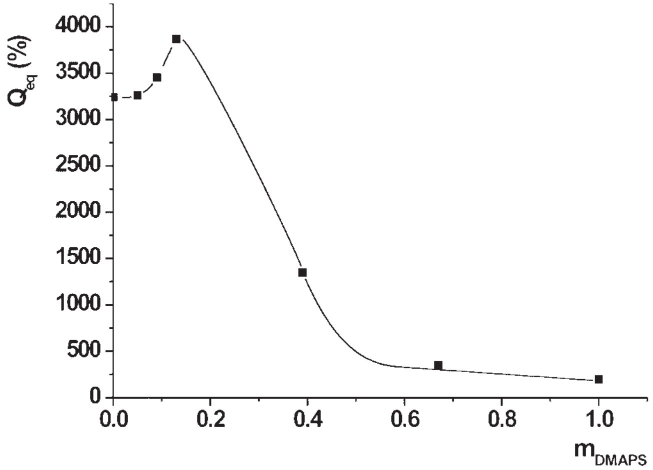

Figure 3.
Dependence of Q_{eq} of p(NIPAM) and p(DMAPS) ($m_{DMAPS} = 0.0$; 1.0), and p(DMAPS-co-NIPAM) networks on DMAPS mole fraction in copolymers ($m_{DMAPS} < 1$). Temperature: 18 °C.

only, not cross-linking, and therefore, Q_{eq} increases.

Temperature Dependence of Q

The temperature dependences of Q with network composition (different m_{DMAPS}) are presented in Figure 4. The peculiarity of this figure is the sharp subdivision of the curves presented into two distinctive classes: those with $m_{DMAPS} > 0.39$, and networks with $m_{DMAPS} < 0.39$. For the first type dependences Q increases monotonically with a low temperature coefficient ($\alpha = 8\%/^{\circ}C$), while for the second class curves, Q decreases and has a temperature interval in which Q drops sharply.

Table 2.
Characteristic temperatures ($T_{0.5}$), and the temperature coefficient (α) at $T_{0.5}$ as a function of m_{DMAPS}.

m_{DMAPS}	$T_{0.5}$ (°C)	α (%/°C)
0.00	33.2	−195
0.05	36.3	−190
0.09	37.6	−180
0.13	39.2	−106

The characteristic temperatures determined ($T_{0.5,}$ defined as temperature at which the hydrogel Q value is the half of the maximum change of this quantity in the investigated temperature interval) and the temperature coefficient (α) values for this type curves are included in Table 2. These hydrogels are with a high content of NIPAM monomer units in the copolymer chains. The increasing with a temperature hydrophobic interaction between these units is the reason for the hydrogel collapse with the temperature. The sharpness of this shrinkage decreases with NIPAM monomer unit dissolution, which corresponds to the decrease of the absolute α values. Furthermore, the curves are shifted to the right ($T_{0.5}$ increases), because of higher temperatures are necessary for the formation of the hydrophobic associates at lower NIPAM monomer unit concentration. Two dependences from the other class characterize the hydrogels with the highest DMAPS content in the macromolecules. The physical junctions in this case are dipole-dipole clusters (Figure 1). The increasing with a temperature Q values in this case could be related to the destruction of these dipole-dipole clusters. This increase is less than Q change during the collapse of the gels from the other class. Therefore, the

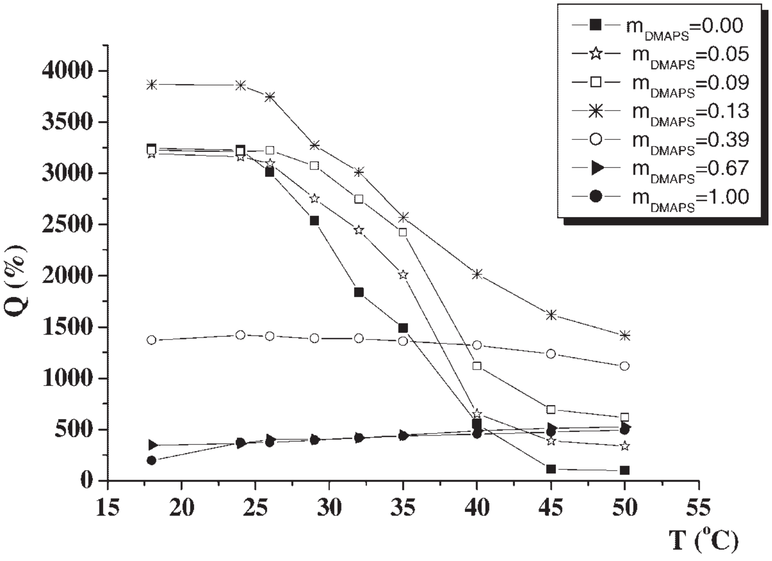

Figure 4.
The temperature dependences of Q in distilled water of p(NIPAM), p(DMAPS)and p(NIPAM-co-DMAPS) networks with different m_{DMAPS}.

dipole-dipole cluster effect on Q values is lower. This could be related to their lower concentration and strength.

The copolymer network with $m_{DMAPS} = 0.39$ is a boundary between these two types of dependences. At the beginning (until 25 °C) its Q values slightly increases, and after that it decreases. The Q increase could be due to dipole-dipole cluster destruction with the temperature, while the Q decreases - to the hydrophobic association with the temperature increase. Hence, for this boundary network the contributions of the both types physical junction in the temperature dependence of Q are comparable. As it can be seen from this curve, the both contributions are insignificant, because of the formation of the nodes from one class prevents the production of the junctions from the other class.

The boundary dependence discussed is outlined clearly after transformation of the temperature dependences presented in Figure 4 via normalization of Q values related to the maximum difference of its values in the chosen temperature interval ($20\,°C \leq T \leq 50\,°C$). The temperature dependences of these normalized Q values ($Q_N = \pm Q/\Delta Q_{max}$) are shown in Figure 5. It is seen that this is the unique dependence with positive and negative Q values. The specific critical temperature, (T_{cr}) in which $Q_N = 0$, i.e. Q value is the same as that at the initial temperature (in this case $T_0 = 20\,°C$) could be determined also. Hydrogels analysis with the same Q values at different temperatures, where the gel structure organization is different is an intrigue challenge from a scientific as applied viewpoint. The T_{cr} value depends on the amphiphilic network composition, the initial temperature selected, and on the temperature interval width. The defined problem for the characterization and application of hydrogels with one or more T_{cr} values is made for the first time, according to the available literature. From the results obtained, the p(DMAPS-co-NIPAM) hydrogel with $m_{DMAPS} = 0.39$ has $T_{cr} = 34.2\,°C$. Its Q value at $T = 20\,°C$ and $T = 34\,°C$ are the same, although the dipole-dipole clusters are dominated physical nodes at 20 °C, while at 34 °C this function belongs to the hydrophobic associates. This hydrogel is swollen in the temperature interval $20\,°C \leq T \leq 34\,°C$, while at $T > 34\,°C$ it is in a collapsed state against its state at the initial temperature.

In Figure 5, the discussed two types of hydrogels are shown clearly. The hydrogels with high m_{DMAPS} values ($m_{DMAPS} = 1.0$; 0.67) are above the "zero" line, while others, with low m_{DMAPS} values - under it. The first one swells, while the second one -

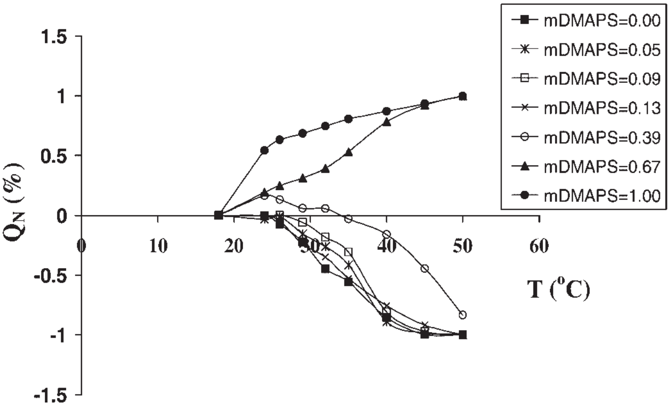

Figure 5.
Temperature dependences of the hydrogel normalized Q values (Q_N) for hydrogels with different m_{DMAPS} in the p(NIPAM-co-DMAPS) networks.

collapses in comparison with their initial state at 20 °C. Therefore, the advantage of the temperature dependences of the normalized swelling degree (Q_N) is the more definite and easier mode for a copolymer hydrogel subdivision.

Network Thermoreversibility

The reversion of the temperature effects on Q values of the discussed already copolymer networks are demonstrated in Figure 6. At the higher temperature (T = 50 °C) the processes (swelling and collapse) are faster than at the lower temperature (T = 18 °C). As it could be expected, p(DMAPS) and p(NIPAM) networks have opposite (mirror-image) responses on the T-change. That's why at 50 °C the p(DMAPS) network swelling and p(NIPAM) network contraction are faster than p(DMAPS) collapse and p(NIPAM) swelling at T = 18 °C. The copolymer network with $m_{DMAPS} = 0.13$ has approximately the same behaviour as that of responses on p(NIPAM) network at a periodically T-change.

Salt Effect on Q

The study of the LMS effect on the discussed above networks swelling is of both scientific and also practical interest. The Q-dependences for p(NIPAM) ($m_{DMAPS} = 0.00$) and copolymer ($m_{DMAPS} = 0.13$) networks on the TBAB concentration are shown in Figure 7. The proximity of the

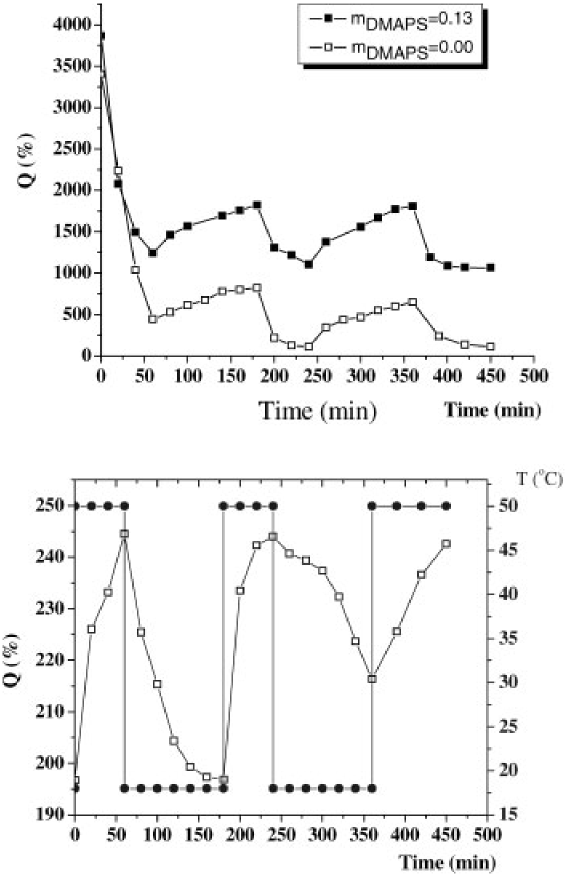

Figure 6.

The Q change of p(NIPAM) and p(DMAPS) and p(NIPAM-co-DMAPS) ($m_{DMAPS} = 0.13$) networks in water at a periodically temperature change from 50 to 18 °C.

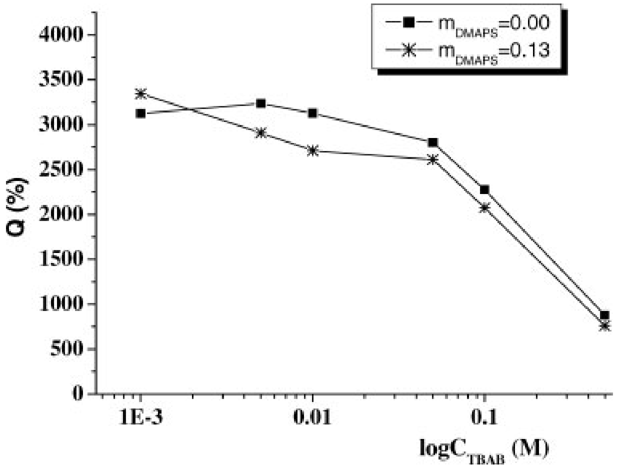

Figure 7.
Dependence of Q on the TBAB concentration of p(NIPAM) ($m_{DMAPS} = 0.00$) and p(NIPAM-co-DMAPS) networks ($m_{DMAPS} = 0.13$) at T = 24 °C.

both dependences is due to the low mole fraction of DMAPS units, operating as a hydrophilic dissolvent for the NIPAM monomer units. It could be seen that both networks are characterized with a sharp hydrogels collapse at $C_{TBAB} = 0.05M$. This could be related to the ion dehydrating effect resulting in the macromolecular network segments association. This dehydrating effect of TBAB is observed clearly by the comparison of the contraction of temperature dependences of both hydrogels in water and in a 0.5 M aqueous solution of the salt (Figure 8). The volume drop of the gel in water is more significant than in the LMS, again because of the high dehydrating effect of the LMS at the initial temperature (18 °C). It is seen that the LMS addition did not change the hydrogel characteristic temperatures: $T_{0.5} = 33.2$ °C for p(NIPAM) ($m_{DMAPS} = 0.00$), and $T_{0.5} = 35$ °C for a copolymer ($m_{DMAPS} = 0.13$) networks. However, the collapse temperature coefficients are changed after the LMS addition. The α value of p(NIPAM) hydrogel decreases from 195%/°C in water to 53%/°C in the LMS, and for copolymer hydrogel α values are 98%/°C in water and 44%/°C in 0.5 M TBAB. The copolymer α value decrease in comparison to that of the p(NIPAM) hydrogel is in a confidence with the assumption for the hydrophilic dissolution effect of NIPAM monomer units after the DMAPS monomer unit addition. This copolymer network hydrophilization is the reason for a considerable Q values difference at 50 °C for copolymer (Figure 8b) and homopolymer- p(NIPAM) (Figure 8a) hydrogels.

Conclusion

The copolymer NIPAM-DMAPS networks over a wide range of m_{DMAPS} are synthesized and analyzed. It is shown the network composition is of crucial importance for an effective control of Q and Q-T dependences. As a result of the combination of the monomer units with two opposite thermoassembling abilities, two classes of the networks are outlined: the networks which hydrogels expel or imbibe water with a T increase. The more clear subdivision is presented after the Q normalization. The boundary Q_N - T dependence, determined for the first time, defines a critical T at which the hydrogel has the same Q value as that at the initial T, though the structure organization of the hydrogel at these

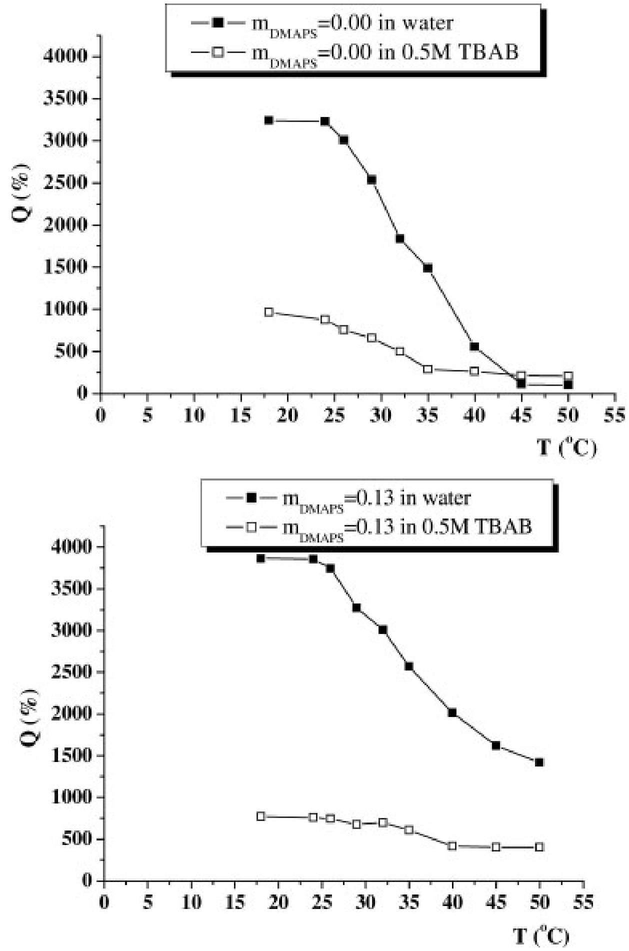

Figure 8.
Temperature dependences of Q of the p(NIPAM) ($m_{DMAPS} = 0.00$; Figure 8a) and p(NIPAM-co-DMAPS) ($m_{DMAPS} = 0.13$; Figure 8b) networks in distilled water and in TBAB solution (0.5 M).

temperatures are quite different. Thermoreversibility of the hydrogels and the salt effect on the Q-T dependences are demonstrated also. Controlled properties of the hydrogels discussed reveal new possibilities for their application.

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