Journal of Earth Science, Vol. 25, No. 1, p. 183–188, February 2014 ISSN 1674-487X
Printed in China
DOI: 10.1007/s12583-014-0411-0

A Novel Model of Predicting Archie's Cementation Factor from Nuclear Magnetic Resonance (NMR) Logs in Low Permeability Reservoirs

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ABSTRACT: The resistivity experimental measurements of core samples drilled from low permeability reservoirs of Ordos Basin, Northwest China, illustrate that the cementation factors are not agminate, but vary from 1.335 to 1.749. This leads to a challenge for the estimation of water and hydrocarbon saturation. Based on the analysis of Purcell equation and assumption that rock resistivity is determined by the parallel connection of numerous capillary resistances, a theoretical expression of cementation factor in terms of porosity and permeability is established. Then, cementation factor can be calculated if the parameters of porosity and permeability are determined. In the field application, porosity can be easily obtained by conventional logs. However, it is a tough challenge to estimate permeability due to the strong heterogeneity of low permeability reservoirs. Thus, the Schlumberger Doll Research (SDR) model derived from NMR logs has been proposed to estimate permeability. Based on the analysis of the theoretical expressions of cementation factor and SDR model, a novel cementation factor prediction model, which is relevant to porosity and logarithmic mean of NMR T_2 spectrum (T_{2lm}), is derived. The advantage of this model is that all the input information can be acquired from NMR logs accurately. In order to confirm the credibility of the novel model, the resistivity and corresponding laboratory NMR measurements of 27 core samples are conducted. The credibility of the model is confirmed by comparing the predicted cementation factors with the core analyzed results. The absolute errors for all core samples are lower than 0.071. Once this model is extended to field application, the accuracy of water and hydrocarbon saturation estimation will be significantly improved.
KEY WORDS: cementation factor, nuclear magnetic resonance (NMR), low permeability reservoir, logarithmic mean of NMR T_2 spectrum, saturation calculation.

1 INTRODUCTION

The cementation factor (*m*) in Archie's equation plays an important role in the calculation of hydrocarbon and water saturation, which are indispensable parameters in the exploration of oil reservoir (Carpenter et al., 2009; Chen et al., 2009; Archie, 1942). It is often assumed to be constant (*m*=2), but applying a constant cementation factor in Archie's equation will lead to wrong estimation of fluid saturation in an oil reservoir (Borai, 1987; Focke and Munn, 1987). In Archie's equation, the cementation factor describes the power to which porosity must be raised, so small changes in *m* can affect the estimated saturation. Therefore, further knowledge of how cementation factor varies is of great importance to water saturation estimation. The Archie's equations can be expressed as the following relations

$$F=\frac{R_o}{R_w}=\frac{a}{\varphi^m} \tag{1}$$

$$I_r=\frac{R_t}{R_o}=\frac{b}{S_w{}^n} \tag{2}$$

where R_o is the resistivity of fully water-saturated rock (Ω·m); R_t is resistivity of the partly water-saturated rock (Ω·m); R_w is the resistivity of water (Ω·m); *F* is formation factor; I_r is resistivity index; φ is the porosity; *a* and *b* are the lithology factors; *m* is the cementation factor; S_w is the water saturation; *n* is the saturation exponent.

In order to obtain accurate cementation factor, the factors which influence cementation factor, such as rock's cementation, grain shape, grain size, grain sorting, pore space geometry, and pore connectedness, have been studied by a large number of pioneers. Archie (1942) postulated that for clean sandstones, *m* depends on cementation and the values of *m* and *a* are 1.8 to

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Manuscript received February 22, 2013.
Manuscript accepted July 8, 2013.

Wang, L., Mao, Z. Q., Shi, Y. J., et al., 2014. A Novel Model of Predicting Archie's Cementation Factor from Nuclear Magnetic Resonance (NMR) Logs in Low Permeability Reservoirs. *Journal of Earth Science*, 25(1): 183–188, doi:10.1007/s12583-014-0411-0

2.0 and 1, respectively. Several researchers have found that the shape of the grain has a great effect on the cementation factor. Wyllie and Gregory (1953) found that for the same porosity, the cementation factor is lowest for spheres. Shapes, such as discs, cubes, and triangular prisms, result in higher cementation factor. Similarly, Jackson et al. (1978) and Ransom (1984) found that the cementation factor depends on the shape of particles, while variations in grain size and sorting have less influence on cementation factor. Knight and Endres (2005) pointed out that cementation factor depends on the geometry of the system or the connectedness of the pore space.

Based on the study of influencing factors on cementation factor and the analysis of experiment data, pioneers have proposed different kinds of cementation factor estimation models. Borai (1987), Focke and Munn (1987), Saha et al. (1993), Mao (1995) reported variation in cementation factor with porosity. They pointed out that cementation factor tends to increase with the increase of porosity. He (2005) concluded that cementation factor is related to synthesized index ($\sqrt{k/\varphi}$) for sandstones. The cementation factor decreases with the increase of porosity when synthesized index is greater than 0.92, but increases when synthesized index is smaller than 0.92. Raiga-Clemenceau (1977) found a relationship between cementation factor and permeability for sandstones and proposed an empirical equation to calculate cementation factor. Olsen et al. (2008) gave a semi-empirical formula to derive the cementation factor from porosity and permeability. Gomez et al. (2010) observed that the formula proposed by Olsen et al. (2008) gave a good estimation for cementation factor. The cementation factor estimation models mentioned above are listed in Table 1. These models proposed by the pioneers have a common character that they are all empirical or semi-empirical models without rigorous logical derivation. In addition, the parameter of permeability in some of these models is difficult to obtain in low permeability reservoir, which limits the use of these models.

Table 1 Summary of the published cementation factor estimation models

Published cementation factor estimation models	References
$m=2.2-0.035/(\varphi+0.042)$	Borai, 1987
$m=1.432\varphi^{0.432}$	Saha et al., 1993
$m=a+b\log_{10}(\varphi)$	Mao, 1995
$m=1.28+2/(\log_{10}(k)+2)$	Raiga-Clemenceau, 1977
$m=2.36e^{-0.02\varphi}$, $\sqrt{k/\varphi} \geq 0.92$	He, 2005
$m=0.03\varphi+1.38$, $\sqrt{k/\varphi} < 0.92$	
$m = 0.09\mathrm{Ln}(\sqrt{(c\varphi^3)/k}) + 1.98$	Olsen et al., 2008

φ is porosity (%); k is permeability ($10^{-3}\mu$m); a, b and c are constant parameters.

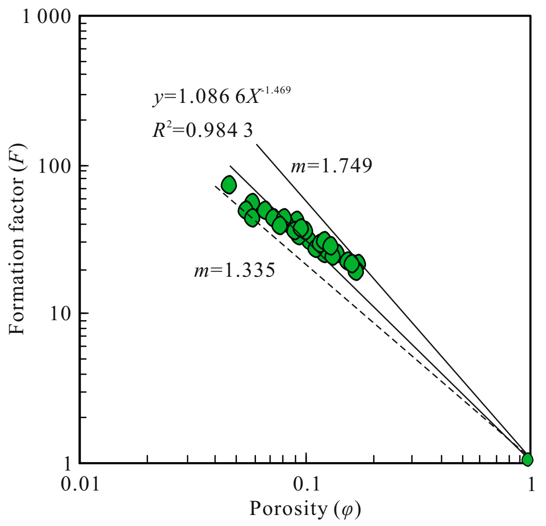

Figure 1. The relationship of the porosity and formation factor for 27 core samples in low permeability reservoirs of Ordos Basin, Northwest China.

Resistivity experimental measurements of core samples drilled from low permeability reservoirs show that the cementation factors are not agminate and the values of cementation factors for core sample vary from 1.335 to 1.749 (Fig. 1). Figure 1 shows that the relationship between the formation factor and porosity for all core samples is not consistent and a fixed cementation factor is difficult to acquire. In this case, hydrocarbon and water saturation calculated by using the regressed fixed cementation factor from all core samples will be inaccurate. The best method is to estimate water saturation by using the variable cementation factors along with the target intervals. In this study, by combining capillary theory, Purcell equation, and SDR model, a novel theoretical model of calculating cementation factor, which is relevant to porosity and T_{2lm}, is derived. The advantage of this model is that all the input information can be acquired from NMR logs accurately. Once this model is extended to field application, variable cementation factors along with the target intervals will be obtained and the accuracy of hydrocarbon and water saturation estimation in low permeability reservoirs will be significantly improved.

2 CEMENTATION FACTOR ESTIMATION MODEL DERIVED FROM CAPILLARY THEORY AND PURCELL EQUATION

2.1 Resistivity of Entire Water-Saturated Rock

Assume that a porous rock with cross-section area A and length L is made up of a large number of parallel water-saturated capillary tubes of equal length but random radius, as shown in Fig. 2. The resistance of the rock can be regarded as a result of parallel connection of resistance of the bundle of capillary tubes, as shown in Fig. 3. In terms of Ohm's law, the resistance of a given water-saturated capillary tube can be expressed as

$$r_i = R_w \frac{L_c}{\pi r_{ci}^2} \tag{3}$$

where r_i is the resistance of the ith water-saturated capillary tube (Ω); L_c is length of the ith capillary tube and r_{ci} is capillary radius (m).

According to the principle of parallel connection of resistance, a relationship for the entire water-saturated rock can be obtained as

$$\frac{1}{r_o}=F_1\frac{1}{r_1}+F_i\frac{1}{r_i}......F_n\frac{1}{r_n}=\sum_{i=1}^{n}F_i\frac{1}{r_i} \quad (4)$$

where r_o is the resistance of water-saturated rock (Ω); F_i is the number of capillary tube with same resistance.

Substituting Eq. (3) into Eq. (4) yields

$$\frac{1}{r_o}=\sum_{i=1}^{n}F_i\frac{1}{R_w\frac{L_c}{\pi r_{ci}^2}} \quad (5)$$

Carrying out some algebraic transformations in Eq. (5) gives

$$r_o=\frac{R_w}{\pi}L_c(\sum_{i=1}^{n}F_i r_{ci}^2)^{-1} \quad (6)$$

Applying Ohm's law to the water-saturated rock, the rock's resistance can also be regarded as

$$r_o=R_o\frac{L}{A} \quad (7)$$

where L is the length of rock (m); A is the cross-section area of water-saturated rock (m^2).

Combining Eq. (6) and Eq. (7) yields

$$R_o=\frac{R_w L_c}{\pi L}A(\sum_{i=1}^{n}F_i r_{ci}^2)^{-1} \quad (8)$$

Carrying out some algebraic transformations in Eq. (8), the expression can be written as

$$R_o=\frac{R_w}{\pi}\tau A_n(\sum_{i=1}^{n}f_i r_{ci}^2)^{-1} \quad (9)$$

where τ (τ=L_c/L) is the tortuosity of capillary tubes; A_n

$$A_n=A/\sum_{i=1}^{n}F_i$$

is apparent average cross-section area (m^2); f_i

$$f_i=F_i/\sum_{i=1}^{n}F_i$$

is percentage of the number of capillary tubes with the r_{ci} radius in all the capillary tubes.

2.2 Purcell Equation

For the porous rock model in Fig. 2, Purcell (1949) proposed a theoretical equation which relates the permeability to the porosity and capillary pressures

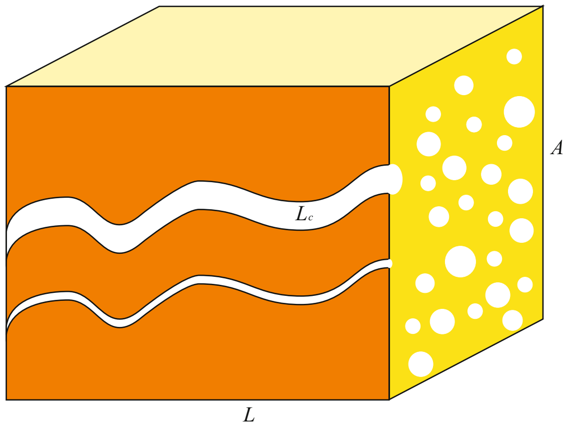

Figure 2. A porous rock model composed of a large number of parallel capillary tubes with equal length but random radius.

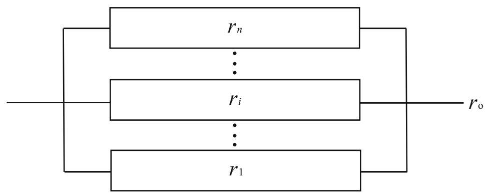

Figure 3. A parallel connection of resistance of bundle of capillary tubes model.

$$k=\frac{(\sigma\cos\theta)^2}{2}\varphi\sum_{i=1}^{n}S_i(\frac{1}{p_{ci}})^2 \quad (10)$$

where k is permeability (10^{-3} μm); σ is interfacial tension (mN/m); θ is contact angle (°); P_{ci} is the ith capillary pressure (MPa); S_i is percentage of the cross-section area of capillary tubes with r_{ci} radius in cross-section areas of the all capillary tubes.

In Eq. (10), P_{ci} can be obtained by the following formula

$$p_{ci}=\frac{2\sigma\cos\theta}{r_{ci}} \quad (11)$$

Substituting Eq. (11) into Eq. (10) yields

$$k=\frac{\varphi}{8}\sum_{i=1}^{n}S_i r_{ci}^2 \quad (12)$$

Comparing $\sum_{i=1}^{n}S_i r_{ci}^2$ with $\sum_{i=1}^{n}f_i r_{ci}^2$ and introducing a constant exponent e to account for the difference between them yield

$$\sum_{i=1}^{n}S_i r_{ci}^2=\mathrm{e}\sum_{i=1}^{n}f_i r_{ci}^2 \quad (13)$$

Combining Eqs. (1), (9), (12), (13) and taking some algebraic transformations result in

$$F = \frac{1}{\varphi^m} = \frac{e\tau A_n}{8\pi}\frac{\varphi}{k} \tag{14}$$

$$\varphi^m = \frac{8\pi}{e\tau A_n}\frac{k}{\varphi} \tag{15}$$

Once the parameters are defined as the following

$$g = \frac{8\pi}{e\tau A_n} \tag{16}$$

Equation (15) can be rewritten as

$$\varphi^m = g\frac{k}{\varphi} \tag{17}$$

Equation (17) displays the relationship between cementation factor, permeability, and porosity. After the value of g has been calibrated by core samples, cementation factor can be calculated if the input parameters of porosity and permeability are acquired. Porosity can be estimated by conventional logs (Xiao et al., 2012; Abushanab et al., 2005), but the calculation of permeability is a tough challenge in low permeability reservoirs due to the generally poor correlation between porosity and permeability (Fig. 4). To obtain accurate cementation factor, Equation (17) should be transformed to avoid requiring permeability but to obtain other information from NMR logs.

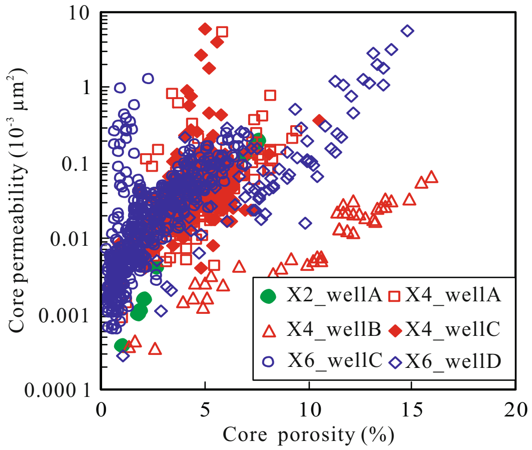

Figure 4. Cross plot of core porosity and permeability; These core samples are drilled from six wells in low permeability reservoirs of Ordos Basin, Northwest China.

3 NOVEL MODEL OF PREDICTING CEMENTATION FACTOR FROM NMR LOGS

An SDR model has been proposed by Schlumberger Doll Research Center to estimate reservoir permeability from NMR logs (Kenyon, 1997; Kenyon et al., 1988) and is written as

$$k = C_1 \times \varphi^{m_1} \times T_{2\mathrm{lm}}^{n_1} \tag{18}$$

where $T_{2\mathrm{lm}}$ is the logarithmic mean of the NMR T_2 spectrum (ms); C_1, m_1 and n_1 are the statistical model parameters that can be acquired from core sample experimental results; Once enough core samples are not available, C_1, m_1 and n_1 can be assigned to empirical values of 10, 4, and 2, respectively.

Equation (18) can be rewritten as follows

$$\frac{k}{\varphi} = C_1 \times \varphi^{m_1-1} \times T_{2\mathrm{lm}}^{n_1} \tag{19}$$

Substituting Eq. (19) into Eq. (17) and carrying out some algebraic transformations, derivative expressions can be written as follows

$$\varphi^m = g \times C_1 \times \varphi^{m_1-1} \times T_{2\mathrm{lm}}^{n_1} \tag{20}$$

$$m\ln\varphi = \ln(g \times C_1) + (m_1 - 1)\ln\varphi + n_1 \ln T_{2\mathrm{lm}} \tag{21}$$

$$m = \frac{\ln(g \times C_1) + n_1 \ln T_{2\mathrm{lm}}}{\ln\varphi} + (m_1 - 1) \tag{22}$$

Once the parameters are defined as following

$$a_1 = \ln(g \times C_1),\ a_2 = (m_1 - 1) \tag{23}$$

Equation (22) can be rewritten as

$$m = \frac{a_1 + n_1 \ln T_{2\mathrm{lm}}}{\ln\varphi} + a_2 \tag{24}$$

Equation (24) shows that cementation factor can be estimated consecutively from NMR logs by the novel model after the values of a_1, a_2 and n_1 have been calibrated by resistivity and NMR experimental data sets.

4 RELIABILITY VERIFICATION

To verify the reliability of the cementation factor estimation model proposed in this study, 27 core samples drilled from low permeability reservoirs of Ordos Basin, Northwest China, are collected, and both resistivity experimental measurement and NMR measurement on the same core sample are conducted. The results of core tests are shown in Table 2. Based on the analysis of the core test results with multivariate regression method, regression model for core samples is established and expressed as

$$m = \frac{-1.262 - 0.047\ln T_{2\mathrm{lm}}}{\ln\varphi} + 0.905,\ R^2 = 0.91 \tag{25}$$

where R is the correlation coefficient. Equation (25) shows that the value of correlation coefficient is very high and closes to 1, which indicates that the m can be calculated from NMR logs precisely.

Comparison of cementation factors acquired from resistivity experimental measurements and predicted from NMR logs is displayed in Fig. 5. This comparison shows that the calculated cementation factors match well with the core experimental results. To quantitatively evaluate the absolute errors of the predicted cementation factors and the core analyzed results, the cross plot of these two kinds of cementation factors is made and showed in Fig. 6. These two figures illustrate that the cementation factors estimated from NMR logs by using the proposed model are credible and the absolute errors for core samples are lower than 0.071. In reservoirs with consecutive NMR logs, this model can be applied to estimate cementation factor, and this will be valuable for the calculation of hydrocarbon and water saturation in low permeability reservoirs.

5 CONCLUSIONS

In low permeability reservoirs, the cementation factors are divergent. Hydrocarbon and water saturation calculated by

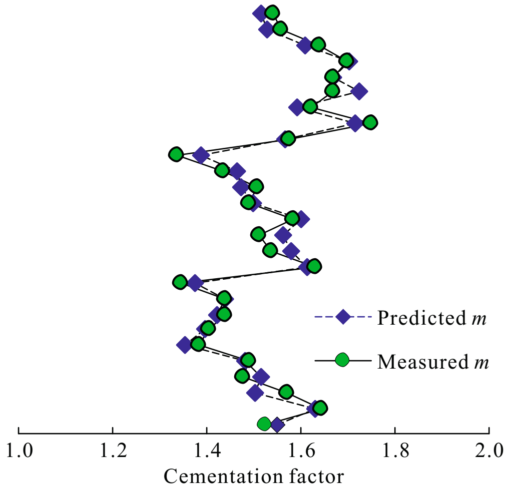

Figure 5. Comparison of the predicted cementation factors and measured cementation factors from resistivity experimental measurements of core samples in low permeability reservoirs of Ordos Basin, Northwest China.

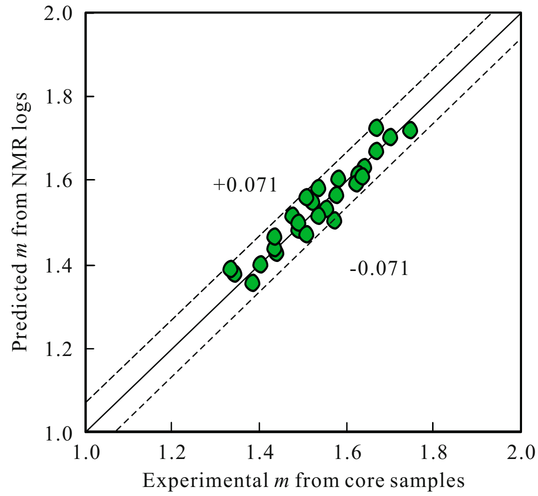

Figure 6. Cross plot of the predicted cementation factors and the core analyzed results in low permeability reservoir of Ordos Basin, Northwest China.

Table 2 Core test result of 27 plugs from low permeability reservoirs of Ordos Basin, Northwest China

Sample number	Depth (m)	Formation factor	Measured m	Porosity (%)	Permeability (10^{-3} μm)	T_{2lm} (ms)	Predicted m	Absolute error
R22	1 595.50	30.621	1.524	10.588	1.033	47.137	1.548	0.024
R23	1 586.65	25.198	1.641	14.002	0.486	30.616	1.629	0.013
R24	1 545.80	41.668	1.572	9.326	0.242	25.211	1.501	0.071
R26	1 498.40	32.909	1.478	9.413	0.855	43.185	1.514	0.035
R27-1	1 490.30	40.423	1.490	8.357	0.496	35.021	1.481	0.010
J16	1 414.70	70.816	1.383	4.596	0.076	13.129	1.354	0.029
J17	1 410.50	53.891	1.405	5.856	0.160	17.898	1.398	0.008
J18	1 409.20	48.839	1.439	6.699	0.201	18.893	1.423	0.016
J19	1 407.20	43.188	1.437	7.281	0.282	17.923	1.438	0.001
J21	1 400.00	48.332	1.343	5.569	0.149	8.262	1.376	0.033
J22	1 405.00	25.000	1.630	13.877	0.575	17.556	1.612	0.018
R16	1 781.00	25.346	1.536	12.197	0.889	29.112	1.580	0.044
R17	1 778.45	26.615	1.510	11.382	0.910	30.525	1.560	0.050
R18	1 766.20	24.354	1.585	13.338	0.573	19.983	1.601	0.016
R19	1 754.35	35.841	1.489	9.039	0.624	29.093	1.496	0.007
R20	1 740.40	43.414	1.507	8.195	0.269	28.180	1.472	0.035
R21	1 722.30	38.877	1.435	7.803	0.498	34.046	1.465	0.030
R2	1 931.00	43.532	1.335	5.922	0.131	8.641	1.387	0.052
R3	1 919.30	29.367	1.576	11.713	0.227	26.928	1.566	0.010
R4	1 902.00	21.207	1.749	17.435	0.227	26.731	1.716	0.033
R5	1 895.80	29.962	1.623	12.315	0.201	44.695	1.593	0.031
R8	1 881.50	18.993	1.669	17.136	0.581	49.927	1.725	0.056
R9	1 871.30	22.202	1.670	15.618	0.170	25.009	1.666	0.003
R10	1 861.50	21.537	1.700	16.429	0.270	43.668	1.702	0.002
R11	1 846.20	27.848	1.639	13.130	0.208	35.603	1.609	0.029
R12	1 840.50	35.274	1.556	10.128	0.211	35.333	1.529	0.027
R13	1 835.15	36.706	1.539	9.617	0.156	33.359	1.514	0.024

using a fixed cementation factor regressed from the cross plot of the formation factor and porosity will be inaccurate.

Cementation factors can be calculated once the parameters of porosity and permeability are obtained. Porosity can be easily determined, but the calculation of permeability is a great challenge in low permeability reservoirs. SDR model can be used to predict permeability if the NMR logs are available, and then a novel cementation factor estimation model can be established when the porosity and T_{2lm} are determined.

The cementation factors predicted from NMR logs by using the proposed model in this paper are credible, and they match well with the core analyzed results. The absolute errors for core samples are lower than 0.071. This demonstrates that the novel cementation factor estimation model is reliable and can be extended to field application to estimate the consecutive cementation factors along with the intervals with NMR logs. The novel model is valuable for the calculation of hydrocarbon and water saturation in low permeability reservoirs.

ACKNOWLEDGMENT

This study was supported by the Major National Oil & Gas Specific Project of China (No. 2011ZX05044).

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