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NUMERICAL MODELING OF ENERGY EFFICIENT SOLUTIONS OF CARBON REMOVAL AND SLAG MODE IN ELECTRIC ARC FURNACE

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In the framework of modern two-stage liquid steel production, electric arc furnace (EAF) is a unit for intensive smelting of intermediate product, with subsequent finishing to specified steel grade by methods of the ladle metallurgy. The EAF technological regulations provide for obtaining a low-carbon melt in the energy-saving mode of slag foamed with gas bubbles. Reduction of the shape factor of steel melting bath (diameter to depth ratio) with an unchanged liquid steel capacity is aimed at increasing the energy efficiency of the EAF due to reduction of heat losses by radiation of the melt surface on the working space water-cooled panels. The transition to a "deep" bath also contributes to the intensification of heat and mass exchange processes under the conditions of forced mixing of the melt, in particular, purging with inert gas. The effect of a "deep" bath on the process of carbon removal on argon and CO bubbles and formation of foamed slag during intensive technology, from the standpoint of the EAF energy efficiency, a numerical study was carried out. The single bubble model and known empirical relations for mass transfer coefficients of reactants under the conditions of diffusion stoichiometry are used. For industrial 120-tons EAF it is shown that reducing the bath shape factor to the optimum, according to the energy efficiency criterion, leads to an increase in the rate of metal decarburization by 5–18% due to the intensification of the mass transfer processes of reagents in the system of iron-carbon melt-floating gas bubble. On the base of known experimental data, under conditions of optimal surface tension and viscosity of the slag, a regression equation was obtained for the height of stable slag foam on process gas flow rate through metal-slag interface. Using a numerical model of radiation heat transfer, is shown that a "deep" bath factor, in this context, contributes to the reduction of radiation heat losses with water by 4% due to more effective shielding of electric arc radiation on water-cooled EAF panels with foamed slag.

Key words: *electric arc steel melting furnace, "deep" bath, purging with inert gas, intensification of decarburization on gas bubbles, foamy slag, energy efficiency.*

Тімошенко Сергій. Чисельне моделювання енергоефективних рішень зневуглецевлення й шлакового режиму в дуговій сталеплавильній печі

В рамках сучасного двостадійного виробництва рідкої сталі електродугова піч (ДСП) є установкою для інтенсивної виплавки напівфабрикату з подальшим доведенням сталі до заданої марки методами ковшової металургії. Технологічний регламент ДСП передбачає отримання низьковуглецевого розплаву в енергозберігаючому режимі спіненого газовими бульбашками шлаку. Зменшення коефіцієнта форми сталеплавильної ванни (відношення діаметру до глибини) за незмінної місткості рідкої сталі спрямовано на підвищення енергоефективності ДСП через зниження теплових втрат випромінюванням поверхні розплаву на водоохолоджувальні панелі робочого простору. Перехід до «глибокої» ванни сприяє інтенсифікації процесів тепломасообміну в умовах примусового перемішування розплаву, зокрема, інертним газом. Шляхом чисельного моделювання досліджено, що з позицій енергоефективності ДСП вплив «глибокої» ванни на процес зневуглецевлення сталі на бульбашках аргону й CO і утворення спіненого шлаку за інтенсивної технології. Застосовано модель одиночної бульбашки і відомі емпіричні співвідношення для коефіцієнтів масопереносу реагентів за умов дифузійної стехіометрії. Щодо промислової 120-т ДСП показано, що зменшення коефіцієнта форми ванни до оптимального за критерієм енергоефективності приводить до збільшення швидкості зневуглецевлення металу на 5–18% за рахунок інтенсифікації процесів масопереносу реагентів в системі «залізовуглецевистий розплав – спливаюча газова бульбашка». На основі відомих експериментальних даних, за умов оптимального поверхневого натягу та в'язкості шлаку, отримано рівняння регресії для висоти стійкої шлакової піни від швидкості потоку технологічного газу через межу «метал – шлак». За допомогою чисельної моделі радіаційного теплообміну показано, що фактор «глибокої» ванни в цьому контексті сприяє зменшенню радіаційних втрат теплоти з водою на 4% за рахунок більш ефективного екранування спіненим шлаком випромінювання електричної дуги на водоохолоджувальні панелі ДСП.

Ключові слова: *дугова сталеплавильна піч, «глибока» ванна, продувка інертним газом, зневуглецевлення сталі на газових бульбашках, спінений шлак, енергоефективність.*

Introduction: state of the art and the research task. The EU Green Deal policy in relation to steel production, against the background of changing consumer demands, will give preferences in the nearest future to energy-efficient and environmentally friendly solutions of hydrogen reduction of iron and electrical steelmaking technologies, particularly, in arc furnaces (EAF) [1]. A technological sketch of modern EAF, in the context of improvement efficiency of carbon removal from the steel and energy saving slag mode, is shown in Fig. 1.

A shape factor of steelmaking bath $k_b = D_b/H_b$ (Fig. 1, a) in the classical EAF technology constitutes 4.5–5.5 [2]. Such geometry provides a developed metal-slag interfacial surface, which is necessary for effective steel refining. In a modern EAF technologies with subsequent finishing of the steel to specified grade by methods of ladle metallurgy, cooling panels in the workspace, forced mixing of the bath, to increase the energy efficiency seems rational the transition to a "deep" bath with a smaller radiating surface due to reduction of k_b [2]. An important advantage of a "deep" bath is the intensification of heat and mass exchange processes under conditions of forced mixing [3]. This factor contributes to reduction of the technological period and time of the heat in general, and ultimately – the energy efficiency of the furnace.

A widely investigated reaction between carbon [C] and oxygen [O], dissolved in the molten steel:

$$[C] + [O] = \{CO\}, \qquad (1)$$

associated with the emerging of gas phase. In a homogeneous melt such reaction is complicated through high value of capillary pressure to form a bubble. Therefore, it flows in the bath mainly on free surfaces, in particular gas bubbles. Chemical composition of the bubbles in the EAF liquid bath conditions is mainly represented by CO, that is the ultimate product of dissolved and injected carbon oxidation through supersonic oxygen lance operation, and argon, which is used during pneumatic mixing. The reaction constant of (1) has the following temperature dependence [5]:

$$k_{co} = p_{co} / [C]_s[O]_s = 10^{(1860/T_m)+1,61}, \qquad (2)$$

where p_{co} – the partial pressure of CO in the bubble (at); $[C]_s, [O]_s$ – surface concentrations of carbon and oxygen at the bubble-melt boundary (wt. %); T_m – metal temperature (K).

The kinetics of metal decarburization due to the reaction (1) on emerging gas bubbles for one-dimensional problem is described by the next differential equation [6]:

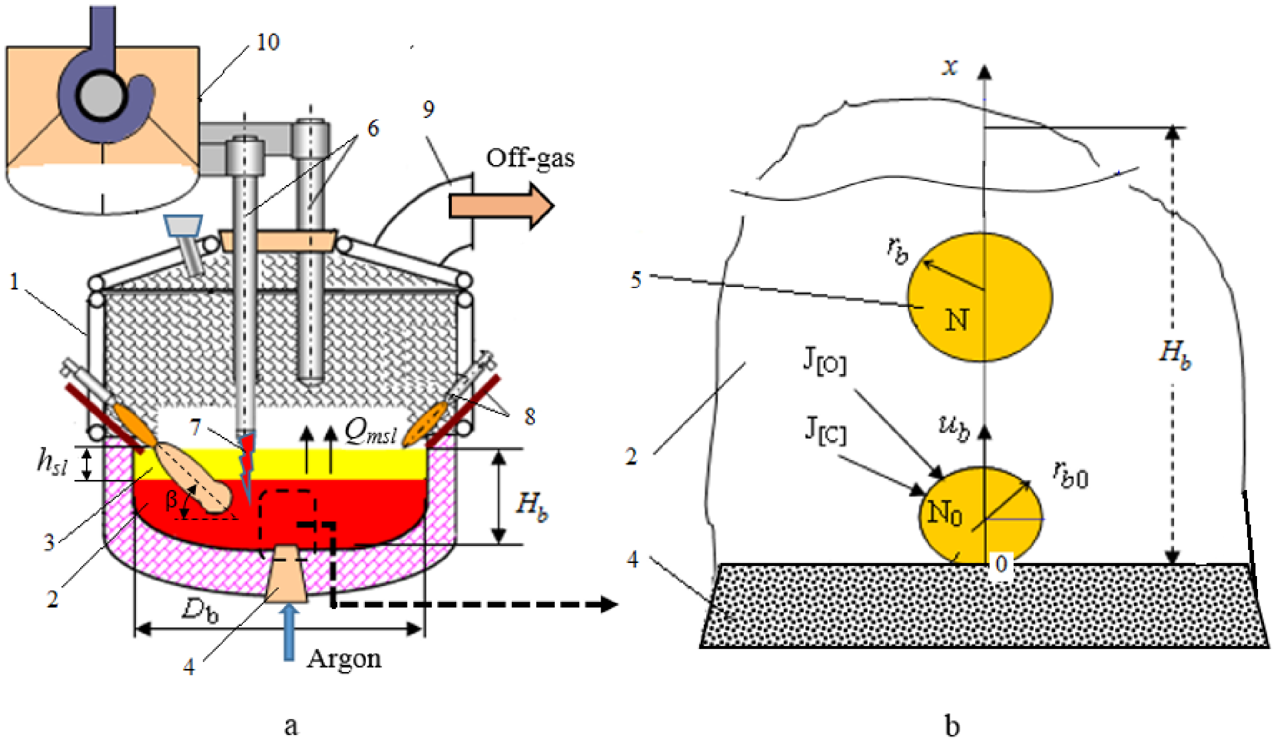

Fig. 1. Technological scheme of EAF (a). Mechanism of decarburization process on floating gas bubbles (b). 1 – EAF, 2 – metal bath, 3 –slag bath, 4 – porous plug, 5 – gas bubble, 6 – electrode, 7 – electric arc, 8 – heat intensification facilities, 9 – aspiration duct, 10 – charging bucket (other designation are in the text)

$$dn / dx = J_{C,O} \cdot F_b / u_b \,, \qquad (3)$$

where n – current by coordinate x (m), amount of CO in the bubble (kmol); F_b – bubble surface area (m^2); u_b - velocity of bubble ascent (m/s); $J_{C,O}$ – flow of reagents from the melt into the bubble [kmol/(m$^2\cdot$s)].

A task of research is to substantiate optimization of the EAF bath form factor, in the context of importance to assess the possibility of intensification the technology-regulated process of carbon removal from steel on gas bubbles with an increase in the depth of steelmaking bath.

Main content: method, results, discussion. The task was completed by numerical simulation in the Mathcad application package.

The ascent of a single inert gas bubble with initial radius r_{b0} in iron-carbon melt in the gravitation field (Fig. 1, b) is considered. Reaction (1) takes place on the bubble surface until equilibrium established with the gas phase in the bubble and surface concentration of carbon and oxygen in the melt, that described by equation (2). In order to correct calculation of equation (2), surface concentrations should be expressed in terms of their volume concentrations, which can be practically determined.

According to reaction (1), diffusion stoichiometry carbon $j_{[C]}$ and oxygen $j_{[O]}$ flows is observed during formation of CO, which gives the expression of Fick's law for a one-dimensional problem the following form [kmol/(m$^2\cdot$s)]:

$$j_{[C]} = \beta_{[C]}([C]-[C]_s)\,f_c = j_{[O]} = \beta_{[O]}([O]-[O]_s)\,f_o = j \,, \qquad (4)$$

where $f_c = 5{,}83;\ f_o = 4{,}38$ – coefficients of conversion reactant concentrations [C], [O] with wt. % in kmol/m^3.

The values of the mass transfer coefficients of oxygen and carbon $\beta_{[O]}, \beta_{[C]}$ (m/s) in the iron-carbon melt-floating bubble system are determined by the following empirical expressions [6]:

$$\beta_{[C]} = a\sqrt{D_{[C]} \cdot u_b / r_b}\,,\ \ \beta_{[O]} = a\sqrt{D_{[O]} \cdot u_b / r_b}\,,\ (5);\ (6)$$

where u_b – ascending bubble velocity in the melt bath (m/s); $D_{[O]}, D_{[C]}$ – molecular diffusion coefficients of oxygen and carbon in molten steel (m^2/s); r_b – fluent bubble radius (m); a – empirical coefficient equal 0,88 for spherical bubble [6].

Expressing one surface concentration from equation (2) in terms of another one, we get the next form:

$$[O]_s = p_{co} / ([C]_s k_{co}) \,. \qquad (7)$$

Let's determine the surface concentration of oxygen from equation (7), taking into account expression (4):

$$[O]_s = [O] - (j / \beta_{[O]}) = p_{co} / ([C]_s k_{co}) \,. \qquad (8)$$

Let's transform equation (7) to find the surface concentration of carbon.

$$[C]_s = p_{co} / [k_{co} \cdot ([O] - j / \beta_{[O]})] \,. \qquad (9)$$

Substituting the value of surface concentration of carbon from expression (9) into equation (8), we get the stoichiometric reagents flux in kmol/(m$^2\cdot$s):

$$j = \beta_{[C]}([C]\,f_c - p_{co} / [k_{co}([O]\,f_o - j / \beta_{[O]})] =$$
$$= \beta_{[O]}[C]\,f_c - \beta_{[C]} p_{co} / [k_{co}([O]\,f_o - j / \beta_{[O]})].$$

Let's transform this equation, reducing it to a square one, and find its roots:

$$j_{1,2} = 0{,}5\,[(\beta_{[O]}[O]\,f_o + \beta_{[C]}[C]\,f_c) \pm \pm \begin{bmatrix} (\beta_{[O]}[O]\,f_o + \beta_{[C]}[C]\,f_c)^2 - \\ 4\beta_{[O]}\beta_{[C]}([C][O]\,f_c f_o - \dfrac{p_{co}}{k_{co}}) \end{bmatrix}^{0,5}]. \qquad (10)$$

The expression $\theta = [C][O] - p_{co} / k_{co}$ in the equation (10) is a driving force of the reaction (1). When the value of $\theta > 0$, diffusion flow of the reagents proceeds from the melt to the bubble; at $\theta < 0$ process take place in the direction from the bubble to the melt. When choosing the root of equation (10), we are guided by the reasoning that in the absence of the driving force of the reaction (1), that is at $\theta = 0$, the flow of reactants approaches zero. Therefore, the actual solution of equation (10) has a (–) sign.

The differential equation (3) for a single bubble of argon and CO, taking into account the expressions for the input parameters, solved numerically per conditions of technological (heating) period in 120-ton EAF, operating with intensive technology. There are: [C] = 0.22%, [O] = 0.01%, temperature of the bath and in the bubble is T_m = 1873 K, diffusion coefficients $D_{[C]}$ = 7.9$\cdot$10^{-9} m^2/s, $D_{[O]}$ = 7.5$\cdot$10^{-9} m^2/s [6]. The depth of the bath and the initial radius of the bubble varied from 1 to 2 m and from 10 to 40 mm, respectively.

In the process of solution, the parameters that are a function of bubble position on the bath height were adjusted according to x coordinate (Fig. 1, b):

– bubble fluent radius $r_b = [(N_0 + N) R_g T_m / [[p_{at} + (H_b - x) / H_g] \cdot 1{,}33\pi]]^{0,33}$ (m);

– fluent pressure in the bubble $p = p_{at} + [(H_b - x) / H_g]$ (at);

– velocity of ascent the bubble in steel bath $u_b = 1{,}02\sqrt{g r_b}$ (m/s) [7];

– mass transfer coefficients according to formulas (5,6) through u_b, r_b (m/s),

where N, N_0 is the amount of gas in the bubble at the exit from the bath and in initial bubble, respectively (kmol), R_g – universal gas constant [J/(kmol·K)], g – gravity constant (m/s^2), H_g = 1.48 – hydrostatic height of liquid steel (m), p_{at} – normal atmospheric pressure (at).

The dependences of relative progress of decarburization reaction on CO and argon bubbles $\alpha_{deC} = (N/N_0)/(N/N_0)^*$ in the "deep" bath (N/N_0) at H_b = 1.75 m and initial basic bath $(N/N_0)^*$ at H_b = 1.1 m versus the initial size of the gas bubble are shown in Fig. 2.

Analyzing the results, it can be seen that with average bubble sizes of 10–20 mm typical for a steel-melting bath [7], increasing the depth of 120-ton EAF bath from 1.10 to 1.75 m allows to count on an increase in the decarburization rate by 5–18% due to the intensification of mass transfer reagents in the melt-bubble system.

A higher result of decarburization on argon bubbles, in comparison with CO bubbles, appears to be regular, when concentrations of carbon and oxygen in the bath are close to equilibrium.

It should be noted that the results, obtained for a single bubble, with mass bubbling will be lower through mutual influence, but the general trend of mass transfer intensification in a “deep” bath will obviously remain.

Carbon removal is accompanied by intensification of melting in the EAF due to powerful mixing of the bath both with oxygen lance jets and with CO bubbles. Increasing the intensity of oxygen blowing the bath through heat intensification facilities (Fig. 1, a) is limited by the possibility of damage to the furnace lining by a high-temperature reaction crater. According to research by P. McGee and G. Irons [8], the penetration depth of a supersonic inclined oxygen jet into a liquid steel bath is proportional to the square of the blowing rate. According to M. Alam, G. Irons, G. Brooks and others [9] the dependence between these parameters is close to linear. Increasing the depth of 120-t EAF bath by ≈ 1.6 times (from 1.1 to 1.75 m) gives the reason to increase the average blowing intensity by ≈ 2 times. Such a change in the regime of oxygen blowing will have a positive effect both on the dynamics of bath homogenization with the increase in number and depth of gas bubbles emergence in the secondary reaction zone [5], and on the mass transfer processes on the crater walls and on the bubbles during metal decarburization [10; 11].

A decrease in k_b relative to the base value leads to the need to shift the oxygen jets from the electrodes by increasing of inclination angle β of oxygen lance axis to the horizon (Fig. 1, a). This operation, according to [9], should give a positive effect due to the reduction of the melt splashing and associated negative effects of water-cooled panels metallization and iron losses.

Among the parameters that determine a mode of slag foaming, in addition to basicity, oxidation degree (content of FeO), surface tension and viscosity of the slag, an important is the specific, per unit area of the bath, intensity of CO gas emission at the metal-slag interface Q_{msl} [m^3/(m^2.s)]. This factor, assuming its uniform distribution over the bath surface, determines a gas dynamic of the

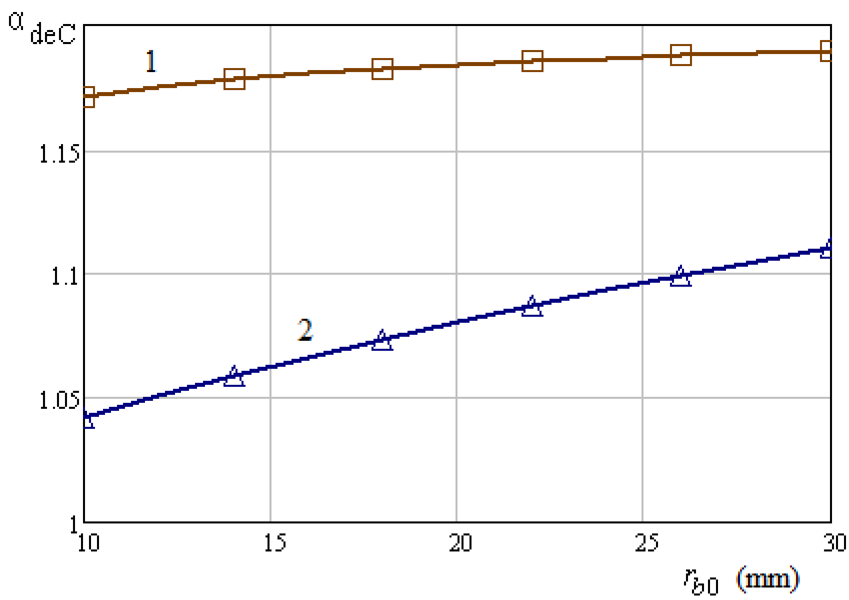

Fig. 3. Relative foaming slag height $\alpha_{h_{sl}}$ and relative energy consumption $\alpha_{W_{el}}$ versus bath form factor k_b for industrial 120-ton EAF

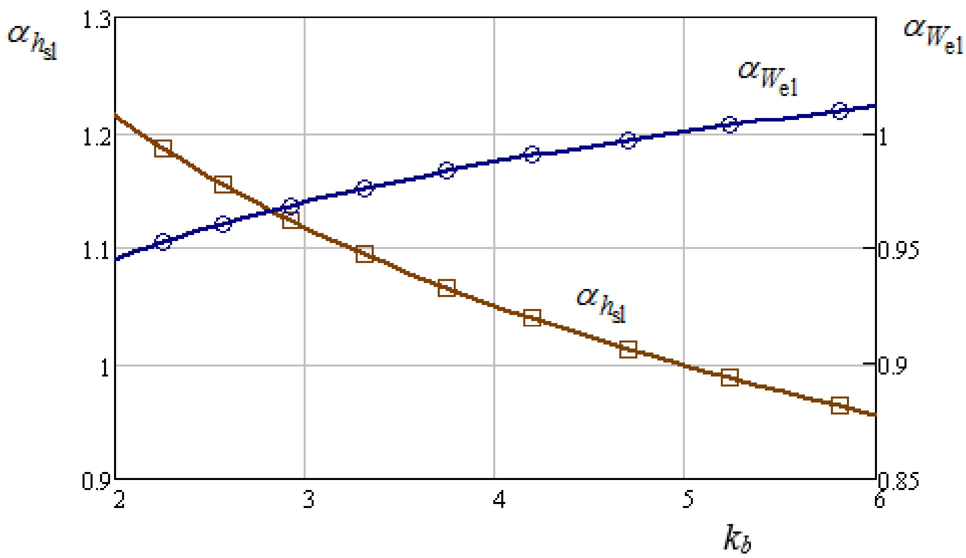

Fig. 2. Progress of carbon removal reaction α_{deC} as a result of transition from base bath to "deep "one versus initial bubble radius r_{b0}; 1 – argon, 2 – CO

slag and, thereby, the height and stability of the slag foam [12; 13].

Based on the analysis of experimental data by S. Aminorroaya, H. Edris [13] on 200-t EAF for the height of foamed slag h_{sl} (mm) depending on Q_{msl} and the specific consumption of electricity W_{el} (kWh/t) depending on h_{sl}, with the content in the slag (FeO) = 25–30%, the following trend line equations are obtained:

$$h_{sl} = 213{,}30\ln(Q_{msl}) - 50{,}26\,. \qquad (11)$$

$$W_{el} = -0{,}26 h_{sl} + 789{,}5\,. \qquad (12)$$

The evaluation of Q_{msl} was carried out with the same mode of heat intensification facilities operation with a specific oxygen consumption of 45 m^3/ton during 15 minutes, blowing, typical for intensive EAF technology. Dependencies (11,12) are used to estimate energy savings when applying the foamed slag regime under the conditions of implementing a "deep" bath in 120-t EAF.

The EAF energy efficiency indicators are presented in dimensionless form (Fig. 3): the relative increase in the height of the foamed slag $\alpha_{h_{sl}}$ and the relative energy savings $\alpha_{W_{el}}$ through transition from the basic bath (H_b = 1.10 m, k_b = 5.0) to the "deep" one (H_b = 1.75 m, k_b = 2.5). The parameter $\alpha_{W_{el}}$ is obtained, basing on a mathematical model of heat exchange by radiation in the EAF [14]. It is characterized by a relative decrease of radiation energy losses in water-cooled panels due to screening effect of increased height of the foamed slag.

Based on shown in Fig. 3 estimates of relative values $\alpha_{h_{sl}}$ and $\alpha_{W_{el}}$ it can be predicted that transition from the base bath to the "deep" one, with corresponding decrease in $k_b = D_b / H_b$ from 5.0 to 2.5, the relative height of the foaming slag increases by 15%, which ensures the energy savings in the furnace by ≈ 4%.

Conclusion. On the basis of numerical modeling of the mass transfer processes in the EAF, it was established that reducing the form factor of steelmaking bath from traditional 5.0 to 2.5, according to the energy efficiency criterion, leads to an increase in metal decarburization rate by 5–18% due to the intensification of the mass transfer processes on ascending gas bubbles. The advantage of the "deep" bath regarding to the slag mode is to increase of allowable, under the conditions of reaction crater action on refractory, intensity of oxygen blowing by ≈ 2 times. Another positive factor is the reduction of radiation heat losses with water in the protective panels by ≈ 4% due to more effective shielding of the arcs with foamed slag. Obtained data should be considered as a further argument in favor of a "deep" bath EAF concept.

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