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FEASIBILITY STUDY OF IMPROVING THE TRANSPORT PERFORMANCE BY MEANS OF SCREW CONVEYORS WITH ROTARY CASINGS

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Paper presents feasibility study for verification of the hypothesis of improving the productivity of reload operations using screw conveyors with rotary casings. For this purpose, an experimental installation was developed and experimental studies were conducted. Research results fully confirmed the hypothesis. On the basis of a feasibility study of casing rotation in screw conveyors, the conveyor performance increased by 24%, with the conveyor capacity thereby increased by 4.5%. Due to the application of rational parameters of the screw conveyor with a rotary casing, overall economic factor was improved by more than 10%. To achieve the economic efficiency of reload operations using screw conveyors with rotary casings, the rotational frequency of the casing should range from 460 to 620 rpm.

Keywords: screw conveyor; rotary casing; productivity; feasibility study

Screw conveyors are widely used in agriculture as conveyors, mixers, feeders, separators, etc. An increase in performance of screw conveyors often causes considerable unjustified energy consumption that makes the process inefficient. Due to this reason, modern screw conveyors with transporting casings should be designed. Such devices will ensure the shift of the material in order to provide the necessary friction of a screw with the material and casing. Therefore, the efficiency of transport operations will be increased.

Fundamentals of the designing and the investigation of screw conveyors have been presented by Owen and Cleary (2010) or Rogatynskiy et al. (2017), etc. Furthermore, it has been determined that flow uniformity depends on the design of a screw operating element and a hopper, as well as shape of particles and force of their friction at the walls (Hou et al., 2014). Results of this investigation contribute to the insight into the use of a screw conveyor for specific materials.

Multiple authors (Pezo et al., 2015; Hui and Wanfu, 2013; Rogatynskiy et al., 2017) have dealt with the operation mode of an inclined screw conveyor with a screw operating element and constant parameters incorporated in it. Kinematics of grain loading has been investigated on the basis of motion equations in a screw conveyor. Analysis of loading movement at constant high-speed mode has been analysed as well.

Numerous researchers (Lyashuk et al., 2015; Fernandez et al., 2011; Sun et al., 2017; Zareiforoush et al., 2010) provide findings on flow patterns of bulk materials depending on constructional and kinematic characteristics of screw operating tools, bunker type and solid particles, as well as frictional forces. Findings of aforementioned researches

show the improvement of characteristics of screw conveyors during transportation of bulk materials. Authors Baranovsky et al. (2018), Hevko et al. (2015) and Hevko et al. (2018a) dedicated their investigations to the solving of aforementioned issues, namely the development of energy-saving designs of screw conveyors and selection of their most efficient parameters and working modes.

Furthermore, researchers Loveikin and Rogatynska (2011) and Lyashuk et al. (2015) have investigated contact interaction of grain-working surfaces and described methods for improvement of operation life of screw conveyors. Their works pay special attention to the selection of parameters of working bodies and processes of materials transportation, proving the relevance of the issue of increasing the productivity and efficiency of transport and technological processes. Objective of work presented is to carry out a feasibility study of improving the transport performance by means of screw conveyors during the rotation of their casings.

Material and methods

In order to increase the productivity of material transportation by screw mechanisms and to reduce energy consumption, modern progressive constructions should be designed (Rogatynska et al., 2015; Klendii, 2007; Lyashuk et al., 2016), screw conveyors with rotary casings in particular. According to the conducted patent search, analysis of scientific literary sources, and synthesis (Hou et al., 2014; Mondal, 2018; Owen and Cleary, 2010; Tripathi et al., 2015), a number of designs of screw conveyors with

rotary casings have been developed and patented. An experimental installation was developed; it is shown in Fig. 1. Screw working body and casing are driven separately by individual motors (screw working body – by an electric motor with a power of 2.2 kW; casing – by an electric motor with a power of 1.5 kW). A number of experimental studies were carried out using this device.

Experimental installation can operate in two modes: accelerated transportation of materials, and mixing bulk materials. In the first case, the casing rotates in the direction opposite to the direction of screw rotation, in the second case – in the direction of screw rotation. The bulk material enters the casing on the screw via the bunker.

The screw and casing rotate by means of electric motors controlled by a PC applying frequency converters. According to the developed methodology of conducting experimental studies, all necessary data are provided in tabular or graphical form.

Fig. 1 General view of the experimental installation:
1 – support for adjusting the height of the material feed;
2 – frame; 3 – rotary casing with a screw inside; 4 – bunker;
5 – unloading nozzle; 6 – screw drive; 7 – casing drive;
8 – point for control of the rotational frequency of the casing and screw drives

Screw conveyor performance at various coefficients of filling the casing and rotational frequencies of the screw and casing is determined in automated mode. Power characteristics can be determined at a smooth and steep start, reversal and simulation of various loads in an automated mode using a frequency converter and a PC.

To determine the effect of the rotary casing use on screw conveyor properties, the performance of the proposed conveyor is determined. Screw rotational frequency n , casing rotational frequency n_c , and conveyor inclination

angle γ were taken into account during the casing rotation in a direction opposite to the screw rotation direction.

The conveyor performance was measured by means of electronic scales. Each of unchanged factors was experimentally studied at least 3 times. Subsequently, the average value of the results was determined and used for further statistical processing of experimental data. The response function, i.e. the performance $Q = f(n, n_c, \gamma)$ determined experimentally, is represented as a mathematical model of a complete quadratic polynomial. Screw rotational frequency n encoded by the index x_1 , casing rotational frequency n_c encoded by the index x_2 , and conveyor inclination angle γ encoded by the index x_3 were adopted as input experiment variables. Characteristics of factors and corresponding level values of the transported materials are given in Table 1.

On the basis of the experiment results in the coded values, a general information on the performance regression equation $Q_{(x_1, x_2, x_3)} = f(n, n_c, \gamma)$ dependent on the changes in the screw rotational frequency n , the casing rotational frequency n_c and the inclination angle of the conveyor γ are as follows:

– during the corn transportation:

$$Q_{(x_1, x_2, x_3)} = 8.88 + 3.373x_1 + 0.487x_2 - 0.29x_3 + 0.181x_1x_2 - 0.109x_1x_3 - 0.006x_2x_3 + 0.139x_1^2 - 0.451x_2^2 - 0.226x_3^2 \quad (1)$$

– during the wheat transportation:

$$Q_{(x_1, x_2, x_3)} = 9.34 + 3.55x_1 + 0.513x_2 - 0.306x_3 + 0.191x_1x_2 - 0.114x_1x_3 - 0.006x_2x_3 + 0.152x_1^2 - 0.473x_2^2 - 0.238x_3^2 \quad (2)$$

– during the barley transportation:

$$Q_{(x_1, x_2, x_3)} = 7.127 + 2.708x_1 + 0.392x_2 - 0.232x_3 + 0.144x_1x_2 - 0.086x_1x_3 - 0.0037x_2x_3 + 0.11x_1^2 - 0.36x_2^2 - 0.18x_3^2 \quad (3)$$

Accordingly, by importing natural values, transformation and simplification, the following expressions were deduced from Eqs. 1, 2, 3:

– during the corn transportation:

$$Q_{(n, n_c, \gamma)} = -1.22 + 1.31 \cdot 10^{-2} n + 5.69 \cdot 10^{-3} n_c + 9.28 \cdot 10^{-2} \gamma + 3.23 \cdot 10^{-6} nn_c - 4.95 \cdot 10^{-5} n\gamma - 2.04 \cdot 10^{-6} n_c\gamma + 3.48 \cdot 10^{-6} n^2 - 5.79 \cdot 10^{-6} n_c^2 - 1.87 \cdot 10^{-3} \gamma^2 \quad (4)$$

– during the wheat transportation:

$$Q_{(n, n_c, \gamma)} = -1.242 + 1.36 \cdot 10^{-2} n + 5.969 \cdot 10^{-3} n_c + 9.741 \cdot 10^{-2} \gamma + 3.41 \cdot 10^{-6} nn_c - 5.182 \cdot 10^{-5} n\gamma - 2.029 \cdot 10^{-6} n_c\gamma + 3.8 \cdot 10^{-6} n^2 - 6.03 \cdot 10^{-6} n_c^2 - 1.967 \cdot 10^{-3} \gamma^2 \quad (5)$$

Table 1 Characteristics of factors and their levels values

Coded designation of the factor	Factor designation	Values of factors levels
x_1	Screw rotational frequency n (rpm)	300–500–700
x_2	Casing rotational frequency n_c (rpm)	200–480–760
x_3	Inclination angle of the conveyor γ (deg)	14–25–36

Fig. 2 Dependency graphs of the screw conveyor performance on the conveyor casing rotational frequency during the corn transportation
screw diameter $D = 96$ mm; screw rotational frequency $n = 700$ rpm: 1) $\gamma = 14$ deg; 2) $\gamma = 25$ deg; 3) $\gamma = 36$ deg

– during the barley transportation:

$$Q_{(n, n_c, \gamma)} = -0.974 + 1.053 \cdot 10^{-2} n + 4.55 \cdot 10^{-3} n_c + 7.342 \cdot 10^{-2} \gamma + 2.571 \cdot 10^{-6} n n_c - 3.909 \cdot 10^{-5} n \gamma - 1.218 \cdot 10^{-6} n_c \gamma + 2.75 \cdot 10^{-6} n^2 - 4.592 \cdot 10^{-6} n_c^2 - 1.488 \cdot 10^{-3} \gamma^2 \quad (6)$$

Results and discussion

On the basis of experimental research results, graphic reproduction of intermediate common regression models in form of quadratic surfaces of the response and their two-dimensional cross sections (Figs. 2–5) of Q , performance was developed as a function, applying two variables $x_{i(1,2)}$ at a constant unchangeable level of the corresponding third factor $x_{i(3)} = \text{const}$. According to the analysis of the aforementioned regression equations, the main factors influencing the performance improvement are factors $x_1, x_2, (n, n_c)$ and combinations of these factors. An increase in the value of factor $x_3 (\gamma)$ led to a decrease in the performance.

Fig. 3 Response surface (a) and two-dimensional cross section of the response surface (b) of conveyor performance dependence $Q_{(n, n_c)}$ during the corn transportation at the screw rotational frequency and the casing rotational frequency
 $\gamma = 14$ deg, $D = 96$ mm

Fig. 4 Response surface of the conveyor performance dependence $Q_{(n_c, \gamma)}$ during the corn transportation at the casing rotational frequency and the conveyor inclination angle
 $n = 700$ rpm, $D = 96$ mm

Fig. 5 Response surface of the conveyor performance dependence $Q_{(n, \gamma)}$ during the corn transportation at the screw rotational frequency and the conveyor inclination angle
 $n_c = 480$ rpm, $D = 96$ mm

According to the research results (Hevko et al., 2018b; Rogatynska et al., 2015; Sun et al., 2017), an increase in the casing rotational frequency n_c led to an increase in the screw conveyor performance Q by 18–24% in contrast to its operation mode utilizing a fixed casing. Furthermore, an increase in the casing rotational frequency n_c exceeding 620 rpm is irrational, since it does not change the conveyor performance. The casing rotational frequency in range from 460 to 620 rpm is rational, since it results in the greatest performance increase of the screw conveyor at different screw rotational frequencies n .

Moreover, the minimal casing rotational frequency to start the screw conveyor after its forced stop was determined. The bulk material moves upward along the axis of the screw working body under the following conditions: the greater the screw working body turn pitch, the more horizontal the axis inclination angle of the screw working body; and the greater the friction coefficient between the material and screw working body surface is, the greater the casing rotational frequency should be.

Moreover, the smaller the radius of the inner surface of the casing and the friction coefficient between the material and the casing surface are, the greater the casing rotational frequency should be:

$$n_c = \frac{30}{\pi} \sqrt{\frac{g \left(\sin \gamma \operatorname{tg} \left(\operatorname{arctg} \frac{T}{2\pi R} + \operatorname{arctg} f_1 \right) \left(1 + \frac{1}{f_2} \right) + \cos \gamma \right)}{R_1}} \quad (7)$$

where:

- T – screw turn pitch in the outer radius
 g – free fall acceleration
 R_1 – casing inner surface radius

Table 2 Measurement results of power and torque (the screw shaft under study) at the corresponding casing rotational frequency

Screw rotational frequency n (rpm)	Power (screw shaft) (%)	Torque (screw shaft) (%)
Casing rotational frequency n_c – 312 (rpm)		
280	5	11.4
420	8	12.8
560	11	13.2
700	14	13.7
Casing rotational frequency n_c – 468 (rpm)		
280	6	13.5
420	9	14.8
560	12	14.4
700	15	14.5
Casing rotational frequency n_c – 624 (rpm)		
280	6	14.3
420	10	17.0
560	14	17.1
700	17	17.8

- f_1 – friction coefficient between the bulk material and screw surface
 f_2 – friction coefficient between the bulk material and casing surface
 R – screw external radius

The experimental power and torque data in percentages are shown in Tables 2 and 3. The data were recorded via PC during a series of experiments using Altivar series frequency converters.

The data of power and torque (the screw shaft under study) during the material reload without rotation of the casing are presented in Table 4.

On the basis of experimental results and information on the power driving the screw, regression equation will be as follows:

– during the corn transportation:

$$N_{(n, n_c, \gamma)} = 0.0625 + 2.02 \cdot 10^{-4} n - 1.51 \cdot 10^{-4} n_c + 6.57 \cdot 10^{-4} \gamma + 1.80 \cdot 10^{-7} n n_c + 2.44 \cdot 10^{-6} n \gamma + 7.28 \cdot 10^{-7} n_c \gamma + 1.38 \cdot 10^{-7} n^2 + 2.14 \cdot 10^{-7} n_c^2 - 1.9 \cdot 10^{-5} \gamma^2 \quad (8)$$

– during the wheat transportation:

$$N_{(n, n_c, \gamma)} = 0.0625 + 2.02 \cdot 10^{-4} n - 1.51 \cdot 10^{-4} n_c + 6.57 \cdot 10^{-4} \gamma + 1.80 \cdot 10^{-7} n n_c + 2.56 \cdot 10^{-6} n \gamma + 7.63 \cdot 10^{-7} n_c \gamma + 1.42 \cdot 10^{-7} n^2 + 2.23 \cdot 10^{-7} n_c^2 - 2.04 \cdot 10^{-5} \gamma^2 \quad (9)$$

– during the barley transportation:

$$N_{(n, n_c, \gamma)} = 0.0480 + 1.58 \cdot 10^{-4} n - 1.15 \cdot 10^{-4} n_c + 4.38 \cdot 10^{-4} \gamma + 1.38 \cdot 10^{-7} n n_c + 1.96 \cdot 10^{-6} n \gamma + 5.89 \cdot 10^{-7} n_c \gamma + 1.07 \cdot 10^{-7} n^2 + 1.70 \cdot 10^{-7} n_c^2 - 1.57 \cdot 10^{-5} \gamma^2 \quad (10)$$

Table 3 Measurement results of power and torque (the casing under study) at the appropriate screw rotational frequency

Casing rotational frequency n_c (rpm)	Power (casing) (%)	Torque (casing) (%)
Screw rotational frequency n – 700 (rpm)		
312	9	20.8
468	10	22.6
624	11	23.2
780	10	22.7

Table 4 Measurement results of power and torque (the screw shaft under study) after stopping the casing

Screw rotational frequency n (rpm)	Power (screw shaft) (%)	Torque (screw shaft) (%)
Casing rotational frequency n_c – 0 (rpm)		
312	8	19.5
468	12	19.1
624	16	19.1
780	20	19.2

On the basis of experimental results and information on the power driving the casing, regression equation will be as follows:

- during the corn transportation:

$$N_{c(n, n_c, \gamma)} = -0.0326 + 7.14 \cdot 10^{-5} n + 3.17 \cdot 10^{-5} n_c + 9.09 \cdot 10^{-4} \gamma + 2.06 \cdot 10^{-7} n_c^2 \quad (11)$$

- during the wheat transportation:

$$N_{c(n, n_c, \gamma)} = -0.0376 + 7.86 \cdot 10^{-5} n + 3.45 \cdot 10^{-5} n_c + 1 \cdot 10^{-3} \gamma + 2.17 \cdot 10^{-7} n_c^2 \quad (12)$$

- during the barley transportation:

$$N_{c(n, n_c, \gamma)} = -0.0262 + 5.74 \cdot 10^{-5} n + 2.45 \cdot 10^{-5} n_c + 7.31 \cdot 10^{-4} \gamma + 1.66 \cdot 10^{-7} n_c^2 \quad (13)$$

On the basis of experimental results and information on the specific energy consumption, regression equation will be as follows:

- during the corn transportation:

$$W_{(n, n_c, \gamma)} = 0.0132 - 9.31 \cdot 10^{-6} n - 6.4 \cdot 10^{-7} n_c + 1.34 \cdot 10^{-4} \gamma - 1.72 \cdot 10^{-8} n n_c + 8.12 \cdot 10^{-8} n \gamma - 7.28 \cdot 10^{-8} n_c \gamma + 1.35 \cdot 10^{-8} n^2 + 3.14 \cdot 10^{-8} n_c^2 + 2.18 \cdot 10^{-6} \gamma^2 \quad (14)$$

- during the wheat transportation:

$$W_{(n, n_c, \gamma)} = 1.065 \cdot 10^{-2} + 1.37 \cdot 10^{-6} n + 3.09 \cdot 10^{-6} n_c + 5.17 \cdot 10^{-5} \gamma - 2.59 \cdot 10^{-8} n n_c - 1.06 \cdot 10^{-7} n \gamma + 4.76 \cdot 10^{-8} n_c \gamma + 7.91 \cdot 10^{-9} n^2 + 2.84 \cdot 10^{-8} n_c^2 + 2.94 \cdot 10^{-6} \gamma^2 \quad (15)$$

- during the barley transportation:

$$W_{(n, n_c, \gamma)} = 0.0115 + 1.57 \cdot 10^{-6} n + 2.29 \cdot 10^{-6} n_c + 5.22 \cdot 10^{-5} \gamma - 2.64 \cdot 10^{-8} n n_c - 1.06 \cdot 10^{-7} n \gamma + 4.78 \cdot 10^{-8} n_c \gamma + 8.06 \cdot 10^{-9} n^2 + 3.02 \cdot 10^{-8} n_c^2 + 3.15 \cdot 10^{-6} \gamma^2 \quad (16)$$

When the casing rotates at the rotational frequency of 468 rpm, the screw performance at a rotational frequency 700 rpm increases by 20%. At the same time, the power driving the screw falls from 20% to 15% (2.2 kW motor), and the power driving the casing falls to 10% (1.5 kW motor).

Subsequently, the total power rise is: $\Delta P_{30} = (10\% \cdot 1.5 / 2.2) - (20\% - 15\%) = 1.82\%$.

Therefore, when the performance increases by 20% (the casing rotates at the rotational frequency 468 rpm and the screw at frequency 700 rpm), there is a rise in power of 1.82%.

Providing the conveyor performance without screw rotation is 100%, the power driving the screw is 20%. When the conveyor performance with the screw rotation increases by 20%, the total power of the conveyor is $20\% + 1.82\% = 21.82\%$. In comparison to the power rise, performance improvement is: $\Delta E_{30} = (100\% + 20\%) / 100\% - (20\% + 1.82\%) / 20\% = 0.109$.

Taking into account the performance improvement and electricity consumption, the productivity of casing rotating

at frequency 468 rpm in a screw conveyor, in which the screw rotates at frequency 700 rpm, is 10.9%.

Accordingly, the annual electricity savings due to the performance improvement of the screw conveyor with a rotary casing with the specified parameters are determined by the following formula:

$$E = P_1 \cdot V_e \cdot \Delta E \cdot N_h \cdot N_t \cdot N_{wd} \cdot K_e \quad (17)$$

where:

- P_1 – price for 1 kW·h⁻¹ of electricity (II class – 1.96 UAH from 1.12.2017 for industrial enterprises and consumers equal to them with the connected power of 750 kVA and more)
- V_e – electricity consumption volume due to equipment operation (kWh) (2.2)
- N_h – number of hours per tour (8)
- N_t – number of tours (1)
- N_{wd} – number of working days per year (240)
- K_e – coefficient of equipment use (0.92)

$$E_{30} = 1.96 \cdot 2.2 \cdot 0.109 \cdot 8 \cdot 1 \cdot 240 \cdot 0.92 = 830.22 \text{ UAH}$$

In addition to this, during feasibility studies of the performance of rotary casings of screw conveyors, the following factors should be taken into account when the operator is involved in the reload process. Providing the performance increases, the amount of working time of the operator involved in the production process of reloading the appropriate amount of materials will be reduced, i.e. the operator's working time should be reduced by a percentage of the reload operation improvement. Subsequently, the savings on the wages of the operator in terms of the single social contribution (0.22 in accordance with the Law of Ukraine of December 21, 2016, No. 1801-VIII "On the State Budget of Ukraine for 2017") will be:

$$E_s = S_m \cdot K_c \cdot 12 \cdot P_n / 100\% \quad (18)$$

where:

- S_m – average monthly salary (8,791 UAH per month in December 2018 according to <https://www.work.ua/ua/stat/>)
- K_c – coefficient with consideration of the single social contribution (1.22)
- P_n – percentage of the number of redundant workers due to performance improvement (%)

$$E_{s30} = (8,791 \cdot 1.22 \cdot 12 \cdot 20\%) / 100\% = 25,740.05 \text{ UAH}$$

Considering all these factors, the total savings resulting from the usage of screw conveyors with rotary casings will be 26,570.27 UAH. Demurrage of drivers and vehicles when loading should be recalculated with taking into account the loading operation improvement, amortization deductions of a vehicle, and saving of drivers' wages. On the other hand, some higher depreciation charges should be considered when using a modernized screw conveyor, because it is constructively more complicated and its manufacture cost is slightly higher.

When the casing rotates at the rotational frequency 4624 rpm, the performance of screw rotating at frequency 700 rpm is increased by 24%. At the same time, the power driving the screw falls from 20% to 17% (2.2 kW motor), and the power driving the casing falls to 11% (1.5 kW motor).

Therefore, the total power growth is: $\Delta P_{40} = (11\% \cdot 1.5 / 2.2) - (20\% - 17\%) = 4.5\%$.

Consequently, when the performance improvement is 24% (the casing rotates at the rotational frequency 624 rpm and a screw at the rotational frequency 700 rpm), the power increase is 4.5%.

If the conveyor performance without screw rotation is assumed 100%, then the power driving the screw is 20%. When the conveyor performance improvement at screw rotation is 24%, the total capacity of the conveyor will be $20\% + 4.5\% = 24.5\%$. Subsequently, according to the recalculation, performance improvement will be, in comparison with the power growth: $\Delta E_{40} = (100\% + 24\%) / 100\% - (20\% + 4.5\%) / 20\% = 0.015$.

Considering both the performance improvement and electricity consumption, the efficiency of casing rotation at the rotational frequency of 624 rpm in a screw conveyor, in which the screw rotates at frequency of 700 rpm, will be 1.5%. Accordingly, the annual savings on electricity thanks to the screw conveyor performance improvement with a rotary casing at the specified parameters will be: $E_{40} = 1.96 \cdot 2.2 \cdot 0.015 \cdot 8 \cdot 1 \cdot 240 \cdot 0.92 = 114.25$ UAH.

Savings on the wages of the operator involved in servicing the conveyor will be: $E_5 = (8,791 \cdot 1.22 \cdot 12 \cdot 24\%) / 100\% = 30,888.06$ UAH.

All in all, the final savings resulting from the usage of a screw conveyor with a rotary casing will be 31,002.31 UAH.

On the basis of presented calculations, the performance improvement of a screw conveyor with a rotary casing is considered economically feasible. Generally, the casing rotation in a screw conveyor allows (if certain structural and technological aspects are met) obtaining of a significant economic effect and increase of the efficiency of transport operations (by 24%) without excessive overconsumption of electricity. The overall economic costs can be reduced up to 10% if the optimal parameters of the screw conveyor with a rotary casing are utilized. In addition to this, material perturbation due to casing rotation leads to further reductions in terms of power consumption.

Conclusion

The most effective parameters of the screw conveyor with a rotary casing include casing rotation frequency of 468 rpm and screw rotation frequency of 700 rpm. Thanks to these parameters, device performance increased by 20% and power driving the screw decreased from 20% to 15% (2.2 kW motor), and power driving the casing is decreased by 10% (1.5 kW motor). Observed total capacity growth was 1.82%. A further increase in the casing rotational frequency led to an increase in the transportation process productivity by 24%, representing a positive phenomenon.

If optimal parameters of the screw conveyor with a rotary casing are applied, overall economic costs can be reduced by more than 10%. Material perturbation occurring due to casing rotation can lead to reduction in overall power consumption.

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