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EFFECT OF HYDRAULIC AND GEOMETRICAL PROPERTIES ON STEPPED CASCADE AERATION SYSTEM

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Abstract

Stepped cascade aeration system is commonly used to aerate the water and wastewater to increase the dissolved oxygen during pre and post treatment process. In the present research, experiments were conducted to evaluate the performance of a rectangular Cascade Aeration System with varying flow rates, risers and tread by maintaining constant width of the channel using water collected from reverse osmosis plant. The experiments were carried out with four different risers such as 0.15 m, 0.18 m, 0.225 m and 0.30 m. Each rise was investigated with five different tread of 0.60 m, 0.55 m, 0.50 m, 0.45 m and 0.40 m. Comprehensive experimental investigations were carried out for different hydraulic loading rates of 0.005 to 0.035 $m^3/s/m^2$. Results obtained from the experiments reveals that increasing dimensionless discharges promotes more aeration, attains a maximum up to dimensionless discharge= 2.22 and beyond this there was a significant decrease in aeration. In addition, the increased in number of steps significantly enhances air entertainment and surface fall rate in the Stepped Cascade Aeration System. A regression equation was derived by keeping aeration efficiency as response with dimensionless discharge and oxygen saturation concentration as influencing parameters. The dimension less discharge is a function of critical depth of the rectangular channel and step height, whereas oxygen saturation concentration represents the ratio of oxygen deficit and oxygen saturation concentration. Based on the experimental results, the optimum design and/or results such as number of steps (12 numbers) and hydraulic loading rate (0.025 $m^3/s/m^2$) with fixed tread width of 0.6 m were identified to achieve maximum aeration rate (0.5-0.60) in Aeration system.

Keywords: Dissolved oxygen, Aeration, Hydraulic flow rate, Stepped cascade.

Nomenclatures

C_s	Saturation concentration, mg/l
d_c	Critical depth in a rectangular prismatic channel, m
d_c/h	Dimensionless discharge
h	Height of steps, m
L	Width of channel, m
q_w	Hydraulic loading rate, m^2/s
r	Oxygen deficit, mg/l
r/C_s	Oxygen saturation concentration

Abbreviations

AAE	Average Aeration Efficiency
BOD	Bio chemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
ES_{U1}	Experimental Set Up 1 (12 steps)
ES_{U2}	Experimental Set Up 2 (10 Steps)
ES_{U3}	Experimental Set Up 3 (8 steps)
ES_{U4}	Experimental Set Up 4 (6 steps)
pH	Power of Hydrogen Ion concentration
PW	Potable water
SCAS	Stepped Cascade Aeration System
TDS	Total Dissolved Solids in mg/l
VOC	Volatile Organic compounds

1. Introduction

Discharge of industrial wastewater and agricultural runoff to the natural water bodies causes serious threats to the aquatic eco system. Treatment techniques have been identified to rehabilitate the contaminated water bodies by means of hydraulic structures. Most of the existing techniques are expensive and not effective or suitable for the diverse nature of pollutants present in wastewater. Aeration is one of the cheap, efficient and versatile techniques currently employed in water and wastewater treatment process [1] Aeration is a mass transfer process in which oxygen molecules are transferred from gaseous phase to liquid phase. When the water is allowed to flow over a series of steps, it causes turbulence and facilitates the oxygen diffusion. The transport of oxygen through liquid phase leads to enhancement of dissolved oxygen (DO) concentration and is called Stepped Cascade Aeration System (SCAS). The uniqueness of flow pattern decides the success of SCAS system and has been classified into nappe, transition and skimming flow [2 - 4]. Energy dissipation occurs by breaking up of jet in the air leading to the formation of nappe flow. A skimming flow is based on the critical water depth and height of step.

Furthermore, flow is possible when it is in an organized stream supported by the recirculation of fluid. It was found from experiments that skimming flow is possible when the ratio of critical depth to the height of the step (d_c/h) was greater than 0.8 and smaller values of d_c/h leads to nappe flow [5]. The major advantage of SCAS flows is that odorous and color due to volatile oil discharged by algae is considerably reduced by this method. In addition, SCAS system is also identified as a cost effective technology for the removal of dissolved carbon dioxide, hydrogen sulphide, oxidation of iron and manganese present in the potable water treatment process [6] Experiments conducted for removal of pollutants yields appreciable results using cascade aeration with combination of bio filtration. SCAS also removes ionic concentrations and chemical oxygen demand (COD) in contaminated water [7].

The flow on SCAS was characterized by its large residence time, vibrant mixing and substantial air bubble entrainment. Irregularity in the pattern of turbulence which acts next to air-water freely contributes the air bubble entrainment. It was also noticed that flow governed by gravity played a significant role in the air entrainment process [8]. Many investigators carried out on their research work using SCAS to investigate degree of air entrainment [9] flow hydraulics especially on nappe flow [10] forecasting related to prediction of transition from nappe to skimming flow [11] and proposing the condition for nappe flow[12]. It is also addressed that the transition flow patterns is not desirable to safety check floods and design discharge. It should be either nappe or skimming [13]. Previous research work focused on hydraulic aspects of cascade system and the existence of the relationship between flow rate and step geometry on aeration was reported [14-18].

SCAS became very versatile in recent years because of its economy and speedy construction. Thus our present work was focused on optimal design of SCAS with the height of 1.80 m.

2. Materials and Methods

All experiments related to this work were conducted in fluid mechanics laboratory at SASTRA University. The investigation set up consists of two steel tank containers positioned upstream and downstream to measure DO concentration. The size of upstream and downstream tank was 0.60 m x 0.60 m x 0.60 m and 0.60 m x 1.20 m × 1.0 m, respectively. The tank at the top and bottom were connected by means of steel flats; over the steel flats pre-casted concrete blocks were laid, which gave a firm support for the construction of steps over it. Brick masonry was adopted for the construction of steps to replicate the same experience in the real field condition. In order to facilitate better visualization from outside, Perspex sheets was used as a side wall of the SCAS and it also restricts the spilling of water on sideways.

A mono-block centrifugal pump with a capacity of 5 HP was used to transfer water from downstream to upstream side. Magnetic flow meter, which is capable of measuring 0.040 m^3/s with an accuracy of 0.0001 m^3/s was used to measure the discharge. A DO meter with probe supplied by HANNA,USA, model HI 9146,was inserted in to the collection tank and stilling tank to measure the concentration of DO in the upstream and downstream, respectively. The DO probe was calibrated periodically at ambient air conditions as per the instructions given by the manufacturer. The water used in the present study was collected from reverse osmosis (RO) plant. The physical and chemical properties of water were analyzed and listed in Table 1.

Once the reading of a particular tread and rise gets over, the entire construction of SCAS was dismantled and a fresh combination of tread and rise were constructed. For every experiment, three readings were taken at the upstream and downstream locations for each sample and average reading was taken for further interpretation. In total, 420 trials were (140×3 = 420) performed in the present work. For de-oxygenation, 10mg/L of sodium sulfite and 0.010 mg/*l* of cobalt chloride was added to the collected water. Figure 1 show the experimental set up used for the present work. The other parameters considered for this experiment are listed in Table 2.

Table 1.Chemical properties of water used.

Parameter	Potable water (PW)	Permissible limit of water (BIS)
pH	6.7 - 7.0	6.5 – 8.5
Temperature (°C)	27	
TDS (mg/l)	40	500
Salinity (mg/l)	37	450
Chloride (mg/l)	29	250
DO (mg/l)	5.5 - 6.0	40% saturation
COD (mg/l)	10	10
BOD (mg/l)	0	60

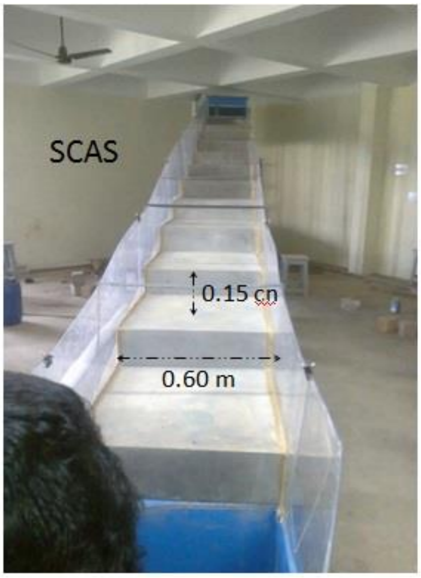

Fig. 1. Experimental set of stepped cascade aeration system (SCAS).

Table 2.Influencing parameters used in the experiment.

Independent	Range	Dependent
Hydraulic loading rate ($m^3/s/m^2$)	0.005 to0.035 @ interval of 0.005	
Rise of each step (m)	0.15,0.18, 0.225, 0.30	Aeration Efficiency (E_{20})
Tread of each step (m)	0.60, 0.55,0.50,0.45, 0.40	
Width of the channel (m)	0.60	
Total height of the system (m)	1.80	
Number of steps	12, 10, 8, 6	

Temperature is one of the critical parameters in the aeration experiments. Hence the following equation was used to find the aeration efficiency at a standard temperature of 20°C) [19]. Oxygen transfer efficiency (E_T) for a hydraulic structure at any temperature T (°C) was expressed by the following equation. The oxygen saturation concentration of water was used based on its temperature [20].

$$E_T = \frac{[C_d - C_u]}{[C_S - C_u]} \tag{1}$$

where E_T is transfer efficiency at actual water temperature, C_d is concentration of DO in the downstream (mg/L), C_u is concentration of DO in the upstream (mg/L), and C_s is saturation concentration (mg/L)

Similarly, aeration efficiency was calculated using the following equation

$$E_{20} = \left[1 - (1 - E)^{\frac{1}{f}}\right] \tag{2}$$

Where E_{20} is aeration efficiency at 20°C and f is exponent given by

$$f = 1 + 0.02103(T - 20) + 8.261x10^{-5}(T - 20)^2 \tag{3}$$

Chanson and Toombes [14] proposed an equation for nappe flow condition which was followed in the present research work and is given below:

$$\left(\frac{d_c}{h}\right) \leq 0.89 - \left(\frac{h}{L}\right) \tag{4}$$

where d_c/h is dimensionless discharge, $d_c = \sqrt[3]{q_w^2 / L}$ is critical depth in a rectangular channel (m), q_w is hydraulic loading rate (discharge per unit width, m^2/s), h is height of steps (m), and L is width of channel (m).

3. Results and Discussion

Enhancement of dissolved oxygen in a stepped channel is predominantly influenced by hydraulic property of the flow such as discharge per unit width and the geometrical features of the step. Boundary layer which develops the affinity between water and atmospheric air is governed by the flow rate. The water which flows over the steps is agitated based on the discharge and width of the stepped channel. The results presented in Figs. 2 to 5 show the relation between a Flow rate per unit width and aeration efficiency (E_{20}) and the effect of discharge on increase in DO. Figure 2 shows the results of the first experiment set up (ES_{U1}), which consist of 12 steps where the height of each step is 0.15 m.

When the flow was in minimal discharge the improvement of DO is very negligible, as the agitation in the liquid surface is very low. A gradual improvement in DO was observed when the flow rate increased. The experimental set up shows consistency in the moderate flow rates, whereas it starts to show a declining trend at the maximum flow rates. This might be due to the effect of channel width, which restricts the water from spreading over the channel and reduces the contact area. The optimum flow rate in this first experiment set up (ES_{U1}) was found to be 0.015 m^3/s and refinement of 46% was witnessed for this particular discharge. Figures 3, 4 and 5 illustrate that the origin of the graph is located in the same point irrespective of their flow rates and some imperceptible improvement was authenticated in the nominal discharge whereas higher flow rates is endorsed with comedown tendency. The entire graphs end in the same points, which shows that performance of the aeration system, is the same for both low and high flow rates. The average aeration efficiency was found to be maximum in 0.015 m^3/s for all the experiments and it was 0.34, 0.41 and 0.47 for ES_{U2}, ES_{U3} and ES_{U4}, respectively. From the result, it is quite evident that the optimum discharge for the present system was 0.015 m^3/s, and that the performance of ES_{U4} almost matched with ES_{U1}. From this conclusion it was proved that system with more number of steps performs well because water flow from one step to other will increase the turbulence within the system which generates more numbers of bubbles and hence easy to pull down atmospheric oxygen. Table 3 shows the outcome of the SCAS based on the geometrical property.

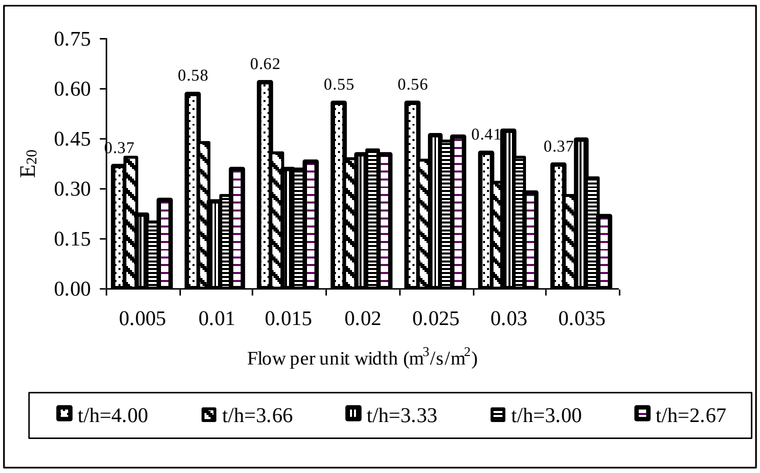

Fig. 2. Relationship between flow per unit width and E_{20} for ES_{U1}.

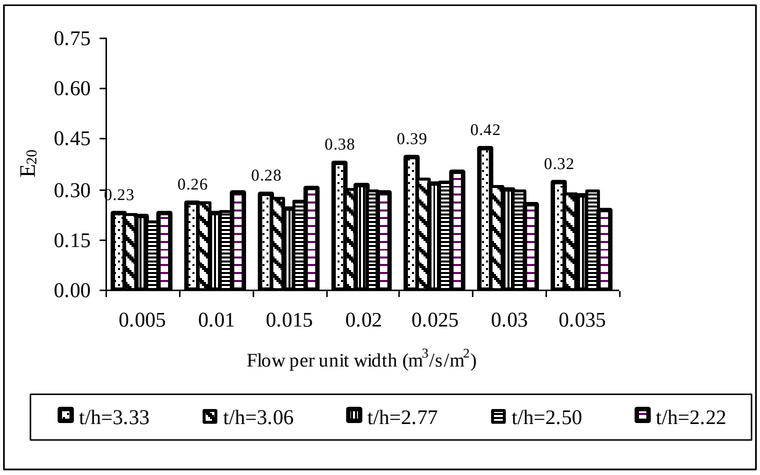

Fig. 3. Relationship between flow per unit width and E_{20} for ES_{U2}.

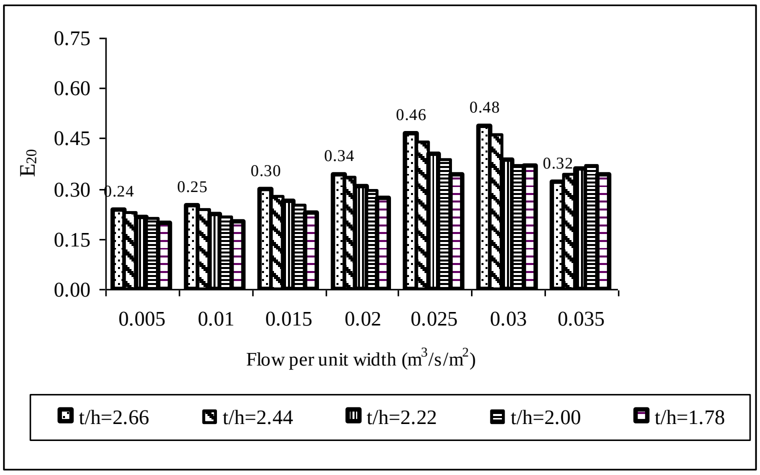

Fig. 4. Relationship between flow per unit width and E_{20} for ES_{U3}.

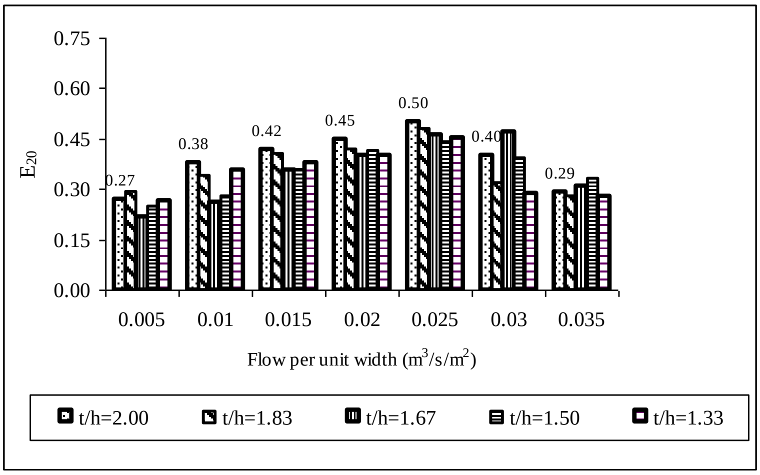

Fig. 5. Relationship between flow per unit width and E_{20} for ES_{U4}.

The tread, rise and width of the steps play a crucial role in the improvement of the surface aeration system. Non dimensional parameter (*t/h*) ratio of tread and height of the step is identified as an influencing component in this system. It was observed that higher values (*t/h*) contribute to greater aeration efficiency. In this experiment, the appreciable aeration was identified when *t/h* = 4.00 (tread = 0.60 m and rise =0.15 m with 12 steps) and displays low aeration when *t/h* = 2.22 (tread = 0.40 and rise = 0.18 m with 10 steps). It was observed that a good relationship between geometrical property of the step and DO improvement was established. Increase in DO concentration is directly proportional to higher *t/h* ratio because the water flows over the increased tread which allows the system to trap more oxygen from the atmosphere. Comparative results between various geometrical combination shows that the system yields same result on same (*t/h*) values. Further, the same proportion is identified in three cases, when *t/h* = 2, 67, 2.22 and 2.00. The average aeration efficiency (AAE) for 2.67 and 2.22 is found same whereas the AAE for *t/h* = 2.00 some noticeable difference is observed. These results highlight the crucial role of geometry property in the stepped cascade channel. A regression analysis was made to analyse the results of the experiments, by considering all the inputs like r/C_s and d_c/h. The equation was predicted keeping aeration efficiency (E_{20}) as response and r/C_s and d_c/h as influencing parameters. Appreciable line of agreement was found between the observed values and predicted values form the developed equation. In addition to the above, confidence level in the correlation was seen in Fig. 6.

Table 3.Data of aeration efficiency with respect to hydraulic property (d_c/h).

d_c/h	t/h=4.00	t/h=3.66	t/h=3.33	t/h=3.00	t/h=2.67
ES_{U1} Height of steps is 0.15m (12 steps)					
0.091	0.37	0.39	0.22	0.20	0.27
0.145	0.58	0.44	0.26	0.28	0.36
0.189	0.62	0.41	0.36	0.36	0.38
0.229	0.55	0.39	0.40	0.41	0.40
0.266	0.56	0.38	0.46	0.44	0.45
0.301	0.41	0.32	0.47	0.39	0.29
0.333	0.37	0.28	0.44	0.33	0.22
d_c/h	**t/h=3.33**	**t/h=3.06**	**t/h=2.77**	**t/h=2.50**	**t/h=2.22**
ES_{U2} Height of steps is 0.18m (10 steps)					
0.076	0.23	0.22	0.22	0.20	0.23
0.120	0.26	0.26	0.23	0.23	0.29
0.158	0.28	0.27	0.24	0.26	0.30
0.191	0.38	0.30	0.31	0.30	0.29
0.222	0.39	0.33	0.31	0.32	0.35
0.251	0.42	0.31	0.30	0.29	0.26
0.278	0.32	0.28	0.28	0.30	0.24
ES_{U3}Height of steps is 0.225 m(8 steps)					
d_c/h	**t/h=2.66**	**t/h=2.44**	**t/h=2.22**	**t/h=2.00**	**t/h=1.78**
0.061	0.24	0.23	0.21	0.21	0.20
0.096	0.25	0.24	0.22	0.21	0.20
0.126	0.30	0.27	0.26	0.25	0.23
0.153	0.34	0.34	0.31	0.29	0.27
0.178	0.46	0.44	0.40	0.39	0.34
0.200	0.48	0.46	0.39	0.37	0.37
0.222	0.32	0.34	0.36	0.37	0.34
d_c/h	**t/h=2.00**	**t/h=1.83**	**t/h=1.67**	**t/h=1.50**	**t/h=1.33**
ES_{U4} Height of steps is 0.225m(8 steps)					
0.046	0.27	0.29	0.22	0.25	0.27
0.072	0.38	0.34	0.26	0.28	0.36
0.095	0.42	0.41	0.36	0.36	0.38
0.115	0.45	0.42	0.40	0.41	0.40
0.133	0.50	0.48	0.46	0.44	0.45
0.150	0.40	0.32	0.47	0.39	0.29
0.167	0.29	0.28	0.31	0.33	0.28

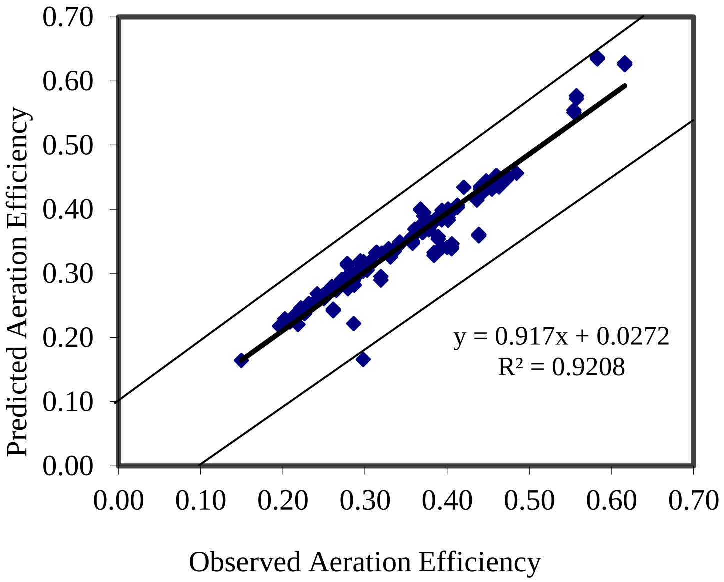

Fig. 6. Comparison on observed and predicted values.

It was also indicated that, comparison of measured and predicted values fell well below the upper and lower bound (10% of peak values) lines and hence results are found to be reliable.

$$E_{20} = 0.0302 + 0.0336\frac{d_c}{h} + 1.05\frac{r}{C_s} \qquad (5)$$

where d_c/h is dimensionless discharges, r/C_s is ratio of oxygen deficit and oxygen saturation concentration for the ambient temperature. The above equation is valid when the experiments are subject to:(i) $0.009 \leq dc/h \leq 0.222$ (ii) $0.13 \leq r/Cs \leq 0.35$ and (iii) H = 1.80 m. The overall aeration efficiency (E_{20}) of a stepped cascade aeration system of 1.80 m is found out by knowing the values of dimensionless discharge, ratio of oxygen deficit and oxygen saturation. It was evident that the aeration enhancement was found to be very consistent $E_{20}>$ (0.40 to 0.55) when system was experimented with higher number of steps (12 nos). Additionally increased tread (0.60 m) width contributes to good aeration improvement. Construction of higher numbers of steps greaten than 12 for this system will necessitate the cost and it should be decided based on the slope profile of that industry.

4. Conclusions

Aeration experiments were conducted to evaluate an optimal design parameter for a stepped cascade rectangular channel of height 1.80 m with varying flow rates, rise and tread of the step. All the features in this system were identified to generate nappe flow conditions only. Based on the experimental results the following outcomes were acquired: (i) Systems with higher number of steps contribute to greater aeration efficiency. Furthermore, additional number of steps enhances the aeration as it increases the surface area of fall which results in generation of more air bubbles (ii) Increasing tread width enhances aeration efficiency because of increased air entrainment (iii) Increment in dimensionless discharge (d_c/h) yields good aeration efficiency up to 0.222 and further increase in it shows a declining trend. This is because flow approaches transition condition with increased hydraulic loading rate (iv) Following optimum values such as height of structure = 1.80 m; number of steps (N) = 12; tread (m) = 0.6; rise (m) = 0.15 and hydraulic loading rate (q_w) = 0.025m^3/s/m^{2}wereobtained to achieve maximum aeration efficiency (0.5 to 0.6) for a SCAS.

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