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Fish deterrent associated with bubble dispersion in bulb turbine

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ABSTRACT

During the maintenance procedures of generating units, the operational maneuver of shutting down the turbine causes low water flow, which may lead to the accumulation of fish inside the draft tube. Considering the principles of ichthyofauna protection, several repulsion systems have been developed to minimize the confinement and the possible risks to the ichthyofauna. The main objective of this study was to investigate the dissuasive effectiveness on the ichthyofauna caused by the dispersion of bubbles along the draft tube during the shutdown of the generating unit. The monitoring of the ichthyofauna in the draft tube was carried out with the aid of a hydroacoustic system. The bubble dispersion procedure was executed using the compressed air injection system built into the draft tube of the Generating Units at the Jirau Hydropower Plant, on the Madeira River, in Rondônia, Brazil. 9 machine shutdowns were tracked. They were carried out in two stages; the first stage was the conventional shutdown and the second was the shutdown of the generating unit with bubble dispersion. During both stages, the movement of the confined ichthyofauna was continuously monitored by a hydroacoustic real-time monitoring system installed in the fixed-wheel gates. The results show a reduction of about 42% in the ichthyofauna movement after the bubble dispersion procedure, making it possible to infer a considerable reduction in ichthyofauna confinement in the draft tube. This observed effectiveness, in an unfavorable environment with the high turbidity of the Madeira River, shows the considerable potential of this robust and low-cost technology for the protection of ichthyofauna in the hydroelectric sector.

Keywords: Ichthyofauna deterrence. Air bubble. Behavioral effect. Madeira River.

1. INTRODUCTION

The Brazilian energy matrix is composed of a variety of sources, including hydroelectric, thermoelectric, wind, solar, biomass and nuclear. With about 12% of the total volume of fresh water available in the world, Brazil, historically, has hydroelectricity as its main source of energy generation. The total installed power in operation in Brazil is 182,974.2 MW, of which about 49.65% come from the hydroelectric sector (ANEEL, 2022).

The Brazilian preference for hydroelectric power plants can basically be justified by the temporal security in the supply of energy (due to the formation of a reservoir) and by the great hydroelectric potential still available in the Brazilian territory (MORETTO et al., 2012). In Brazil, the remaining water potential is in the Amazon Region and the great hydroelectric interest facing this region is the result of the large topographic drops existing in the tributaries of the Amazon River from the Brazilian Shield (in the southern part of the region) and the Guiana Shield (in the north side), in addition to the values of potentials studied and estimated in the region (FEARNSIDE, 2013). The decision-making process for the positive balance of a hydroelectric project is extremely complex and must be carried out carefully and based on environmental, technical and economic criteria (MENDES et al., 2017). Although hydroelectricity is considered a sustainable source, with low greenhouse gas emissions, the Electric Sector enterprises face several concerns related to the environment during all phases, from planning to operation. Among them, one of the most obvious issues concerns the effects caused on aquatic life, especially the impacts on the ichthyofauna (CEMIG, 2015; DA SILVA et al., 2021).

During maintenance procedures, the operational maneuvers of scheduled and/or untimely generating unit shutdowns lead to low operating water flow, which may cause an accumulation of ichthyofauna inside the draft tube, mainly in rivers with high levels of fish, which poses risks to the aquatic community (SCHILT, 2007). Rescuing the ichthyofauna trapped in the draft tube demands complex operations that follow strict work safety protocols for the rescue teams, which can lead to economic liabilities if the period without electricity generation is extended. In this perspective, new operating rules, and various technologies for the protection of ichthyofauna have been developed in order to minimize possible impacts and optimize maintenance procedures (DA SILVA et al., 2022; FIGUEIREDO et al., 2022; SANTANA et al., 2022).

In Brazil, the occurrence of about 2,600 valid fish species is recorded (HILSDORF & MOREIRA, 2008). In the Madeira River, around 920 species were inventoried, which gives this river the title of having the highest species richness of ichthyofauna recorded in the Amazon (DE QUEIROZ et al., 2013). The migratory movement of fish is extremely important in modulating their reproductive physiology, as they are necessary for the development of the gonads (ovaries and testes) and for the maturation of gametes after spawning, in addition to promoting the dispersion of eggs and larvae (HILSDORF & MOREIRA, 2008). Facts like this, associated with the great diversity of fish found in the Madeira River, demand the development and use of more comprehensive methods of monitoring and repelling the ichthyofauna from hydroelectric projects located in this region.

The physical or mechanical barriers (screens and grids) used in the hydroelectric sector are indicated for a wide range of species, however, they require costly and constant preventive and corrective maintenance (DE ANDRADE et al., 2012). Other ichthyofauna protection technologies are behavioral barriers, which use sound stimuli, strobe lights, electric currents and bubble curtains to reach the sensory systems of fish (ZIELINSKI et al., 2014; DIAS et al., 2020; FIGUEIREDO et al., 2021). Behavioral responses are complex and species-specific for certain sensory stimuli, in addition to being influenced by environmental conditions, such as flow and turbidity (PERRY et al., 2014).

Considering the principles of ichthyofauna protection, this study investigates the dissuasive effectiveness on the ichthyofauna caused by the dispersion of bubbles along the draft pipe of a bulb-type hydroelectric turbine at HPP Jirau, on the Madeira River - Rondônia.

2. METHODOLOGY

2.1. Study area

The Jirau Hydroelectric Plant (HPP Jirau) is in the Amazon region, on the Madeira River (**Figure 3.1**). HPP Jirau has an installed capacity of 3,750 MW, making it the fourth largest generator of electricity in Brazil, representing about 3.7% of all hydroelectric power in the country. The plant has 50 bulb-type generating units, distributed in two powerhouses (CF1 and CF2), with a nominal discharge of 550 m^3/s and a physical guarantee of 2,211.6 MW (ESBR, 2022).

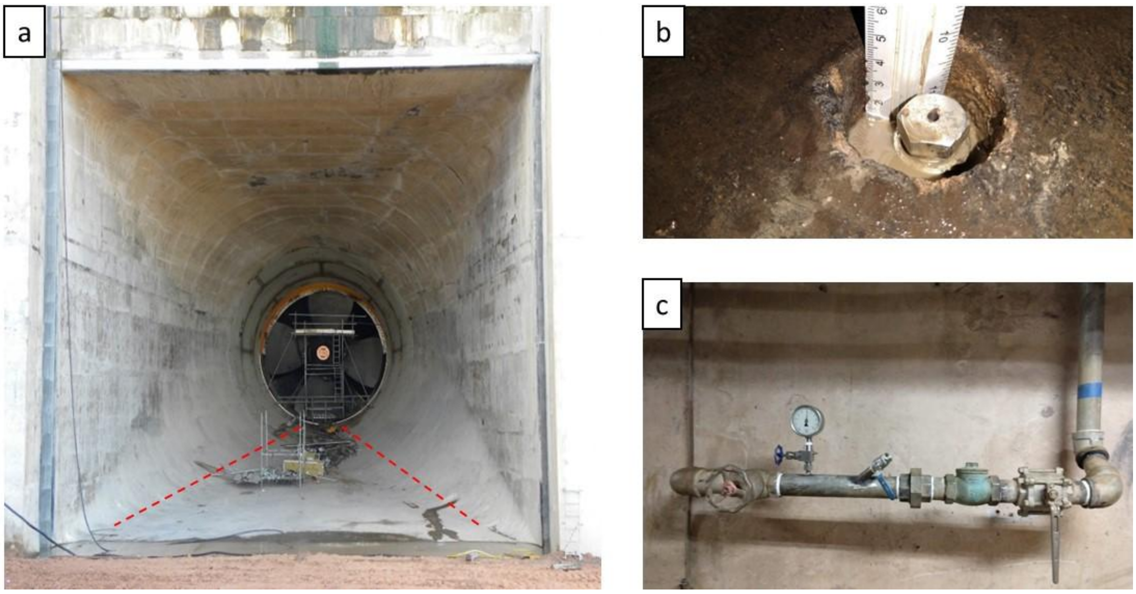
Figure 1 - Structure of the study areas at HPP Jirau, on the Madeira River, Rondônia.

Source: Jirau Energia – ESBR.

2.2. Ichthyofauna dissuasion operational maneuver

The structure of the draft tube of the bulb-type generating units at HPP Jirau has a built-in compressed air injection system, consisting of 8 hexagonal injector nozzles equally distributed on the sides with spacing of 6.0 m (Figure 2). The operational maneuver to dissuade the ichthyofauna starts with the full opening of the manual actuation valve of the compressed air injection line (7 bar) with the draft tube open. The descent of the fixed-wheel gate occurs only after 15 minutes of bubble dispersion along the draft tube. Immediately after confirming the closure of the generating unit, the mechanical block (86 M) is manually activated, the compressed air injection line valve is closed, and the unit shutdown procedure is consolidated. Immediately after confirming the closure of the generating unit, the mechanical block (86 M) is manually activated, the compressed air injection line valve is closed, and the unit shutdown procedure is consolidated.

Figure 2 – Compressed air injection system in the draft tube of the generating unit at HPP Jirau. **a** – Front view and indication of the location of the injection nozzles; **b** – Hexagonal injector nozzle; **c** – Compressed air injection manual activation valve.



Source: Author.

2.3. Confined Ichthyofauna monitoring

The real-time evaluation of the movement of the confined ichthyofauna in the draft tube is carried out using the low and high frequency sweeping hydroacoustic system, developed by Venturo Consultoria Ambiental. On the fixed-wheel gate, 2 transducers were fixed at about 9.0 m above the bottom of the fixed-wheel gate, so that the transducer is in the center of the draft tube after closing the generating unit. The transducers are connected to the hydroacoustic equipment by specific and resistant cabling, on the upper slab of the downstream face of the powerhouse (**Figure 3.3**). The image generation system used different frequencies, allowing the demarcation of areas of specific coverage of the ichthyofauna movement in the draft tube of the bulb-type generating unit. The hydroacoustic system was adjusted to frequencies from 250 to 350 kHz, with a horizontal beam width of 0.9°, a vertical beam width of 39° and a vertical inclination angle of 26° (DA SILVA et al., 2022).

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Figure 3 – Hydroacoustic system coupled to the face plane of HPP Jirau fixed-wheel gate (Patent No. BR 102015000457-5 A2). a – Fixed-wheel gate; b – Detail of the transducer's fixation; c – Cabling detail; d – Operation of the hydroacoustic equipment.

Source: DA SILVA et al (2021).

2.4. Evaluation of the dissuasive effectiveness of ichtyofauna

In order to evaluate the effectiveness of deterring the ichthyofauna by dispersing bubbles, the scheduled shutdown procedures of nine generating units in HPP Jirau (May to August/2022) were carried out in two stages. In the first stage, the shutdown of the generating unit occurred in a conventional manner, without any method for deterring the ichthyofauna. While, in the second stage, the shutdown of the generating unit occurred with the execution of the ichthyofauna deterrent operative procedure. In both stages, after complete sealing of the draft tube, the movement of the confined ichthyofauna was monitored for about 20 minutes. The images were archived and later analyzed using software for visualization, with adjustment of color composition of false color "Blue - Turquoise" and pixel value of 0.000361 m². Movements of confined ichthyofauna specimens were classified according to size on the software interface screen in the categories < 1.0 cm; $\geq$ 1.0 to $\leq$ 2.0 cm and > 2.0 cm (DA SILVA et al., 2021).

3. RESULTADOS

The hydroacoustic system with transducers installed in the phase plan of the fixed-wheel gate (SeeSub System) allowed the visualization in real time of the movement of the ichthyofauna confined in the draft tube during the planned generating unit shutdowns, protecting against any impacts to the ichthyofauna.

The real-time multifrequency underwater images showed a decrease in ichthyofauna movement after the execution of the ichthyofauna deterrent operative maneuver (**Figure 4**), and it is important to emphasize that the two adjacent generating units remained in operation. The real-time assessment makes it possible to interrupt, quickly and robustly, the operating procedure to stop the generating unit if there is a risk of damage to the confined fish assemblage.

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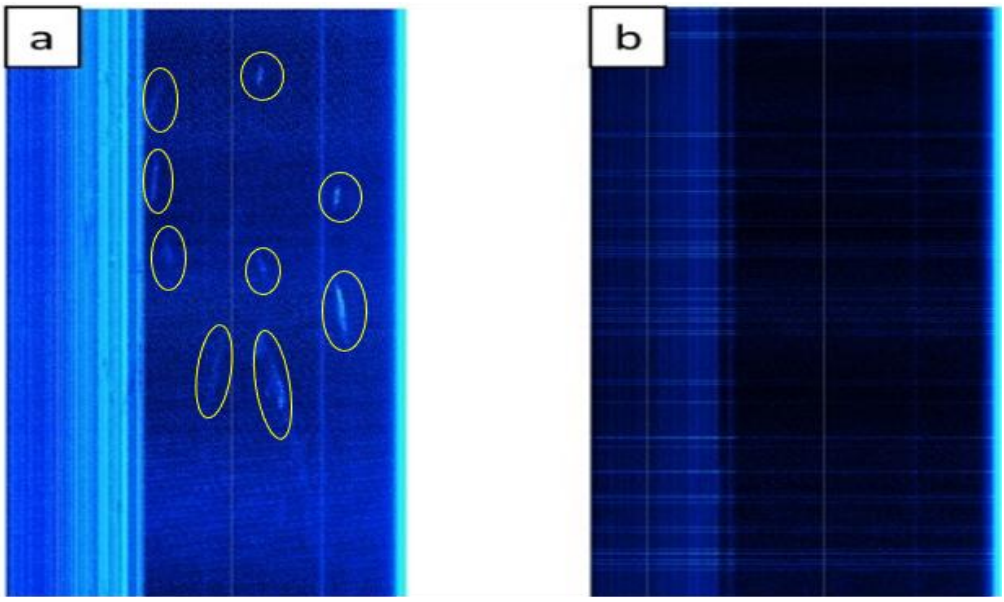
Figure 3.4 – Examples of multi-frequency underwater images of the draft tube during the first stage (a) and second stage (b) of the planned generating unit shutdown at HPP Jirau.



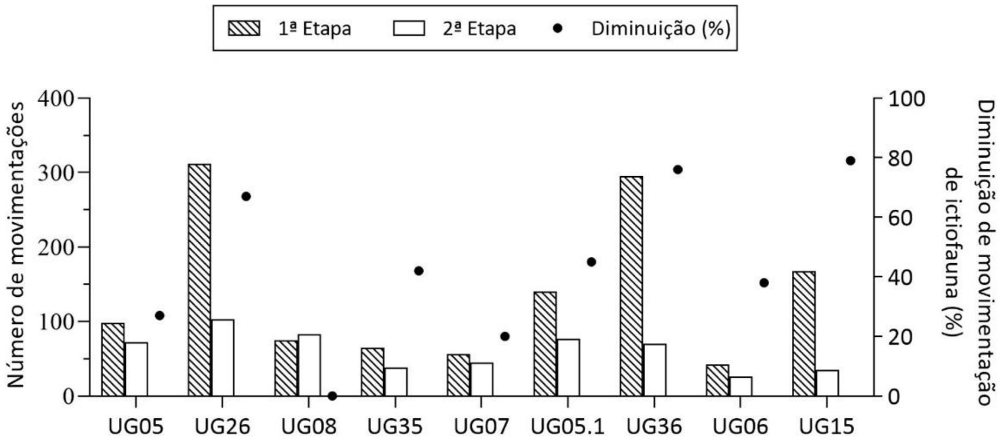
Source: Author.

Additionally, the results obtained in the quantitative evaluation after the first stage indicated a median of 98 and an average of 139 ± 96 movements for 20 minutes. Whereas in the second stage, after executing the ichthyofauna dissuasion procedure by bubble dispersion, the median movement was 70 and the average was 61 ± 24. The integrated analysis of the results obtained for the two experimental groups (first and second stage) showed a significant difference in the movement of the ichthyofauna confined in the draft tube (Mann-Whitney test, $p < 0.05$), making it possible to estimate a reduction of approximately 42% in the ichthyofauna movement in the draft tube after the ichthyofauna dissuasion procedure (Figure 5).

Considering all the analyzed generating unit shutdowns, the efficiency of the draft tube ichthyofauna dissuasion maneuver was observed in only 15%. This fact is possibly related to various external issues or even to the presence of predators that may have minimized the deterrence of the specimens.

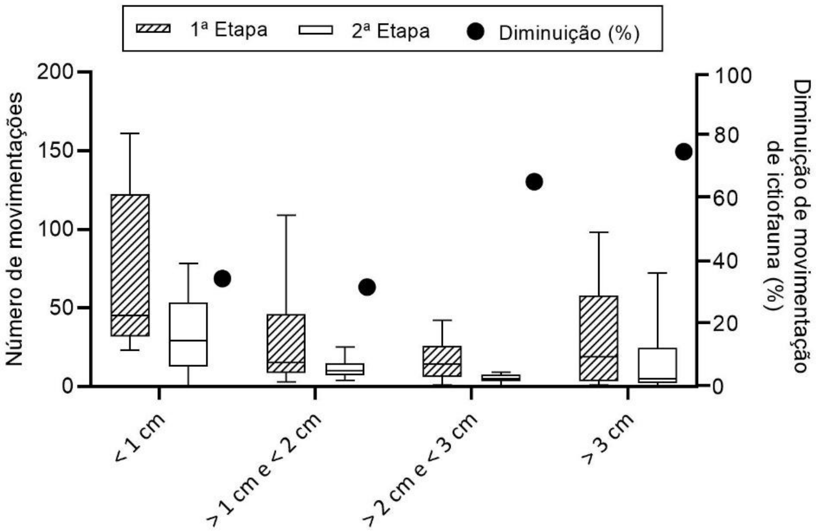
By stratifying the confined ichthyofauna in the draft tube according to the size on the software interface screen in the categories < 1.0 cm; $\geq$ 1.0 to $\leq$ 2.0 cm; and > 2.0 cm during the generating unit shutdowns, it was possible to observe the effectiveness of the operational maneuver to dissuade the ichthyofauna in the different size ranges of the specimens (Figure 6). It is important to highlight that the dissuasion maneuver minimized the confinement of larger specimens (> 3 cm) with 68% of relative effectiveness, which is of great importance when considering the human and material effort for the development of rescue activities of confined ichthyofauna in the draft tube.

Figure 5 – Quantitative assessment of the movement of the confined ichthyofauna in the draft tube during the first stage (conventional) and second stage (dissuasion procedure) of the planned shutdowns of the generating units of HPP Jirau.



Source: Author.

Figure 6 – Stratification according to the relative size of the ichthyofauna confined in the draft tube during the first stage (conventional) and second stage (deterrence maneuver) of the planned shutdowns of the generating units of HPP Jirau.



Source: Author.

The results of the ichthyofauna deterrent maneuver clearly indicate the efficiency of using bubble dispersion to repel fish from bulb-type turbines. In this operational procedure, the occurrence of sound and tactile stimuli in the inner part of the draft tube and a possible effect of attractiveness of the ichthyofauna in the outer part of the draft tube and close to the surface, due to the effervescence of air bubbles, can be inferred.

The underwater image transverse to the outlet of the draft tube of the generating units during the ichthyofauna dissuasion operational maneuver shows the effervescence in the region of the upper sealing of the draft tube and a gaseous dispersion plume, with the formation of a school of fish near the downstream face of the generating unit (Figure 7).

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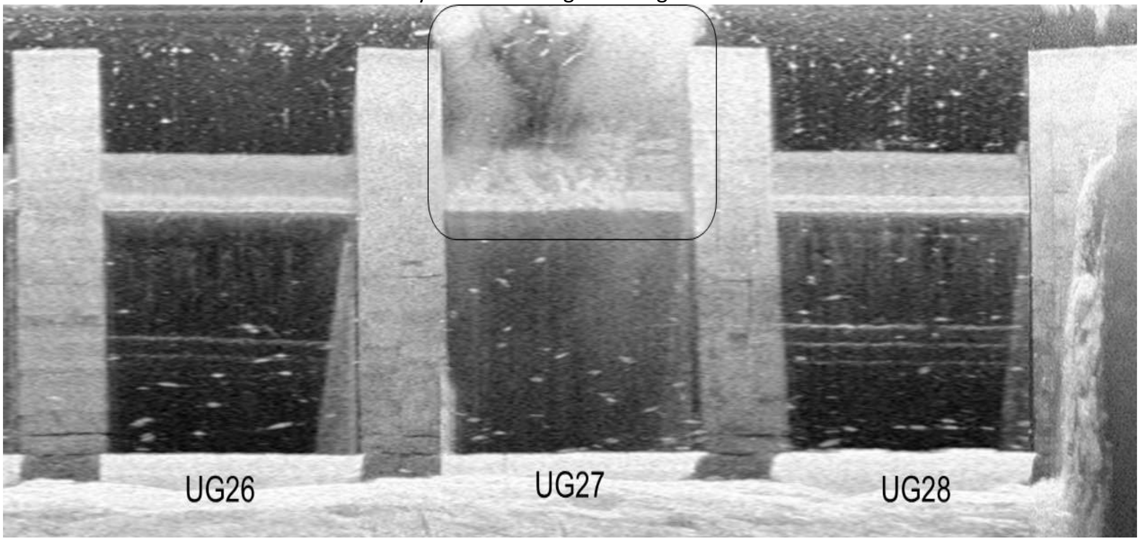
Figure 7 – Underwater image in transverse profile of the draft tube outlet during the operational maneuver to dissuade the ichthyofauna in the generating unit UG27 of HPP Jirau.



Source: Author.

4. DISCUSSION

Currently, physical barriers are widely used in the hydroelectric sector due to their efficiency with regard to preventing the passage of fish to the turbines. However, these technologies require a lot of maintenance and can be relatively expensive (ZIELINSKI et al., 2014). Furthermore, these methods neglect biological and behavioral aspects of fish species, considering only purely physical aspects (JESUS et al., 2019).

In this perspective, behavioral barriers for fish have proven to be effective in reducing the impacts caused by the hydraulic structures of dams, as, in addition to preventing the access of ichthyofauna to the electrical production turbines, pumping systems, adductor systems, among others, they also help in directing the ichthyofauna towards the fish transposition systems (FTS), promoting the ecological continuum and reducing the possibility of fish mortality and injuries. These barriers work through the controlled emission of primary stimuli, aiming to reach the sensory systems of the fish and provoke desired reactions, whether of attraction or repulsion. The modulation of the emitted stimuli makes it possible to develop the desired reactions in target individuals, helping to create effective and selective barriers (ZIELINSKI et al., 2014; JESUS et al., 2019).

Jesus et al. (2019) studied, under laboratory conditions, the repulsive effects of the bubble curtain alone and combined with strobe light (600 flashes/minute) on *Salmo truta* species, during day and night periods. Behavioral differences were observed in the bubble curtain tests, with a repulsive effect being observed during the day and a slightly attractive effect during the night tests. On the other hand, in the tests that used both stimuli together (bubbles and light), the species showed a superior repulsive behavior than the bubble curtain alone, during both periods (day and night).

In a study on the efficiency of the bubble curtain to divert the migration of Atlantic salmon, Leander et al. (2021) found that in the laboratory the bubbles diverted 95% of the fish, and in natural environments 90%. However, in this experiment, the bubbles did not affect migration in the dark, indicating that visual cues are necessary for the real efficiency of this system.

The Madeira River presents high turbidity, mainly in rainy periods, causing a great degree of attenuation of light intensity when crossing the water due to the presence of suspended solids, such as inorganic particles (sand, silt, clay) and organic detritus, algae and bacteria, plankton, among others (BARBOSA et al, 2018). Thus, the high turbidity of this ecosystem prevents the passage of light, which can reduce the efficiency of bubbles as a repulsive procedure for ichthyofauna.

The effectiveness observed in deterring the ichthyofauna in this highly turbid environment at HPP Jirau infers considerable potential for this robust and low-cost technology for the protection of the ichthyofauna in the hydroelectric sector.

5. CONCLUSION

The ichthyofauna deterrent operational maneuver using compressed air dispersion along the draft tube aggregates primary repulsion stimuli inside the draft tube and attractive stimuli in the external region of the draft tube close to the surface. The operational maneuver reduced the movement of ichthyofauna in the draft tube by 42%, inferring a smaller amount of confined fish, being effective in all sizes of fish. Thus, the use of this operational procedure as a deterrent system for confined ichthyofauna in the draft tube of bulb-type generating units proved to be an innovative and efficient strategy in protecting the ichthyofauna.

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