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ELECTRICAL POWER GENERATION BY TIDAL FLOW ACCELERATION

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ABSTRACT

Hydropower is a significant contributor to the renewable power generation sector, but the energy in tidal currents is not commonly used to generate electricity. This is due to the relatively slow speed of tidal currents which does not allow for the economic development of underwater turbines in tidal regions. This paper investigates whether it is possible to increase locally the current speed in regions where the tidal current is normally not strong enough to generate significant power. The device proposed to increase current speed is composed of an arrangement of vertical walls made of poles supporting a thin membrane with suitable profile, referred to as Tidal Current Accelerating Structure or TCAS. Current turbines are to be placed in areas of accelerated flow to convert the current energy into electricity. In this paper, results of model tests that were performed to quantify the ability to increase current speed are discussed. It was found that the increase in flow velocity was not as significant as expected, probably due to interactions between the turbines and the current accelerating devices. Recall potential theory's flow speed around a disk yields a velocity factor increase of 2 at 90 degrees from the stagnation point.

KEYWORDS

Ocean Renewables, Tidal Current Energy, Accelerating Structure

INTRODUCTION

Ocean renewable energy is a rapidly expanding field, however offshore wind turbines and wave energy extracting devices are far more advanced than ocean current turbines. There are many offshore wind turbines connected to various power grids and a few ocean wave projects such as the pelamis or the aquabuoy which are very close to being commercialized. Inland, dams such as “La Rance tidal barrage” have been producing electricity for decades, however turbines placed on the sea bed and gathering energy from ocean or tidal currents are still in a “proof-of-concept” state. MCT's twin axial rotor flows or Hammerfest, blue concept tidal stream turbines are examples of technologies leveraging the wind energy knowledgebase with concepts that are similar to onshore wind mills. The Gulf stream energy project (Hoover 2006), or the San Francisco Tidal Power Plant projects propose to use devices similar to the Lunar Energy Rotech Tidal Turbine, in which an horizontal axis multi-bladed turbine is located in a duct.

Some of these concepts have been proven feasible, but none have been commercialized yet. The significant hurdle is that they become economical in areas where the current speed is large. The Power from a wind or water turbine is given by $P=\eta\ \rho\ D^2\ V^3$. Based on the power output of existing and commercially viable wind turbines, and with assumptions on the structural limitations of underwater turbines (i.e. 20 ft diameter), the minimum required current speed is estimated to be 3 knots to achieve similar output as wind turbines in 20 knots wind. These are very specific locations and have often significant additional environmental constraints. The entrance of San Francisco Bay, as many other bay inlets or straights, is a high maritime traffic area and requires current devices to be sufficiently deeply submerged.

To increase the tidal current speed to a level where electrical power can be efficiently generated a device made of large vertical walls would be arranged in a channel like fashion. This Tidal Current Accelerating Structure (TCAS) is compatible with most type of energy extracting devices, including the ones mentioned above and the VIM circular cylinders of Bernitsas's VIVACE (2006).

To quantify the expected increase in power generation a series of model tests was conducted. A 1: 40 test scale: was chosen. Since it is envisioned that the structure would be 20 feet high in 40 feet of waterdepth with a turbine of approximately 6 feet in diameter.

Instead of measuring the flow field directly, the force on a turbine-like disk was investigated. This is more representative of the system since the impact of the presence of the turbine on the flow is important. Potential flow theory could model well the flow field around the structure; however predicting the force on the turbine is more challenging as one recalls d'Alembert paradox null force if a potential flow solver was used, i.e. The irrotational flow of a nonviscous fluid about an object produces no drag on the object due to the symmetry of the pressure field around the object). Expected interactions between the performance of the turbine and the amount of water flowing through the structure require complex three-dimensional CFD solutions. For this reason, it was believed that an experimental program was more appropriate. The goal of this paper is to report the interesting conclusions that were drawn from this series of tests.

TEST SETUP

The tests were performed in a tow tank, rather than a flume. Since all the runs were performed at constant speed and the finite basin length was not an issue, the use of the carriage was preferable due to the flexibility in varying the tow speeds.

The primary objective of these tests was not to measure the current speed in the middle of the TCAS, but the change in flow speed on a turbine that would be placed in the middle of the structure. Hence, an apparatus of a blockage similar to a turbine had to be used, Therefore, a disk mounted on a rod piercing the free surface was connected to a force gauge. (See figure 1a). The force was measured in the tow direction only.

The TCAS model was placed on a plate suspended from the carriage with streamlined struts as shown in the schematics of figure 1b. The plate submergence was adjusted to model the sea floor, and the scale 1:40 was selected to minimize the overall blockage effects in the tank due to the model. In the base case with the cylinders, the blockage ratio was 1.25 %. The spacing between the wall and the cylinder edge was ten diameters. The bottom plate representing the sea bed was 4 feet from the tank bottom.

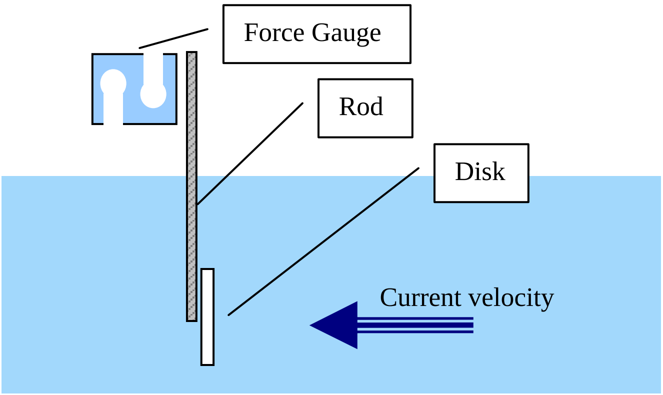


Figure 1a. Schematic of the measuring apparatus.

The scaling of 1:40 is typical of such experiments where the change in viscous effects are neglected, since it is not possible to match the Reynolds number, and Froude scaling is used to obtain full scale data. The flow around the disk is almost independent of Reynolds number over a very large range, however, separation around the circular column may not scale as well. Note that the 1:40 scaling is arbitrary as the full scale prototype may vary in dimensions based on site and project specifics. Hence all results are reported herein in model scale. The model dimensions were chosen such that the clearance in the basin was sufficient (as far as blockage) and the tow speed was reasonable to obtain a sufficient test duration (> 30 seconds of steady state data) and accurate speed measurement.

The TCAS model consisted of the various configurations shown in Figure 1c, including circular and elliptical cylinders at various orientations.

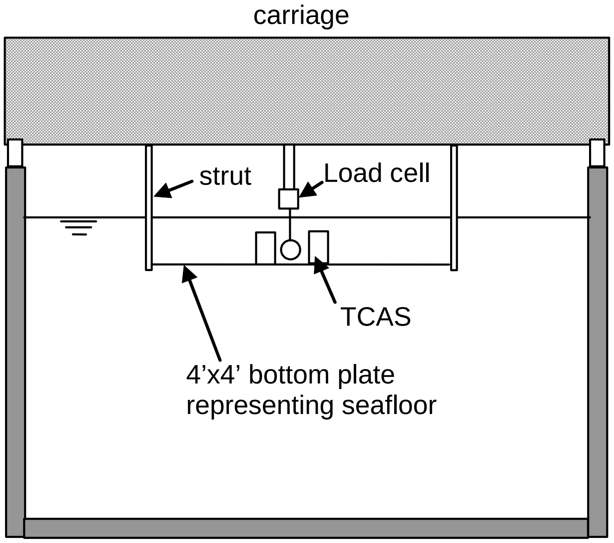
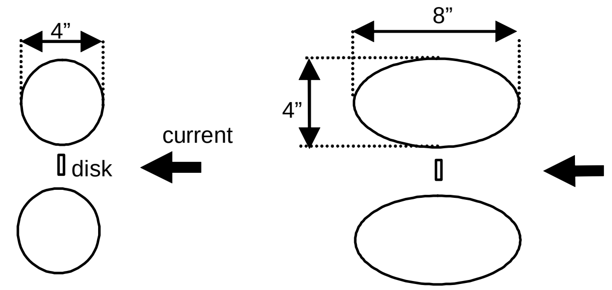
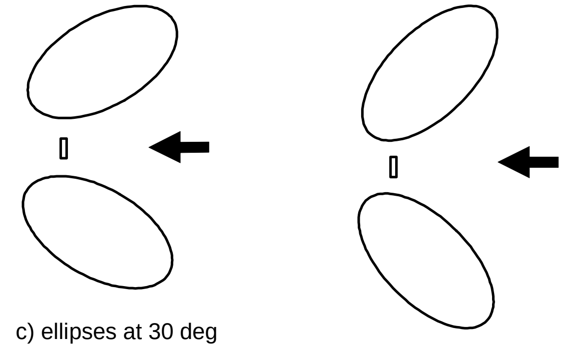


Figure 1b. Schematic of the towing tank setup



a) circular cylinders

b) ellipses



c) ellipses at 30 deg

d) ellipses at 45 deg

Figure 1c. Schematic of the various TCAS configurations tested

By measuring the force on the disk and mast, and the tow speed, the drag coefficient of the measuring structure can be computed.

$$C_d = \frac{F}{\frac{1}{2}\rho A V^2} \qquad (1)$$

Where A is the projected area, r the water density, V the current speed and F the measured force. Note that the Cd of the disk alone is 1.17 (Horner, 1965) and the one of a turbine 0.9 (Burton, 2001), so the effect of the turbine on the flow are well approximated by a disk with an area that is approximately 80% of the turbine projected blade area.

To understand the effect of the TCAS, a base case with no structure around the disk was done first. Figure 2 shows these results. This was done for two disks sizes.

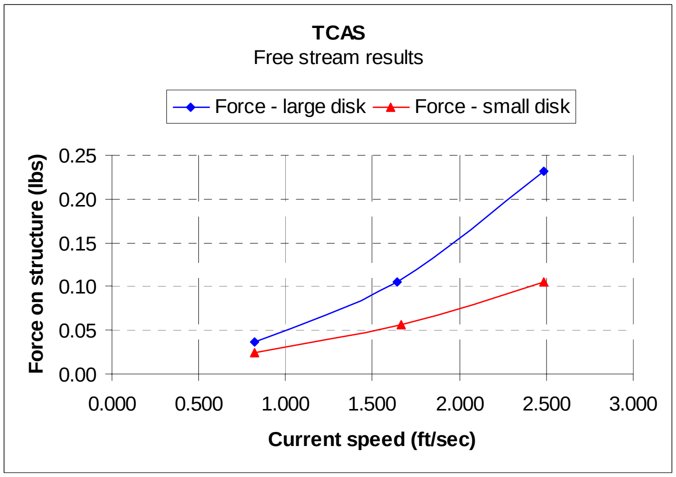


Figure 2. Free stream results. Large and small disks.

Table 1 summarizes the rod and disk dimension. The Cd of the system is obtained following equation (1).

Table 1 Instrumentation apparatus dimension

	Large Disk	Small disk
Disk diameter	2 in	1.25 in
Rod diameter	.2 in	.2 in
Rod height	7.5 in	7.5 in
Projected Area	3.14 in^2	1.23 in^2
Measured Cd	1.22	1.02

The lower Cd for the small disk configuration can be explained by the fact that the force component on the rod is relatively more significant than for the larger disk (the same rod was used in both cases).

The TCAS model comprises two structures whose dimensions are summarized in table 2.

Table 2 Instrumentation apparatus dimension

	Circular section	Ellipsoidal section
Column height	6 in	6 in
Minor diameter	4 in	4 in
Major diameter	4 in	8 in
Water depth	9 and 12 in	9 and 12 in
Heading tested	0º	0,30 & 45º

Pictures of four of the configurations are shown in Figure 3 (a–d).

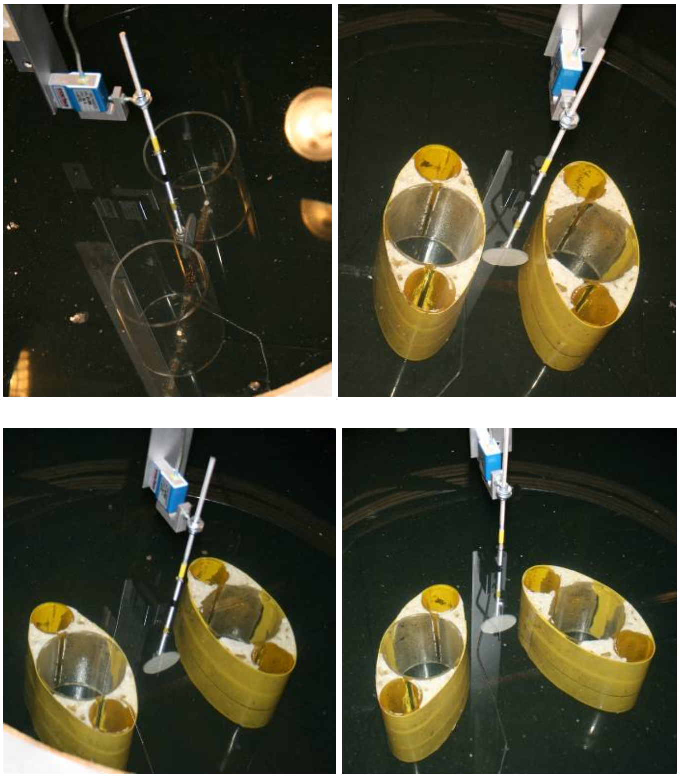


Figure 3. (a) TCAS of cylindrical cross-section, (b) ellipsoidal cross-section – small gap, (c) ellipsoidal cross-section – large gap, (d) ellipsoidal cross section – funneled at 30 degrees.

The main goal of this series of test was to investigate the effect of the structure on the turbine. The test program was devised to address the following points:

Base case: Circular cylinder

- Variation on gap size
- Variation on water depth
- Sensitivity, one column only

TCAS Case: Ellipsoidal cylinder

- Variation on gap size
- Variation on water depth
- Variation on primary axis heading

There is a plethora of ways to present the data. For clarity sake, the results in next section are all presented as a ratio of the measured force to the free stream force (no structure in place) shown in Figure 1. The flow velocity is of lesser importance for this particular investigation but can be inferred by taking the square root of the force ratio.

In most cases three speeds were investigated: .82, 1.64 and 2.46 f/s (= .5 to 1.45 knots) model scale. The force measured at the smallest scale was quite low, but well within the accuracy of the instrumentation.

The force on the disk was averaged over a 30 sec period after establishment of a steady-state. The base case was repeated several times and little variability was observed (< 5%).

RESULTS AND DISCUSSION

Cylindrical columns

The first case that was tested was a circular column TCAS. Figure 4 shows the force ratio for gaps ranging between 2.5" to 6". The first interesting conclusion was that when the gap between the TCAS walls was only slightly larger than the size of the turbine (1/4 in clearance on both sides), the force ratio was very close to 1. The effect of the structure on the overall flow is clearly evident. As the gap was increased to 3.5", the force ratio increased, but to much smaller levels than expected. The force ratio stabilized and started to decrease once the gap reached 3 times the disk diameter.

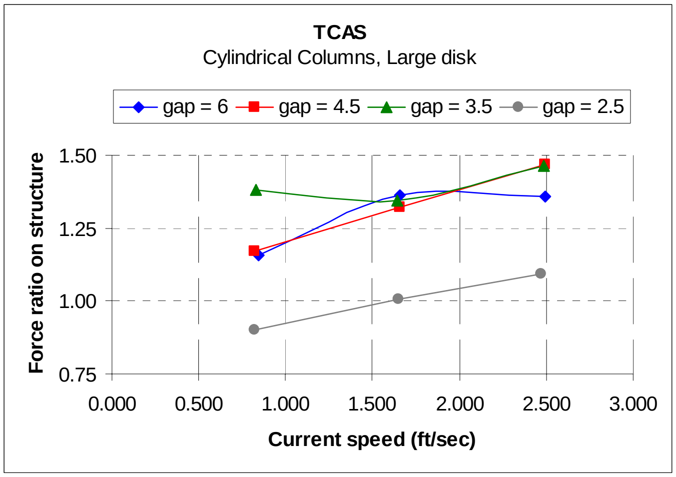


Figure 4. Circular column results: Effect of gap – large disk.

The same configuration and gaps were tested, this time with a disk of 1.25" in diameter. The results are shown in Figure 5. This time the gap did not prove to be a significant contributor to the change in force ratio. At the 2.5" gap, the force on the small disk was not significantly lower than for the other gaps, which leads to the conclusion that the very high blockage of the large disk configuration was responsible for the decrease in force ratio observed.

One of the circular columns was removed to investigate the symmetry effect. The results are shown in Figure 6. As expected the 3.5' gap configuration in the 2 column case is higher than the single column. For the 2.5" case, the one column force ratio was greater than the 2 column case, because the reduction in forces due to impact of the large blockage discussed above was not present in the 1 column case. Lastly, when comparing the 2.5 vs 3.5 gap in the single column configuration, as expected we see a decrease in force ratio as the disk is separated further from the column.

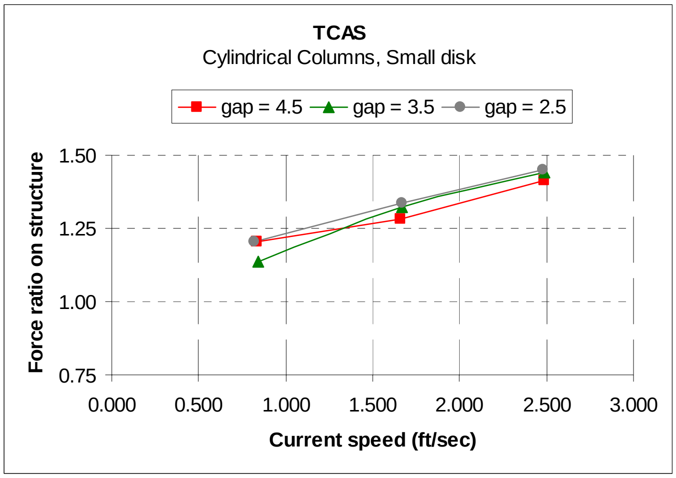


Figure 5. Circular column results: Effect of gap – small disk.

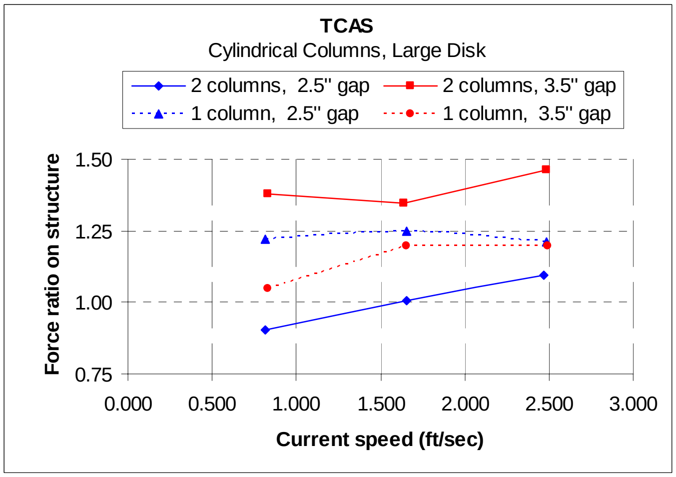


Figure 6. Circular column results: 1 vs 2 columns– large disk.

Elliptic columns

The circular cross section was tested as an academic exercise to understand the fundamental behavior of the system. TCAS Preliminary design considerations targeted an elliptic column with an angled primary axis. Figure 7 shows the comparison between the circular columns and the elliptic columns at 0 degree for 2.5 and 3.5 inches gaps. The elliptic columns did not perform as expected, and for the 3.5 inches gap, it performed significantly worse than the circular column.

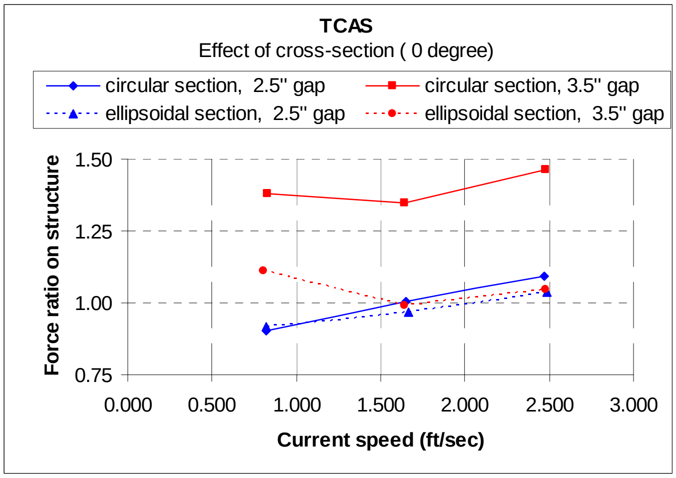


Figure 7. Effect of cross section shape– large disk results.

Figure 8 summarizes the various heading and gap variations performed in the search of an optimal configuration. This is plotted for the largest speed. It was found that 30 degrees and a 4.5 inch gap gave a force ratio of 1.5. The test was repeated and yielded similar results (Column 4 and 5). The absolute value was a bit deceiving, since it only is equivalent to a 22% increase in current speed.

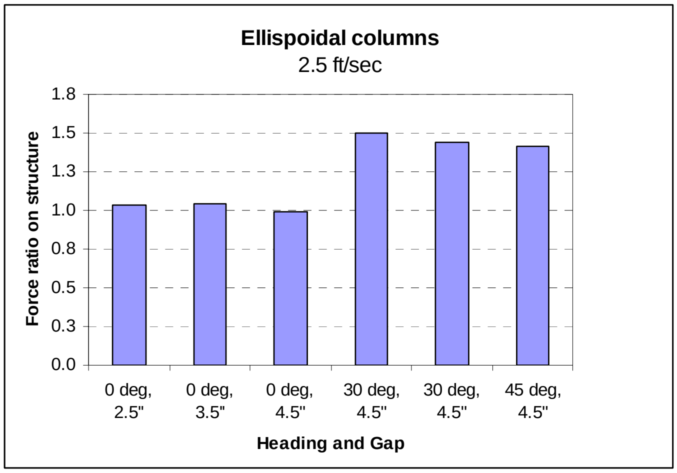


Figure 8. Elliptic column results: Effect of gap and structure heading

Water depth influence

As a sensitivity, the water depth was decreased by half of the structure height. Recall the structure was 6" tall and was in 12" of water. The results shown in Figure 9 show that the water depth does not affect significantly the behavior of the structure.

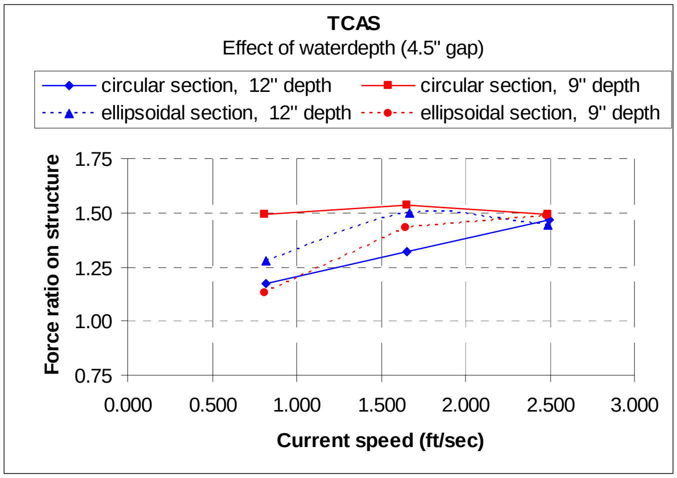


Figure 9. Effect of structure submergence– large disk results.

CONCLUSIONS

In this paper, the influence of a large structure proposed to accelerate the current flow locally on a submerged turbine was investigated. The force on a disk was measured and compared to a force on the same disk without the large structure. This is believed to be more appropriate than simply measuring the current speed at a location inside the structure, since the interference between the disk and the structure cannot be neglected. Two structure shapes were investigated: a circular column and an elliptic column. It was found that the maximum force increase was around 50 %, when the elliptic columns were angled at 30 degrees, forming a funnel shape. It was also found that when the gap is very small and the blockage very large, the force increase was minimal. This would not have been observed by simply measuring the flow speed with a non-interfering probe.

Overall the performance of the structure on increasing the force on a disk was disappointing. From a simple potential theory approach a force increase was expected to be over 200% while the maximum increase was only around 50%. This is caused by the three dimensionality of the flow going above the structure and the fact that blockage affects the flow field in the vicinity of the structure since the governing equation is elliptical, thereby reducing the velocity field near the disk, over the similar case with no disk. Since the actual flow velocity was not directly measured, due to the unavailability of Laser Doppler Velocimetry equipment, no quantification of flow acceleration in the absence of the disk could be performed.

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