Turbomachinations

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Khan, Iqbal, Hinchey, and Masek present power data for two types of Savonius rotor when deployed as a water current turbine.

Who should read this paper?

Business people and researchers with an interest in generating renewable energy from marine currents will find this paper to be of interest. It will also be of interest to autonomous subsea instrument developers who are looking for an economical means to power their devices.

Why is it important?

A Savonius rotor is simple, easy to build and robust. It will accept flow from all directions, and has a high starting torque. However, this type of rotor is characterized by relatively low efficiency and slow running speed. The work reported here is part of a larger effort to develop, deploy and power autonomous measuring devices on the deep seafloor. This component of the work is focused on the potential of using a Savonius rotor to power such devices. An important goal in the effort was to see if scaling laws could be used to accurately predict prototype performance. Results reported here indicate that scaling laws can be used to present data for Savonius water current turbines in a form that would allow one to predict full scale behaviour. Two simple theoretical models were developed for turbine power: one based on impulse momentum and the other based on wake drag. The data presented suggest that, for an actual turbine, impulse momentum is the dominant mechanism. The authors postulate that these results will be useful in helping to model the dimensions of turbines for various applications. They also believe that these results prove that one can accurately estimate the amount of power that can be harvested at different flow speed from the ocean current. Completion of the larger effort is scheduled for the end of 2012, including development of a functional energy conversion unit for marine current.

About the authors

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ON SCALING LAWS FOR SAVONIUS WATER CURRENT TURBINES

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ABSTRACT

The Savonius rotor was initially developed as a wind turbine. Here, we present power data for use of the rotor as a water current turbine. The data is presented in nondimensional form. Two different geometries and two different sizes were tested in water and in air. The data shows that for the Savonius rotor the scaling laws work and so can be used to predict prototype behaviour.

KEY WORDS

Savonius, water current turbines, dimensional analysis, power coefficient, speed coefficient

NOMENCLATURE

C_P	=	power coefficient	T	=	time
C_Q	=	flow coefficient	V	=	current speed
C_S	=	speed coefficient	W	=	wake speed
D	=	diameter	μ	=	viscosity
I	=	flow	ρ	=	density of fluid
L	=	length	A	=	profile area
M	=	mass	Re	=	Reynolds Number
N	=	rpm	J	=	drag coefficient
P	=	dynamic pressure	Pw	=	wake pressure
Q	=	volumetric flow rate	Pv	=	free stream pressure
r	=	moment arm	U	=	flow speed
$r\omega$	=	tip speed	R	=	power ratio
s	=	rotor flow area			

INTRODUCTION

This work is part of a much larger project known as the Seaformatics project. The goal of that project is to develop an array of instrumentation pods that can be deployed on the seabed for exploration of resources beneath it. The pods are to be powered by the local current. This work explores use of the Savonius rotor, which was developed initially as a wind turbine, for this application. The work obtained data for the rotor from a series of model tests. An important goal of the work is to see if scaling laws for turbines may be used to present data in a nondimensional form so that it may be used to predict prototype behaviour. The paper reviews the development of scaling laws for turbines as there may be readers unfamiliar with them.

SCALING LAWS OF TURBINES

For turbomachines, we are interested mainly in the power of the device as a function of its rotational speed. The simplest way to develop a nondimensional power is to divide power **P** by something which has the units of power. The power in a flow is its dynamic pressure P times volumetric flow rate Q. For a flow, the dynamic pressure **P** is

$$P = \rho V^2/2 \tag{1}$$

where ρ denotes the density of fluid and V is the speed of the flow. Volumetric flow Q is the speed of the flow V times the profile area of the turbine A. So, a reference power is

$$\rho V^2/2 \;\; VA \tag{2}$$

So, we can define a power coefficient C_P

$$C_P = P \;/\; [\rho\, V^3/2 \;\; A] \tag{3}$$

To develop a nondimensional version of the rotational speed of the turbine, we can divide the tip speed of the blades rω by the flow speed V. So, we can define a speed coefficient C_S

$$C_S = r\omega / V \tag{4}$$

These coefficients can be found in most papers on turbines. It is customary to use the symbol λ instead of C_S.

For a turbine, the flow speed V is something imposed by the surroundings, and it is appropriate to use it for dynamic pressure. For a pump, the rotational speed is set by the surroundings. All flow speeds would scale as the tip speed rω. Also, the flow area A would scale as r^2. So, in this case, the power coefficient would become

$$C_P = P \;/\; [\rho\; (r\omega)^2/2 \;\; r\omega \;\; r^2] \tag{5}$$

and the speed coefficient would become

$$C_S = V / r\omega \tag{6}$$

It is customary to use diameter D instead of r and rpm N instead of rω and to drop constants. In this case, one gets

$$C_P = P \;/\; [\rho\, N^3 D^5] \tag{7}$$

The speed coefficient becomes

$$C_S = V / ND \tag{8}$$

For pumps, one is usually interested in flow not speed. In this case, one can define a flow coefficient C_Q

$$C_Q = Q / ND^3 \tag{9}$$

One can look upon a pump as a negative turbine. So, the C_P and C_S defined for pumps should also work for turbines. We will test this hypothesis below.

One could derive the power and speed coefficients using a more formal procedure known as the Method of Indices. Most fluids text books [eg. Potter and Wiggert, 2002] call this the Buckingham π Theorem. For this, the variables and parameters of interest are divided into primary and secondary categories. Power would be primary. Things like the properties of the fluid and conditions imposed by the surroundings would be secondary. When using the Buckingham π Theorem, each nondimensional coefficient is known as a π. For power, the goal is to find π_P where

$$\pi_P = P \; V^a \; \rho^b \; A^c \tag{10}$$

We need to find the *a b c* that make the right-hand side dimensionless. In terms of the basic units of mass M and length L and time T, one can write

$$M^0L^0T^0 = M\,L/T^2 \;\; L/T \;\; [L/T]^a \;\; [M/L^3]^b \;\; [L^2]^c \tag{11}$$

Inspection shows that

$$a = -3 \quad b = -1 \quad c = -1 \tag{12}$$

With this, π_P becomes

$$\pi_P = P \; / \; [\rho V^3 \; A] \tag{13}$$

Similarly, for speed, the goal is to find π_S where

$$\pi_S = \omega \; V^a \; \rho^b \; r^c \tag{14}$$

Manipulation shows that

$$a = -1 \quad b = 0 \quad c = +1 \tag{15}$$

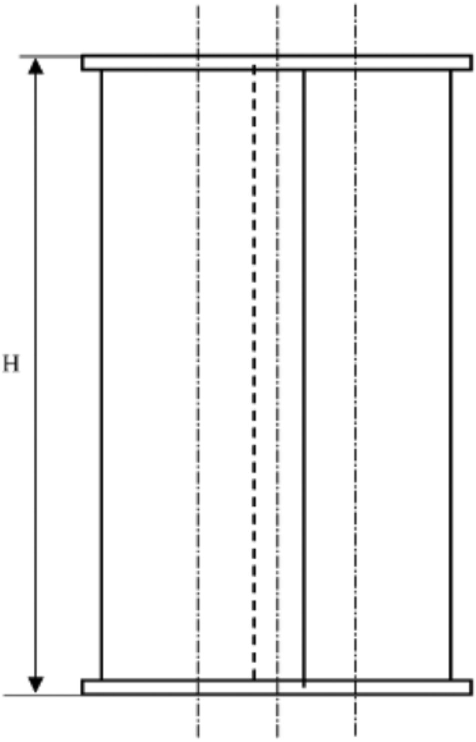
With this, π_S becomes

$$\pi_S = r\omega / V \tag{16}$$

As can be seen, the π coefficients are basically the same as the C coefficients. If we had included the viscosity μ in the list of variables, the π theorem would have produced the Reynolds Number Re as a nondimensional parameter. One might expect this to be important, but it turns out that this is not the case. The character of the flow is not a strong function of Re.

SAVONIUS WATER CURRENT TURBINE

In this study, data for the Savonius water current turbine was used to check the scaling laws. On the positive side, this turbine is simple and easy to build. It is robust, and it has low maintenance. It accepts flow from all directions, and it has high starting torque. On the negative side, it has low efficiency and slow running speed. The basic Savonius rotor [Savonius, 1931] consists of two semicircular buckets with a small overlap between them. A schematic of the rotor is shown in Figure 1. There are two ways such a turbine can extract power from a flow. Imagine that the flow is moving upwards from below in Figure 1. Such a flow would produce a wake drag load above; on top of the left bucket and stagnation pressure load below the right bucket. Each load has a moment arm r which creates a torque about the rotor axis. Multiplying each torque by rotation



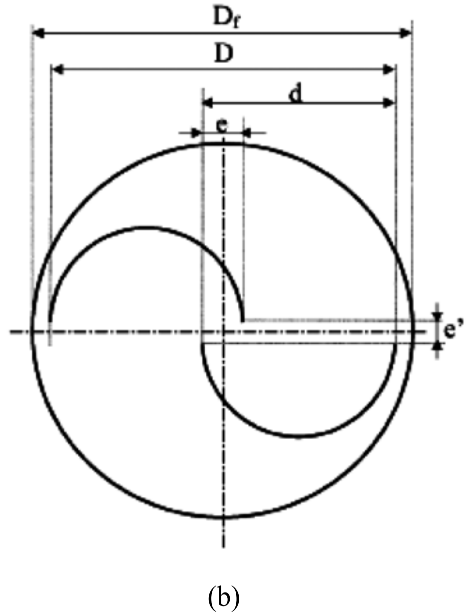


Figure 1: Scheme of a single-step [Savonius, 1931] Savonius rotor. (a) Front view; (b) Top view (conventional Savonius rotor: e'=0) [Menet, 2004].

speed gives power. The net power is

$$I\ s\ \rho/2\ \ (V - r\omega)^2\ r\,\omega \quad - \quad J\ s\ \rho/2\ (V + r\omega)^2\ r\,\omega \tag{17}$$

where I and J are drag coefficients. Fluids texts [Potter and Wiggert, 2002] suggest that for the bucket moving away from the flow I is around 2.3 while for the bucket moving into the flow J is around 1.0. However, for the latter case, the presence of a jet in the wake region could make J much lower: the ideal would be J=0.

For the turbine, there would also be impulse load where a sheet of water moves first along the inside of the left bucket and then along the inside of the right bucket. One can imagine the turbine absorbs momentum when the sheet hits the left bucket and expels momentum where it leaves the right bucket. Each momentum has a moment arm r which creates a torque about the rotor axis. Multiplying each torque by rotation speed gives power. Here we assume that the flow going into the turbine moves at the current speed V. The speed of the flow relative to the bucket is V minus rω the speed of the bucket. The speed of the flow at the exit would be the relative speed minus the bucket speed. Let the rotor flow area be s. The impulse momentum absorbed is

$$\rho V s\ \ V \tag{18}$$

while the impulse momentum expelled is

$$\rho V s\ (V - r\omega - r\omega) \tag{19}$$

The net power is

$$2\rho V s\ (V - r\omega)\ r\,\omega \tag{20}$$

This equation shows that the power is zero when the bucket speed rω is zero and when it is equal to V. Differentiation shows that the power peaks when the bucket speed is half V.

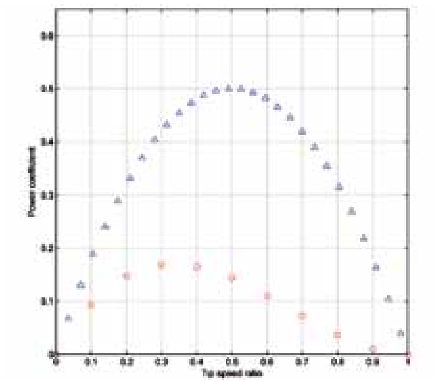


Figure 2: Comparison of impulse power and drag power coefficient for turbine modeled as positive turbine.

Δ Impulse power coefficient
0 Drag power coefficient

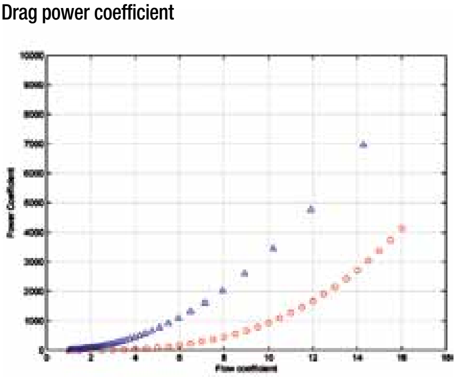


Figure 3: Comparison of impulse power and drag power coefficient for turbine modeled as negative pump.

Δ Impulse power coefficient
0 Drag power coefficient

Figure 2 compares the theoretical power coefficients when the turbine is modeled as a turbine. Figure 3 compares the coefficients when it is modeled as a negative pump. One can easily see that the drag power coefficient is much lower than the momentum power coefficient. So, it appears that momentum is the dominant mechanism.

Most papers on turbines [eg. Ushiyama and Nagai, 1988] mention an upper limit on power known as the Betz limit. Upstream of a turbine, the pressure associated with the free stream is

$$P_V = \rho V^2/2 \tag{21}$$

where V is the stream speed. Downstream of the turbine, the pressure associated with the wake is

$$P_W = \rho W^2/2 \tag{22}$$

where W is the wake speed. At the turbine itself, the flow speed is approximately

$$U = (V+W)/2 \tag{23}$$

The power associated with the pressures is

$$P = (P_V - P_W)UA \tag{24}$$

Dividing P by the upstream power gives the power ratio

$$R = P / [\rho(V^2/2)VA] \tag{25}$$

Letting R = W/V allows one to rewrite R as

$$R = (1-R^2)(1+R)/2 \tag{26}$$

Setting dR/dR equal to zero shows that a peak power ratio occurs when R is 1/3. Back substitution shows that the peak power ratio is R=0.59. This is the Betz limit. Figure 4 plots power coefficient C_P versus tip speed ratio C_S for various turbines. One will note that none of turbines have a C_P greater than the Betz limit.

BASIC SAVONIUS ROTOR MODELS

The first set of tests was done on a basic Savonius rotor like that shown in Figure 1. To test the scaling laws, two geometrically similar

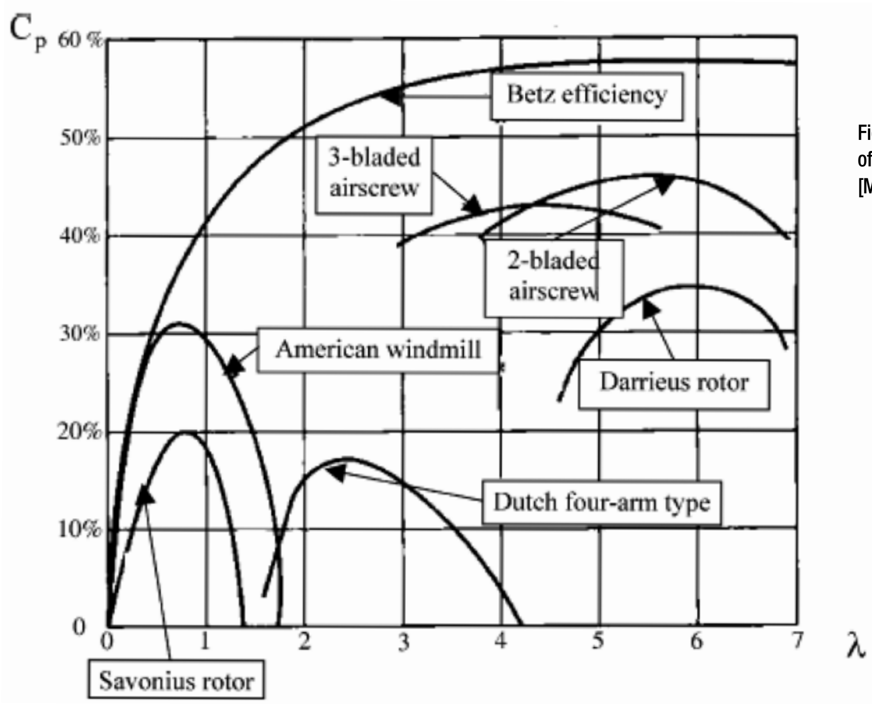


Figure 4: Performances curves of main conventional turbines [Menet, 2004].

Figure 5: Large single stage Savonius rotor.

Figure 6: Small single stage Savonius rotor.

turbines of different sizes were constructed. They were tested in water and in air. Figure 5 shows the larger turbine. It is 0.40 m high by 0.22 m wide. Figure 6 shows the smaller turbine.

The smaller model was designed to give half the output power of the larger model. Scaling laws suggest that the power coefficient for a given speed coefficient must remain the same for both models. If we keep the speed coefficient the same, then this means that V must scale as r, assuming ω is fixed. Substitution into the power coefficient indicates that power must scale as r^5. So, if the output power is cut in half, the smaller model must be 87% of the larger model. This was how the size of the smaller model was determined.

EXPERIMENTAL SETUP

Experiments were carried out in the wave tank and in the wind tunnel at Memorial University of Newfoundland (MUN). The wave tank is 54 m x 5 m x 3 m. It is equipped with a towing carriage with a maximum speed of 5 m/s and a wave maker capable of producing waves up to 0.5 m in height. The motion of the carriage is used to simulate a current. The wind tunnel test area is 1.5 m x 2 m. It has a centrifugal blower at one end and the other end is open. The maximum wind speed is 14 m/s and this occurs when the inlet control vanes are fully open.

The rotors were mounted in a box frame that was open on all sides. The dimensions of the box were 35 cm x 35 cm x 50 cm. The frame was made from aluminum in order to avoid rusting. Bearings were used to support each rotor top and bottom as shown in Figure 7. A prony brake was used to measure the torque produced by each rotor. It used a button load cell (LCKD-5 OMEGA DYNE) to measure brake load. Load times moment arm gave torque. The rpm of each rotor was measured using tachometer (Lab Volt EMS 8931-00). Basically the same setup was used in the wind tunnel.

EXPERIMENTAL RESULTS

The two rotors were first tested in the wave tank at MUN. The water current speed was varied from 0.4 m/s to 1 m/s. Then the two rotors were tested in the wind tunnel at MUN.

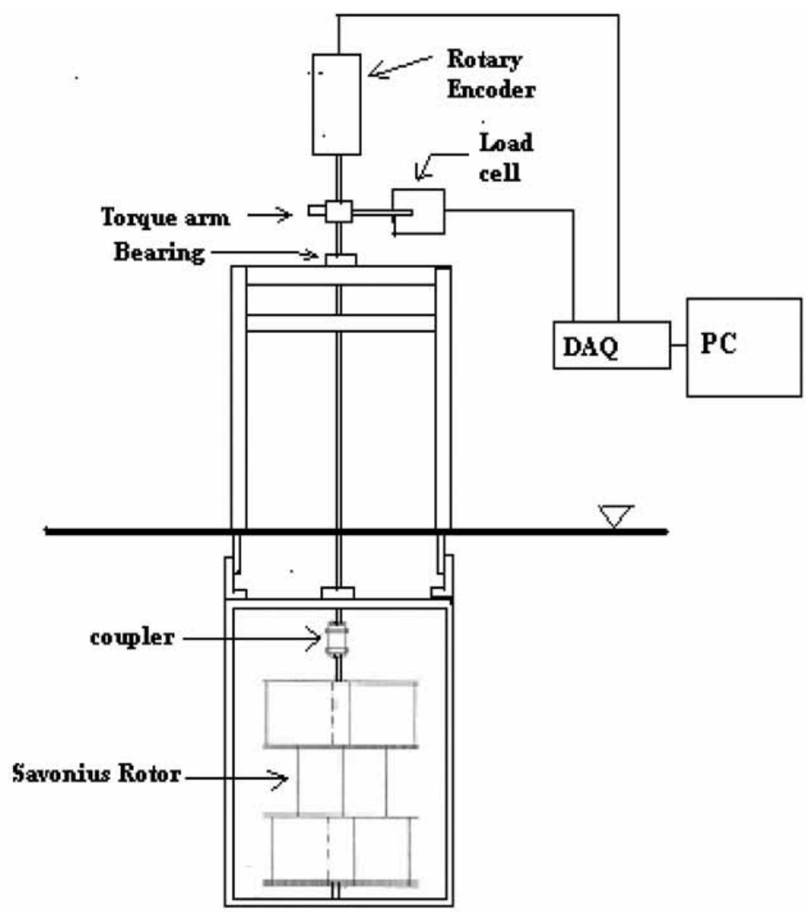


Figure 7: Set up of DAQ system with encoder and load cell.

In that case, the wind speed was varied from 5 m/s to 14 m/s. The large rotor was also tested with both sides of the frame covered in a flume tank. Matlab was used to analyze the data obtained from the two rotors. Figure 8 shows the nondimensional powers of the two rotors when modeled as turbines. Figure 9 shows these powers when the rotors are modeled as pumps. As can be seen, in both cases, the scaling laws work. In the wave tank, the setup width was only 7% of the tank width. In the wind tunnel, the setup width was 40% of the tunnel width. The larger percentage in the wind tunnel case suggests that the gap between the setup and the walls might influence the data. However, the fact that all of the data lies on the same curve suggests that blockage was not a problem.

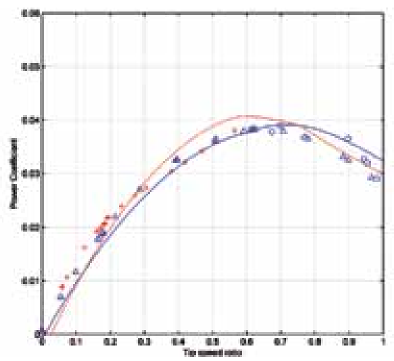


Figure 8: Turbine power coefficient of single step Savonius.

- \- Large Savonius in Wave Tank
- -- Small Savonius in Wave Tank
- Δ Large Savonius in Wind Tunnel
- \+ Small Savonius in Wind Tunnel
- 0 Large Savonius with Side Walls

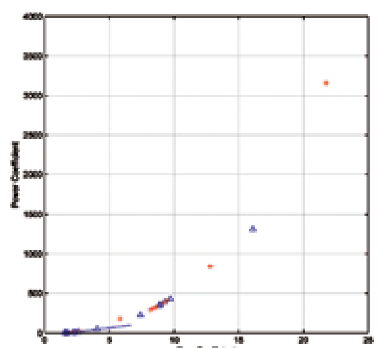


Figure 9: Pump power coefficient of single step Savonius.

- \- Large Savonius in Wave Tank
- -- Small Savonius in Wave Tank
- Δ Large Savonius in Wind Tunnel
- \+ Small Savonius in Wind Tunnel
- 0 Large Savonius with Side Walls

DOUBLE STEP SAVONIUS ROTOR MODELS

In addition to the above experiment, two double step Savonius rotors were tested [Menet, 2004]. The small scale rotor has a dimension of 0.40 m high by 0.22 m wide and is shown in Figure 10. The large scale rotor has a dimension of 1 m high by 0.5 m wide and is shown in Figure 11.

Figure 10: Small double step Savonius rotor.

Figure 11: Large double step Savonius rotor.

The small scale rotor was tested using the experimental set up shown in Figure 7 in the wave tank of MUN. The large scale rotor was tested in the flume tank of the Marine Institute at MUN. The apparatus used was an electromagnetic brake, an S type load cell, and an encoder. The power curves of the turbines are plotted in Figure 12. They show that the scaling laws also work for the double step Savonius rotors.

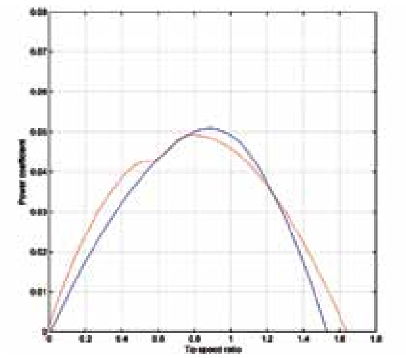


Figure 12: Turbine power coefficient of double step Savonius.

- Large Savonius in Flume Tank
-- Small Savonius in Wave Tank

CONCLUSIONS

The data presented have shown that scaling laws can be used to demonstrate data for Savonius water current turbines in a form that would allow one to predict full scale behaviour. Two simple theoretical models were developed for turbine power: one was based on impulse momentum and the other was based on wake drag. The data shown suggest that, for an actual turbine, impulse momentum is the dominant mechanism. One could study the rotor flows in greater detail using Computational Fluid Dynamics. One could also study them using flow visualization in a water tank.

ACKNOWLEDGEMENTS

The authors would like to thank the Atlantic Innovation Fund and Memorial University of Newfoundland for their financial support of this research. We also thank technicians Paul Bishop and Brian Pretty for their contributions.

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