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Wave Dragon.
Wave Power Plant using Low-head Turbines.

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ABSTRACT

The paper describes the wave energy converter Wave Dragon placed in a real sea environment. The energy converter in question is the 237-tonne Wave Dragon Nissum Bredning Prototype. Wave Dragon is an energy converter of the overtopping type, using a set of low-head Kaplan turbines as power take off system. A description of turbine performance in the salt sea water environment is given.

KEY WORDS: Wave Energy; Prototype Testing; Wave Dragon; Low-Pressure Turbine; Kaplan turbines;

INTRODUCTION

Figure 1: The Wave Dragon Nissum Bredning Prototype.

The Wave Dragon is an offshore wave energy converter of the overtopping type. Installed power will be 4-11 MW for a full scale unit placed in the North Sea, the power of the small scale Nissum Bredning prototype is 18.2 kW.

Figure 2: Location of the Nissum Bredning Prototype

Basically, Wave Dragon consists of two floating wave reflectors focusing the waves towards a ramp, a floating reservoir for collecting the overtopping water, and a number of low-head Kaplan hydro turbines for converting the pressure head into power.

Over the period 1998 to 2001, extensive testing on a scale 1:50 model was carried out at Aalborg University. During recent months, testing has started on a prototype of the Wave Dragon designed for a Danish Broad, Nissum Bredning. The Nissum Bredning prototype is a 1:4.5 scale model of a North Sea prototype.

Figure 2 shows the location of the Nissum Bredning Prototype, indicated on the map by the ellipse. The Nissum Broads (Nissum Bredning) are just off the North Sea, separated from it by two tongues of land. Due to the limited fetch length, the waves in the fjord are about 1:4.5 smaller compared to those out in the North Sea, thus suiting the scale of the prototype.

Figure 3 shows the average wave energy density in the Broads. The upper arrow on the figure indicates the present location of the Nissum Bredning Prototype; the lower arrow shows the most exposed location in the Broads, to which the machine will be moved during early summer 2004.

The present location was chosen to test the functionality of the device, as easier access to the platform makes it possible to sort out the inevitable 'teething troubles' before deploying it in the most exposed position.

The Nissum Bredning Prototype was grid connected at its first location (upper arrow on figure 3), thus making it the world's first offshore wave energy converter delivering power to the grid.

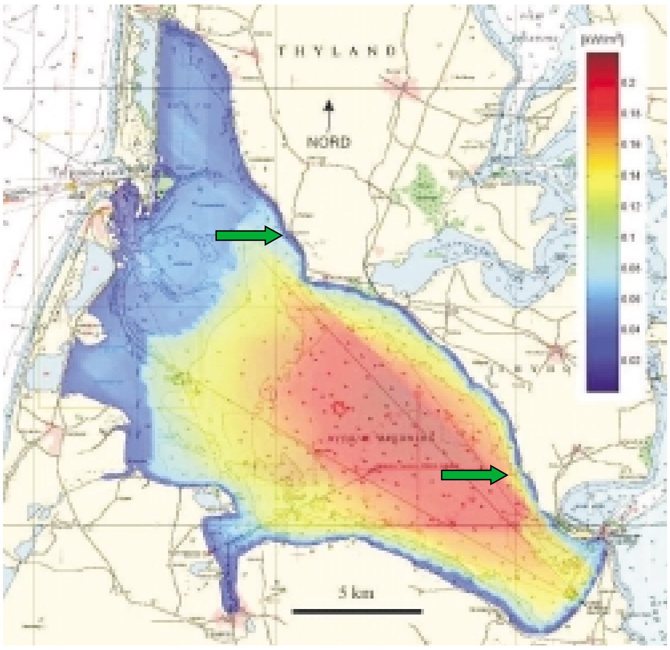

Figure 3: Energy density in Nissum Bredning. The figure also shows the 2 different locations where the machine will be placed.

The Wave Dragon Nissum Bredning Prototype has a total weight of 237 tonnes, still it is only a scale 1:4.5 of the planned North Sea Prototype.

Over the next 2 years, an extensive measuring program will establish the background for optimal design of the structure and regulation of the power take-off system. Planning for a full scale deployment within the next 2-3 years is in progress (Sørensen et. al. 2003). Such a structure will probably be placed somewhere in the North Sea, or in the North Atlantic Ocean.

The Nissum Bredning Prototype is instrumented to monitor power production, wave climate, forces in mooring lines, stresses in the structure, and movements of the Wave Dragon reservoir and the reflecting arms.

The present paper focuses on the description of the Kaplan turbines being used and performance of these Kaplan turbines running in the salt sea water environment.

THE WAVE DRAGON CONCEPT

The Wave Dragon consists of three main elements:

- Two wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially, and thereby increase the energy captured by approx. 100% under typical wave conditions.
- The main structure consisting of a doubly curved ramp and a reservoir.
- A set of low head Kaplan-propeller turbines for converting the hydraulic head in the reservoir into electricity.

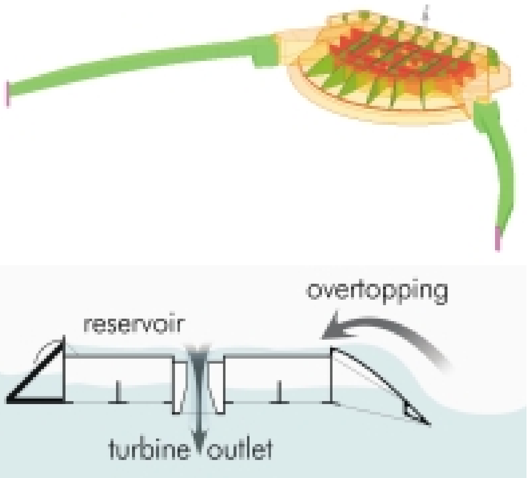

Figure 4: The Basic principle of the Wave Dragon.

When the waves overtop the ramp, this water is filled into the floating reservoir at a higher level than the surrounding sea, and this hydraulic head is utilised for power production through the specially designed hydro turbines.

Through an advanced pneumatic system it is possible to adjust the floating level. The entire main body of the Wave Dragon can be raised or lowered, and in this way the crest freeboard can be varied in order to maximise energy output from the Wave Dragon under the sea conditions prevailing at any time. This level adjustment happens continuously. The used time scale for the operation corresponds to approx. 250 wave periods.

Knowledge about overtopping rates is pivotal for establishing the optimal regulation strategy for the Wave Dragon and for the efficiency achievable from the Wave Dragon. What is the optimal floating level for a given sea condition? When is the optimal time to switch on or switch off the turbines?

Equations predicting average overtopping rates for the Wave Dragon were established through tank tests at Aalborg University on a scale 1:50 model, see e.g. Martinelli and Frigaard (1999), Hald and Frigaard (2001) and Kofoed (2003). Hald and Frigaard (2001) presented the following equation to predict overtopping:

$$q = 0.015 c_d \cdot exp(-40 \frac{R_c}{H_s} \sqrt{\frac{S_{op}}{2\pi}}) \frac{L\sqrt{gH_s^3}}{\sqrt{\frac{S_{op}}{2\pi}}}$$

where,

q = discharge due to overtopping
c_d = reduction coefficient accounting for directional spreading effects, $c_d = 0.9$
L = length of structure ramp; a length of 86.6 meter was assumed (21.3 meter for the Nissum Bredning Prototype)
S_{op} = $H_s/L_{op}, where L_{op} = \frac{g}{2\pi}T_p^2$
T_p = peak period; a constant ratio 1.2 between the peak and the mean period was assumed
H_s = significant wave height
R_c = crest freeboard

In addition, an overtopping simulation software tool had to be developed, allowing real time simulations of overtopping rates (Jacobsen and Frigaard 1999). The design of the reservoir and the turbine configuration of the Wave Dragon had to be based on a reasonable input discharge history. The time history was considered a random process, and it was generated according to a distribution of overtopping volumes per wave consolidated in literature and mean values obtained by the tests previously described.

The probability of occurrence of wave overtopping for vertical structures, cf. Franco et al. (1994) and for rubble mound dikes, cf. van der Meer and Janssen (1995), can be given in the form of a Rayleigh type distribution:

$$P_{ov} = exp(-(\frac{R_c}{cH_s})^2)$$

where,

c = a constant; set to 1.21
c can be interpreted as a roughness factor.

According to van der Meer and Janssen (1995), the distribution of the overtopping volumes of the individual waves, given that overtopping takes place, is given by a Weibull distribution with shape parameter 0.75:

$$P_{V|ov} = P(V \leq V_{mean}|o) = 1 - exp(-(\frac{V_{mean}}{a})^{0.75})$$

where,

a = $\frac{qT_m}{P_{ov}}$
q = mean overtopping discharge
T_m = mean wave period
P_{ov} = the probability of overtopping given in the equation above
$V_{mean}|o$ = mean overtopping of wave, given wave is overtopping

Note that the scale factor a used for the quantification of the overtopping, given that overtopping takes place, is the average overtopped volume, magnified due to the 'average' overtopping probability.

The probability P_v, that a generic wave (the coming wave) is associated to a overtopping volume V less or equal to V_{mean} is:

$$P_v = P(V \leq V_{mean}) = P_{V|ov} \cdot P_{ov}$$

Kofoed and Burcharth (2000) verified the equations giving the time variations of the overtopping for smooth slopes

TURBINE CONFIGURATION

In order to maximise energy output from the Wave Dragon, the device is equipped with several small turbines rather than one larger turbine. In this way it is possible e.g. to switch on only a part of the installed power in sea conditions producing relatively small amounts of overtopping water. Furthermore, this construction allows a single small turbine to be switched on or switched off depending on the actual amount of water coming from a single wave.

Knapp et. al. (2001) showed that taking into account the demand for a turbine concept with minimum maintenance requirements, high efficiency, low specific installation costs and a relatively uniform power delivery a turbine configuration with 16 variable speed on/off turbines was the optimal solution for the Wave Dragon. Future benefits which can be expected from serial production of a big number of small turbines and from further development of the frequency converter technology make this concept even more attractive.

Figure 5: Kaplan turbine with Siphon inlet

The regulation strategy for the Wave Dragon comprises 3 tasks. Firsty, the optimal crest freeboard (float level) for the actual sea condition needs to be determined. For this calculation a time scale corresponding to approx. 250 wave periods is used. Second, the 'work span' for the turbines needs to be defined. The 'work span' is defined as the accepted variation in the water level in the reservoir. Once the water level reaches the top of the 'work span' in question, all turbines will be switched on. And correspondingly, when the water level reaches the lowest level of the 'work span' all turbines will be switched off. Third, controlling the speed of the turbine in order to have maximum efficiency for the actual pressure head.

The function describing the number of turbines to be switched on and off between these extreme points must be optimised to maximise energy production and minimise spilling losses. As a different turbine operation strategy may lead to a different optimal crest height, the determination of optimal operating parameters is a complex task.

In order to solve this task, a software simulation package has been devised which simulates the operation of the Wave Dragon. A number of different operating strategies will be tested on the prototype during the coming years in order to verify and calibrate these simulation routines. The end result will be a planning tool that enables a full scale Wave Dragon to be designed for optimum energy conversion in the wave climate given in any proposed location.

Figure 6: Kaplan turbine with cylinder gate.

Ideally, the Wave Dragon would be equipped with 16 identical small variable speed on/off turbines. The configuration on board of the small scale prototype, however, consists of three different turbine types:

- A Kaplan turbine with siphon inlet, see figure 5 and figure 8. The turbine was developed through the EU CRAFT project: Low–Pressure Turbine and Control Equipment for Wave Energy Converters (Wave Dragon). The runner diameter of the siphon turbine is 0.34 meter, and the unit speed and discharge in the chosen operating point are $n_1^{'} = 170min^{-1}$ and $Q_1^{'} = 2.75m^3/s$, resulting in a specific speed of $n_q = 280min^{-1}$. Calibrated flow is 0.22 $m^3/sec.$ at 0.5 meter head, and rated power output is 2.6 kW, which corresponds to 500 kW in a full scale North Sea Wave Dragon.
- 6 Kaplan turbines with cylinder gates, see figure 6. These turbines have the same runner diameter and performance data as the siphon turbine. The turbines were fabricated in Austria by Kössler GmbH, and they were installed in September 2003. Installation of switchgear and generators was finished in February 2004.
- 3 dummy turbines, see figure 7. These turbines are not able to produce power, they are merely calibrated valves which let the overtopped water run back into the sea. The diameter of the valves is 0.43 meter, and discharge is about twice the one of the real turbines. The dummy turbines were introduced due to financial constraints in the project; they permit to simulate the discharge from further 6 real cylinder gate turbines at a fraction of their cost.

Figure 7: The 3 'dummy' turbines.

The cylinder gate and siphon turbines are using the same design of guide vanes and runner blades, thus their performance characteristics are almost identical. In view of the hostile seawater environment and the limited possibility for maintenance, a very simple and rugged turbine with fixed guide vanes and non-adjustable runner blades had been chosen.

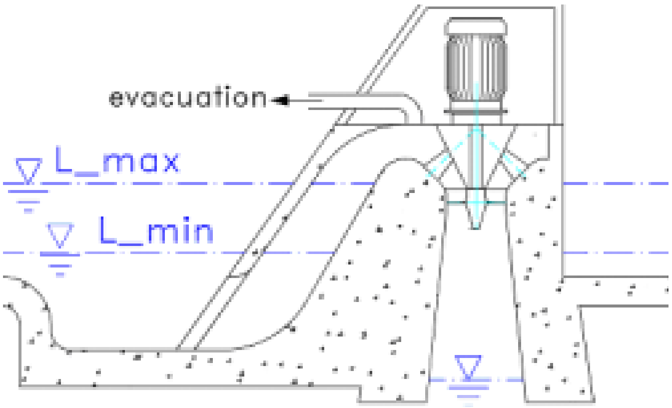

Figure 8: Principle of siphon type on/off turbine.

Due to the wide distribution of the wave height, the turbines have to operate in a fairly wide range of turbine heads, ranging from 0.1m to 0.6m. In order to grant a high turbine efficiency throughout this range the turbines are connected to permanent magnet generators controlled by frequency inverters, allowing the turbines to be operated at variable speed.

However, due to the stochastically time distribution of the overtopping, some of the turbines need to be switched on and off quite frequently, sometimes as often as 1 time per minute. In order to make this feasible, the two alternative solutions mentioned above have been devised: a hydraulically operated cylinder gate upstream of the guide vanes and a siphon intake. The advantage of the cylinder gate is that it can be opened and shut very quickly; on the prototype a time span of about one second has been measured. A water hydraulic system is used for reasons of environmental safety.

With the siphon inlet, the waterway is carried up above the maximum reservoir level, see fig. 5. and fig. 8. The turbine is started by applying negative pressure to the inlet chamber, thus sucking the water up until it reaches the wicket gate. Then the water starts flowing through the turbine, taking the rest of the enclosed air along with it. For stopping the turbine, a small aeration valve on the top of the turbine is opened, thus breaking the hydraulic circuit. The advantage of this solution is that it requires less moving parts and is thus less prone to wear. The starting and stopping times, however, are longer compared to the cylinder gate. As the added reliability might well outweigh this disadvantage, it was decided to test both versions on the small scale prototype.

Based on measurements of the instantaneous pressure head, and knowing the number of currently open turbines, it is possible to calculate the flow through the turbines. The opening period is defined as the period from starting time of the opening process to starting time of the closing process. Obviously the periods of the opening and closing operations will be accompanied by some uncertainty. In particular, the actual amount of water passing the turbines during the opening and closing time will be slightly lower than calculated, as the energy loss through the turbines is not linearly depending on the head. However, relative to the typical duration of the operations of the turbines (open valves), the duration of the opening and closing processes of the valves are insubstantial.

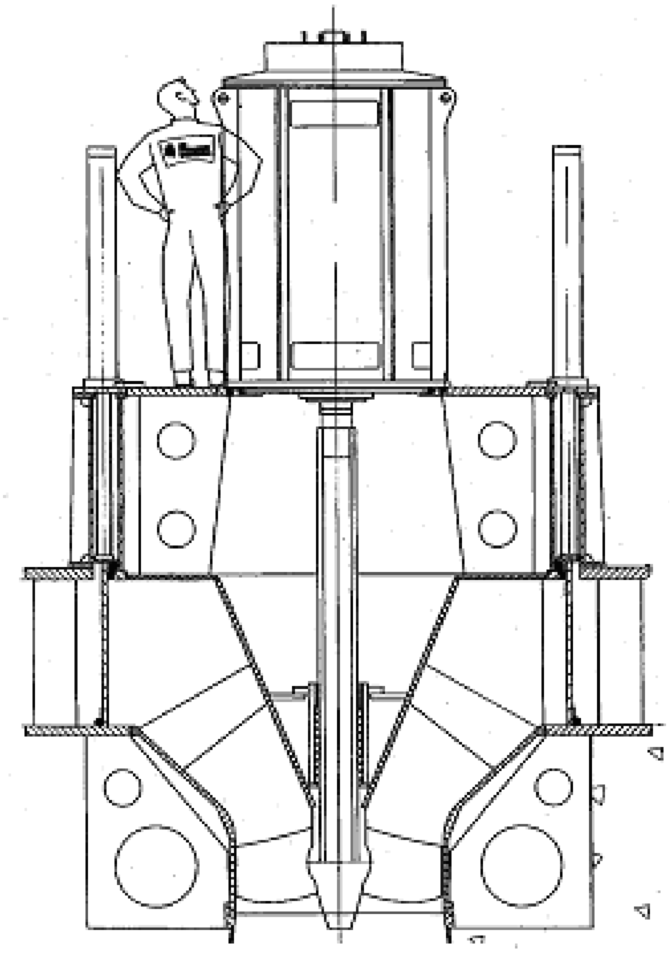

Figure 9: Principle of cylinder gate on/off turbine. The shown size of the turbine corresponds to a North Sea power plant.

WAVE MEASUREMENTS IN NISSUM BREDNING

Waves are measured indirectly through a pressure transducer placed approx. 2 meter under the sea surface. The pressure transducer is mounted on an arm attached to the mooring pile of the Wave Dragon. The transformation from pressure to surface is done by linear wave theory.

Wave parameters are calculated continuously in a 16 minutes long time window. The length of the time window corresponds to 250 - 300 waves.

OVERTOPPING

During the winter of 2003/2004 and over the coming winter season, overtopping results have been and will also be collected continuously, in periods without down time of the instruments.

Obtaining measurements in a real sea condition is difficult. And it has indeed turned out to be even more difficult and more time-consuming than expected. The sea is extremely rough on the instruments. Nevertheless, throughout the months of November and December 2003 average overtopping rates have been successfully monitored on the Nissum Bredning Prototype, both under ordinary conditions and also under storm conditions (Kofoed and O'Donovan 2003).

It is assumed that all water overtopping the ramp passes through the turbines. This means that no spill is expected. Visual observations support this assumption; at least in calmer wave conditions.

Therefore, an estimate of the overtopping amount of water can be calculated, knowing the characteristics of the turbines, the head of the free surface and the opening time of the turbines.

Figure 10 show some of the measurements. Unfortunately, it is difficult to see the measurements clearly in the figure; however, the purpose of including the plot is to give an idea of the large variations in the signals.

The x-axis represents the time. In the figure the length of the axis is 5 minutes corresponding to a little less than 100 waves.

The y-axis shows 5 curves: 'work span' (in this example app. 10 cm), water level within 'work span' (in this example 0% - 100%), number of running turbines (0-10 in the example), wave height (approx 50 cm in the example) and water level in the reservoir (50-60 cm in the example).

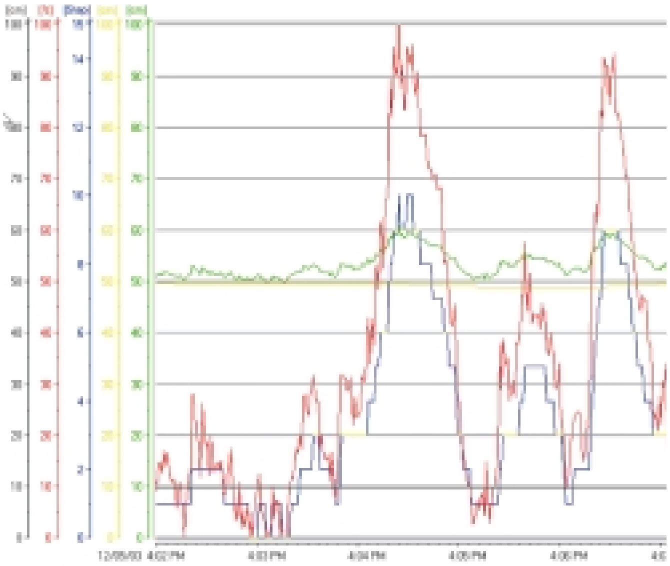

Figure 10: Measured data as shown in the control program.

From figure 10 each of the individual overtopping waves can be recognized as a change in the water level in the reservoir. This can be seen most clearly when studying the curve for the water level within the 'work span' (red curve).

Figure 10 also demonstrates the frequency for the turbines to be switched on (and later switched off). The situation seen on the figure corresponds to a turbine being switched on almost every 10 second in average.

In general, a turbine is expected to be switched on and off approx. 1 time per minute.

The outlet is calculated as:

$$Q_{overtop} \simeq Q_{out} = \int_{time} \sum_{i=1}^{N} F_i(h) G_i dt$$

where,

i = turbine number
N = number of installed turbines
h = instantaneous head in reservoir
F = calibrated function describing flow out through a turbine
G = function describing whether the turbine valve is opened or closed. At present this function can only take the values 0 or 1.

Overtopping data from the Nissum Bredning Prototype show good agreement with the laboratory overtopping data. Figure 11 gives an example of such a comparison.

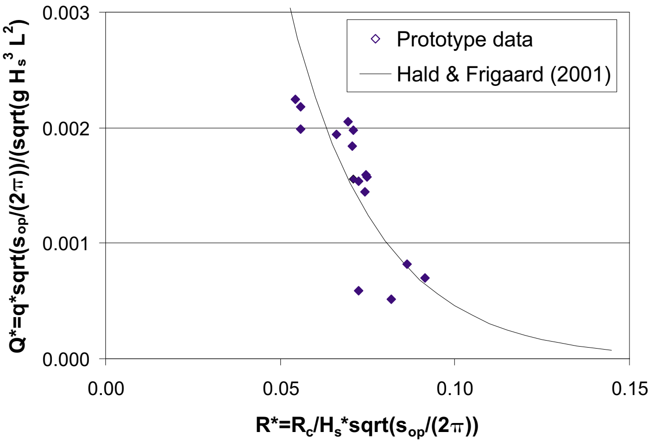

Figure 11: Example of Overtopping results

PERFORMANCE OF THE TURBINES

All turbines have demonstrated functionality in the rough salty sea environment. It must be stressed, that our experience with the turbines is still rather limited, but it seems like there are no problems with the high air content in the salt water.

More or less all rubbish entering the platform will have to go out through the turbines. Therefore the turbines are encircled by a grid of trash racks with a mesh size of approx. 5 cm.

The grid must be manually cleaned occasionally.

There were no problems with the smaller items passing the grid. This is actually surprising because some sea wheat passes the grid in between.

Figure 12: Part of trash rack surrounding turbine area.

MAINTENANCE OF THE TURBINES

Experience has shown the importance of using stainless steel or other corrosion-resistant materials for all moving turbine parts. This seems advisable even for small parts of the turbines being mounted on the 'outside' of the turbines. For example did the turbine with the Siphon inlet create problems, because the valves used to control the siphon system broke down due to corrosion within a few month as they were made of unsuitable materials.

Maintenance at sea is difficult to perform, so any possibility to setup systems, that can be transported on shore for maintenance will lower the maintenance costs.

Fouling of the guide vanes, runner blades and draft tubes is a problem to be foreseen during design. From the limited experience available up to now, it appears that marine growth is not a problem in regions of high flow velocity, i.e. in the turbine runner and guide vane area. All other parts along the waterway, especially the lower part of the draft tubes, need to be coated with an efficient anti-fouling paint.

CONCLUSION

The functionality of the Wave Dragon overtopping concept has been proven.

The use of low-head Kaplan turbines for energy production in salty sea waters has been shown.

Overtopping has been measured on the Nissum Bredning Prototype of the Wave Dragon.

ACKNOWLEDGEMENTS

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MORE INFORMATION

Futher information on the project can be found at one of the Web pages: www.wavedragon.net or www.civil.aau.dk for further information on the project.

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