# Undersea Electronics Powered by Large Surface Area Benthic Microbial Fuel Cells

J.A. Kagan, A. Higier, L. Hsu, D.B. Chadwick
Environmental Sciences
Space and Naval Warfare Systems Center-Pacific
San Diego, United States

***Abstract*— Benthic Microbial Fuel Cells (BMFC) have the potential to provide long-term, sustainable power for undersea devices. BMFCs operate by harnessing organic matter in the sediment as a fuel source. They typically output 10 to 100mW. To increase the power output, BMFCs with larger electrodes are needed. However, past work has shown that power output does not scale linearly with electrode surface area. To build a large surface area BMFC capable of greater than 100mW power output, experiments were conducted to: 1. determine at what surface area the power output deviates from scaling linearly; 2. determine if independent anodes could be wired together and maintain their power density; 3. determine the proximity independent anodes could be from one another and maintain their power densities; 4. Determine the anode to cathode relationship that prevent cathode limitations. Experiments showed that: 1. anode surface areas of 1-2m$^2$ provide a good balance between power output and complexity when incorporated into a larger system; 2. independent anodes could be wired together and maintain their power density; 3. anodes could be 2-3cm apart and maintain their power densities; 4. 1:1 anode to cathode surface areas prevent cathode limitations. Based on the results of lab experiments, a BMFC deployment sled was designed to deploy a BMFC with two 10m$^2$ modular anodes, spaced 5cm from one another, and successfully deployed this BMFC in San Diego Bay without the use of a diver. The BMFC sustained 250mW and powered environmental sensors and transmitted data over an acoustic modem.**

***Microbial Fuel Cell; Deployment; Benthic; Sediment; Carbon Fabric; Large scale***

## I. INTRODUCTION

The allure of sustainable, remote, long-term power for undersea electronics has been a driving force for the recent attention benthic microbial fuel cells (BMFC) have received. These BMFCs convert chemical energy to electrical energy through the catalysis of microorganisms. BMFCs operate by taking advantage of a natural potential of approximately 750 mV between the anode and cathode [1,2]. To do this, the anode is buried in an anaerobic environment, typically around 10 centimeters below the sediment water interface (Fig. 1). Bacteria present in the sediment generate electrons during their metabolism by oxidizing organic matter. Bacteria in a wide range of environments have been shown to be capable of donating these electrons to an anode that is electrically connected to a cathode in the overlying aerobic water as an alternative to other electron receptors in the sediment. These electrons create a usable current to support the remote powering of undersea devices [3]. The fuel supply in the sediment is naturally replenished as organic matter settles on the sediment surface. This allows BMFCs to operate for long periods of time without the need for refueling/recharging [4].

To date, published power levels from these systems has been limited to the range of about 10-100 mW [3,5]. In order to improve the performance of BMFCs a number of factors need to be investigated and improved. The power harvested from BMFCs is dependent on electrode surface area, electronics power requirements, temperature, organic content, oxygen and grain size as well as other factors still being investigated. The number of electrons harvested by the BMFC has been found to be directly related to anode surface area and bacteria's metabolic reaction rate [6, 7]. An et. al. investigated the correlation between the depth of the anode in the sediment and power output. The experiment used rigid graphite plates placed under various sediment depths and found that voltage and current output are improved with increasing anode embedding depth and that overall anode embedding depth is a significant factor in sediment based MFCs[8]. Furthermore, studies have shown that anode surface area is a significant factor that an almost direct correlation between surface area and power output exists [9]. Hong et al. conducted a study to evaluate the limiting factors affecting output from BMFCs. The results proposed optimum anode to cathode surface areas as well as operating temperatures [10].

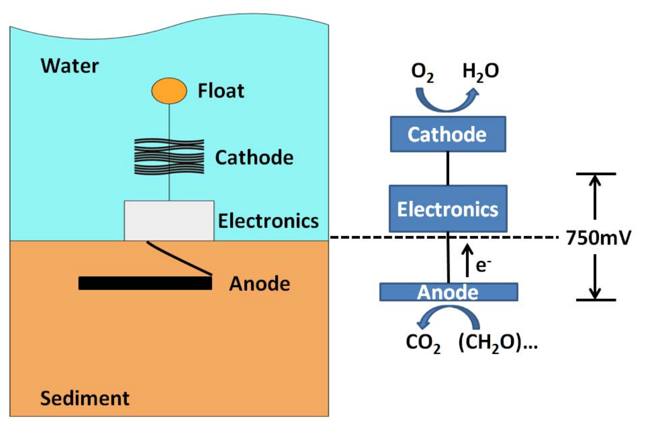

Fig. 1. BMFC schematic.

In many cases, the current state of the BMFC technology the power output is too low to operate any usable system. Some groups have experimented with ways to manage the power in order to operate usable systems and sensors. Donovan et. al. developed a unique power management system for sediment based MFCs. The study found that, since the continuous power output is so low for BMFCs and often times the sensors being used require more power than that produced by the BMFCs a power management system enabling a SMFC to power a remote sensor consuming 2.5 W of power was developed. The system is designed to store microbial energy in capacitors and use the stored energy in short bursts thereby allowing for higher power sensors to be used [11]. Finally, work conducted by the authors on previous BMFC deployments has shown that BMFCs may serve as a viable power source in the ocean however; a method for deploying large area anodes easily and effectively must be developed if the desired power levels are to be achieved. As part of that study a boat-towed sled deployed 10 meters squared of anode. Utilizing a technique which buried the anode as it was deployed. This initial sled design deployed a BMFC that generated approximately 80mW of continuous power with $6mW/m^2$ of anode surface area [5]. Further data analyzed after the publication of that work showed three main limiting factors were identified as impeding maximum power output. They are:

1) Ohmic losses in the anode material and their effect on diminishing power generation;
2) Anode configuration;
3) Cathode limitation.

It is clear from previous studies that if BMFCs are to become a viable option for undersea power an effective method for developing and deploying the anodes must be demonstrated. BMFCs have typically been diver deployed, however, as the BMFCs with larger anode surface areas are deployed, diver deployments will become too costly in both time and money. It is, therefore, the objective of this work to develop an effective method for deploying large scale anodes that have the potential to reach the power ranges necessary to operate an underwater acoustic transponder which operates in the power range greater than 100mW.

## II. Method

A number of experiments, both in the laboratory and in field deployments were conducted to work to improve the overall power output of the BMFCs.

### A. *Laboratory Experimental Setup*

In order to correlate anode size to power output five sets of BMFCs were set up with anode sizes ranging from 0.0025 – $0.64\ m^2$. Each of the anodes for these systems was fabricated to maintain similar aspect ratios to the deployed system and shared a common graphite brush cathode.

Two different configurations of anodes were examined, taking into consideration both anode size and system footprint. The anodes were then electrically connected together by size. This configuration was adopted to determine whether or not the performance of the systems would deteriorate when grouping the anodes at a common node. A second anode configuration experiment was used to determine whether anodes could be vertically stacked within the sediment without losses. For these experiments, sheets of carbon fabric were used as layers in separate systems containing 1, 2, and 3 anodes. For the 2 and 3 anode systems, each fabric layer was separated by approximately 2-3 cm of sediment.

To assess the effects of cathode limitation, a BMFC system was set up with a $1.75\ m^2$ anode and a 1.42 m carbon brush with a titanium core (The Mill-Rose Company; Mentor OH). Once operating at maximum power density, the system was perturbed by incrementally removing 0.35 m of the cathode. Each removal of cathode was performed after a new steady-state operating point had been established following the previous removal.

### B. *Field Deployment*

In order to test the ability of the system to power an acoustic transponder a next-generation approach to the sled in [5] was designed to include: a multi-layer anode burial sled, a segmented carbon fabric anode array, and an enlarged instrument pod with larger cathode capacity.

#### 1) *Sled Modifications*

The modified sled (double-blade sled) is similar to the first generation BMFC sled (single bladed sled[5]) but differs in that: 1) two anode sheets deploy instead of one; 2) the width is larger to accommodate stock carbon fabric (PX30FBPW06 Panex 30; Zoltek; St. Louis, MO); 3) it has an improved anode loading capacity. A comparison between the single-blade and double-blade sled is shown in Fig 2.

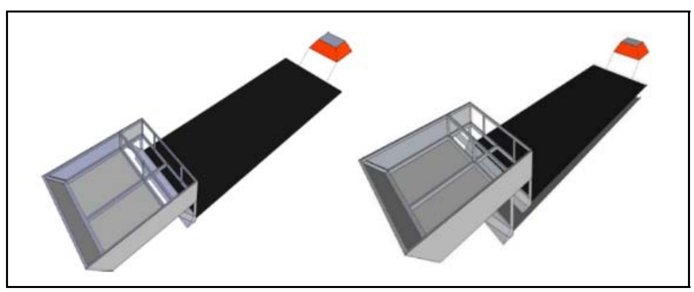

Fig. 2. Side by side comparison of single-blade and double blade sled.

The sled system is designed to be towed by a boat and autonomously launch an instrument pod which triggers the unfurling of the anode from the sled. The anode is buried as sediment flows over the sled blades. After the entire anode is deployed, the sled is then recovered by the boat, leaving the BMFC behind and fully deployed.

### 2) Anode Configuration and Construction

The segmented carbon fabric anode was developed based on the results of the initial field testing with the single blade BMFC sled in [5], and the subsequent laboratory scaling, ganging and layering tests. The anode consists of two anode sheets to be deployed by the multi-layer deployment sled. Each sheet is comprised of 10x $1m^2$ carbon fabric sheets each physically isolated by a 3 inch wide non conductive fabric mesh. Each $1m^2$ sheet is further referenced as a module (Fig. 3). Each module has two titanium wires running across it at ¼m spans, so that each square meter of fabric has an independent collecting conductor. The titanium collector wires are then electrically connected to two insulated copper flat-wires running down the full length of the anode (Fig. 4). The copper flat-wires are sealed to prevent corrosion. The copper flat-wires run the length of the entire anode connecting to the titanium on all of the modules. At one end of the anode, they are pressed by an aluminum clamp that runs across the anode and is connected to a copper underwater cable. The aluminum clamp and underwater cable connection is potted in epoxy inside a PVC pipe. This design limits the amount of current running through the resistive carbon fabric and titanium wire to reduce potential losses. When deployed, the BMFC containing this anode is expected to produce 500 mW of continuous power.

Fig. 3. From left to right 1. An array of anode modules 2. An anode module.

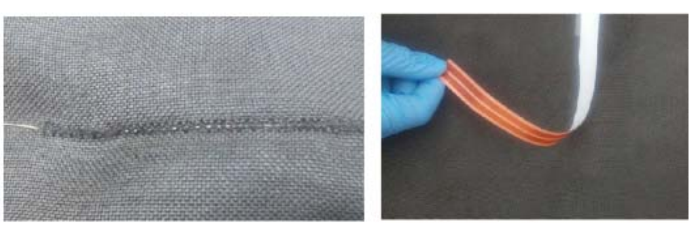

Fig. 4. Titanium and copper wire connections to an anode module.

### 3) Instrumentation pod and cathode

A new instrumentation pod was designed with a larger cathode rack to address cathode limitation as the anode area increases (Fig. 5). The pod consists of a hard plastic container with an open back side and holes in the front for flooding the pod to reduce buoyancy. A PVC rack has been created to hold either end of the carbon brushes. The PVC holds aluminum that clamps on the titanium brushes, and is attached to a copper underwater pluggable cable. The PVC sealing/titanium clamping approach is the same as that used for the previous deployment [5]. The rack is rectangular and hugs the walls of the electronics pod. 16 carbon brushes, 60 inches long were attached to the instrument pod. Half of the carbon brushes run width wise and the other half run length wise. The carbon brushes stand approximately 3 ft high in the water column.

Fig. 5. New instrumentation pod with larger cathode carrying capacity.

## C. Deployment

To prepare the BMFC for deployment, the anodes were rolled onto their axles and loaded into the sled. The instrument pod, with the cathodes, was loaded into the instrument pod bay at the rear of the double-blade sled. The underwater cables from the anodes were attached to the electronics inside the instrument pod. Paracord was used to link the instrument pod to the anodes. The assembly was loaded onto a boat and lowered down onto sediment in the water at Marine Corp Recruiting Depot (MCRD) which is in San Diego Bay. The boat towed the sled 30m to ensure proper BMFC deployment. A diver was used to verify proper deployment of the BMFC.

## D. Power Budget

Based on the design considerations described above. A power budget was developed for electronics powered by a multi-layered BMFC deployed at MCRD. The power budget was based on an electronics configuration that included the energy harvesting electronics, power conversion to 12V, storage in a lithium cell, powering the ESM1 and associated sensors, and transmitting the sensor data over a simple acoustic modem data link (SAM-1). As shown in Table 1, the combination of the ESM and the acoustic modem cycling at once per hour require approximately 94 mW.

TABLE I. POWER BUDGET FOR POWERING AN ACOUSTIC MODEM.

| Double-Blade Power Budget for ESM Sensor/Logger & SAM-1 Acoustic Modem | | | |
|---|---|---|---|
| **Parameter** | **Value** | **Units** | **Notes** |
| MFC Power | 160 | mW | Double-blade system at MCRD |
| 12V Power | 104 | mW | ~65% conversion efficiency to Li ion battery pack |
| Sample Size | 64 | bits | Pressure and temperature record + overhead |
| Sampling Frequency | 2 | 1/hr | |
| Sample Duration | 50 | sec | Averaging 1/sec plus overhead |
| Transmit Frequency | 2 | 1/hr | |
| Transmit Rate | 100 | bits/sec | Useable data rate |
| Transmit Duration | 10 | sec | Including latencies |
| | | | |
| ESM Active | 0.033 | hr/hr | 65mA at 12V |
| ESM Standby | 1.000 | hr/hr | 0.12mA at 12V |
| Modem Active | 0.006 | hr/hr | 1000mA at 12V |
| Modem Standby | 1.000 | hr/hr | 0mA at 12V (power shut off by ESM) |
| | | | |
| ESM Power | 27.440 | mW | Active + Standby |
| Modem Power | 66.667 | mW | Active + Standby |
| **Total Power** | **94.107** | **mW** | |

The BMFC and electronics were configured as shown in Fig. 6. The anode and cathode are connected to the MFC electronics which charges a battery. The MFC electronics power the ESM unit which triggers the data transmission through the acoustic modem. An acoustic modem connected to and powered by a computer receives the transmitted signal. It is important to note that the computer is not providing power to the acoustic modem that is connected to the ESM unit.

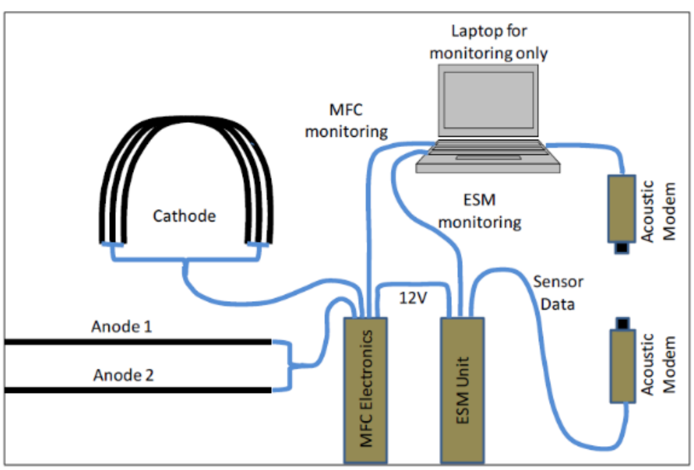


Fig. 6. Schematic of BMFC powered acoustic modem data transmission.

## III. RESULTS AND DISCUSSION

### A. *Lab experiments*

Results of the anode scaling experiments showed that power increased with anode size until the surface area began to approach $1m^2$. These results show agreement with numerical predictions using power laws. This suggests anode size/length is a critical design consideration in next-generation BMFCs (Table 2). Numerical predictions previously conducted also suggest that only about 30% of the power degradation is related to ohmic losses, and the majority is related to the potential drop and resulting operation of those portions of the anode at suboptimal cell voltages. Interestingly, the majority of the ohmic losses occur near the root of the anode (connected end) where the cumulative current becomes very high, while the majority of the suboptimal cell voltage losses occur toward the free end of the anode where the cell voltage approaches the open circuit potential.

TABLE II. LAB, FIELD AND NUMERICAL PREDICTION OF POWER DENSITY AS A FUNCTION OF SURFACE AREA.

| | Power Density ($mW/m^2$) | | | |
|---|---|---|---|---|
| **Surface Area ($m^2$)** | **Lab** | **Field** | **Numerical Prediction (r=1 ohm/m)** | **Numerical Prediction (r=0.25 ohm/m)** |
| 0.003 | 23.0 | - | 22.0 | 22.0 |
| 0.010 | 22.5 | - | 22.0 | 22.0 |
| 0.160 | 18.0 | - | 21.5 | 22.0 |
| 0.120 | 20.5 | - | 20.0 | 21.5 |
| 0.180 | 15.5 | - | 15.0 | 20.0 |
| 10.100 | - | 7.0 | 4.0 | 8.0 |

Results from layering anodes showed that two and three anodes separated by 2-3cm operate with no negative impact on power density (Fig. 7).

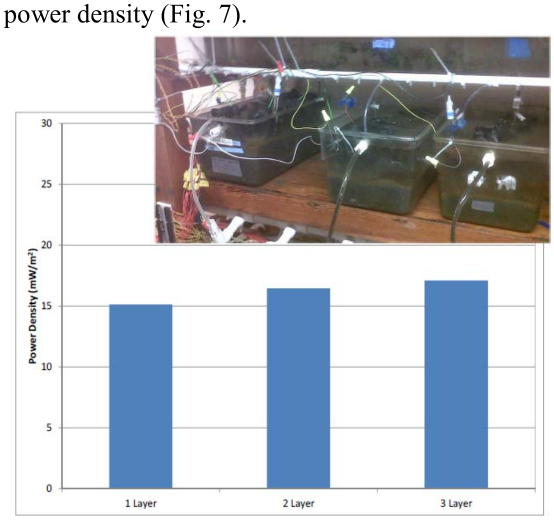


Fig. 7. Layered anode experiment.

The effects of systematically reducing the cathode size showed that at least a 1:1 ratio of surface area to cathode brush length is required to avoid cathode limitation. Based on the results of these initial field and lab tests, a next-generation BMFC sled was developed.

### *B. Field experiments*

The sled was first tested in dry sand where the system successfully demonstrated proper anode deployment (Fig. 8). Successful deployment included autonomous release of the instrument pod, full burial of the entire length of both layers of anodes, and 2-3 inches of separation between the anode layers. A test deployment was then conducted underwater off a pier at a 20 ft depth (Fig. 9) in order to confirm proper deployment underwater in sediment. A diver confirmed the successful deployment though no BMFC experiments were conducted.

Fig. 8. Dry land testing of the double-blade sled. The arrow points to the two anodes.

Fig. 9. Underwater test deployment.

The system was deployed at at the Marine Corp. Recruit Depot (MCRD) (Fig. 10) on December 21, 2012 with two 1 × 10 m segmented anodes, the instrument pod containing carbon brush cathodes, and the electronics configuration described above. The sled successfully deployed the BMFC; both anodes were verified by diver to be buried to the desired depths with the deeper anode at about 8-9 inches and the shallow anode at about 5-6 inches. Within the first week, the electronics package flooded due to an o-ring failure, and the electronics module had to be replaced. The module was replaced on January 8, 2013 and has operated without issue since then (Fig 11). The results show that the system has maintained a stable cell potential between 350-400 V for the last ~6 months of its deployment. During the first two months of the deployment, the power steadily increased until reaching a stable level of about 250 mW around February 1, 2013. MFC power remained stable at this level for about 3 months (May 1, 2013) when the power started to slowly decrease to about 200 mW on July 1, 2013. While these power levels are the highest we have yet to achieve, they are lower than the 500mW we had expected from the system.


Fig. 10. Depiction of deployment footprint at MCRD.

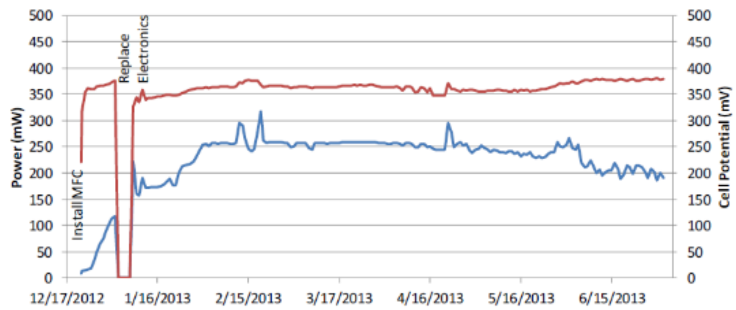


Fig. 11. MCRD deployed BMFC power output and cell potential.

Grouped anode systems showed no significant difference in power density, when compared to the single anode systems. This suggests that multiple anodes may be combined into one system with no impact on system performance. The power densities resulting from grouped anode systems showed no negative impact of layering anodes in this configuration.

Despite a power output 2x less than expected, the BMFC was able to power the SAM-1 acoustic modem and transmit data to a receiving SAM-1 connected to a computer at a rate of twice per hour. A power output consistent with the expected 500 mW would allow for more frequent data transmissions from the acoustic modem.

Diagnosing the reason for the lower than expected performance has proved challenging. The design of the system is such that all anode panels are connected together, and only the bulk MFC potential and current, along with the 12V potential and current are monitored. To work around this, a reference electrode was installed on the electronics pod with a cable running back to the pier. A second conductor from this cable was clamped to the cathode to independently check the cathode potential. Measurements conducted on July 1, 2013 showed the cathode in the range of 307-339 mV(Ag/AgCl) which is typical for a system that is not cathode limited. On the same day, we also used a diver-held probe to evaluate the potential on individual anode panels. The probe (Fig. 12) consisted of a short piece of titanium wire bent with a stopper loop, a coil of wire that is too large to penetrate the fabric, about 1 inch above the tip so the diver could push the probe into the fabric and then it would stop on the loop and make electrical contact with the anode. The anode potentials were then measured against the reference electrode. The results are shown in Fig. 13 for the shallow anode. An attempt was made to probe the deep anode, but the results were more ambiguous because it is buried beneath the shallow anode and difficult for the diver to accurately probe.


Fig. 12. BMFC module probe.

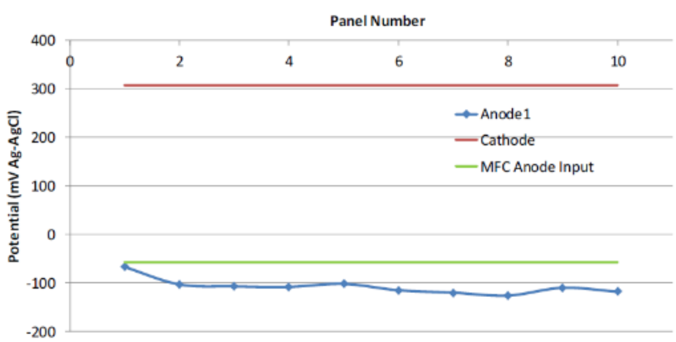


Fig. 13. Shallow anode module voltages vs. Ag/AgCl Reference electrode.

The results show that the first panel (Panel 1) had a relatively high potential, and the remaining panels all had lower potentials. The difference ranged from about 40-60 mV. These results suggest that Panels 2-9 are subject to a voltage drop that is likely associated with higher resistance in the connections to these anodes. The main difference between the connections in Panel 1 and the other panels was that Panel 1 was clamped directly to the aluminum bus bar at the anode termination, while the remaining panels were all connected through the flat wires and the titanium feed wires. The primary source of this voltage drop is likely due to the connection between the titanium feed wires and the copper flat wire. These connections were difficult to establish and seem to be the most likely source of high resistance. This high resistance impacts power in two ways, first through IR losses, and secondly by forcing the anode to operate at a non-optimal potential.

## IV. CONCLUSION

Previous work showed that large surface area BMFC power did not scale linearly with anode surface area. Internal resistance and cathode limitations were identified as key factors in diminishing the expected power output. To overcome these challenges, laboratory experiments showed that: 1. 1m$^2$ anodes provide a good balance between power output and ease of integrating into a larger BMFC system; 2. independent anode modules may be connected together and maintain their power densities; 3. anode modules may be separated by 2-3cm and maintain their power densities; 4. 1:1 anode to cathode surface areas prevent a BMFC from becoming cathode limited.

A diver-less BMFC deployment sled was designed and field tested in San Diego Bay to deploy a BMFC with two 10m$^2$ modular anodes, separated by 5cm. The BMFC produced 250mW of continuous power; the BMFC successfully powered environmental sensors and acoustically transmitted the data via an acoustic modem. Future improvements to the system include further reducing internal resistance and developing multi-channel harvesting systems for the modular anodes.

## ACKNOWLEDGMENT

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