Anode Design and Analysis for an Undersea Cabled Observatory with a Seawater Ground

Donna M. Kocak[1], dkocak@harris.com
Howard Painter[2], hpainter@dti-subsea.com
Glenn Anderson[1], gander01@harris.com

[1]HARRIS CapRock Communications
1025 West NASA Boulevard
Melbourne, FL USA
www.HARRIS.com

[2]Dyna Technologies Inc.
1670 Tropical Park Drive
Sanford, FL USA
www.dti-subsea.com

***Abstract* — Providing power to the seafloor to operate sensors and equipment reliably for long-term use requires a well thought out power return system as there are numerous obstacles in the harsh undersea environment. Cabled observatories typically employ commercial-off-the-shelf (COTS) telecommunications cables that contain optical fibers and a single power conductor, where the return path utilizes a seawater ground anode at the other end of the cable rather than a second (ground) conductor. Dissolution of the anode substrate, stray current effects, resistance, and hydrogen and chlorine concentrations must all be carefully considered in the design otherwise insurmountable problems can result and the life of the observatory can be shortened. For example, hydrogen can cause an increase in the attenuation of silica-based optical fibers and can degrade the performance of certain electronic components over time. These consequences result in costly cable and equipment replacement.**

This paper describes the design of an anode recently deployed on an undersea observatory in nearly 2400 meters of seawater, and includes discussions of the mechanical analysis, tipping moment calculations, skid design, rigging and redundancy. The life of the anode is expected to exceed 20 years, which makes this a practical solution for long-term offshore energy applications. In addition to the design, analysis is presented that assisted in optimal selection of the final design parameters. The minimum physical size of the electrodes, anode frame material, distance from the anode to the cable termination and physical positioning (i.e. buried or not buried in seabed sediments) of the anode and cathode are some examples of these parameters. This analysis considers potentials between the anode and cathodes, stray current effects from sea electrodes, chlorine concentrations in the vicinity of the anode, hydrogen concentration in the vicinity of the cathode, and the effects of hydrogen evolution at a platinized titanium cathode. Results from the design and analysis were taken into account in electrical models and simulations. This allowed careful examination of the transmission of DC power through the telecommunications cable and posing (and answering) "what if" questions that might arise to minimize potential problems during operation. Cabled observatories present the inherent challenge that complete system testing is normally impossible as key elements, such as the telecommunications cable, are only integrated at deployment. Even had the cable been available for integration testing, its reactive properties are different deployed than at a test facility. The potential cost implications of such an unexpected interaction post deployment could result in unrecoverable loss. Finally, techniques used to install and operate the anode on the ocean observatory are presented along with actual footage from the deployment. Current and voltage drop measurements taken during deployment were in good agreement with those predicted from our analysis and simulations, which help to validate this design and analysis process. Taking a thorough systems engineering approach from the start of this small but critical piece of the cabled observatory more than justifies the investment when the system performs and operates as expected.

***Keywords* — seawater ground, electrodes, anode, cathode, cathodic protection, cabled observatory, ocean observatory, undersea network, offshore communications backbone**

I. INTRODUCTION

CSnet's Offshore Communications Backbone (OCB) is a hybrid buoy/cabled observatory that was deployed last fall (2010) as a Tsunami Warning and Early Response system of Cyprus (TWERC) [1]. The system was designed for up to 3,000 meters water depth and a minimum 10-year service life. The initial sensors support tsunami and seismic detection, but there is good potential for connecting other sensors to observe environmental parameters and control/monitor subsea equipment as energy exploration expands into this region [2]. The baseline configuration in Figure 1 depicts a surface buoy (based on the HARRIS OceanNET™ design [3]) connected to a seafloor array of nodes via a single point mooring riser cable, anchor, anchor interface and backbone cable. The seafloor array system requires DC power to be distributed to seafloor nodes via cathodes and a common anode located at each node, which results in a parallel power feed arrangement.

The OCB power system employs a seawater return for delivering DC (direct current) voltage from the surface communications buoy to the seafloor nodes and sensors. The buoy provides up to 5kW of power to the seafloor from on-board generators and 3Mbps communications to and from the seafloor via a satellite link. Power and data are transmitted

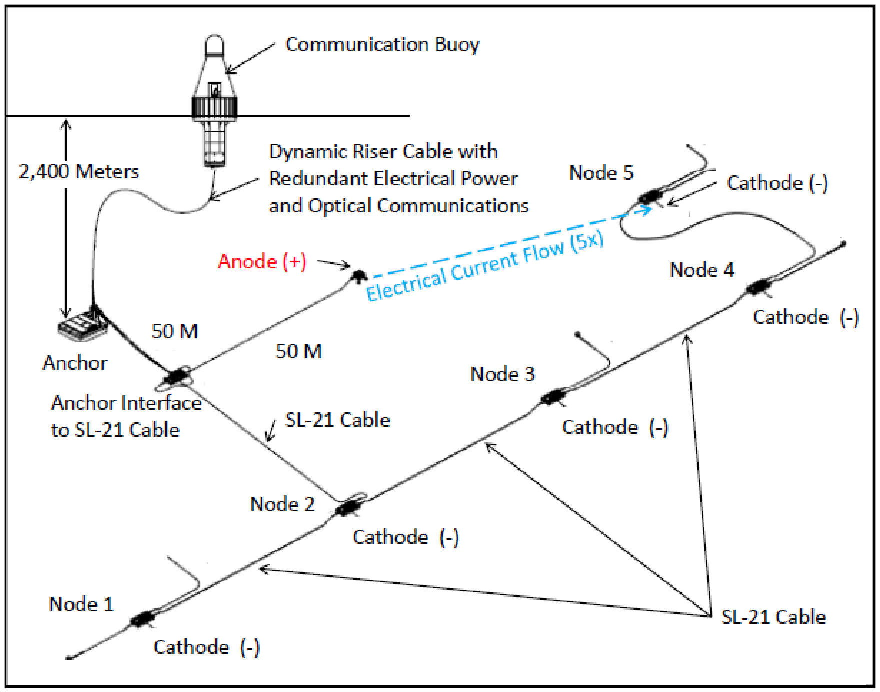


Figure 1. TWERC OCB seafloor baseline configuration

over redundant conductor pairs and fiber optics, respectively, through the mooring riser cable connected to the anchor. From the anchor, data and power take redundant paths to the anchor interface, where the voltage is combined into a single conductor and merged onto the backbone cable along with the fiber optics. The anchor interface also provides connection to dual (redundant) anodes for the seawater return. Cathodes located at the nodes provide the electrical conductivity between the internal node circuitry and the seawater.

The use of a seawater return eliminates the need for a second conductor, which reduces the backbone cable weight, cost and size. This design makes use of commercial-off-the-shelf (COTS) telecommunications cable that contains twelve optical fibers and a single power conductor. The conductive electrodes are arranged such that the voltage along the backbone and at each node is negative with respect to the electrodes connected to the anchor interface. Thus, the electrodes at the seafloor nodes function as cathodes while the electrodes near the anchor interface function as anodes. This return system contains many redundant features that make it a robust design expected to last a minimum of twenty years.

This paper describes the design of the OCB TWERC anode for the seawater return. Section II describes the mechanical design and the analysis that drove our selection of specific parameters. This analysis considered potentials between the anode and cathodes, stray current effects from sea electrodes, chlorine concentrations in the vicinity of the anode, hydrogen concentration in the vicinity of the cathode, and the effects of hydrogen evolution at a platinized titanium cathode. Final design specifications were considered in finite element models and electrical models/simulations presented in Section III. This allowed careful examination of the transmission of DC power through the telecommunications cable and posing (and answering) "what if" questions that might arise to minimize potential problems during operation [4]. Finally, Section IV describes considerations and methods used to deploy the anode on the OCB TWERC. Although this discussion is focused on the OCB, the analysis, considerations and methods presented herein are applicable to any cabled ocean observatory employing a seawater return system.

II. Design and Analysis

A. Anode

The anode provides the positive seawater return path via two platinized titanium rods. We chose a dual anode design that provides redundant conductor paths from the buoy, through the riser cable and into the anchor interface to minimize impact to the system should a failure occur in one of the paths. The two conductors are diode "ORed" into a single conductor on the backbone cable at the anchor interface.

Platinized titanium electrodes were chosen for both the anode and cathodes due to platinum's high conductivity and low consumption rate (~8-16 mg/year/Amp). Platinum anodes are usually produced by electroplating a thin layer of platinum over a corrosion resistant substrate such as titanium, niobium or tantalum, which all form an insulation oxide film under anodic conditions. To avoid dissolution of the titanium at un-platinized locations on the anode surface, the operating voltage of the anode must be less than the anodic breakdown potential of titanium, which is in the range of 9 to 9.5 V in the presence of chlorides (seawater). Therefore, the maximum operating voltage of a platinized titanium anode is usually limited to ~ 8V. In the OCB TWERC implementation, the maximum anode current is 4.6A; thus, the electrode resistance to the surrounding medium must be less than or equal to 1.74 ohms to avoid dissolution. The physical size of the electrode required to provide a resistance less than 1.74 ohms depends on the resistivity of the medium surrounding the anode. Therefore, various electrode sizes (diameter vs. length) have been considered for anodes residing in free seawater and buried within seabed sediments (worst case) and the results are summarized in Figure 2 and Table 1. In the plots, the red dashed line represents the resistivity limit (1.74 ohms).

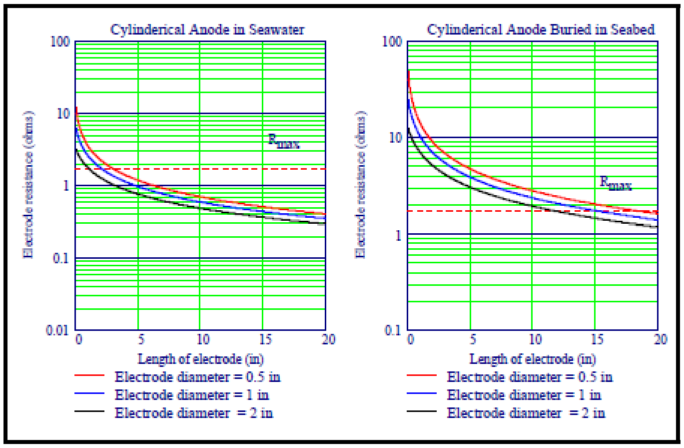


Figure 2. Electrode resistance for diameter anodes vs. length anode

To ensure that the maximum electrode potential cannot be exceeded, it is prudent to select the electrode dimensions for the worst-case scenario where the anode is buried in seabed sediment. For a standard diameter of 1 inch (25 mm) and a current of 4.6A, the anode must have a minimum length of 14.8 inches to maintain the electrode potential below 8V. For our design, we selected a 1 inch diameter by 18 inch long platinized titanium anode with 10 µm platinum thickness [5]. The performance parameters are shown in

Table 2.

If both the anode and cathode are identical, then the resistance between the electrodes will be ~3 ohm with the electrode buried in the seabed and ~0.75 ohm with the electrodes surrounded by seawater. These resistances are consistent with long haul submarine telecom systems, where the power feed return resistance is required to be < 5 ohms for return currents of ~2A.

Table 1. Cylindrical anode requirements where anode current = 4.6A

Electrode dia (in)	Anode Surrounded by Seawater		Anode Buried in Sediment	
	Min Length (in)	Max Current Density (Am^{-2})	Min Length (in)	Max Current Density (Am^{-2})
0.5	2.9	1522	17.9	252
1	2.0	1025	14.8	151
2	1.0	770	11.4	95

Table 2. Performance summary for a cylindrical Pt/Ti anode

Parameter	Value	Unit
Anode material	Platinized Titanium	-
Platinum thickness	10	µm
Outside diameter	1	inch
Electrode length	18	inch
Max anode current	4.6	A
Electrode resistance	1.49 (buried) 0.37 (non-buried)	ohm
Electrode potential at max current	6.9 (buried) 1.7 (non-buried)	V
Max current density at max current	125	Am^{-2}
Electrode life at max current	>20	years

With reference to the system configuration, the maximum sea return resistance expected (~ 3 ohms) is equivalent to only ~4 km of SL-21 telecommunications cable (0.75 ohm/km), or ~270m of the dynamic riser cable (11 ohm/km).

In our design, the two anodes are mounted on a frame approximately 24 inches above the seafloor and any potential build-up of sediment (assuming max of 2 inches per year over the service life or 1 inch per year over the minimum design life) to ensure they are only exposed to seawater. This was done to maintain an electrode resistance of less than 1 ohm as well as to minimize the chlorine concentration. Chlorine gas is generated at the anode due to the conventional current (or positive ions) leaving the surface and entering the electrolyte. The chlorine gas is quickly converted to aqueous chlorine in seawater. Analysis of the chlorine generation [6] determined that surrounding the anode with seawater combined with the presence of low seabed water currents maintains the chlorine concentration very low (< 0.007 cc/cc). Although this concentration is low, the anode assembly and, particularly, any polymers and elastomers contained therein must be resistant to attack by chlorine. We conservatively selected materials based on compatibility testing using sodium hypochlorite (bleach). Household bleach is typically a ~5% sodium hypochlorite solution in water, which yields a chlorine content of 25% by weight.

Next we considered the effects of chlorine and stray current corrosion, and confirmed adequate cable distance from the anode to the termination [7]. Stray current corrosion occurs when an object is placed in the sea near the anode. The surface of the object will attain the same potential as the sea and if the object is conductive a current will flow through the object from high to low potential locations. The point where current enters will be cathodically protected and hydrogen will result. The point where current exits the object can be conducive to corrosion of metals, which is shown schematically in Figure 3.

To minimize the stray current flowing in conductive elements surrounding the anode, we have located the anode nearly 50 meters from the anchor interface using a non-metallic, oil-filled hose assembly to make the connections. The potential at this distance is estimated to be ~7 mV, thus the stray currents induced through the anchor interface will be very small and corrosion is not expected. In addition, the anode frame is fabricated using titanium and non-metallic materials such as polymers, composites and reinforced marine concrete. This will provide mounting that is inherently immune from stray current corrosion.

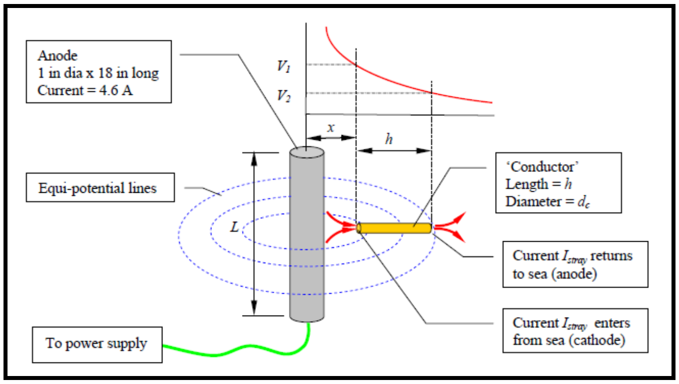


Figure 3. Stray current corrosion of a conductive object near the anode

Hydrogen will be produced at the sea cathodes located in proximity to the subsea node housings. One concern is that hydrogen can cause an increase in the attenuation of optical fibers and degrade the performance of certain electronic components over time. The return current is carried by ionic conduction though the sea and the transition of current from metallic to ionic conduction takes place on the anodes and cathodes via electrochemical reactions. The reaction on the cathode is a buildup of calcareous deposits, which can increase resistance of the cathode to the sea and the current density on the cathode surface [8]. However, based on our analysis using a 4-inch square platinized titanium plate cathode, an expected maximum cathode current of 2.1 A and stagnant water conditions, hydrogen will not diffuse further than ~6m from the cathode over a 15-year period (see Figure 4) [9]. Assuming a seabed current of 1 cm/sec, the maximum hydrogen partial pressure in the seawater flowing over the cathode will be ~0.3 atm. In practice, the flow is unlikely to be laminar and may carry hydrogen away from the node rather than toward it leading to negligible hydrogen levels around the node housings. Nevertheless, this worst-case pressure may be used to determine the maximum hydrogen concentration within the node housings over the service life.

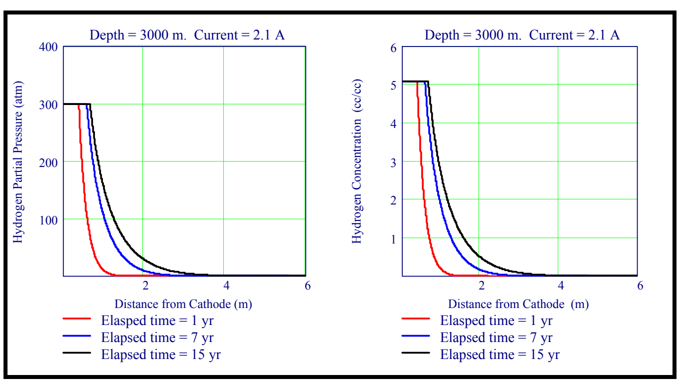


Figure 4. Hydrogen partial pressure and concentration vs. distance from cathode

Based on the above analysis, the anode specifications are shown in Table 1 and the actual anodes are shown in Figure 5.

Table 3. Anode specifications based on analysis

Material	Platinized Titanium, CP Grade 2
Diameter	25 mm (1-inch)
Length	450 mm (18-inches)
Platinum Thickness	200-300 micro inches
Electrode Resistance	1.49 ohms (buried) 0.37 ohms (non-buried)
Electrode potential at max current	6.9 V (buried) 1.7 V (non-buried)
Max current density at max current	125 Amps/m^2
Electrode life @ max current	>10 years


Figure 5. Anodes

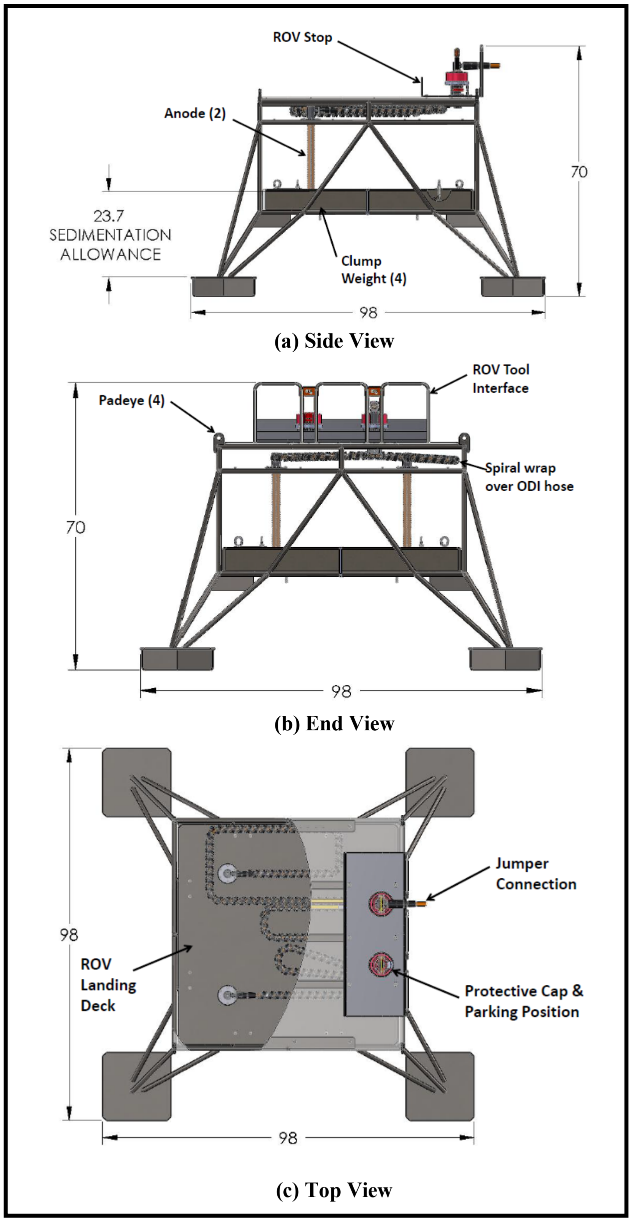
B. Anode Skid

A specialized frame was designed to hold the anodes based on the above analysis and the requirements that it must provide a stable platform for a remotely operated vehicle (ROV), allow for easy connect/disconnect of the wet mate connectors (WMCs), and be easily deployed. The final design is depicted in Figure 6 (a-c).

The skid is predominantly a welded Titanium Grade 2 tubular assembly with a marine concrete clump weight and has an approximate weight of 1400 lbs in air (850 lbs in water). The ROV landing deck is high density polyethylene. The ROV stop, tooling interface and connector mounting are based on an existing design successfully deployed on the anchor assembly. The clump weight is attached to the assembly using titanium bolts. The anode ROV connector was developed based on proven geometry employed on the anchor shown in Figure 7; however, the anode ROV connection has a higher stiffness for better performance. Four padeyes located on each corner of the skid are used during deployment.

A tipping moment calculation determined that inclining the skid at 10 degrees reduces the force required at the ROV interface (approximately 69 inches above the seabed) from about 604 to about 542 lbs or 10.3%. The overturning moment is 3,117 ft-lbs.

Other analyses considered for this design included finite element modeling of the skid and connector assemblies (presented in the next section), load cases, and resonances and frequencies during road and shipboard transportation.



(a) Side View

(b) End View

(c) Top View

Figure 6a-c. Anode assembly drawing (units in inches)

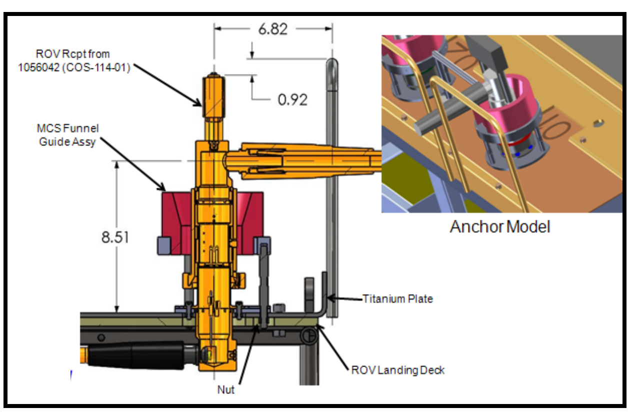


Figure 7. Anode skid assembly and details of ROV connector mount

III. MODELING

A. Mechanical

A finite element model (FEM) of the skid assembly has been created based on a parasolid geometry file. Several load cases were analyzed to ensure safe lifting and general handling, support of ROV landing, no buckling under operational loadings, and no damage due to ground transportation (per MIL-STD-810g) and shipboard vibration (per MIL-STD-167-1A). Stresses were analyzed in the tubular frame, lift lugs, all plate elements, ROV deck, baffle plates and marine concrete clump weight. A separate detailed analysis was performed for the ROV connector assembly with the model shown in Figure 8. For this analysis, we assumed a worst case scenario of 250 lbs at 30 degree angle of attack (the design load for upper deck) for the ROV landing. The ROV connector mate/demate load force is 100 lbs maximum. The load application point and the angle of applied load is not clearly defined, so we assumed a 100 lb load is applied 1 inch above the top of the male connector, in each of the axes individually. The lateral loads are probably conservative but this will give a good indication of the stress levels for a 10 lb load. The initial analysis did not include contact between the plates. Based on this conservative analysis and including a safety factor of 2.5, the minimum margin of safety is 2.4 in the split titanium plate. Results are shown in Figure 9.

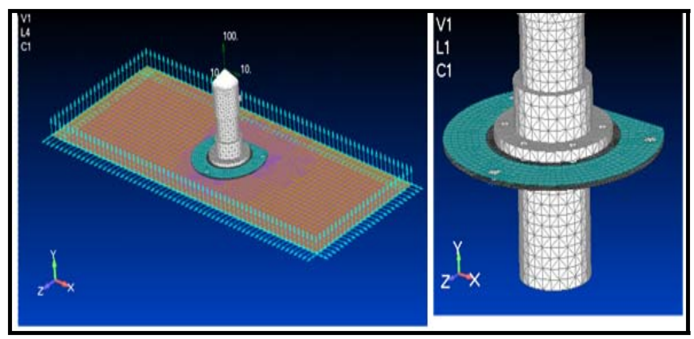


Figure 8. Anode connector assembly FEA model

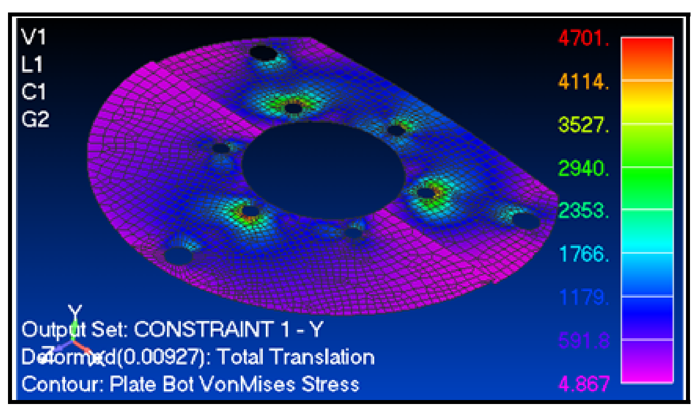


Figure 9. Split Ti plates FEA results for conservative combined 10 lb X 100 lb Y 10 lb Z case

(Stresses are 7.34 Ksi; the 100 lb Y load stress is 4.7 Ksi resulting in 2.40 M.S.)

B. Electrical

Results from the analysis were taken into account in our electrical models and simulations to allow for careful examination of the transmission of DC power through the telecommunications cable. For example, the anode length and diameter are 18 and 1 inch respectively, and the resistance of this electrode to the sea as a function of radial distance from the electrode is shown in Figure 10 [10].

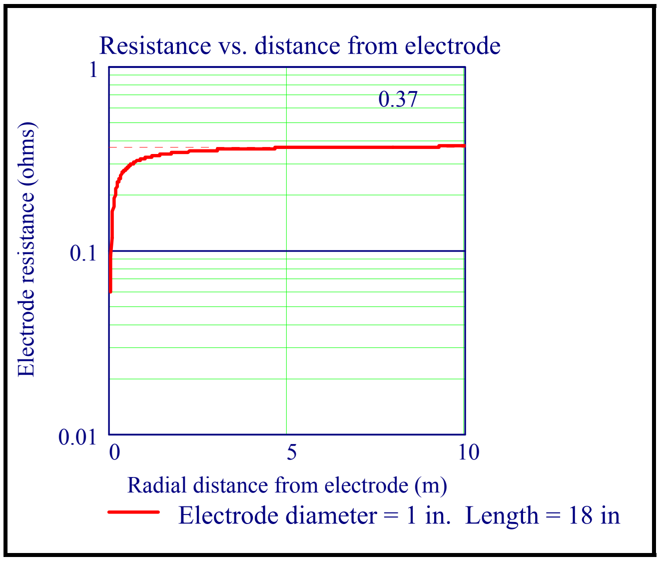


Figure 10. Electrode resistance vs. distance from cylindrical electrode

From the figure it is apparent that beyond ~6m from the anode the resistance becomes a constant ~0.37 ohms. Similarly, beyond ~6m from the present plate cathodes, the cathode resistance to the sea becomes ~0.46 ohms. Equivalent circuits for the parallel power feed (neglecting the internal resistance of the nodes) are shown in Figure 11, with the system being powered by a constant current of 4.6 A. The resistance between points *A* and *B* (anode to cathode) for the single node (node 2, left circuit) is 0.83 ohms, which equates to a potential difference between the anode and cathode of ~ 3.8 V for a current of 4.6 A. With two nodes powered (nodes 2 and 3, right circuit), the resistance between points *B* and *C* is 0.453 ohms. The total current passing through this parallel network resistance is 4.6 A, which gives a voltage drop across the network (i.e. between *B* and *C*) of 2.085 V. Therefore, the current passing from *C* to *B* (i.e. through $R_{Cathode}$) is 4.532 A and the current passing from *C* to *D* is 0.068 A. If the power feed arrangement has been interpreted correctly, it is not expected that current will flow from one cathode to another via the sea.

Additional electrical models of the system, presented in [4], were created in PSpice that allowed us to pose (and answer) "what if" questions related to potential problems that might arise during operation. Actual current and voltage measurements were taken after each node was deployed and were in good agreement with our predicted analysis and simulation results, which helps to validate this design and analysis process.

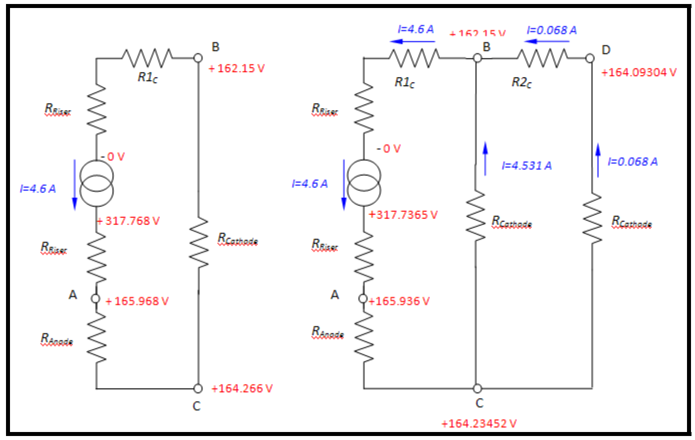


Figure 11. Equivalent circuit for parallel power feed of nodes 2 and 3 only
(Left: One node; Right: Two nodes)

IV. DEPLOYMENT

The anode assembly was deployed to the seafloor by a lift line with an acoustic release and beacon shown in Figure 12. Four synthetic slings held the skid through the padeyes using ROV-friendly shackles, with the contingency that three of the slings could fail. Our hydrodynamic drag calculation estimated an overturning moment of 158 ft-lbs, or about 5% of that required to turn the skid. The anode was monitored for set down by the ROV to ensure placement within 50 meters in of the anchor interface assembly.

Figure 12. Anode assembly during deployment

Once the anode was set down, the ROV swam the pressure balanced oil filled (PBOF) cable from the anchor interface to the anode without putting tension on the cable. A special mating tool shown in Figure 13 was used by the ROV to insert the electrical Nautilus WMC into the anode connector. Figure 14 shows the OCB TWERC anode deployed on the seafloor.

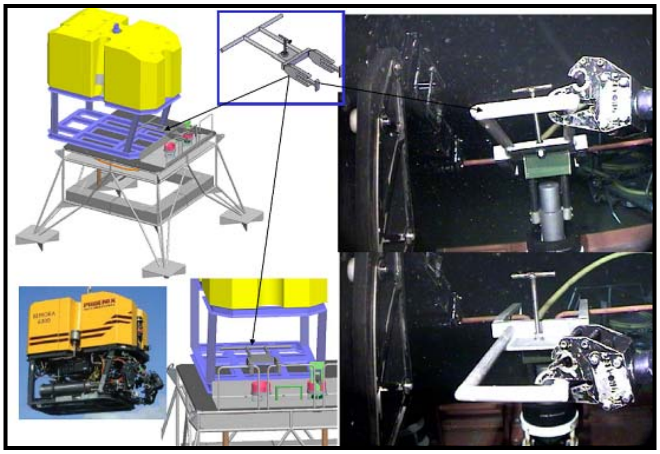


Figure 13. Anode connector ROV mating tool

Figure 14. Anode deployed on the seafloor at a depth of 2380 meters offshore Cyprus

V. CONCLUSIONS

The analysis presented herein assisted in optimal selection of the final design parameters of the anode seawater ground return system. For example, we considered the minimum physical size of the electrodes, anode frame material, distance from the anode to the cable termination, and physical positioning – buried or not buried in seabed sediments. All of these factors are critical to avoiding problems such as dissolution of the titanium substrate, corrosion of metallic bodies near the electrodes, stray currents effects, effects of hydrogen evolution at the cathode, etc. By taking a thorough systems engineering approach from the start of this small but critical piece of the observatory, we feel more confident that the system will perform as expected over its long service life. Though the additional upfront investment of this analysis adds to the total life cycle cost, the return will be more than justified when the system performs and operates as expected.

ACKNOWLEDGMENT

The authors are grateful to CSnet International Inc. and the Cyprus Oceanography Centre in Nicosia for supporting the development and coordinating the implementation of OCB TWERC, respectively. Special thanks and acknowledgement go to Richard Jones of ENS Consulting LLC who performed the analytical studies and from whose reports many of the figures and material for this paper were derived.

REFERENCES

[1] A.M. Clark and D.M. Kocak, "Installing Undersea Networks and Ocean Observatories: The CSnet Offshore Communications Backbone (OCB)", Proc. MTS/IEEE OCEANS 2011 Conference, Kona, HI, September 2011.

[2] A.M. Clark, "CSnet's Offshore Communications Backbone in Cyprus", Touch Briefinings,Exploration & Production, 9(1), pp. 4, 2010.

[3] A.M. Clark, H. Sekino, "Development of a Long Term Ocean Observatory for the Sea of Japan", Proc. MTS/IEEE OCEANS 2001 Conference, Honolulu, HI, November 2001.

[4] A.M. Clark, D.M. Kocak, K. Martindale, A. Woodroofe, "Numerical Modeling and Hardware-in-the-Loop Simulation of Undersea Networks, Ocean Observatories and Offshore Communications Backbones", Proc. MTS/IEEE OCEANS 2009 Conference, Biloxi, MS, October 2009.

[5] R.K. Jones, "Design Study for the Anode of an Array Sea Earth Return", Report No. DTI-118-2009 Rev A, pp. 18, April 13, 2009.

[6] R.K. Jones, "Chlorine Concentration in the Vicinity of the Anode of a Power Feed Return", Report No. DTI-119-2009 Rev A, pp. 15, May 3, 2009.

[7] R.K. Jones, "Stray Current Effects from Sea Electrodes", Report No. DTI-120-2009 Rev A, pp. 15, June 12, 2009.

[8] R.K. Jones, "Hydrogen Concentration in the Vicinity of the Cathode of a Power Feed Return", Report No. DTI-121-2009 Rev A, pp. 18, June 30, 2009.

[9] R.K. Jones, "Effects of Hydrogen Evolution at a Platinized Titanium Cathode", Report No. DTI-126-2009 Rev A, pp. 25, November 30, 2009.

[10] R.K. Jones, "Potentials between the Anodes and Cathodes of Node Assemblies", Memorandum, pp. 5, August 5, 2009.