Numerical Modeling and Hardware-in-the-Loop Simulation of Undersea Networks, Ocean Observatories and Offshore Communications Backbones

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Abstract – This paper discusses the importance of taking a systems engineering approach when designing undersea networks, ocean observatories and offshore communications backbones. A design that utilizes modular components and systems, and places diligence in modeling and testing communications, power and data bandwidth requirements is essential for sustained operation and economic feasibility. An example is the modular seafloor communications network described – CSnet’s Offshore Communications Backbone (OCB). The systems engineering approach that shaped OCB’s design, the modeling, simulation, testing as well as data collected during the test and development phases is presented. Subsea networks 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. To mitigate these risks, a rigorous systems engineering approach must be adopted that includes system level studies, analysis and theoretical, numerical and physical models of key areas such as power distribution and communications. The OCB seafloor element consists of both submarine cabling and multiple nodes. The nodes are modularly designed; independent of location and position. The network is redundant and expandable to accommodate additional nodes and buoys. Discussed is the theoretical analysis performed of the system architecture to determine the optimal selection of fiber type and network equipment to ensure robust and reliable communications. Also described is the thorough optical budget analysis conducted taking into account optical link loss, dispersion and optical signal-to-noise (OSNR). Computer simulation and Hardware-in-the-Loop Simulation (HILS) testbeds using the actual hardware being considered in the nodes were employed to validate the theoretical findings. Ethernet benchmark tests were performed to analyze throughput, back-to-back testing, latency and frame loss in the network. Attenuators as well as full scale network fiber lengths measuring hundreds of kilometers were used to test and evaluate multiple fiber types. Results are presented of the power system analysis and transient study utilizing computer models, critical in determining “worst case” voltage and current transients. By using an accurate representation of the cable parameters and system variables, an optimal design of the medium voltage converter (MVC) and high voltage power supply (HVPS) is achieved. Protective measures intended to prevent single point failures, particularly those that may short the backbone cable and bring down the entire network, are evaluated. Physical cable modeling and seawater return analysis were included in the analysis and simulations. Instrument loading (power and data bandwidth) in a hierarchy of combinations intended to simulate the range of possible user applications were simulated to ensure the network’s robustness through future expansions. Although the capital expenditure (CAPEX) associated with the rigorous process described of this initial design is significant, the potential cost avoidance and savings over the deployment and operation of both the initial and future network’s operational expenditure (OPEX) more than justifies this investment.
I. INTRODUCTION

Both scientific seafloor observatories and industrial submarine communications networks have become increasingly prevalent over the past several years [1, 2]. Considerable experience and expertise with these systems has now been amassed in both communities and opportunities to both share that knowledge as well as combine efforts on joint projects also continue to emerge [3-6]. CSnet International, Inc (CSnet) is capitalizing on this body of knowledge and experience to develop a carefully engineered and rigorously tested modular and expandable system, the Offshore Communication Backbone (OCB), capable of being readily deployed to support either scientific or industrial applications – or both. To undertake this, a strategic alliance has formed a team comprised of the designers, developers and operators of some of the largest and most complex seafloor communication systems operating today [7-11]. Figure 1 depicts the OCB concept of individual network elements (each may cover hundreds of sq-km of seafloor) that can be linked together in virtually any configuration. Power and communications may be supported by a high bandwidth moored surface buoy, offshore platforms or shore-ended cables.

This paper discusses the importance of taking a systems engineering approach to designing undersea networks, ocean observatories and offshore communications backbones so that their overall objectives can be met. A design that utilizes modular components and systems, and places diligence in modeling and testing communications, power and data bandwidth requirements is essential for sustained operation and economic feasibility. Subsea networks 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. To mitigate these risks, a rigorous system engineering approach must be adopted that includes system level studies, analysis and both theoretical and physical models of key areas such as power distribution and communications. With decades of experience designing, deploying and now operating some of the world’s most complex seafloor communication networks, both for science and industrial applications, The OCB development team has encountered myriad examples where an early investment in system design and modeling either did – or could have – resulted in a more robust and reliable system with ultimate savings in time and cost. A plethora of experience with seafloor observatories has been gained through existing cabled observatory projects. Over the course of these initiatives, the benefits of disciplined systems engineering and testing were repeatedly realized. A few recent cases encountered by members of the OCB development team that illustrate this are provided here.

A. Lessons Learned: Example of catching a system issue during design – over voltage transients on long cables

An example of the importance of simulation and test verification occurred during a recent observatory design where power was to be delivered over long cables to an instrument interface. Requirements for a specific interface focused primarily on its operational voltage range, leaving other factors to be defined during the design phase. While operation requirements were defined including its ability to operate at the end of extension cables up to 10km in length and to switch loads of up to 6kW at
400V, limiting attention solely at the component level would have been insufficient to uncover larger system issues. Only when stepping back from the component level to consider the entire system did important interactions between the various requirements become apparent. In particular, an overall system view revealed that rapid current changes due to switching a load on or off at the end of a 10km cable might surface. To better understand these interactions, the source, extension cable, and instrument interface load switches and loads where simulated [12]. A simulation of a load change is shown in Figure 2 when a 3kW load was suddenly removed from the instrument interface, for example if a breaker were to trip or turn off. Due to the tight band between the maximum working voltage of the instrument interface (400VDC) and the maximum safe working voltage of the internal electronics (425VDC), passive voltage suppression was not suitable. Instead an active over voltage protection (OVP) circuit was developed, based on a linear regulator, to dissipate voltage transients up to 1200VDC. To confirm the design prior to final build and deployment, a physical cable simulator was built using discrete LCR components to mimic the characteristics of the extension cable. These tests showed results in excess of the simulation, but due to suitable design margins, the system performed as expected and the OVP protected the internal electronics during all load changes. Without stepping back to look beyond the immediate set of requirements, this problem – gone unchecked – may have limited the operation of the system.

![Figure 2. Simulation of 3kW load removal.](image)

**B. Lessons learned: Example of missing a system issue during design – ground faults**

In another recent example, power was supplied to each of several sensors on an instrument interface via an isolated DC-DC converter. In order to detect the first fault to ground in any instrument port’s power supply, a monitor circuit provided a high impedance reference to seawater. In this specific example, the reference point was set via the pressure vessel and the reference current was limited to a few micro amps. Any material loss attributable to a potential ground fault was expected to be negligible as it was assumed that any instrument that experienced a ground fault would be turned off upon this discovery, in order to prevent further damage. However, during early field trials, it became apparent that many instruments were exhibiting inherent ground faults. The reluctance to halt collection of scientific data led to continuation of operations on these ports with ground faults for a period a six months. This resulted in subsequent material loss from a penetrator fitting comprised of a material slightly less noble than the pressure vessel. The pressure vessel itself was never at risk of being compromised, nonetheless, the ground fault circuit was subsequently modified to reference detection to a dedicated anode. This modification was intended to restrict the area where any future material loss might occur. This is another example that highlights the importance of thoroughly considering how all elements of a system will interact together during their long term operation. It also indicates that not all potential problems will necessarily be revealed through modeling or simulation and that there remains an irreplaceable benefit to in-water testing prior to final deployment.

**II. THE OCB ARCHITECTURE**

Figure 1 depicted how several OCB modular network elements may be linked together in order to cover a greater spatial area. In the following example, power and communications are being supported by an Ocean Net® buoy [13] though the same configuration could alternatively be supported by a shore-ended cable. Figure 3 provides a simple block diagram of one of these modular network elements, consisting of a surface buoy, a buoy riser (mooring/power and communications) cable, anchor, anchor interface, four nodes and seafloor cable. Power is provided from the surface buoy to the seafloor nodes via copper conductors in the riser cable that merge into a single conductor at the seafloor backbone cable, with positive polarity seawater return path. Each node has three connection points. Any one of these may be used to expand the seafloor backbone cable (to another node) or to return to a surface platform or shore. Unused connection points are typically outfitted with a length of cable with loop-back (“expansion stub”) of sufficient length that it can be retrieved to the surface for future expansion of the network.
“Skip Node” Architecture

A schematic of one unique feature of the OCB fiber optic communications network is depicted in Figure 4. This feature is designed to provide redundant communication paths to each node such that failure of one or more non-adjacent nodes will not prohibit data from the other functioning nodes to reach shore. We have dubbed this architecture “Skip Node”. In the simple example shown, nodes 1 and 3 can fail, or nodes 2 and 4 can fail, and data transmission from the other functioning nodes will continue unimpeded. In Figure 4, node 3 is highlighted in red to depict a failure and is therefore in the “skipped” state.

Each path in the figure represents a fiber pair for transmit (Tx) and receive (Rx) signals. The green fiber paths represent the active path of data transmission in this failed state; the blue fiber paths are inactive. When failure occurs in a node path, the optical equipment within the “skipped node” is circumvented by the Rapid Spanning Tree protocol (IEEE 802.1w) to allow data to pass through the stub path. A node path designates a fiber optic connection between two nodes over some distance. A stub path designates a cable “expansion stub” typically deployed terminated with a loopback connector. In order for the Skip Node architecture to work, the sum of the cable distances connecting three adjacent nodes, together with 2 times the stub path length (as it is looped back) of the center (“skipped”) node, combined with all the losses incurred by connectors, splices etc. must be less than the link budget of the optical equipment. In this example, the backbone segment distances are B1, B2 and B3 as indicated in Figure 3. The stub distance shown is S, and is typically at least 2.5 times the water depth, enabling it to be retrieved to a vessel at the surface for future retermination. Thus, the Skip Node path length is the sum of the distance from the first node to the skip node (B2), plus the distance out and back through the loop of the stub path (2 x S), plus the distance from the skipped node to the third node (B3). Skip paths are used only as backup paths when a backbone segment or center node fails. The fiber paths with arrows at either end of the figure simply indicate continuation of the network.
III. MODELING, SIMULATION AND TEST VERIFICATION

A. Optical

Proper selection of the fiber and other optical components is critical to ensure maximization of communication step-out distances and speeds, and minimize system latencies and bit error rates (BERs). By analyzing optical characteristics for a given configuration, suitable network switches, transceivers, fiber optics and connectors can be selected to optimize the system. Among the optical parameters that were numerically modeled and tested for the OCB were: optical power losses, dispersion and optical signal to noise (OSNR).

Optical Power Losses

Optical loss in a fiber optic link occurs primarily due to connector losses, splice quality, fiber attenuation and any devices connected to the fiber. The optical link budget for each network path (link) in Figure 3 was computed using four different fiber types to identify the optimal candidate. All analyses were based on single-mode fiber at a wavelength of 1550 nm and maximum data rate of 1 Gbps. A system margin of 3 dB was used to account for unforeseen factors such as temperature extremes, cable bends, aging, etc. [14]. Thus, the total link loss must be within the optical equipment’s link budget plus the system margin. Conservative estimates levied for fusion splices (0.1 dB), mechanical joints (0.7 dB) and wet mate connections (0.75 dB) in the nodes ensured additional margin. Table I provides results for a fiber type with cable attenuation of 0.210 dB/km and a suite of optical equipment with a combined link budget of 30 dB. Note that each link margin listed in the table is greater than +3 dB (the system margin). The maximum link distance of this example is 95 km still yielding +5.1 dB margin. The theoretical maximum length (to reach the 3 dB system margin limit) that includes all losses within the nodes would be 105 km (“Lmax” in our Figure 3 example).

<table>
<thead>
<tr>
<th>Link</th>
<th>Distance (km)</th>
<th>Attenuation (dB)</th>
<th>Margin (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node Path (B1, B2, B3)</td>
<td>40</td>
<td>-11.90</td>
<td>+18.1</td>
</tr>
<tr>
<td>Expansion Stub (S)</td>
<td>7.5</td>
<td>-3.65</td>
<td>+26.4</td>
</tr>
<tr>
<td>Riser Cable (R)</td>
<td>3</td>
<td>-0.60</td>
<td>+29.4</td>
</tr>
<tr>
<td>Skip Node 3 Path (B2+B3+2S)</td>
<td>95</td>
<td>-24.95</td>
<td>+5.1</td>
</tr>
<tr>
<td>Buoy Path (R+S)</td>
<td>10.5</td>
<td>-9.13</td>
<td>+20.9</td>
</tr>
<tr>
<td>Buoy to Skip Path (R + S + B1)</td>
<td>50.5</td>
<td>-18.23</td>
<td>+11.8</td>
</tr>
<tr>
<td>Buoy to Skip Path (R + S + B2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test verification of the links was performed both to confirm published minimum fiber specifications and to compare to those computed in the numerical analysis above. These measurements were recorded over fiber bobbins of varying types and lengths using an Optical Time Domain Reflectometer (OTDR). In all cases, the measured attenuation was less than that published or predicted in the computations. Fusion splice losses were also lower – typically 0.02 to 0.04 dB rather than the 0.1 dB estimate carried in the optical link budget calculations.

Dispersion

Dispersion can contribute to optical signal impairment by introducing losses and, if it becomes too large and is not compensated for, also limiting bandwidth [15]. There are two types of dispersion: chromatic dispersion and Polarization Mode Dispersion (PMD). PMD increases approximately linearly as the data rate increases but is of little relevance at bit rates less than 10 Gbps [16]. However, the effect of chromatic dispersion is cumulative and increases linearly with the transmission distance but quadratically with the data rate. As a digital signal is transported over a long length of fiber, the signal quality degrades with distance due to dispersion. This degradation coincides with a decrease in receiver sensitivity, expressed in dB as a dispersion penalty. Typically, designers strive to keep the dispersion power penalty below 2 dB [17]. The dispersion power penalty (dB\(_D\)) is calculated as follows:

\[
dB_D = 10\log_{10}(1 + c \times ( F_R \times L \times \omega \times D_\lambda \times \pi / \ln(4) / 1000)^2).
\]

It is also important to limit the bit spreading, typically to less than 20%. Bit spreading and dispersion over the fiber length are computed as follows:

\[
\text{Dispersion} = D_\lambda \times \omega \times L
\]
\[
\text{Bit spreading} = \frac{\text{Dispersion} \times F_R}{10}.
\]

Plots of the dispersion penalty are shown in Figure 5. Only one of the fibers evaluated, the HDF-2 fiber, provided less than 2 dB dispersion penalty over fiber lengths greater than 65 km.
Dispersion was measured over two fiber types at various lengths. One example using 120.25 km of HDF-2 fiber is shown in Figure 6. The vertical line highlights values at 1550 nm where the measured dispersion was -2.67 ps/(nm*km), very nearly matching the -2.85 ps/(nm*km) published vendor specification. These measurements are key to ensuring a design that will not be dispersion limited.

Optical Signal to Noise (OSNR)
A minimum optical signal-to-noise ratio (OSNR) must be maintained to transmit a digital signal over a fiber link. OSNR decreases due to attenuation and dispersion in the fiber but the effect is generally small. Amplifiers, passive components, and signal encoding cause losses that affect the OSNR. OSNR is computed as follows:

\[
    OSNR = P_s(\lambda_1) - L - N_F - 10 \log_{10}[h\nu\Delta\nu/\lambda_1].
\]

\( P_s(\lambda_1) \) = output power per wavelength (dBm)  
\( L \) = span loss of the fiber between amplifiers (dB)  
\( N_F \) = amplifier noise figure (dB)  
\( N \) = number of amplifiers in a chain  
\( h \) = Planck’s constant  
\( \nu \) = optical frequency (Hz)  
\( \Delta\nu_0 \) = optical bandwidth detector (nm)

Computing OSNR is critical for an amplified system. While the current example is of an unamplified system, the OSNR was still considered and computed as the OCB is expandable. At a computed 51 dB, the OSNR is sufficient to provide a low BER. For comparison, an OSNR of 12 dB corresponds to a BER of \(10^{-9}\) and an OSNR of 14 dB corresponds to a BER of \(10^{-12}\) [18].
was measured across the different fiber types at varying lengths. All OSNR values were on the order of 40 dB, which differ slightly from the calculated value of 51 dB. Again, in all cases the OSNR was more than sufficient to ensure a BER better than $10^{-12}$. These analyses and measurements corroborate that the network switches, transceivers, connectors and fiber optics selected through the modeling process meet the OCB requirements for transmission distance, data rate, link margin, and acceptable power penalties.

B. Electrical

Transmission of DC power through the backbone cable must be examined carefully to minimize potential problems during operation. Modeling of the power distribution is typically accomplished using circuit analysis software programs. For the OCB, a PSpice model was built to examine the complete power transmission path and to provide the means to create various scenarios to pose (and answer) the “what if” questions that might arise with so expandable a network. This model includes sub-models of the node converters, delays, fuses, thermistors, the buoy power supplies, sea water return, and all cabling. Various node combinations were used to simulate a variety of different potential expansions.

Example: Fuses

One possible single point of failure to be avoided is a short circuit occurring in the node’s Medium Voltage Converter (MVC) to the backbone cable. One means of protecting the backbone cable from this is the use of fusing. A fuse is required to melt at a certain current as specified by the fuse vendor’s time-versus-current melting time. The fuse’s arcing or clearing time is dependant on the equivalent L/R time constant dictated by the circuit characteristics. The fuse’s melting time is fairly easy to model by using curve fit models to derive values that follow the time-versus-current curves. However, the clearing or arcing time is more challenging to model and was not included in this simulation. It is important to select a fuse with an adequate DC voltage rating. The fuse under consideration here is a Ferraz Shawmut 4000 volt DC rated 1.5 ampere fuse [19]. AC fuses do not necessarily have a valid DC rating despite some manufacturers’ suggestion to simply de-rate them by half (i.e., 50% below their AC rating). This is because AC voltage has a zero crossing voltage that helps extinguish the arc. The time verses current for the fuse can be approximated by the model depicted in Figure 7.

![Figure 7. Fuse model.](image)

The high voltage power supply (HVPS) in the OCB buoy has an over-current protection circuit. This circuit will latch the power supply off if an over-current greater than 4.6 amperes occurs. This is intended to prevent stresses in the power supply but has the disadvantage that it limits the current that would be necessary to blow the fuse. A simulation using this fuse model was run to investigate the potential of successfully blowing the selected fuse under these conditions. Figure 8 shows a case when a short was applied to node 2. The initial high current spike is caused by the capacitance at the output of the backbone cable being discharged, followed by a lower current which blows the fuse as intended. In this case, the fuse protected the backbone cable. Since arcing time was not included in this model, the turn-off time of the fuse was less than 1 microsecond, causing the voltage transient shown in the figure. This was examined and determined not to be significant (less than a 400 volt transient). However, another simulation yielded different results. In this simulation, a short was applied at the same node but with a slightly different configuration (only a single HVPS at the buoy). The plot in Figure 9 reveals that the fuse did not blow. Instead the power supply latches off and protects the fuse from blowing. Since the fuse model does not include the arcing time and it is possible for the fuse not to blow, relying upon fusing to protect the backbone appears to be risky. This implies that use of fuses should not necessarily be considered a reliable solution for protecting the backbone cabling unless very careful modeling and actual testing of the fuses is performed.
PSpice models were also built and simulations run for numerous cases to reveal potential failures occurring from short circuit voltage transients. These models and their results will be verified through the use of Hardware-in-the-Loop Simulations (HILS). HILS is a form of real-time simulation that uses actual hardware components, providing an effective tool for designing so variable a network as the OCB. Tight development schedules and high burden rates associated with deploying and testing actual hardware of a seafloor network are compelling reasons to consider the additional investment of time and funds to employ HILS. One HILS testbed utilizing actual first article electrical hardware going into the system along with cable simulators is shown in Figure 10. Electrical power HILS were conducted using the redundant Medium Voltage Converter (MVC) to be installed in each node, the HVPS that will be installed in the surface buoy, and cable simulators and a variable load bank as surrogates for the actual submarine cable. Preliminary testing not only confirmed proper operation and functionality of the equipment, particularly under fault conditions such as short circuits, but also provided a means for verifying numerical modeling results.

Other Examples

Figure 8. Plot of the current through the fuse with short applied to the load at Node 2 using two high voltage power supplies.

Figure 9. Short applied at Node 2 using single high voltage power supply where fuse does not blow.
C. Communications

HILSs were conducted to optimize the data throughput and other communication aspects of the OCB. One simulation utilized the Communications Testbed shown in Figure 11. This testbed contains network switches and transceivers that represent four nodes and a surface buoy, utilizing hardware identical to that being built in the deployable system. Optical attenuators added to the fiber jumpers between transceivers simulate the link distances, and circuit breakers on each network switch allow power outages to be simulated to confirm redundancy of the skip paths. This testbed was used to simulate both optical power and data throughput performance.

BER tests were conducted at 100Mbps and 1Gbps data rates using the Communications Testbed. Long term testing over distances of 180 km of HDF-2 fiber at 100Mbps produced a BER of $10^{-12}$ with 99% confidence. Tests run over 198 km of SMF28e+ fiber at 1Gbps produced a BER of $1.28 \times 10^{-12}$ with 99% confidence. Both these fiber types were determined to provide suitable BER for the OCB network, and these BER results were comparable to those estimated from the OSNR calculations and measurements.

RFC 2544 Ethernet benchmark tests were performed to evaluate throughput (performance availability), back-to-back frames (link burstability), frame loss (service integrity) and latency (transmission delay) on the Communications Testbed. A photograph of the test setup is shown in Figure 11. The RFC 2544 tests use standard frame sizes (64, 128, 256, 512, 1024, 1280 and 1518 bytes) in a test matrix comprised of varying time periods. The testbed was modified to conduct these procedures to simulate a number of different potential paths, evaluating different fiber types and varying lengths. Of particular interest in the RFC 2544 test was latency. The plot in Figure 12 shows the latency across varying distances of HDF-2 fiber for the different frame sizes. In all cases, results indicate latency through the network paths are less than 1ms.
Transmit power and receive sensitivity were measured on each transceiver in the testbed using a variable attenuator. The attenuator was set to maximum attenuation and then reduced, while a test computer was used to transmit UDP data (“datagrams”) over the path. At the point where data begins to transmit, the attenuation is increased until the link is extinguished and then decreased again until data is restored. At this point, the attenuation is measured and recorded. The same test is performed with the Rx-Tx path reversed. By doing this, each transceiver is thoroughly evaluated to confirm its reliable operation within the link budget of the communications equipment.

IV. CONCLUSION

A rigorous systems engineering approach that includes system level studies, analysis and theoretical, numerical and physical models of key areas including power distribution and communications is critical for the design and development of undersea networks, ocean observatories and offshore communications backbones. The examples herein illustrate how numerical models and physical models were built to simulate network characteristics and then were verified by benchmarking them against actual hardware. Once validated, these models and simulators represent powerful tools; enabling the OCB designers to consider a limitless number of possible configurations and conditions. This is particularly critical in the design of the OCB, which is a modular and expandable network that will be subjected to a limitless number of potential applications. Once groundtruthed, these numerical and physical models (including HILSs incorporating actual deployable hardware) were used to select and confirm that the optical and communications network equipment and fiber type were optimal for the OCB’s variable configurations, affording ample margin for future expansion. This was demonstrated for optical power margins, dispersion, OSNR, Rx sensitivity and Tx power, BER and RFC2544 parameters for throughput, back-to-back frame testing, frame loss as well as latency. Results indicate that under all its intended applications the OCB will maintain an optical margin greater than 3dB, will not be dispersion limited through rates up to 1 Gbps. nor will OSNR be a limiting factor. The anticipated Quality of Service (QOS) of the network also appears high based upon the measured BER and latency simulations. This extensive investment in modeling, simulation and testing result in high confidence that the OCB seafloor network will perform as intended but, more importantly, they have helped to flush out potential problems that may have otherwise only surfaced after deployment. The power modeling and simulation conducted was essential to the component selection and network optimization and served to identify and mitigate critical single point failures regarding fuses and potential short circuits. The software and hardware modeling described enabled simulations of instrument loading (power and data bandwidth) in a hierarchy of combinations simulating a vast range of possible user applications. Although the capital expenditure (CAPEX) associated with the rigorous process described of this initial design is significant, the potential cost avoidance and savings over the deployment and operation of both the initial and future network’s operational expenditure (OPEX) more than justifies this investment.

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